Article

Thermal Performance of Single-Storey Air-welled Terraced House in Malaysia: A Field Measurement Approach

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Abstract: The provision requirement of 10% openings of the total floor area stated in the Uniform Building by Law 1984 Malaysia has been practiced by designers for building plan submission approval. However, the effectiveness of thermal performance in landed residential buildings, despite the imposition by the by-law, has never been empirically measured and proven. Although terraced houses in Malaysia have dominated 40.9% of the total property transaction in 2019, such mass production with typical designs hardly provides its occupants with thermal comfort due to the static outdoor air condition and lack of external windows, where the conventional ventilation technique does not work well, even for houses with an air well system. Consequently, the occupants need to rely on mechanical cooling, which is a high energy-consuming component contributing to outdoor heat dissipation and therefore urban heat island effect. Thus, encouraging more effective natural ventilation to eliminate excessive heat from the indoor environment is critical. Since most of the research focuses on simulation modelling lacking sufficient empirical validation, this paper drawing on field measurement investigates natural ventilation performance in terraced housing with an air well system. More importantly, the key concern as to what extent the current air well system serving as a ventilator is effective to provide better thermal performance in the single storey terraced house is to be addressed. By adopting an existing single storey air welled terrace house, the existing indoor environmental conditions and thermal performance were monitored and measured using scientific equipment, namely HOBO U12 air temperature and air humidity, the HOBO U12 anemometer and the Delta Ohm HD32.3 Wet Bulb Globe Temperature meter for a six-month duration. The findings show that the air temperature of the air well ranged from 27.48°C to 30.92°C, while the mean relative humidity were from 72.67% to 79.25%. The mean air temperature for a test room (single sided ventilation room) ranged from 28.04°C to 30.92°C with a relative humidity of 70.16% to 76%. These empirical findings are of importance, offering novel policy insights and suggestions to potentially revising the existing building code standard and by laws; since the minimum provision of 10% openings has been revealed to be less effective to provide a desired thermal performance and comfort, mandatory compliance with, and the necessity for, the bylaw requirement should be revisited and further studied.

Keywords: air shaft, solar chimney, air well, field measurement, natural ventilation, tropical climate, terrace house, passive cooling design

1. Introduction

Natural ventilation in a building occurs when the pressure differences generated by wind or buoyancy forces which undertake single or multiple openings in the building envelope. It is an important and significant sustainable building design strategy for human being as one of the basic living environment criteria (Linden, 1999; Kleiven, 2003; Kubota, Chyee and Ahmad, 2009; Tan and Wong, 2014; Han et al., 2018). Following the Malaysia Uniform Building By Law 1984, under the Uniform Building By Law 39, the requirement of minimum 10% of the total floor area of residential and business spaces has to be fulfilled by all the submission to the local authorities as a requirement for approval in order to commence a construction process on the ground. The similar requirement has been stated in the Building & Construction Act of Singapore as well as in other countries, such as Australia and some others Commonwealth Countries. Hence, it is plausible that natural ventilation is important and necessary to be included as a habitable building design strategy under the circumstances that mechanical ventilation system does not provided.

As the standard of living has enhanced, the coziness of residential and working conditions have been recognized to be one of the important factors for occupants' life at present (Han et al., 2018). In Malaysia, terraced houses have a limited amount of exposed building envelope due to the constraint of design layout with adjacency party walls. The constraints have limited the natural ventilation strategy to be applied on the external fenestration. Hence, mechanical ventilation systems have become the choice of occupants in terrace house as substitution to solve the thermal comfort problem. Mechanical ventilation systems require high electricity to run, for instance, in some cities air-conditioning requirements take full capacity of electricity grids (Linden, 1999; Khanal and Lei, 2011). According to Toe and Kubota (2015) final energy use in residential and commercial sectors in Malaysia has been increased more than sevenfold between 1980 and 2007 at a higher rate than total amount of energy demand growth rate based on the Ministry of Energy, Water and Communications Malaysia National Energy Balance 2007 report. In residential buildings, a large portion of electricity consumption was attributed by the air conditioning systems as the ownership of the air-conditioner expanded from approximately 12,000 to 764,000 households from 1970's to 2000's (Malaysia, 2000; Mahlia et al., 2004; Toe and Kubota, 2015).

In general, the mechanical ventilation system has been used to manage air quality and the indoor ventilation rate. An air conditioning system or also known as HVAC system applying the forced ventilation supplies fresh air and regulates the supplied air temperature and humidity for an indoor environment (Han et al., 2017, 2018). The phenomenon of highly dependent of mechanical ventilation system by buildings' occupant has critically depleted natural resources and increased the greenhouse gases. Back to the basic, natural ventilation is still an ideal alternative for residential buildings.

In recent years, the natural ventilation topic has attracted a strong growing interest due to its potential benefits over mechanical ventilation systems in terms of economic, energy consumption and environmental advantages (Khanal and Lei, 2011). There were also some trials to enhance the performance of natural ventilation by using renewable energy, whereas some authors have categorized it as a hybrid ventilation (Han et al., 2018). This has proven that research on natural ventilation is widely explored for the purpose of achieving the reduction of use of air-conditioning systems for the ventilation purpose. An application of natural ventilation to provide thermal comfort is a sustainable approach as the method applied uses renewable energy resources, such as solar energy, and minimizes the usage of energy consumption in buildings (Baharvand, 2014)

The thermal performance of an indoor environment under a hot climatic condition is highly affected by various passive design techniques, for instance: space dimensions, facade colors, fenestration ratio, glazing type; and vertical and horizontal shading devices (Ali Ahmed, 2012). The principle of an air well effect is resulted by the combination of both solar assisted stack ventilation as well as wind driven ventilation. The solar heating causes hot air rises, and due to the light density of the hot air, it escapes from shaft outlets. Meanwhile, the cooler air withdraws into the indoor environment from the fenestrations via the pull effect complemented by the push effect from the outdoor environment (Allocca, Chen and Glicksman, 2003; Tan and Wong, 2014; Han et al., 2018). In the past decades, there were a plenty of research on ventilation shaft configurations and strategies to improve the ventilating system, for instance, the improvement of the solar chimney performance by using different types of glazing, increasing the air gap, width, depth and height of solar chimney, integrating the Trombe wall with a roof solar collector, changing the inclination angle of the solar chimney (Bansal, Mathur and Bhandari, 1994; Bansal et al., 2005; Mathur, Mathur and Anupma, 2006; Chantawong and Khedari, 2018; Serageldin, Abdelrahman and Ookawara, 2018).

Most of the above ventilation strategies studies were mainly using the simulation method, and due to data collection constraints in obtaining real data, only few were validated with field measurement results. However, even though some studies manage to adopt and justify the simulation methodology, which is sufficiently deemed accurate and valid, and some have been conducted, specifically on ventilation shafts focusing on courtyard, solar chimney, and trombe wall at domestic residential buildings in the tropical climate area (Gamage et al., 2017; Nugroho and Ahmad, 2007; Nugroho et al., 2020; Khanal and Lei, 2011; Chung et al., 2015; Khosravi, Fazelpour and Rosen, 2019; Leng et al., 2019; Bachrun et al, 2020; Zhang et al., 2020; Nugroho et al., 2020; Elghamry and Hassan, 2020; Soflaei, Shokouhian and Mofidi Shemirani, 2016), there is still a lack of empirical field measurement research conducted specifically investigating the effectiveness and impact of an air well (as a ventilator), especially in a tropical climate country, such as Malaysia. More precisely, albeit the importance of natural ventilation is emphasised, and it is part of the legal requirement of the Bylaw to provide the minimum percentage of opening (10%), the workability/ practicality and effectiveness of the minimum amount of the opening imposed (i.e., an air well) is still unknown because by far no single empirical research has been carried out in this regard. Since terraced houses are dominant in Malaysia[1] primarily using an air well system, it is therefore vital to understand the current ventilation and thermal performance of the existing room via a field measurement. More importantly, the key concern as to what extent the current air well system serving as a ventilator is effective to provide better thermal performance in the single storey terraced house is to be addressed.

This paper adds value in several ways; it contributes theoretically, methodologically, as well as empirically which hence provides pragmatic policy implications not only to the Malaysian housing architectural and construction fields but also to other parts of the world. Generally, the study investigated the thermal performance of the air shaft of the existing terraced house in Malaysia via a field measurement method. The analysis was discussed based on the results from field measurement results collected from the single storey terraced house with an air well. Based on the literature review, the thermal performance of the air shaft in the existing terraced house has the potential to increase the natural ventilation. The significance of the thermal performance of the air shaft terraced house could be studied extensively in future with the current field measurement results. In this paper, the terminologies of air shaft such as air well and solar chimney were mentioned based on the different context but referring to the same studied tool. Besides, this study is in line with Sustainable Development Goals (SDG), as governments and all the agencies from profit or non-profit organisations are committed to achieving the goals in order to reduce the urban energy consumption

1 In Malaysia, residential units dominate the overall property record, especially terraced house. According to the Summary of Property Market Report 2019, under the section of Overall Performance Malaysia's Property Stock, Planned Supply and Incoming Supply, the residential types property recorded the highest figure as 5,727,814 units followed by shops record 526,079 units and service apartments 253,056 units; out of the 5 million over units of residential type were built, terraced house comprises of 40.9% or 85,669 units compared to other residential types such as high-rise, vacant plot, semi-detach, detach and others. (NAPIC, 2019).

to 80% of global energy. Since a building has accounted for 40% of the total energy consumption, the design of energy efficient building in passive design (natural ventilation) could make a significant contribution to meet SDGs 11 and SDGs 13 (Di Foggia, 2018). Hence, it is critically important that the passive design of a terraced house becomes a focal point in order to achieve the SDG target by 2030.

The remainder of the paper is structured as follows. First it resumes with a literature review that focuses on effectiveness of ventilation shaft and its' empirical study in thermal performance and second the methodology emphasizing the empirical field measurement on the selected case study on single storey terraced house, and lastly followed by the interpretation and discussions of empirical results on the thermal performance of air well and test room within the terrace house.

2. 2. Background Study of Terrace House and Ventilation Strategies

2.1. Background Study of Terrace House in Malaysia

Malaysia terraced house evolved from the Malacca townhouses, which can be dated back to the colonial period (seventeenth to nineteenth century). The earliest types of townhouses were built during the Dutch occupation. However, townhouse planning and design was only introduced during the British colonial period, hence the influence of Western design principles in the layout (Rahim and Hashim, 2012). Hence, the terraced house of the early 1970s was no longer similar to the Malacca townhouse or shophouses, as the revolution by the British has significantly affected the housing scenarios in Malaysia.

According to Uniform Building by-Laws 1984, the definition of terraced house can be described as follows

> *The building for dwellers which has been designed as a single unit linked-house known as 'terrace' that consists of no less than three such buildings.*
>
> (Uniform Building by-Laws 1984)

In Malaysia, a typical single terraced house unit consists of a built-up area of 650-700 square feet with 6.5m of front width, and 11m in length. The terraced house is usually sandwiched by two sides of party walls with minimum front and rear width exposed to the external environment. Terraced house usually has a narrow frontage and the party walls are shared with the adjacent houses (Azzmi, Norazura Mizal and Jamaludin, Nazhatulzalkis, 2014) Other than that, some literature stated that a terraced house could be referred as any residential building which is designed as a single dwelling unit, and forming part of a terrace of not less than three such residential buildings (Malaysia, 1984).

2.1.1 Layout Study and Fenestration of Terrace Housing in Malaysia

The room layout of the terraced housing lot determines the location of living area, bedroom and kitchen. The internal partition walls within the narrow terrace housing layout define the spaces. Other than the main spaces of terraced houses, the sub-factors which do not cause significant design issues for internal layout are entrance of driveway, culverts, fencing, back lane, position of manhole and other facilities or amenities (Nugroho, 2007b).

In general, the common spatial characteristics of the internal layout of terraced housing do not change much. Most of the single storey terraced housing has a minimum of two to three bedrooms and bathrooms, a unit of utility room, an open space accommodating living and dining space, as well as a kitchen at the rear side of the terraced house. A car porch is provided at the frontage of the house which could accommodate one to two units of car (Figure 1). (Erdayu Os'hara Omar et al., 2010)

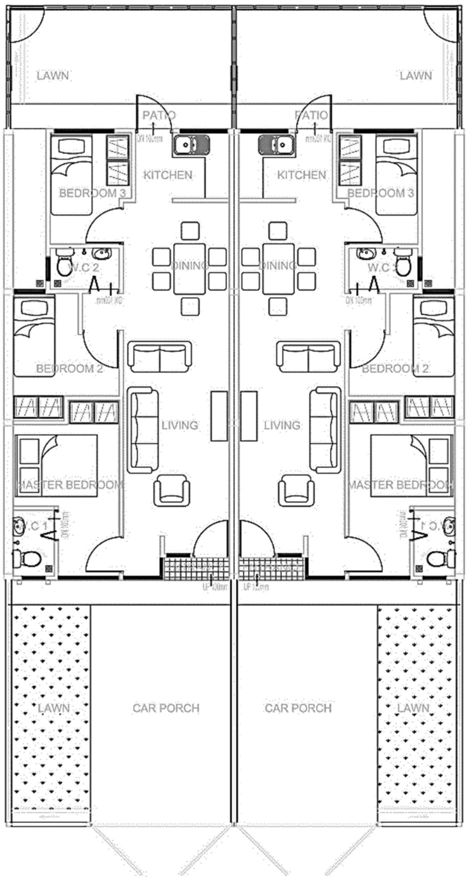

Figure 1. Typical internal layout of single storey terraced housing

An air well is a typical feature in a traditional shophouses. It provides natural daylight and ventilation to the internal space. It is a vertical shaft or opening penetrated from roof to floor, connecting the internal space to the open sky. However, the size of an air well opening is huge which would lead to security issues. Thus, the feature has been replaced with atrium or elevated clerestory in modern terraced houses. In order to improve the thermal performance in terraces houses, the air well has been modified into a solar chimney following the Malaysia building regulation, thus keeping the house secured. Most of the time, the air well in a modern terraced housing is located in the intermediate room, utility or bathroom as shown in Figure 2 (Nugroho, 2007b). It is the most versatile feature of traditional row houses, where the number of air wells may range from one to three or four based on the length of the house (Rajeh, 1989).

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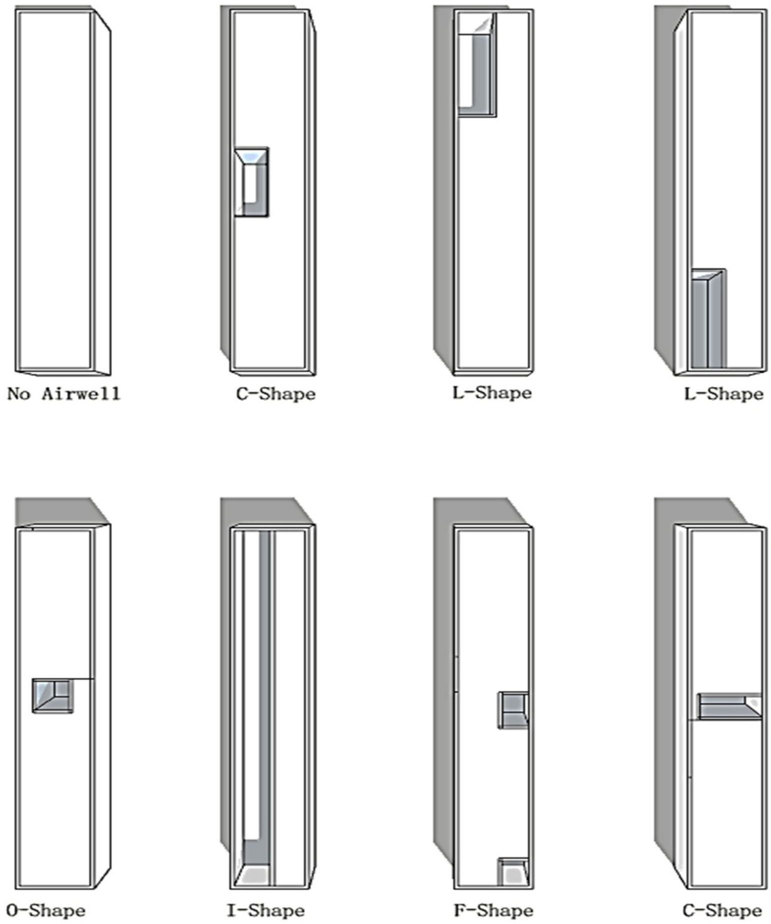

Figure 2. Possible position of air-well of single storey terrace house (Nugroho, 2007b)

Other than layout of terrace housing, one of the important features of the terrace housing is opening design. House features and components which can induce and generate natural ventilation are window opening, air-well, door opening, fenestration wall, and ventilation louvres or panels (Rajeh, 1989). Improper design of the features leads to thermal and visual discomfort to the occupants which would cause the high cooling load of mechanical ventilation system to solve the thermal issues.

According to (Gurupiah, 1999), the basic window size opening is ranged between 1.5m to 2m wide and 1m in height (as shown in Figure 3). The size of window openings is usually calculated based on ratio of total floor area of the specific space, and the researcher found that most terraced housing window met the minimum requirement as stated by UBBL, which is minimum 10% of overall floor area. The sill height of most windows is 1m, which is the standard height for basic window in most Malaysia terraced housing. The airflow rate regulated by openings of window/door is based on few factors, which are façade shape, indoor and outdoor thermal environment, surrounding terrains, size and shape of openings, adjacent buildings and rooms as well as room characteristics. Those factors are considered as transient phenomenon which could lead to effectiveness of the openings to induce ventilation (Fracastoro et al., 2002). In this study, the standard window would be modified for higher airflow rate complemented by the enhanced solar chimney.

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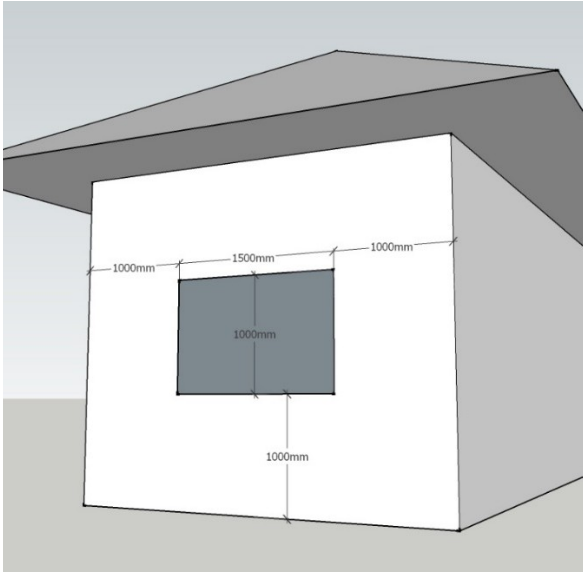

Figure 3. Possible typical window sizes and position of typical single storey terrace house

2.1.2 Building Regulation and Standard

There are several guidelines and regulations focusing on terraced houses in Malaysia. The legislations of policies and programmes planning are executed by the Ministry of Housing and local government in Malaysia. Under the Federal Constitution, Part IV stated that the housing sector is listed under the authority of state government. Hence, local government was formed under aegis of Ministry of Housing in order to serve the local community in the administration and legislation aspects while supplying services and facilities to the local government to establish their own administration system. Other than that, the National Housing Department was formed under the Ministry of Housing and Local Government in order to advise and consult state government, especially in the issues of affordable housing projects (Saji, 2012).

There are several acts and by-laws which are related to planning and design of terraced houses, namely Local Government Act 1976 (Act 171) for Peninsular Malaysia or Local Government Ordinance 1961 (Sarawak No.11 of 1996) for Sarawak or Local Authority Ordinance 1996 (Chapter 20) for Local Government in Sabah, Road, Drainage and Building Act 1974 (Act 133), Town and Country Planning Act 1974 (Act 172), Uniform Building By-Laws 1984 (UBBL), and so forth. The function of acts and by-laws is to control the quality of buildings and protect public health, safety and general welfare.

The current Uniform Building By-Laws 1984 (As at 1st November 2013) is one of the intended building codes that is applied by architects and building designers prior to the building plan submission. One of the significant sections which is related to natural ventilation is specified in Clause 39 (1) under Part III (Space, Light and Ventilation) in UBBL. It designates minimum requirements for openings in wall for natural daylighting and ventilation as follow:

"Every room designed, adapted or used for residential, business or other purposes except hospitals and schools shall be provided with natural lighting and natural ventilation by means of one or more windows having a total area of not less than 10% of the clear floor area of such room and shall have openings capable of allowing a free uninterrupted passage of air of not less than 5% of such floor area." –Clause 39(1)

and

"Every water-closet, latrine, urinal or bathroom shall be provided with natural lighting and natural ventilation by means of one or more openings having a total area of not less than 0.2 square

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meter per water-closet, urinal latrine or bathroom and such openings shall be capable of allowing a free uninterrupted passage of air." – Clause 39(4)

Other than that, UBBL has included air well guidelines in Clause 40 as follow:

" (1)(a) The minimum size of each air-well where provided in all buildings shall be as follows:

For buildings up to 2 storeys in height, 7 square metres;

For buildings up to 4 storeys in height, 9 square metres;

For buildings up to 6 storeys in height, 11 square metres;

For buildings up to 8 storeys in height, 13 square metres;

For buildings more than 8 storeys in height, 15 square metres;

(b) The minimum width of such air-wells in any direction shall be 2.5 metres

(2)(a) The minimum size of each air-well for lavatories, water-closets and bathrooms shall be as follows:

For buildings up to 2 storeys in height, 3.5 square metres;

For buildings up to 4 storeys in height, 4 square metres;

For buildings up to 6 storeys in height, 4.5 square metres;

For buildings up to 8 storeys in height, 5 square metres;

For buildings more than 8 storeys in height, 5.5 square metres;

(b) The minimum width of such air-wells in any direction shall be 2 metres."

In general, UBBL designates minimum requirements for openings on wall to induce natural ventilation and daylighting. The purpose of opening requirements is to enhance natural ventilation in enclosed space and ensure that the windows or openings protect the indoor and occupants from direct sun and rain. The requirements stated in UBBL are not specified in terms of dimension, design or position in order to allow the flexibility and creativity of architects to be played in design.

Other than UBBL, Malaysian Standard MS1525:2007 (Malaysia, 2007)- Code of Practice on Energy Efficiency and Use of Renewable Energy for Non-Residential Buildings, Malaysian Standard MS2680:2017 (Malaysia, 2017) – Code of Practice on Energy Efficiency and Use of Renewable Energy for Residential Buildings, has further mentioned about the thermal comfort and visual comfort guidelines, building design and energy efficiency guidelines. The standard could be complemented with the UBBL to be applied as design reference for architects.

2.2 Ventilation Strategies

Ventilation and thermal performance play important roles in domestic building designs, especially in residential buildings. In the previous section of literature review, ventilation strategies of naturally ventilated terraced houses were discussed. In general, two types of ventilation strategies were discussed by researchers, which are cross ventilation and single-sided ventilation (Allocca et al., 2003; Stabat et al., 2012b). (Mohit and Mahfoud, 2015) have carried out a survey on Malaysian preferences on residential types. He found out that terraced house, especially double storey terraced house, could not satisfy the occupants' needs for thermal and natural lighting comfort. Thus, most of the occupants go for mechanical ventilation system to solve the ventilation problem (Tetsu Kubota et al., 2011).

2.2.1 Previous Study on Air Shaft

(Nugroho *et al.*, 2007) have carried out the preliminary study about thermal comfort in single storey terraced house in Malaysia context. The findings of the study show that the design of the single storey house in Malaysia is not effective in providing the thermal comfort through natural ventilation. In their study, the field measurement to investigate the thermal comfort and thermal performance in the test room is insufficient to achieve thermal comfort. The single-sided ventilation system in the test room (master bedroom of the terraced house) reduces the effectiveness of the ventilation in the room. Furthermore, the paper has stated about the proposed solar chimney to induce natural ventilation.

The study supports the use of solar chimney as a passive cooling tool which can improve the indoor thermal condition in hot humid climate. Other than that, (Leng *et al.*, 2015; Punyasompun.S *et al.*, 2009; Tan and Wong, 2012) support the application of solar chimney in tropical climate. The findings show that the application of ventilation shaft in buildings could enhance the natural ventilation. (Agung Murti Nugroho and Ahmad, 2014) have carried out an experimental study on a single storey terraced house in Malang, Indonesia with solar chimney cum vertical landscape. The findings show that the mean air temperature of the indoor environment is within the acceptable comfort range. The combination of both solar chimney and vertical landscape could reduce the use of mechanical ventilation system in domestic buildings, as well as provide natural passive cooling effect to the indoor environment.

There are plenty of ways to resolve the problem of thermal comfort in terraced houses. One of the practical ways to generate natural ventilation in terraced houses is modified air well to solar chimney (Nugroho, 2007b). In hot humid climate, solar chimney can function as both thermal comfort and natural daylight tool for the terraced house. Hence, the following sections would further explore the possibilities of using the solar chimney for ventilation and also the variables in order to improve the thermal and ventilation performance in Malaysian terraced houses.

The solar chimney (SC) concept has been one of the widely applied natural ventilation tool for several decades, especially in domestic buildings. The function of solar chimney has been applied to buildings in order to induce the air movement via air pressure and air temperature gradient from the inlet of building and pass through the occupied zone. The cool air replaced the hot air via air convection and the hot air is released through the solar chimney outlet due to the temperature differences (Punyasompun.S *et al.*, 2009). The basic solar chimney composed of glass, enclosed extruded concrete wall, absorber and air gap. The concept of applying the solar heat gain to generate passive cooling has been getting more attention by designers and researchers, especially in the hot climate regions. There are various literature and research efforts published in order to refine solar chimney and specify for each of the climatic condition, the building type, as well as the controlling factors such as inlet and outlet configurations, materials, room depth, forms and so forth.

Wei *et al.* (2011) have carried out a series of connected solar chimney on roof with inclination angle as well as a vertical section facing south wall. In the findings, the researchers stated that the optimal ratio of length to width was found to be 12:1 while the optimal inclination angle to be 4° via mathematical modelling. In another case, Amori and Mohammed (2012) have studied the effects of integrating the phase change material (paraffin) with solar chimney on its thermal behaviour. Computational Fluid Dynamic (CFD) analysis was used to predict the thermal performance as well as the two-dimensional fluid flow. The findings show that the phase change material extended the ventilation hours during night time by discharging the storage energy from 13:00hr to 22:00hr for 9 hours. N.K.Bansal *et al.* (1993) have developed a numerical model for solar chimney in order to enhance the effect of thermally induced ventilation in buildings. Sizes of the openings of solar chimney and the values of the discharge coefficient were chosen as the variables of the experiment.

The findings show that air velocity of 140 m^3/hr to 330m^3/hr were induced by solar radiation of 200W/m^2 and 1000W/m^2 respectively with 2.25m^2 solar collector areas in the solar chimney. Kasaeian et al. (2014b) have constructed a fundamental numerical model for solar chimney in Tehran. The results findings show that the optimum solar chimney configuration for Tehran should be as follow: collector inlet of 6cm, solar chimney height of 3m, and solar chimney diameter of 10cm where the velocity of air could speed up to 4 to 25% in different cases. The solar chimney height and diameter are critical physical variables to determine the efficiency of solar chimney. Mathur et al. (2006b) have investigated the effects of solar chimney's depth and the inlet height on air change

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rate. The results show that the air change rate increased with the depth of solar chimney, and is in direct proportion to the solar irradiance. Chungloo and Limmeechokchai (2007) have investigated the timber structure room. The research study examined the solar chimney effect as well as wetted roof. Results show that the timber material caused the room temperature to drop by 1.0 to 1.3°C during hot afternoons.

3. Methodology

The analyzed measured data for this paper was taken at year 2013 to 2014. However, regardless of the time of measurement, the significance of the data is to evaluate the effectiveness of the air well in terraced housing as thermal performance moderating tool. Furthermore, the measured data is valid as the deviation range of the air temperature is insignificant and consistent. Literature has supported the fact that very slight change in variation of average air temperature throughout 10 years in Kuching with increment of 0.39°C from 2005 to 2015 (Rostam Afshar, 2018). It is also clear that through the 30 years (2005-2040) forecasts study, the air temperature rises linearly within the range of 26°C to 28.5°C. According to the ten years' climatic data of Kuching, Sarawak from 2006 to 2019 recorded by Malaysia Meteorological Centre, the average annual outdoor air temperature ranged from 26.2°C to 27.3°C while the annual mean maximum air temperature ranged from 31.3°C to 32.5°C. In the other hand, the annual mean minimum air temperature ranged from 22.9°C to 23.8°C while the average wind speed ranged from 5.9m/s to 7m/s. The deviation of the maximum and minimum for the average annual temperature from 2006 to 2019 is 4.03°C while the deviation of the max and min for the annual average max temperature throughout the years is 3.69°C (as shown in Figure 4)

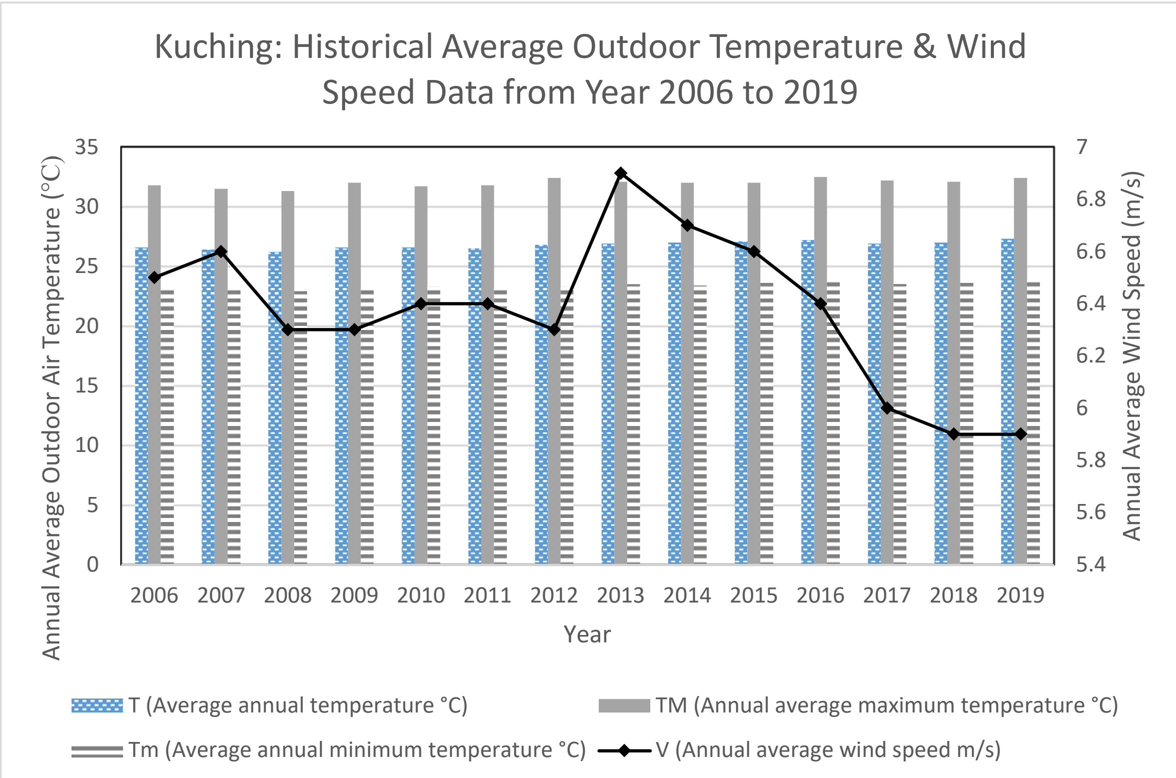


Figure 4. The historical data on annual average outdoor air temperature and wind speed in Kuching from 2006 to 2019

3.1 *Climate Condition of Malaysia*

Malaysia, one of the South-East Asian countries, is located in a tropical region close to the equator. In geographical aspect, it consists of two distinct regions separated by the South China Sea. The coordinate of the country lies between 1° and 7° of North latitude, and 100° to 119° East longitude.

As a tropical climate country, high temperatures and relative humidity with light and variable wind conditions, as well as long hours of sunshine throughout the year with heavy rainfall, and overcast sky along the year, have become the characteristics of Malaysia climate (Bakar, 2002; Makaremi *et al.*, 2012). This section reviews Malaysia climatic condition prior to the climatic analysis of this case study.

3.2 Analysis of Climatic Data at Kuching, Sarawak, East Malaysia

Kuching is the capital city of Sarawak, located at the south of Sarawak state, East Malaysia. The data set analysis of this section is based on the measurement from Kuching meteorological station with the coordinates of 1.467° North and 110.317° East located at Kuching Airport, Sarawak. Weather analytics is a weather data service provider incorporated with the local meteorological centre and the provided data has been validated (Weather Analytics, 2013).

3.2.1 Wind Climate

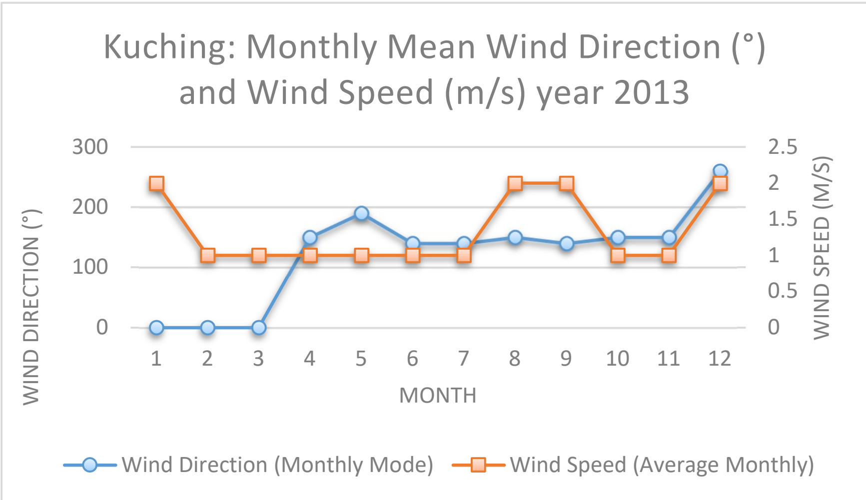


Figure 5. The frequency of wind direction and monthly mean wind speed of year 2013 in Kuching, Sarawak. (Source: Kuching Meteorological Station)

Figure 5 shows the frequency of wind direction and monthly mean wind velocity in Kuching. From the record, the wind velocity falls around 1 m/s most of the time throughout the year 2013 and the prevailing wind direction mostly from south-eastery direction. According to the data obtained from Malaysia meteorological department, Kuching receives winds from all the directions in different time of the year. Located at the intermediate location of the Monsoon pathway, Kuching receives northerly wind that prevails from November to April while the southerly wind prevails from May to September. Both of the dominant prevailing winds are affected by the Northeast and Southwest Monsoon season which pass by Malaysia from November to March and May to September respectively. Figure 6 shows the wind rose for Kuching, Sarawak which indicates the frequency of the wind direction. From December to end of March, the wind blows from west to north direction while during April to November, the southerly wind is the most dominant direction which happened most frequent throughout year 2013.

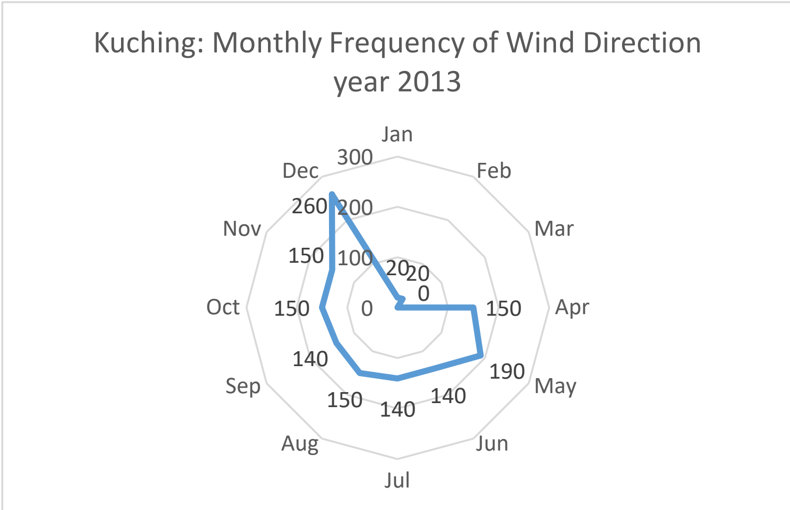


Figure 6. Wind rose in Kuching, Sarawak for year 2013 (Source: Kuching Meteorological Station)

The average monthly wind speed ranged from 0.45m/s to 5.2m/s according to Figure 7 while average hourly wind speed ranged from 0.98m/s to 2.02m/s (Figure 7). The highest wind speed occurred in August with the value of 11.3m/s while the lowest is recorded at 0 m/s (measured 12 meters above ground level). From the diagrams above, the wind direction and wind speed fluctuated throughout the year. The inconsistent wind speed would be one of the factors affecting thermal comfort of the terraced house occupants. The mean air speed of Northeast Monsoon season was slightly higher compared to Southwest Monsoon period except August and September. This could be due to the occasional weather phenomenon. The wind velocity and wind direction study are important as the average data indicated the overall wind flow in microclimatic context.

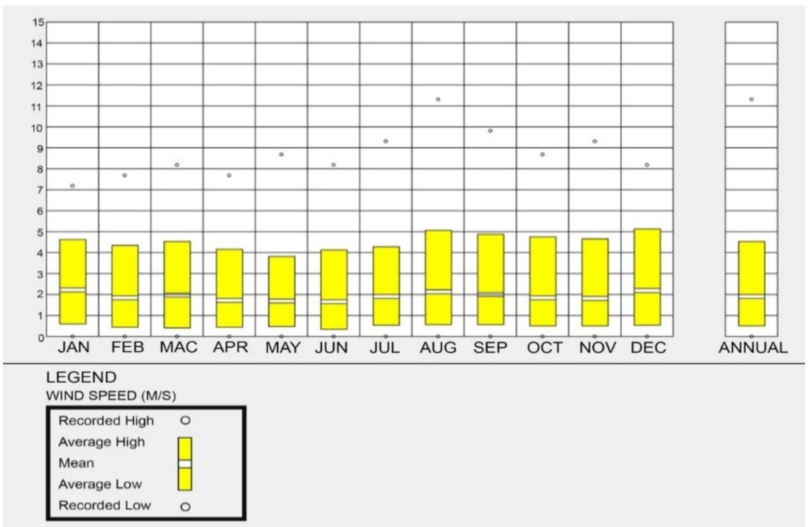


Figure 7. Comparison of the monthly wind speed year 2013 (Source: Kuching Meteorological Station)

3.2.2 Solar Radiation

The monthly solar radiation for Malaysia is approximately around 4.21kWh/m² to 5.56kWh/m² in total and it increased during the Northeast monsoon season and decreased during the Southwest monsoon season (Mekhilef, 2010; Sarawak Energy, 2013). According to recorded data by Haris (2010) quoted by Mekhilef (2010), yearly average solar radiation of Kuching is the lowest among other cities in Malaysia, which is 1470Wh/m² while the highest value recorded as 1900Wh/m² at Kota Kinabalu, 1809Wh/m² at Bayan Lepas and 1785Wh/m² at George Town. From Figure 8, the highest average value recorded as 1271.18Wh/m², which happened in June 2013 while the max value of solar radiation happened in March and April with the value of 2692Wh/m². Compared to the yearly average solar radiation, the highest mean solar radiation of year 2013 is 13.52% lower.

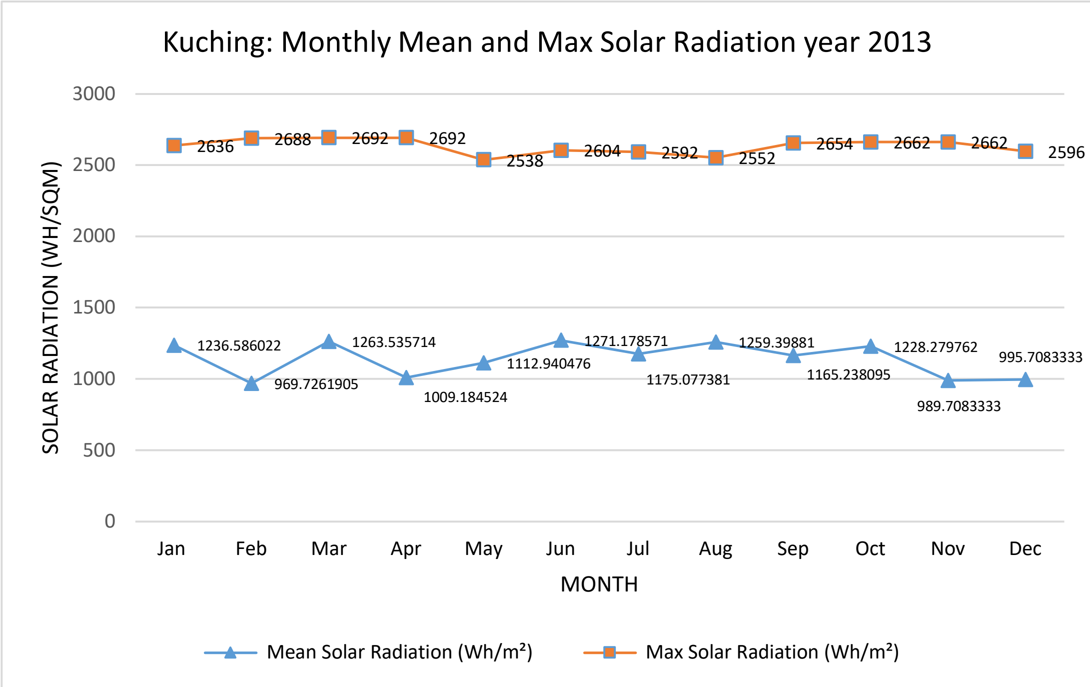
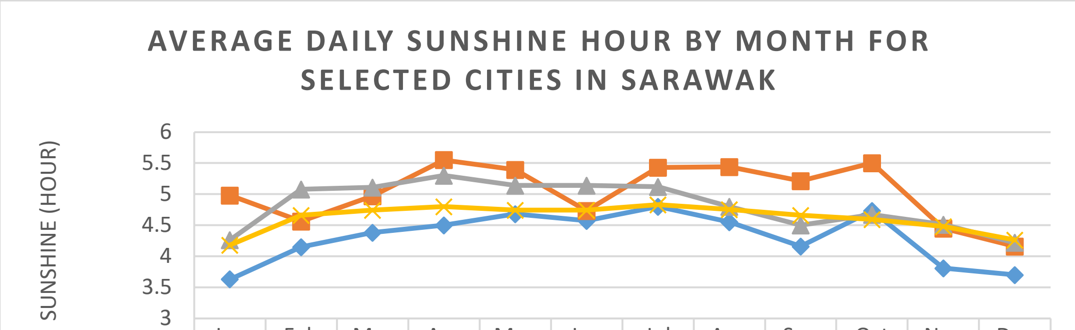


Figure 8. Comparison of monthly mean and max solar radiation (2013) (Source: Kuching meteorological station

Other than that, compared to other cities, Kuching has the lowest average daily sunshine hour (Figure 9) compared to other cities like Miri, Kapit and Sibu. The longest sunshine hour is 4.73 hour falls in October. Both low solar radiation and short hours of sunshine are due to heavy cloud cover which cut off the sunlight penetration to the ground level and seasonal wind factors which caused rainy clouds to form often.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kuching	3.63	4.15	4.38	4.5	4.68	4.57	4.8	4.55	4.16	4.73	3.81	3.7
Miri	4.98	4.56	4.97	5.55	5.39	4.73	5.43	5.44	5.21	5.5	4.45	4.16
Sibu	4.26	5.08	5.11	5.3	5.14	5.14	5.12	4.8	4.5	4.67	4.51	4.22
Kapit	4.18	4.66	4.74	4.8	4.74	4.74	4.83	4.75	4.66	4.59	4.48	4.26

Figure 9. Average daily sunshine hour by month for selected cities in Sarawak. (Sarawak Energy, 2013)

The microclimatic study in Kuching is important before the field measurement and study on ventilation shaft has being begun, the local climate study verified the maximum and minimum ranges of climatic characteristic of the studied area, which set as a benchmark and regulatory range for the output of the air well study. Comparative analysis for the field measurement and microclimatic data determines the thermal performance of the indoor environment of case study building.

3.2. Selection of Case Study House

In order to study the thermal performance of single storey terraced house, a case study house with air well has been selected. The selection of the terraced house type is based on the classification data of terraced house. Classification of terraced house types in Malaysia was sorted as shown in Figure 10 (Toe, 2008). The sample of the classified terraced houses in Malaysia ranged from the earliest modern terraced houses to the new terraced houses of 2012-2016. Out of 219 floor plans, 1% of the designs are from the 1960s, 21% are from the 1970s, 8% are from the 1980s, 17% are from the 1990s and 53% of the designs are from the year 2000 onwards. The classification was focused on the internal layout and total floor area (gross floor area) of collected floor plans. Figure 10 shows the four types of single storey terraced houses and five types of double story terraced houses layout plan and its classification (Toe, 2008) . From the classification chart (Figure 10), the case study house in this research study was classified as typical layout group with total floor area ranging from 85-90m². Thus, the selected terraced house could represent the typical unit in Malaysia as a case study building for stack ventilation study in a typical single storey terraced house (Leng Pau Chung, 2016).

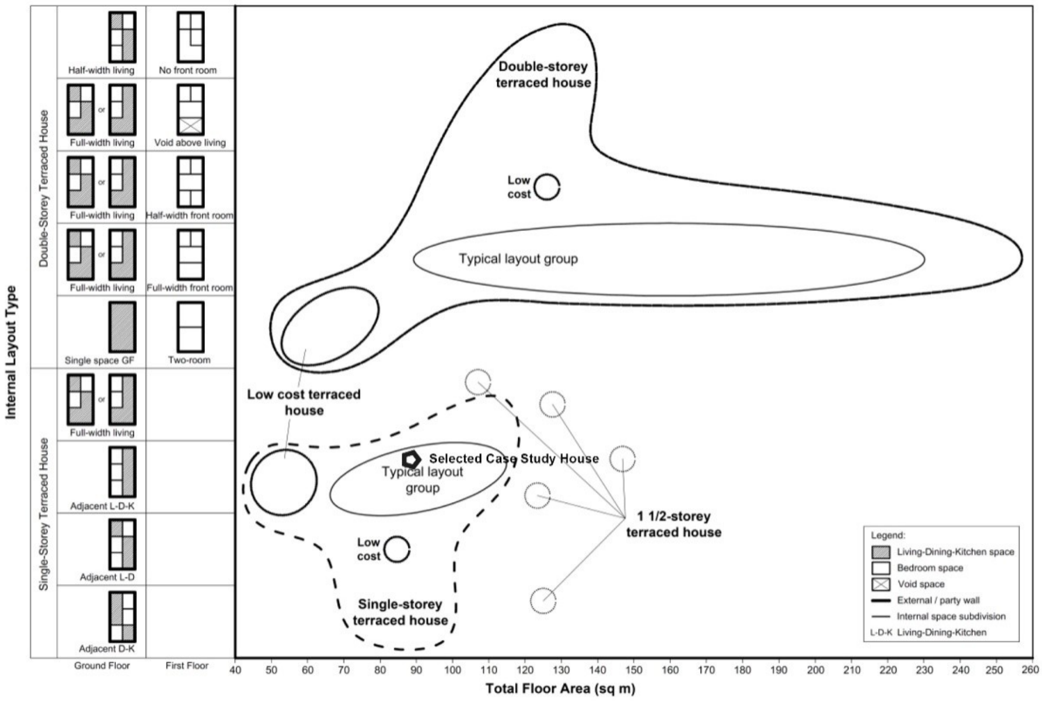


Figure 10. Classification of typical Malaysian terraced houses by internal layout (Toe, 2008)

3.2. Selection of Case Study House

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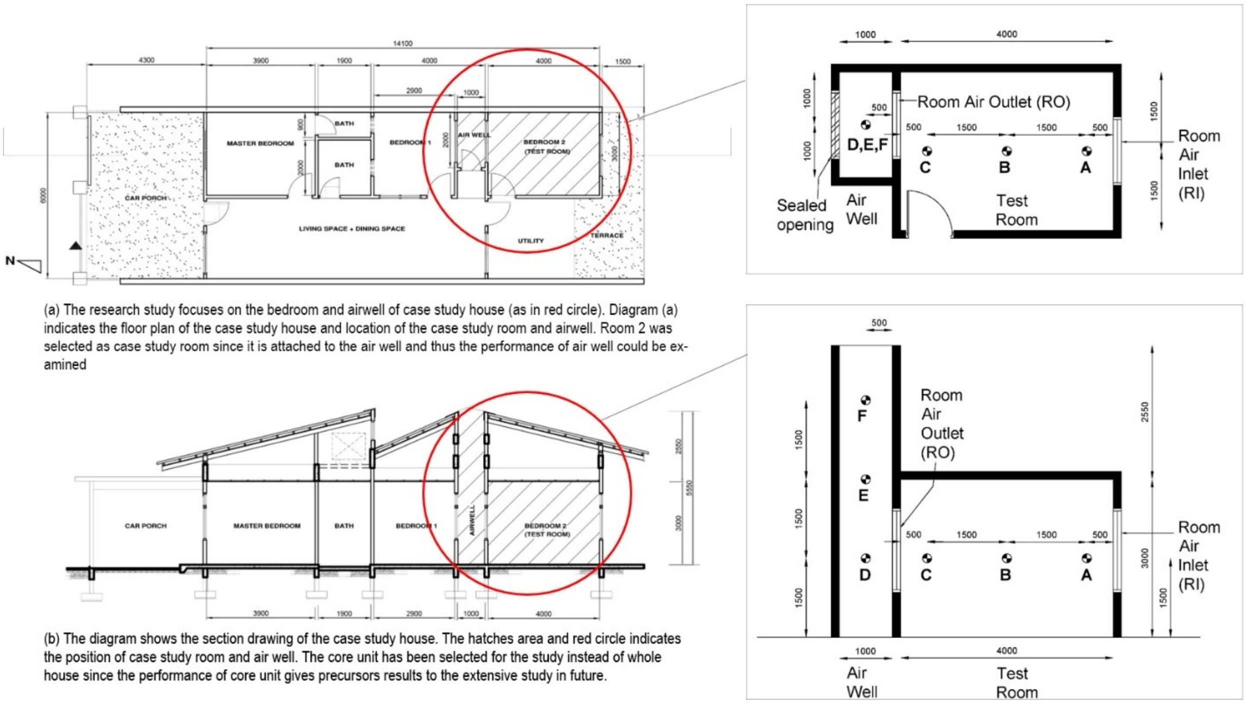
In this study, the objectives of the research were to investigate the current thermal performance of the typical single storey terraced house in Malaysia. The dimensions of the study model were taken from the case study house in 1:1 scale. This was done to understand the thermal performance of the existing room with single sided ventilation, which is experienced by enclosed spaces in terraced house in Malaysia. Other than that, the field measurement in selected terraced house were to



(a) The research study focuses on the bedroom and airwell of case study house (as in red circle). Diagram (a) indicates the floor plan of the case study house and location of the case study room and airwell. Room 2 was selected as case study room since it is attached to the air well and thus the performance of air well could be examined

(b) The diagram shows the section drawing of the case study house. The hatches area and red circle indicates the position of case study room and air well. The core unit has been selected for the study instead of whole house since the performance of core unit gives precursors results to the extensive study in future.

Figure 11. Field measurement/ case study house floor plan (a) and section (b). The hatched areas in red circle indicate the focus area in this research study (simulation)

understand the problems faced by today's terraced house in Malaysia and evaluate the current thermal performance of the house and the outdoor weather conditions. In order to quantify the facts about thermal performance of the single storey terraced house, a case study house located 5.65km to the west of the city of Kuching, Sarawak, East Malaysia was selected for field measurement. (Figure 12). In particular, the indoor thermal condition was evaluated to understand the thermal comfort of occupants. In short, the field measurement was carried out in order to understand the few existing conditions of the typical single storey terraced house in Malaysia:

- Outdoor weather condition in Malaysia
- Thermal performance of room with single-sided opening
- Thermal performance of the room attached to existing air well
- Thermal performance of air well

Based on the case study house model as shown in Figure 11(a) and (b), the dimension of the air well and test room (bedroom 2) were modelled. The house frontage faced North orientation, sandwiched by two party walls on both sides. The total walled up floor area of the house was 84.6m^2 with elongated length 14.1m and width 6m. There were three bedrooms in the house. Bedroom 1 and Bedroom 2 were attached to the air well while the Master Bedroom was a single-sided opening room facing north orientation. In this scenario, Bedroom 2, with total floor area 12m^2 and ceiling height 3m was selected as the test room since its end wall was attached to the air well while opposite wall openings faced the external environment. The study focused on the test room and air well only (as shown in Figure 11(b))

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Figure 12. The highlighted area indicated the location of case study house – Taman Yen Yen, Jalan Matang, Kuching, which is 5.65km away from Kuching city (Image courtesy from Google Map)

The floor-to-ceiling height of the house was 3.0m. The measurement instruments used are listed in Table 1. All measurements were auto-logged at 15 minutes' intervals. The field measurement was carried out from 3 January to 29 June at outdoor environment of the case study house, air well, test room (between air well and external) and bedroom 1 (intermediate room attached to air well).

Table 1. Description of measurement instruments used in field measurement

Space	Data Type	Equipment	Description
Bedroom 2 (test room)	Air temperature Relative humidity Globe temperature Air velocity	Delta Ohm HD32.3 PMV en PPD (Figure 16)	Purpose: to understand current thermal performance of residential room in Malaysia
Bedroom 1	Air temperature Relative humidity Air velocity	HOBOware U12 air temperature and relative humidity data logger (Figure 14) & HOBOware U12 air velocity data logger (Figure 15)	Purpose: to investigate the thermal performance of intermediate room with air well
Air well	Air temperature Relative humidity Air velocity	HOBOware U12 air temperature and relative humidity data logger (Figure 14) & HOBOware U12 air velocity data logger (Figure 15)	Purpose: to investigate the thermal performance of air well
Outdoor	Air temperature Relative humidity Solar radiation Wind velocity Wind direction	HOBOware U30 weather station (Figure 13)	Purpose: results of measurement were taken as controlling factor and compare with the thermal performance of indoor environment.

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Figure 13. Outdoor field measurement setup (HOBO U30 outdoor weather data logger)

Figure 14. HOBO U12 Data logger to measure the air temperature and air humidity

Figure 15. HOBO U12 air velocity unit to measure the indoor air speed.

Figure 16. DELTA OHM HD32.3 PMV & PPD unit to measure indoor air temperature, humidity, air velocity and globe temperature

4. Results and Findings

4.1 Performance of Typical Single Storey Terraced House in Malaysia: Field Measurement at Case Study House in Kuching, Sarawak

The field measurement was carried out from 3 January to 29 June (178 days) at a single storey terraced house in Kuching, Sarawak, Malaysia. A 3m x 3m bedroom with external window and opposite wall attached to an air well was installed with experimental instruments. The measured data including air temperature, air humidity, indoor air velocity, and radiant heat temperature. However, the focus parameters in this research are air temperature and indoor air velocity. This section will discuss about the overall field measurement results (measured outdoor macroclimatic data, test room field measurement results, and existing air well air temperature) and followed by results of selected days (hottest and coldest days throughout the measurement period).

4.1.1 Selected hot days (10 to 24 June 2014) [>27.88°C]

Selected hot days throughout the measurement period were chosen based on the max mean air temperature. According to the data, 10 to 24 June 2014 marked the hottest week throughout the 2nd quarter of 2014. The average air temperature was 27.88ºC hence the selected week is above average air temperature throughout the field measurement. The hot days happened from May to June, which was around South West Monsoon season. The hottest air temperature obtained throughout the field measurement was 42.99ºC on 19 June at 17:00. The mean air temperature for the selected days ranged from 27.81ºC on 13 June to 33.55ºC on 19 June 2014. The average deviation of the mean air temperature from field measurement and meteorological data for the selected days is 2.074ºC.

According to the meteorological data and measured data during the hot period (10 June to 24 June 2014), the minimum temperature difference was 0.51ºC on 13 June 2014 while the maximum temperature deviation was 3.14ºC on 19 June 2014. The minimum difference of 1.84% and maximum difference of 9.35% between both measured and meteorological data shows the differences are insignificant for extreme hot days. On the other hand, the average relative humidity for the selected hot period was marked as 91.41%. The relative humidity was inversely proportional to the air temperature. The highest mean air temperature day (19 June 2014) was recorded as the lowest mean relative humidity day with the value of 66.24% while the lowest mean air temperature day (13 June 2014) was marked as the highest mean relative humidity day with the value of 86.34% throughout the selected hot period. In order to understand the temperature variation of hot day, 19 June 2014 is selected to be analyzed.

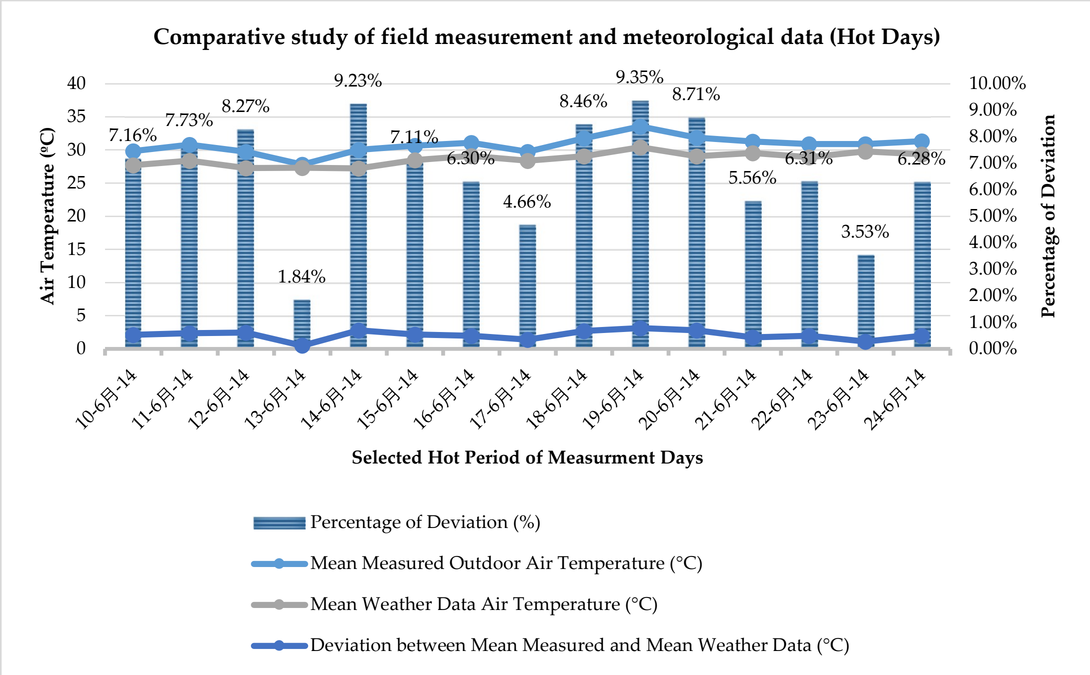


Figure 17 Comparative study of field measurement and meteorological data for selected hot days (10 June to 24 June 2014) throughout the study period.

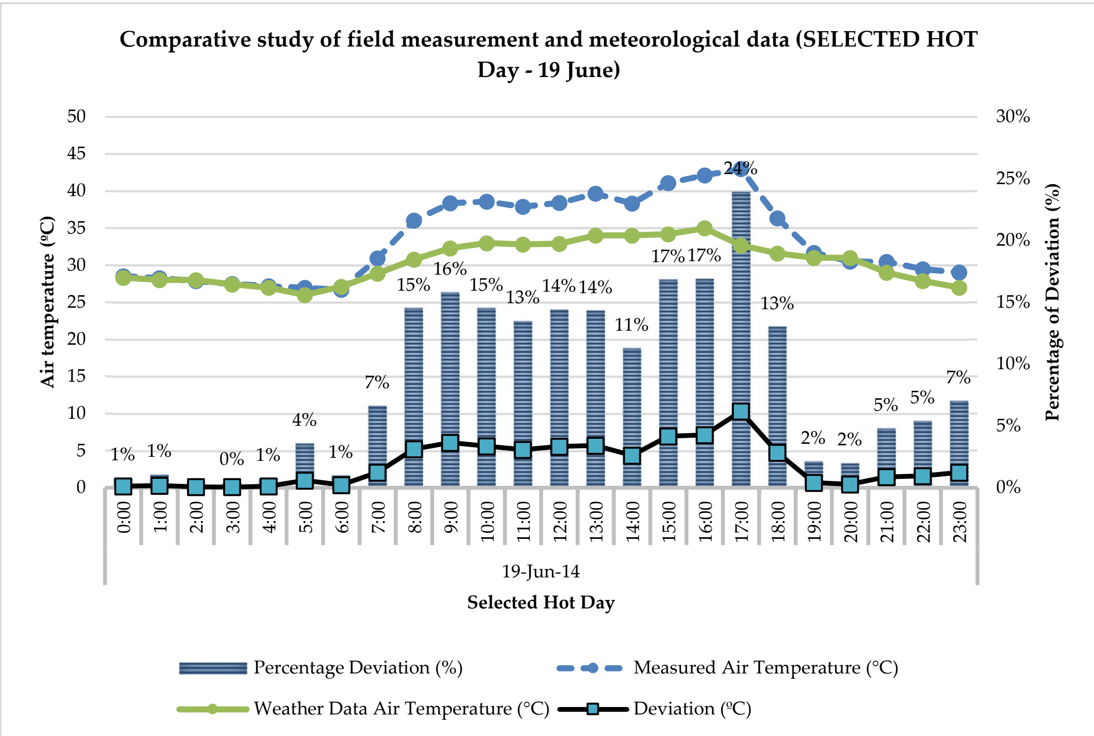


Figure 18 Comparative study of field measurement and meteorological data for selected hot day (19 June 2014) throughout the study period.

According to Figure 18, the selected hot day was the hottest day throughout the study period with the highest air temperature of 42.99ºC at 5:00pm. Even though the temperature differences between the two sets of data at the hottest hour was recorded as 24%, which is the highest deviation, the variation pattern for both sets of data fluctuated at similar tempo. At 5:00pm, the meteorological data air temperature was recorded as 32.7ºC which is one of the highest air temperatures throughout the day. The deviation of air temperature ranged from 0.115ºC at 3:00am to 10.292ºC at 5:00pm, which was 10.117ºC different between maximum and minimum deviation values. This indicates the existence of variations are accepted since the fluctuation patterns are within the same direction and range. In the relative humidity aspect, the overall mean relative humidity of the selected day was 66.24%, with highest value recorded as 90.8% at 6:00am and lowest value 35.75% at 7:00pm. The impact of hot day would directly cause thermal discomfort to the occupants since the heat gain from outdoor environment was transmitted via radiation, convection and conduction of air and building material to the occupants. The analysis of hot day could predict the air temperature for indoor environment and refine the solution to reduce the thermal discomfort of the occupants.

4.1.2 Selected cold days (11 Jan to 24 Jan 2014) [<27.88°C]

1.

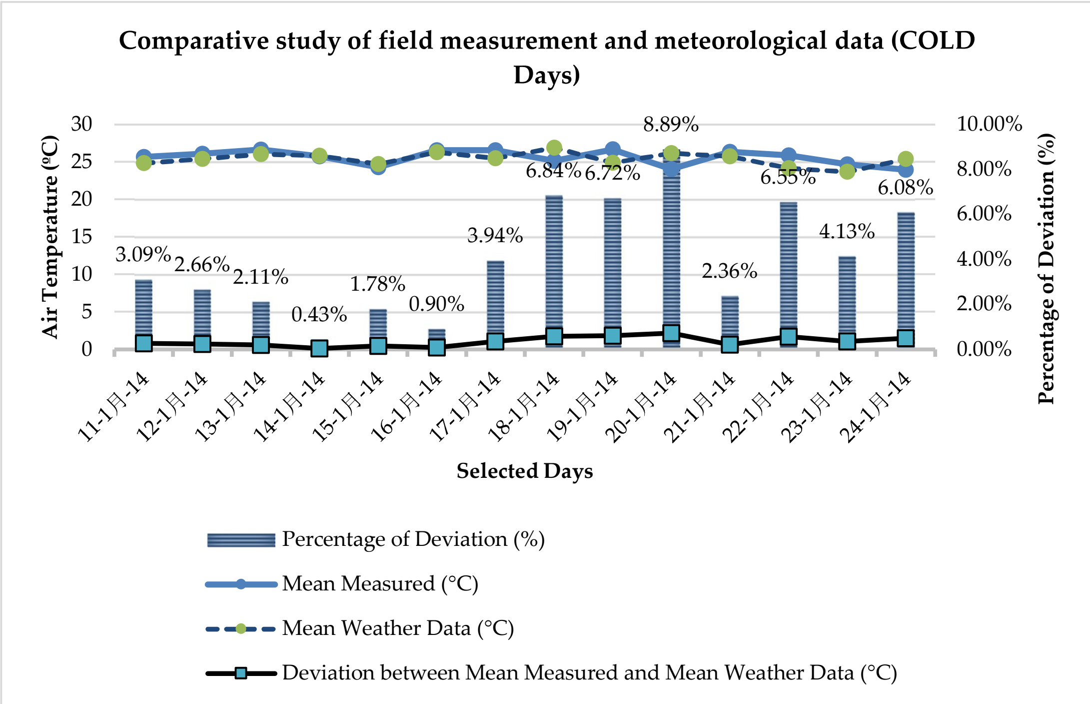
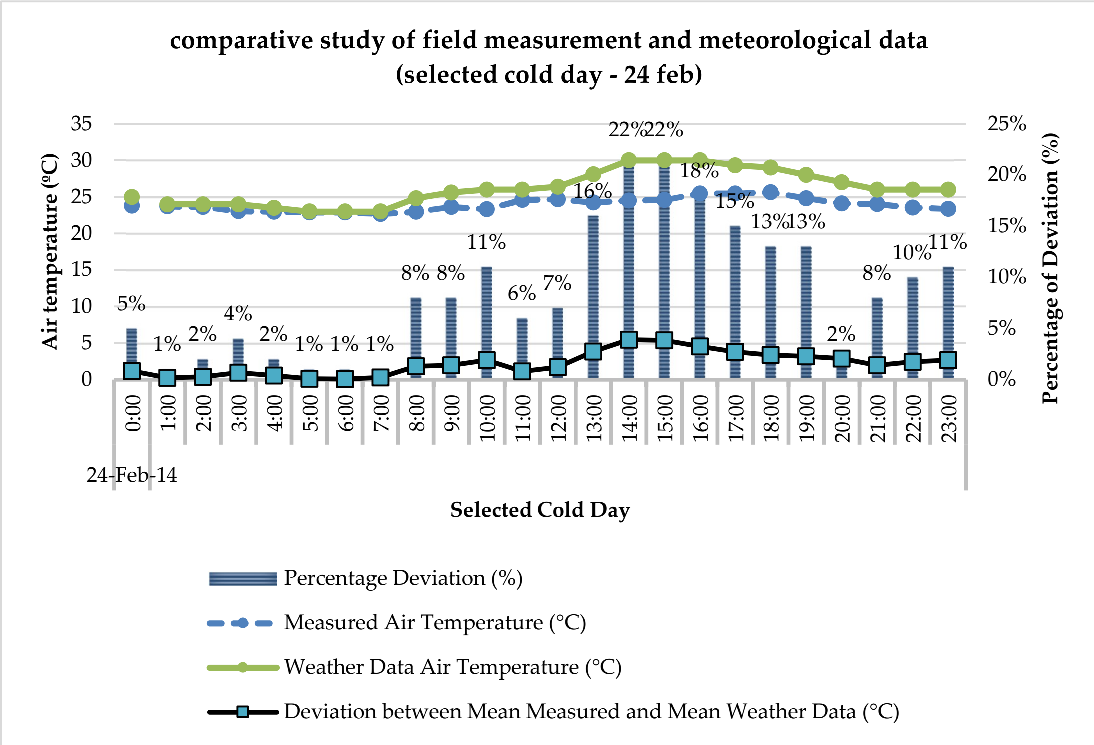


Figure 19 Comparative study of field measurement and meteorological data for selected cold days (11 Jan to 24 Jan 2014) throughout the study period.

2.



3.

Figure 20 Comparative study of field measurement and meteorological data for selected cold day (24 Feb 2014) throughout the study period.

After analyzing the selected hot day condition for the case study house, an analysis for the cold days is important to be done to understand the microclimate for the case study. The cold days happened towards the end of December to early February, which was the peak season of North East Monsoon season that tend to cause heavy rainfall. Figure 20 shows that from 11 Jan to 24 Jan 2014, the field measured mean air temperature ranged from 23.94ºC, which happened on 24 Jan 2014, to 26.66ºC on 19 Jan 2014. Throughout the field measurement period from 3 Jan to 29 June 2014, the lowest mean air temperature happened on 5 Feb 2014 with 19.57ºC, and the most frequently happened mean air temperature below overall mean air temperature was 24.73ºC. Hence, the selected period to represent cold days possessed mean air temperature ranging from 23.94ºC at 24 Jan to 26.66ºC on 19 Jan 2014.

The average deviation of the field measurement data and weather data was 1.02ºC, which is considered as acceptable and insignificant. The highest deviation mean value throughout the selected cold days was 2.15ºC on 20 Jan 2014 where the weather station showed 26.17ºC and the field measurement was 24.01ºC. The massive and dynamic atmospheric circulation happened in the spacious flat topography caused the weather station data to have lower air temperature compared to the case study field measurement. The lowest deviation value was 0.11ºC on 14 Jan 2014 with field measurement value of 25.73ºC and weather data of 25.85ºC, which was 0.43%.

The mean relative humidity for selected cold days ranged from 80.31% on 16 and 17 Jan 2014 to 95.57% on 15 Jan 2014. Similar to hot days' condition, the day with higher air temperature was accompanied with lower relative humidity while the day with lower air temperature came with higher relative humidity. The selected cold days with highest relative humidity, which was 95.57% happened on 15 Jan 2014 with mean air temperature of 24.27ºC. On the other hand, the cold days with lowest relative humidity, which was 80.31% on 16 and 17 Jan 2014 happened at mean air temperature of 26.53ºC. The fluctuation of relative humidity in cold days was lower compared to the hot days. The relative humidity ranged from 66.24% to 86.38% and the cold days from 80.31% to 95.57%. This shows that relative humidity for cold days was not only high but stable.

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When the study specified selected cold day, as shown in Figure 19, the fluctuation pattern of the graph shows a more dynamic pattern compared to the selected days graph as shown in Figure 20. Selected cold day is represented by 24 Jan 2014. In general, the measured data were lower than the weather station air temperature value. The deviation of both set data was 2.21ºC with 8.87%. The measured mean air temperature ranged from 22.681ºC at 7:00am and 25.635ºC at 6:00pm while the weather station data air temperature ranged from 23ºC at 5:00am, 6:00am and 7:00am to 30ºC at 2:00pm, 3:00pm and 4:00pm. The data from the weather station was more general compared to the field measurement data. The percentage differences between both sets of data ranged from 1% to 22%. The deviation gaps were larger when the air temperature got higher, which was in the afternoon. The field measurement data shows more stable and consistent pattern while the weather station data possesses more significant fluctuation range. The field measurement data was recorded based on microclimate condition, since the field measurement instruments were located at human level height.

Furthermore, relative humidity for the cold day recorded was 60.44% at 2:00pm and 95.96% at 7:00am. The relative humidity from 12:00am to 8:00am on 24 Jan 2014 was above 89% but it gradually dropped after 9:00am till 8:00pm. When night fell, the relative humidity increased from 72.99% at 7:00pm, 78.52% at 8:00pm, 81.34% at 9pm, 82.75% at 10pm and 83.89% at 11pm. Diurnal air temperature and diurnal relative humidity maintained the high temperature low humidity relationship even though it was categorised as cold day. The impact of cold day to the indoor environment was not as critical as hot day since thermal performance of hot days would cause significant impact on thermal comfort of occupants in the tropics.

4.1.3 Selected normal days (31 Jan to 13 Feb) [+-27.88°C]

After looking into selected hot and cold days from the field measurement days, it is important to look into outdoor air temperature and relative humidity of normal days, which falls on the total average of air temperature throughout the field measurement. The total average air temperature of field measurement was 27.88ºC. The selected normal days were between the end of January to around the end of April, during the intermonsoon period.

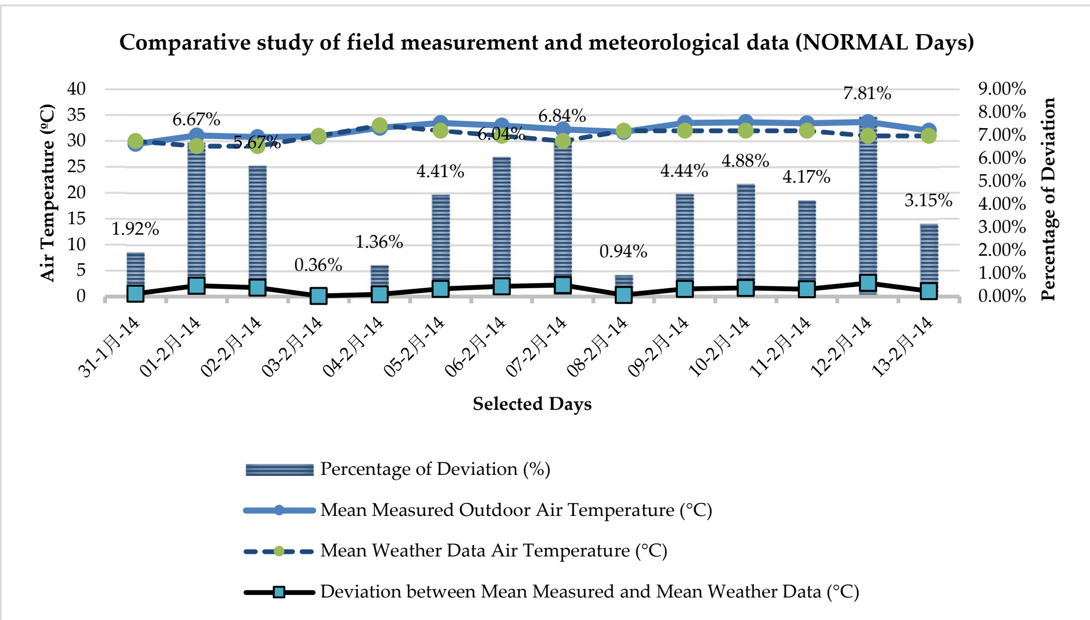

Figure 21 5.1 Comparative study of field measurement and meteorological data for selected normal days (31 Jan to 13 Feb 2014) throughout the study period.

Figure 21 shows the variation and deviation of air temperature between field measurement and weather station for normal days. In general, the percentage deviation between both sets of data was acceptable since the highest percentage of deviation throughout the selected days was not more than 7%. The mean air temperature of the selected normal days obtained from field measurement ranged from 25.34ºC on 31 Jan to 28.53ºC on 12 Feb 2014 while the data from the meteorological centre ranged from 25.38ºC to 28.04ºC on 3 February and 11 February 2014 respectively. The average deviation for both sets of data was 0.64ºC, which was not significant and acceptable. During the normal days, the highest deviation percentage between both sets of data was found on 13 Feb 2014 with deviation of 6.36% while the closest value was found on 4 Feb 2014 with deviation of 0.03%. However, the highest percentage of deviation on 13 Feb was only 1.67ºC while the lowest percentage deviation was 0.007ºC on 4 Feb 2014. It can be inferred that the measured data is reliable and similar to the weather station data.

For the relative humidity, the highest relative humidity and lowest relative humidity value were 81.53% and 67.28% respectively. The highest relative humidity happened on 31 Jan while the lowest on 5 Feb 2014. The average relative humidity from 31 Jan to 13 Feb was recorded as 77.27%. Mean relative humidity for selected normal days was similar to the range suggested by Malaysia (2013b).

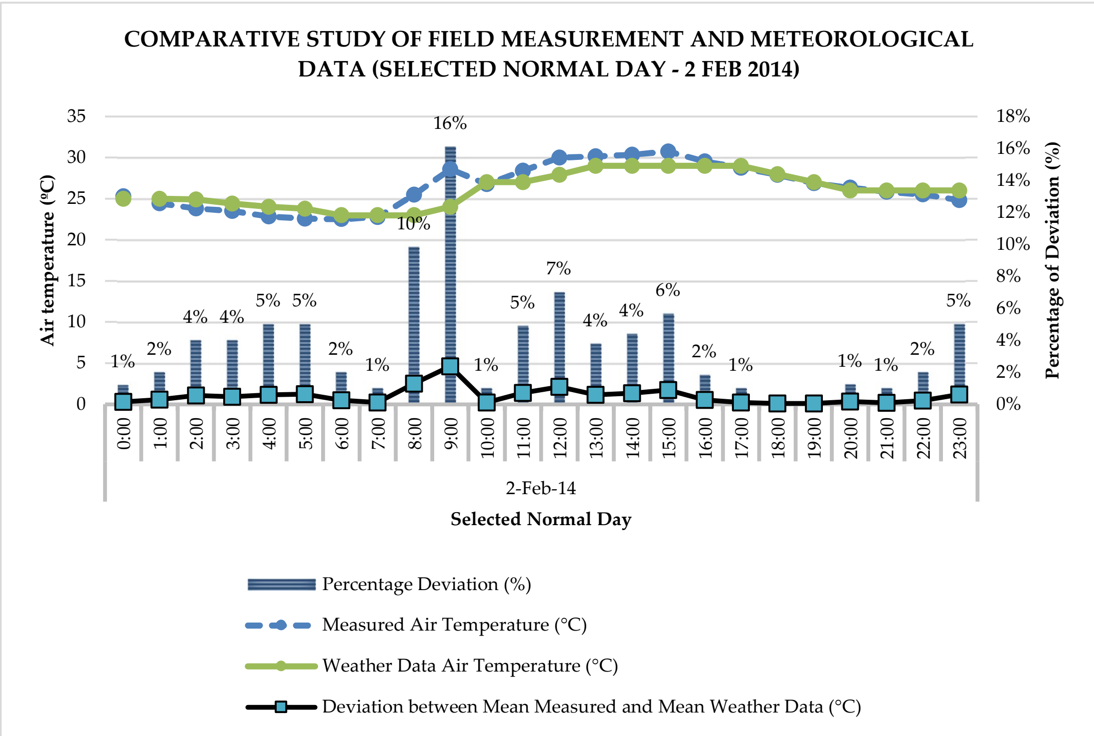

Figure 22 Comparative study of field measurement and meteorological data for selected normal day (2 Feb 2014) throughout the study period.

Figure 22 shows that the selected day to study the daily air temperature and relative humidity variation was 2nd February 2014. The variation order for both meteorological data and field measurement data were agreed in agreement with each other and had similar pattern except for 8:00am and 9:00am, which showed 10% and 16% respectively. Out of 24 hours of the selected normal day, each of the deviation was not more than 8% except for 8:00am and 9:00am The field measurement data at 8:00am and 9:00am showed 25.51ºC and 28.61ºC while the weather data showed 23ºC and 24ºC. The deviation happened around sunrise when radiation started to warm up the air. The weather station was located at a flat terrain where the water vapour density was higher, which caused the air temperature to be lower. The mean air temperature for field measurement ranged from 22.52ºC at 6:00am to 30.74ºC at 3:00pm. Since 2 February 2014 was selected to represent a normal day, the mean air temperature range could indicate that before sunrise and after sunset (nocturnal), the case study house experienced lower air temperature as well as high mean daytime (diurnal) air temperature. This means that day time thermal performance is more critical compared to night time thermal performance.

Relative humidity for normal day could range from 63.24% to 93.18%. The lower relative humidity happened at the hottest hour which was 3:00pm while the highest relative humidity happened at one of the coldest hour which was 7:00am. A difference of 29.94% between highest and lowest air humidity shows that the occupants in tropical climate experience dynamic changes of thermal comfort within 24 hours, from daytime to night time throughout the year. This demonstrates that the thermal comfort could be an issue for a free running building especially during day time since the climate is hot and humid throughout the year.

In the next section, an analysis of outdoor air temperature would be detailed through the discussion on daily max and daily mean for air temperature, relative humidity, solar radiation, wind velocity and wind direction.

4.2 Field study results: outdoor climate

This section examines the four different main climatic parameters, namely air temperature, solar radiation, relative humidity and wind velocity. In this case, daily maximum temperature was selected to discuss, since the maximum daily air temperature is important as worst case scenario boundary condition for modelling simulation.

4.2.1 Daily Maximum

Daily maximum of parameters is considered to be more important compared to daily minimum. Under the hot and humid tropical climate condition, extreme and high air temperature, relative humidity, solar radiation, high intensity of outdoor wind during certain period of time especially Monsoon seasons and so forth could directly and indirectly affect the indoor thermal performance. Hence, this sub-section discusses about the daily max of the following selected parameters.

4.2.1.1 Air temperature

Figure 23 shows the daily maximum for outdoor air temperature throughout the field measurement days. The maximum air temperature of each day was recorded in order to investigate the extreme condition of microclimate throughout the field measurement. The overall daily maximum air temperature ranged from 25.35ºC to 42.99ºC at 20 January and 19 June respectively. The air temperature difference of 41.11% between maximum and minimum values shows that microclimate change significantly according to the monsoon seasons. North East monsoon, which usually happens around January, causes high volume of rainfall and directly lowers the air temperature. According to McGinley (2011), Sarawak receives minimal rainfall in June and July annually. Without adequate rainfall, the phenomenon directly causes draught around the coast due to high intensity of solar radiation and hot air convection. Therefore, June and July are considered as critical months for thermal comfort. Furthermore, haze pollution which happens from June onwards would be one of the reasons causing extreme high temperature around mid-year (Roger C Ho *et al.*, 2014).

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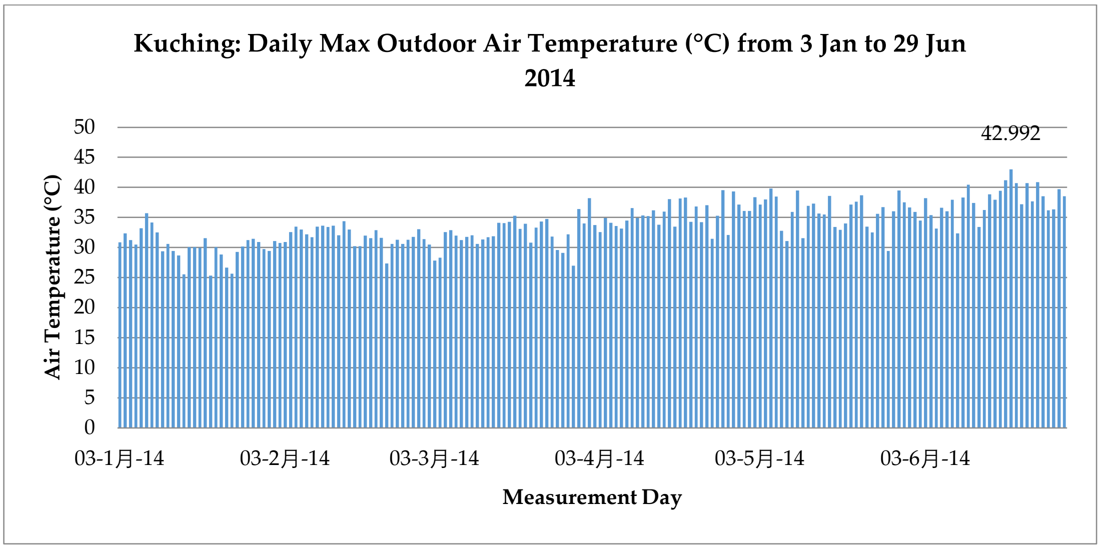

Figure 23 Daily max outdoor air temperature throughout the field measurement (3 Jan to 29 June 2014)

4.2.1.2 Solar Radiation

The daily max of solar radiation for Kuching throughout the field measurement ranged from 86W/m² at 6:00pm on 27 May 2014 to 1022W/m² at 1:00pm on 3 March 2014. The solar radiation directly influenced the air temperature through conduction and air convection. The air temperature for the studied day could be deduced from the daily max solar radiation. According to Makowski (2009), since the solar flux only influences the diurnal daylighting, it affects significantly on daily max air temperature compared to daily min air temperature while the nocturnal air temperature variation is affected by thermal radiative exchanges. Night time surface air radiative cooling relies on the atmosphere capacity to absorb and conduct the thermal radiation towards the earth surface. In this case, daily max study was significant to understand the effect of diurnal condition especially daily max air temperature and solar radiation in order to deduce the extreme thermal condition for indoor environment.

Figure 23 indicates the daily maximum solar radiation throughout the field measurement. In comparable to Figure 24 the highest daily maximum air temperature was 42.99°C on 19 June while the highest daily maximum solar radiation was 1022W/m² on 3 Mac 2014. The maximum air temperature for 3 Mac 2014 was 27.88°C even though it had the highest daily maximum solar radiation. In general, high solar radiation is accompanied by high air temperature.

This rare case could be due to other factors such as high cloud cover rate, high evaporation rate on the measuring area, high wind velocity and others. According to Graham (1999), low and thick cloud (example: stratocumulus) could reduce the earth surface and air temperature since it reflects the solar radiation while high and thin cloud (example: cirrus cloud) allows direct sunlight to penetrate through which causes high air temperature. The high and thin clouds also trap heat and infra-red radiated from earth surface.

Other than that, clear moving air, humidity, and clouds also balance the air temperature on earth. In order to explain the condition that high solar radiation could slightly increase the air temperature, three randomly selected days with high solar radiation throughout the field measurement are discussed briefly. The chosen dates are 5 Mac 2014 with air temperature of 30.91°C at 1:00pm; 28 April 2014 with air temperature of 36.17°C at 1:00pm and 18 June 2014 with air temperature of 41.19°C at 2:00pm. The solar radiation value was 1019 W/m², 981 W/m² and 903W/m² respectively. From the selected field measurement results, it can be deduced that high solar radiation cause high air temperature in general, due to the high reflectivity rate of emitted radiation from solar radiation to earth surface.

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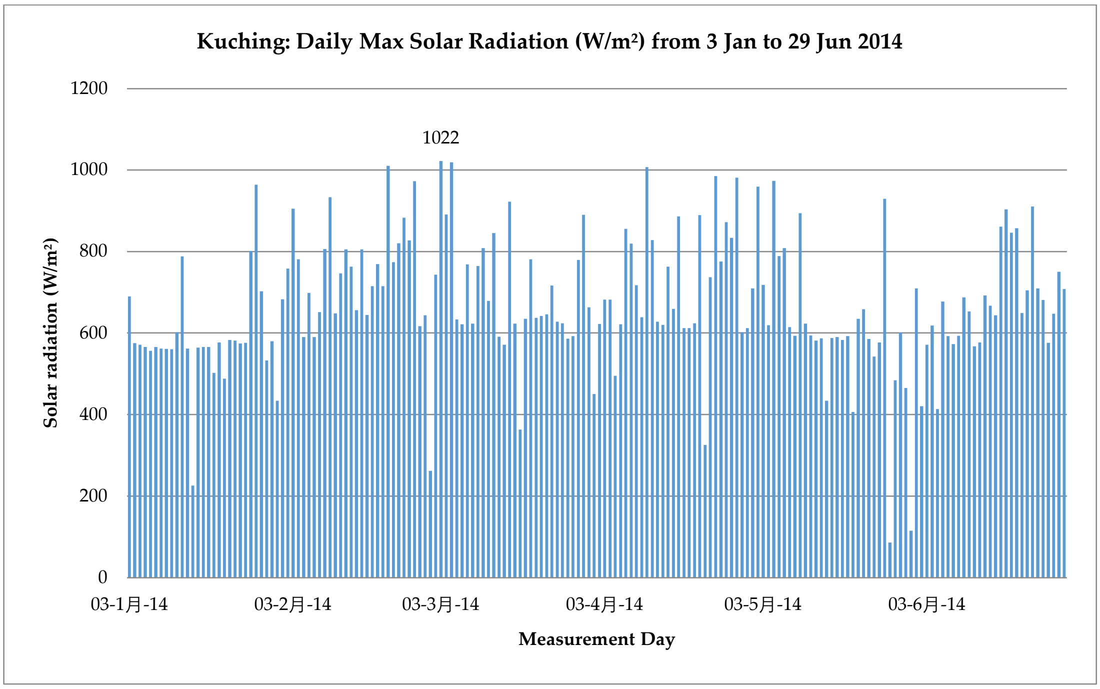

Figure 24 Daily max solar radiation throughout the field measurement (3 Jan to 29 June 2014)

4.2.1.3 Wind velocity

Wind velocity near to earth surface is one of the most influencing thermal comfort parameters for the indoor environment. In order to understand the indoor thermal performance, the intensity and speed of outdoor wind velocity must be determined. According to Beaufort scale of wind speed, the wind speed more than 5.4m/s could lead to uncomfortable condition to the occupants. The recommended comfortable range in tropical context based on Beaufort scale ranged from 1.6 to 5.4m/s (Sahabuddin, 2012). Figure 25 depicts the daily maximum air velocity throughout the field measurement. Out of 4270 data for each of the hours within the field measurement periods, 2641 data ranged from 1.6m/s to 5.4m/s at daily maximum condition. The highest daily maximum wind velocity was marked as 8.334m/s on 19 May 2014 while for the normal hour it could be as low as 0m/s. The extremely huge range of wind velocity would be a critical dilemma for indoor environment since it could not give consistent cooling effect to the indoor environment. Furthermore, the poor layout design of the modern terraced housing hardly creates pressure gradient between indoor and outdoor environment to induce wind ventilation.

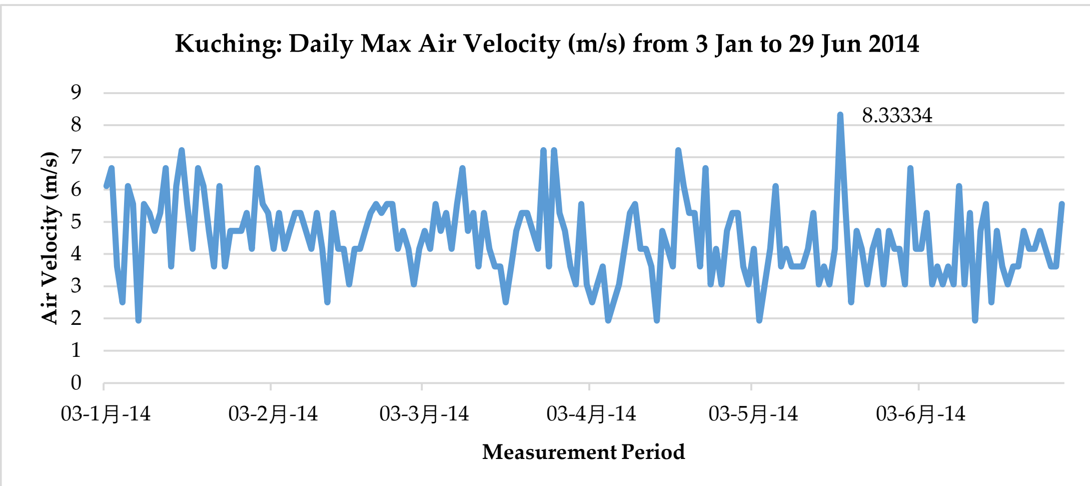

Figure 25 Daily max solar radiation throughout the field measurement period (3 Jan to 29 June 2014)

The daily maximum wind velocity in Figure 25 shows the highest wind velocity of each day throughout the field experiment. The highest daily maximum and lowest daily maximum wind velocity ranged from 1.95m/s on 13 June to 8.34m/s on 19 May 2014. The highest daily maximum wind velocity happened during the Monsoon season while the lowest daily maximum wind velocity occurred during the end of inter-monsoon season. The effect of Monsoon wind directly influences the climate in general.

4.2.1.4 Relative Humidity

The other important parameter which could affect the thermal comfort in the tropics is relative humidity. Other than high air temperature throughout the year, high relative humidity is also one of the critical factors that contributes to thermal discomfort. According to Figure 26, daily maximum relative humidity obtained throughout the field measurement ranged from to 82.89% to 100% happened on 20 June, as well as 6 Jan and 29 June. High relative humidity usually happens during the lowest air temperature, which is during rainy days or night time.

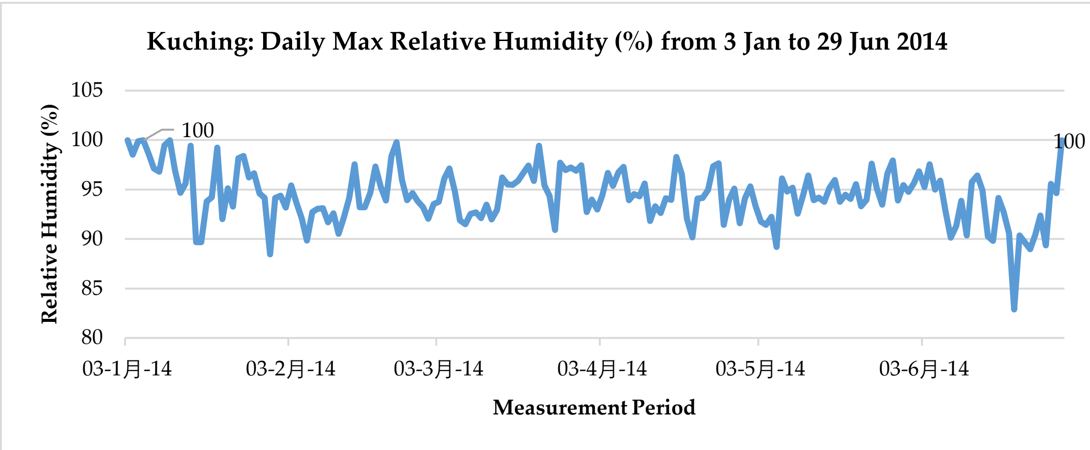

Figure 26 Daily max solar radiation throughout the field measurement period(3 Jan to 29 June 2014)

The lowest daily maximum relative humidity is considered as above average or high value. Sahabuddin (2012) stated that the ideal relative humidity range for indoor thermal comfort in tropical climate ranged from 30% to 60%. In comparing the outdoor lowest daily maximum relative humidity, the critical number could be one of the factors that need to be noted while considering the passive cooling architectural design. However, natural ventilation method is hardly implemented widely due to the lack of research. Hence, increasing air velocity to reduce air temperature and promote thermal comfort in tropical climate is one of the most reliable solutions under natural ventilation method. (Givoni, 1969; Olgay, 1973; Szokolay, 1984),

4.3 Field study results: comparative study of min, mean and max of thermal performance between air well, test room and outdoor climate condition

In order to investigate the relationship between outdoor climatic condition, thermal performance for air well and single-sided ventilated test room, the comparison studies were carried out as follows:

4.3.1 Comparison of daily max air temperature and relative humidity for outdoor, test room and air well from 3 Jan to 29 June

A comparison between max air temperature for three locations, outdoor, test room and air well, justifies the correlation between each other. Understanding of the mutual relationship between outdoor and test room (single-sided ventilation); outdoor and air well (performance of stack ventilation tool); as well as test room and air well would enhance the research study background in improving the thermal performance of habitable room in a single storey house.

Figure 27 and 28 show daily max air temperature and relative humidity for outdoor, test room and air well. Both figures are intended to display the variation of overall thermal performance for outdoor, air well and test room. In the previous section, outdoor weather data taken from field measurement was discussed. However, the same data was applied to compare with the measured indoor environment as reference.

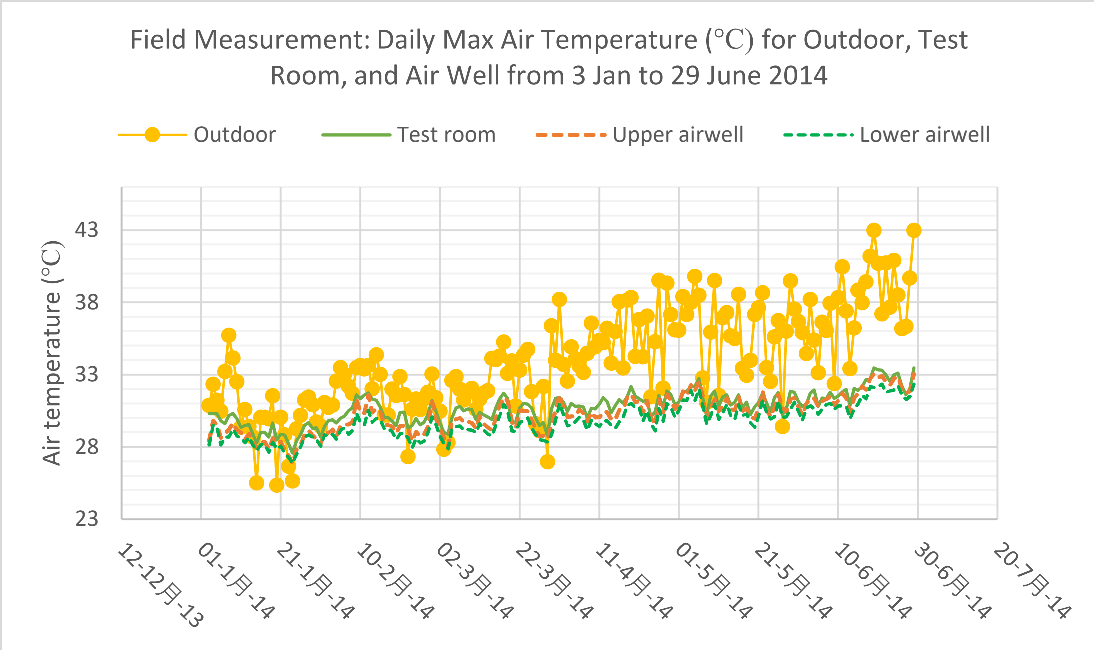

Figure 27: Daily max air temperature for outdoor, test room and air well throughout the field measurement (3 Jan to 29 June 2014)

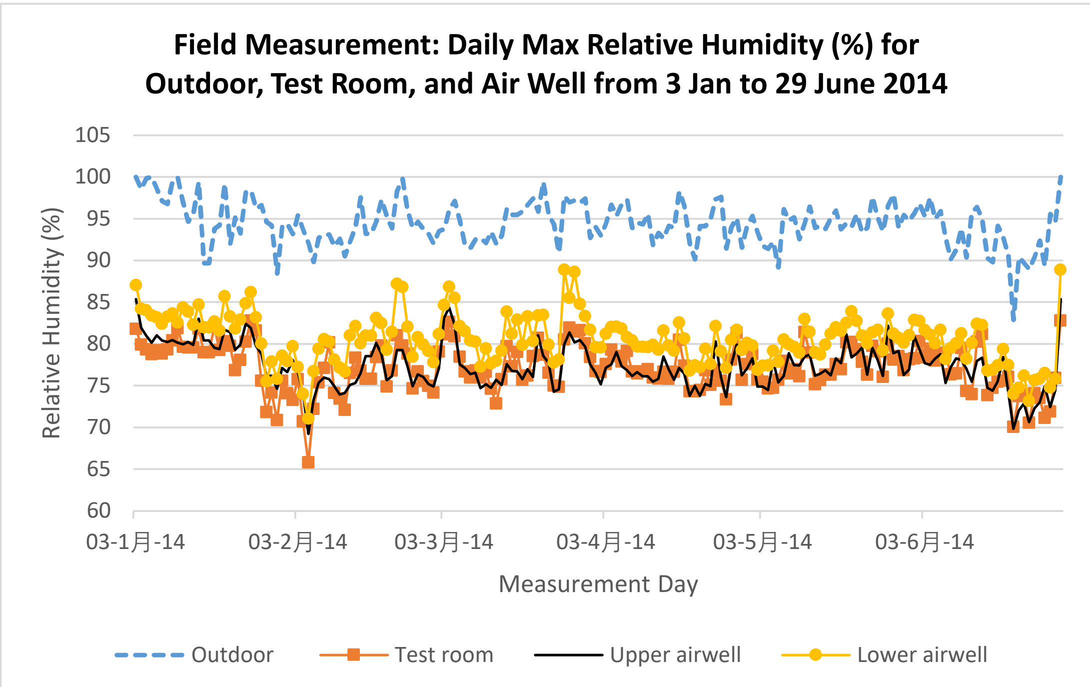

Figure 28 Daily max relative humidity for outdoor, test room and air well throughout the field measurement (3 Jan to 29 June 2014)

In general, daily maximum air temperature for outdoor, test room and air well fluctuated upwards gradually since January to June. Since relative humidity was inversely proportional to air temperature, overall variation pattern fluctuated downwards gradually. The phenomenon infers that air temperature increased since March.

Total average of daily maximum outdoor air temperature was 3.19°C and 3.92°C higher compared to both test room and air well respectively. Furthermore, total average of daily maximum outdoor relative humidity was 17.26% and 15.47% higher than test room and air well respectively. The highest daily maximum air temperature deviations for outdoor-test room and outdoor-air well were 9.52°C and 10.41°C respectively, while the lowest daily maximum air temperature deviations were 3.13°C and 2.71°C respectively. The highest deviation happened on the hottest day, which was 19 June while the lowest deviation occurred on a cold day, which was 20 January 2014. From the findings it is evident that thermal performance of indoor environment was stable since the fluctuation patterns were more consistent.

The study summarized the thermal performance of the existing single storey terraced house condition discussed in this study. In general, the thermal performance of the case study house was summarized in the table form. Table 2 summarized field measurement of the outdoor weather data for the selected days – high air temperature day (hot days), low air temperature day (cold days) and normal days; Table 3 summarized the mean and max or outdoor air temperature and relative humidity for selected highest air temperature day (hot day), lowest air temperature day (coldest day) and normal day. As mentioned in Figure 4, the measured outdoor air temperature and relative humidity falls within the range of average, min and max value throughout the 10 years' data as recorded by Kuching meteorological center. The comparison between both set of data has verified the consistency and insignificant of fluctuation range of climatic condition in Kuching, Sarawak Malaysia since 2006 to 2019. Furthermore, the significance of the field measurement of microclimate condition for building thermal performance study

In the other hand, as summarized in Table 4, the thermal performance of the test room for the selected days with high air temperature, low air temperature and normal air temperature show the predicted mean vote of thermal comfort while Table 5 summarized the air temperature, relative humidity, PMV and PPD of test room. Table 6 summarized thermal performance of air well for the selected days while while Table 7 summarized the thermal performance of the existing air well in the single storey terraced house.

Table 2. Summary of field measurement – Outdoor weather data for selected days (hot, cold and normal days)

Condition	Mean Outdoor Air Temperature (ºC)	Max Outdoor Air Temperature (ºC)	Mean Outdoor Relative humidity (%)	Max Outdoor Relative humidity (%)
Hot Days (10/6/2014 - 24/6/2014)	30.74	38.90	73.48	91.42
Cold Days (11/1/2014-24/1/2014)	25.58	28.69	86.45	95.13
Normal Days (31/1/2014 - 13/2/2014)	27.95	32.01	79.87	92.25

Table 3. Summary of field measurement – Outdoor weather data for selected day (hot, cold and normal day)

Condition	Mean Outdoor Air	Max Outdoor Air	Mean Outdoor Relative humidity (%)	Max Outdoor Relative humidity (%)

	Temperature (ºC)	Temperature (ºC)		
Hot Day (19 June 2014)	33.55	42.99	66.24	90.56
Cold Day (24 Jan 2014)	23.94	25.63	75.59	95.95
Normal Day (2 Feb 2014)	26.42	30.74	79.64	93.18

Table 4. Summary of field measurement – thermal performance of test room for selected days (hot, cold and normal days)

Condition	Mean Testroom Air Temperature (ºC)	Max Testroom Air Temperature (ºC)	Mean Testroom Relative humidity (%)	Max Testroom Relative humidity (%)	Average Testroom Mean Radiant Air Temperature (ºC)	Max Testroom Mean Radiant Air Temperature (ºC)	Max PMV	Mean PMV	Max PPD (%)	Mean PPD(%)
Hot Days (10/6/2014 - 24/6/2014)	31.10	32.42	70.16	75.15	30.42	31.67	2.58	2.32	94.63	87.73
Cold Days (11/1/2014-24/1/2014)	28.04	28.84	76.00	79.79	27.33	28.09	1.80	1.64	66.96	58.55
Normal Days (31/1/2014 - 13/2/2014)	30.39	31.3	70.52	76.5	29.62	30.6	2.30	2.15	88.34	82.70

Table 5. Summary of field measurement – thermal performance of test room for selected day (hot, cold and normal day)

Condition	Mean Testroom Air Temperature (ºC)	Max Testroom Air Temperature (ºC)	Mean Testroom Relative humidity (%)	Max Testroom Relative humidity (%)	Average Testroom Mean Radiant Air	Max Testroom Mean Radiant Air	Max PMV	Mean PMV	Max PPD (%)	Mean PPD(%)
Hot Day (19 June 2014)	32.11	33.48	67.91	76.05	31.42	32.75	2.78	2.53	97.59	93.31
Cold Day (24 Jan 2014)	28.92	29.95	70.86	78.83	28.18	29.16	1.99	1.80	76.37	66.89
Normal Day (2 Feb 2014)	28.81	29.8	69.70	73.28	28.11	29.03	1.97	1.77	75.26	65.51

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Table 6. Summary of field measurement – thermal performance of air well for selected days (hot, cold and normal days)

Condition	Mean Air well Air Temperature (ºC)	Max Air well Air Temperature (ºC)	Mean Air well Relative humidity (%)	Max Air well Relative humidity (%)
Hot Days (10/6/2014 - 24/6/2014)	30.92	31.75	72.67	76.26
Cold Days (11/1/2014-24/1/2014)	27.48	28.06	79.25	81.87
Normal Days (31/1/2014 - 13/2/2014)	29.76	30.05	73.76	78.06

Table 7. Summary of field measurement – thermal performance of air well for selected day (hot, cold and normal day)

Condition	Mean Air well Air Temperature (ºC)	Max Air well Air Temperature (ºC)	Mean Air well Relative humidity (%)	Max Air well Relative humidity (%)
Hot Day (19 June 2014)	31.74	32.58	71.44	75.79
Cold Day (24 Jan 2014)	28.24	28.83	75.72	79.58
Normal Day (2 Feb 2014)	28.37	28.77	74.30	78.90

5.0 Conclusion

In general, the outdoor mean air temperature ranged from 25.58°C to 30.74°C with relative humidity ranged from 73.48% to 86.45%. The mean air temperature of air well ranged from 27.48°C to 30.92°C while mean relative humidity from 72.67% to 79.25%. The mean air temperature for test room (single sided ventilation room) 28.04°C to 30.92°C with relative humidity 70.16% to 76%. Even though the air temperature of the test room is similar to the outdoor air temperature range but the relative humidity caused the heat trapped at indoor environment and lead to static condition (0m/s) of the indoor environment. The findings have demonstrated that an air well in the terrace house has potential to function as thermal regulator and buffer for the test room while the outdoor air temperature changes drastically, however, further study could be conducted in order to substantiate the ventilation effectiveness of an air well for the indoor room of a terrace house.

Hence, as a suggestion, the current thermal performance of the existing terraced house in Malaysia could be improved by increasing the air flow and decreasing the air temperature with improved air well and external louvres. These empirical findings are of importance offering novel policy insights and suggestions to the existing building code standard and by laws; since the minimum provision of 10% openings has been revealed to be less effective, strict compliance with, and necessity for, the by law requirement should be revisited and further studied. More potential studies could be conducted in order to further validate the current findings and therefore improve the future design and configuration of terraced housing from thermal and ventilation performance perspectives.

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