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REVIEW

A literature review on the improvement strategies of passive design for the roofing system of the modern house in a hot and humid climate region

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Cool roof;
Ventilated roof

Abstract
Increase of indoor temperature compared with outdoor temperature is a major concern in modern house design. Occupants suffer from this uncomfortable condition because of overheating indoor temperature. Poor passive design causes heat to be trapped, which influences the rise in indoor temperature. The upper part, which covers the area of the roof, is the most critical part of the house that is exposed to heat caused by high solar radiation and high emissivity levels. During daytime, the roof accumulates heat, which increases the indoor temperature and affects the comfort level of the occupants. To maintain the indoor temperature within the comfort level, most house designs usually depend on mechanical means by using fans or air conditioning systems. The dependence on a mechanical ventilation system could lead to additional costs for its installation, operation, and maintenance. Thus, this study concentrates on reviews on passive design and suggests recommendations for future developments. New proposals or strategies are proposed to improve the current passive design through ventilated and cool roof systems. It is possible to achieve the comfort level inside a house throughout the day by reducing the transmitted heat into the indoor environment and eliminating the internal hot air. These recommendations could become attractive strategies in

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providing a comfortable indoor temperature to the occupants as well as in minimizing energy consumption.

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1. Introduction

Malaysia is located at 3° N from the equator in the tropical region and experiences an equally distributed amount of rainfall throughout the year. High temperature (between 22 °C and 33 °C) is felt because of high solar radiation level and high relative humidity (Al Yacouby et al., 2011). The average solar radiation level for a tropical climate ranges from 4.21 kW h/m^2 to 5.56 kW h/m^2 per year (Azhari et al., 2008) and receives a duration of sunlight of up to 8.7 h per day (Malaysia Meterological Department, 2014). Abdul Rahman et al. (2009) showed that the hottest time of the day is between 11.30 a.m. and 4.30 p.m. Jones et al. (1993) indicated that the acceptable thermal comfort temperature inside a house for the Malaysian climate is between 25.5 °C and 28.5 °C. In compliance with ASHRAE 55-1992 (1992) standards, the recommended comfort temperature under the climatic condition for the dwellers is around 24 ± 1 °C. Noor Aziah (2008) identified that the concrete terrace houses in Malaysia are thermally comfortable to be occupied for only a few hours per day. The indoor temperature within the thermal comfort temperature is only at a certain period before it exceeds the comfort temperature level. Fig. 1 shows the outdoor temperature versus the daily indoor temperature.

Fig. 1 shows that the indoor temperature of the concrete house reached peaks of more than 30 °C during daytime. The increase in temperature is due to the poor passive design of the house. Passive design could help maintain the temperature inside the house within the comfortable temperature range. The heat transmitted through the roof building and the poor passive design of the structure are the main reasons for the discomfort of occupants in a non-air conditioned building (Vijaykumar et al., 2007). A roof design problem occurs because of the poor ventilation provisions in the modern low-income housing design (Ibrahim, 2004). Thus, the main concern of the present study is the top part of a building that is exposed to direct sunlight. An amount of heat, which is transmitted from the roof surface, is trapped in the attic area. Thus, this creates a higher temperature in the upper part of the house. Because of poor passive design, the trapped heat generates a higher temperature in the attic area, especially during peak hours in the hot climate region. Heat transmits from the roof to the ceiling, stores inside the concrete walls and floor slabs, and creates greater indoor temperature because of stagnant air (Abdul Wahab and Ismail, 2012). Tinker et al. (2004) showed that the internal temperature of the modern low-cost house is higher than the required temperature for an occupant's comfort level. Therefore, it could lead to high power usage of mechanical means and increase energy consumption. The highest daily electricity demand of 345.25 GW h was reported in 2013, which increased by 5% from 2012. Meanwhile, the annual electricity demand also

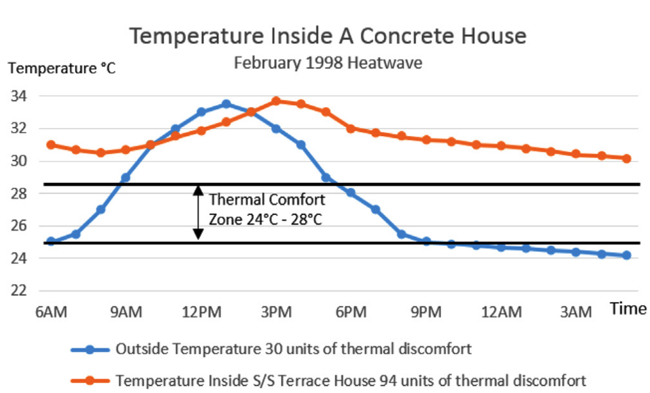

Fig. 1 Temperature inside a concrete house.
Source: Reducing urban heat island effect with thermal comfort housing and honeycomb township (Davis et al., 2005).

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surged by 3.6%, from 108,473 GW h in 2012 to 112,358 GW h in 2013 (Energy Commision, 2014).

Al Yacouby et al. (2011) indicated that about 75% of Malaysians depend on the air-conditioning system to maintain the indoor temperature within the comfort level. In the residential sector, dwellers use electricity to power the mechanical cooling system, which would increase the expense for operation and maintenance (Cowan and Smith, 1983). The amplified demand of energy issues arise because of concern on modern comfort standards, social customs, and design practices, which made mechanical cooling one of the important factors in daily life (Abdul Rahman et al., 2013). Thus, this study is important to discuss the weaknesses of the current passive design and generate recommendations to improve its local practice, especially in modern house design. The findings from this study would reduce and maintain the indoor temperature of the modern house design. In addition, it would minimize and mitigate the cost of electricity consumption.

2. Review on the current passive design

The 2010 Census revealed that the total population of Malaysia increased from 23.3 million in 2000 to 28.3 million in 2010 (Department of Statistic Malaysia, 2015). In recent years, the growth in population and economy resulted in an increasing number of demands for residential housing among urban areas in Malaysia. Akbari et al. (2008) estimated that roofs and pavements cover 60% of urban areas. Furthermore, the surface temperature in urban areas would greatly increase in the next 10 years or less due to population expansion (Tursilowati, 2007).

The color of the roof surface should be one of the elements that need to be considered in passive design. The majority of roof tiles in Malaysia are dark in color, which means that it absorbs more heat (Al-Yacouby et al., 2011). Table 1 shows the variety of roof tile color used in Malaysia.

Givoni (1994) found that a roof painted with a gray or dark color records a higher ceiling temperature compared with a roof painted with a lighter color. It was also justified that a dark colored roof has a higher indoor temperature than the outdoor climate. The study concluded that the incidence of solar radiation on the roof surface depends on the color and thermo-physical properties of the roof (Givoni, 1994).

A black aluminum sheet for a flat roof or a 0° roof pitch records the highest indoor temperature (Al-Obaidi et al., 2014c). Ibrahim et al. (2014a) showed that the indoor temperature reading is higher than the outdoor temperature for a lower roof pitch because of the large amount of heat it absorbed. Looking at the current modern house design in Malaysia, most parts of the roof are constructed within a 10° roof angle. Abdul Rahman et al. (2009) wrote that a flat roof design in the tropical climate could not be considered as a good elemental design because of some factors that would lead to leakages, such as the ponding of water on the flat roof surface, and would require additional costs for major restructuring. Apart from saving construction costs, developers prefer the easiest and simplest method to design and construct the houses, especially in the upper part of the structure.

Table 1 Color of roof tiles in Malaysia.
Source: Al-Yacouby et al. (2011).

Roof color	Percentage (%)
Red	38.0
Brown	25.9
White	9.5
Beige and blue	7.8
Black	4.9
Gray	2.9

The material used for building the roofing system is an issue. Lau et al. (2008) estimated that the types of roof materials used for current houses are mostly made of 85% concrete roof tiles, whereas clay tiles and metal deck comprise 10% and 5%, respectively. Contractors would prefer the use of roof tiles because it could prolong the life span of the roofing system and require minimal maintenance compared with other roofing materials. For the design of modern low-cost houses in Malaysia, spandex or metal roof is preferred because of its lower construction costs in contrast with concrete or clay roof tiles. Lau et al. (2008) reported that most of the houses built are affected by high solar radiation transmission due to the non-reflective materials used, which leads to a high temperature inside the building. Ibrahim et al. (2014a) revealed that spandex is not suitable as a roofing material in modern low-cost house design because it creates a higher indoor temperature than outdoor temperature.

It is suggested that ceramic roof tiles would provide better performance in the reduction of heat transmitted into a house. Miller et al. (2007) concluded that the heat, which enters from the ceramic tiles of the roof surface into the ceiling, decreases up to 60% or less than asphalt shingles. As ceramic roof tiles became wet during nighttime and dry during daytime, it would help in minimizing the heat transfer from the roof surface into the attic area. The reduction of heat transfer is due to the ability of the material to bounce back the radiated heat to the atmosphere. Although the Chinese had already practiced the use of ceramic as a roofing material for centuries, this choice is not well understood because of modernization and vast development (Miller et al., 2007).

The passive design of a modern terrace house is not very suitable for a hot and humid climate such as that in Malaysia (Davis et al., 1997). For a house with a modern low-income design, the indoor temperature is as high as 31 °C; while the outdoor temperature is around 30 °C with air speeds as low as 0.1 m/s (Tinker et al., 2004). The recorded indoor temperature is higher than the temperature of a human's thermal comfort. Although the house has many openings, such as windows and doors, it still cannot achieve thermal comfort because the upper part of the house is not properly designed. Similar research is conducted on the same design for a modern low-cost house in two different locations. Ibrahim et al. (2014a) showed that lack of natural ventilation design increases the indoor temperature.

Aziah (1994) concluded that the traditional Malay house design records a lower indoor temperature compared with the modern terrace house design. Furthermore, the traditional Malay house design is the best example of good natural ventilation, since it mostly depends on the natural cooling

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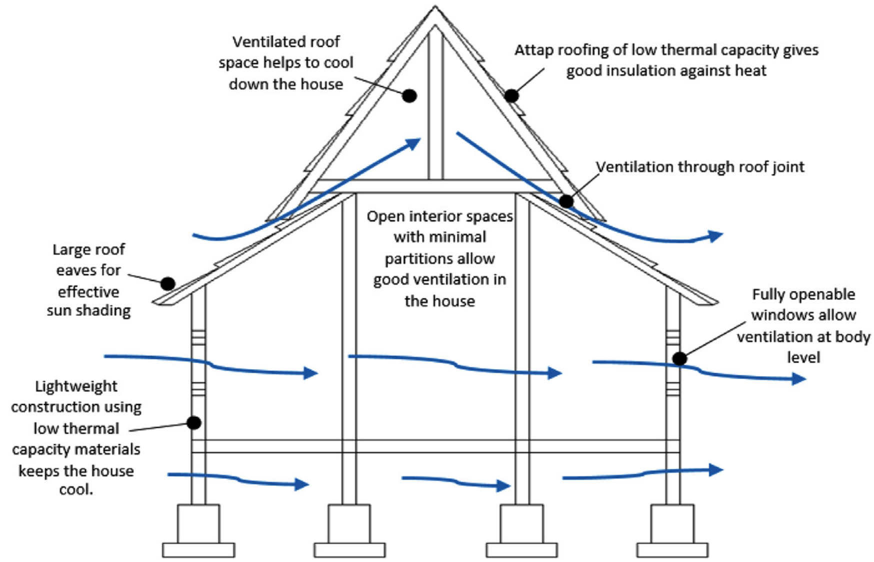

Fig. 2 Air movement for traditional Malay house.
Source: The traditional Malay house, rediscovering Malaysia's indigenous shelter system (Lim, 1987).

system through the flow of air via windows, doors, roofs, and others (Lim, 1987). However, the application of the traditional Malay concept house has become unpopular due to the modernization of the house design and the limitation of timber supplied for the building material, such as wood and Nipa palm leaf (*Nypa fruticans*). Fig. 2 shows the openings in a traditional Malay house that could help ease the movement and remove heat.

Nowadays, the Malaysian modern roofing system is designed with less ventilation or unvented attics to save costs for construction, fire resistance, rain protection, and increase in security. The modern concrete house built in Malaysia would experience high temperature rises during daytime and would slowly cool down during nighttime (Abdul Rahman et al., 2009). Wolfert and Hinrichs (1974) showed that the roof sheathing temperature of an unvented attics condition and ceiling temperature might reach up to 71 °C and 66 °C respectively, while the outdoor temperature is only around 32 °C. However, a well-designed ventilated roof can improve the overheated condition at the attics, particularly at a moderate height and a wide area of the building (Ciampi et al., 2005).

The most affected element because of poor passive design is the energy demand for the mechanical operation. When the condition of the indoor temperature is higher than the comfort level, a large amount of energy is needed to generate mechanical ventilation to achieve the level of comfort (Tinker et al., 2004). However, the condition could become worse because of poor ventilation and air circulation design. The openings in Malaysian houses are located mostly at the front and back parts of the houses, especially in intermediate terrace house design.

3. Recommendations to improve the current practice on passive design

This study proposed the recommendations to improve the current passive design. It is targeted to reduce or maintain the indoor temperature within the comfort temperature range. The recommendations in this study focused on:

(1) Reducing the heat transfer into the building by using a reflective cool roof with an optimum roof pitch approach.
(2) Removing the heat from a building through a ventilated roof or opening on the roof surface technique.

This study concentrates on minimizing the heat gained through color and roof pitch, and removing heat from the building to the outdoor environment through natural ventilation or opening on the roof surface. Hence, the application of both recommendations in roof design could help lessen energy demands.

3.1. Reflective cool roof with optimum roof pitch approach

The combination of a reflective cooling roof with an optimum roof pitch is a strategy that aims to reduce the heat transfer from the roof surface into the house during sunny days. Reflective roof is the concept that targets to reduce the effect of heat gained into the building during a hot temperature in daytime (Akbhari et al., 2006). A cool roof is one of the best examples of a reflective roof. Al-Obaidi et al. (2014b) showed that developed countries in South East Asia have not yet implemented the reflective roof strategy. The characteristics of cool roofs could enhance indoor thermal comfort without needing to switch on the air conditioning unit. The cool roof supports in extending the roof's life span and reducing the trapped heat from the attic and other building spaces by reflecting the solar rays back into the atmosphere (Al-Obaidi et al., 2014b). A cool or reflective roof also acts as both a good heat emitter and a reflector of invisible short or long wave electromagnetic radiation.

The color of a roof surface is another element that must be considered in designing a cool roof. A darker color would absorb more heat than lighter ones, because a light color is capable of reflecting heat on its surface. The application of a new cool roof with solar reflectance of 0.41 reduces the attic air temperature than the conventional roof type, which has a solar reflectance of 0.10 (Akbari et al., 2006). Many studies have agreed that the reflective approach could reduce the maximum solar heat gain by reflecting the solar radiation back up to 90%, thus lessening the electricity consumption for a mechanical cooling system (Asimakopoulos et al., 1996; Oberndorfer et al., 2007; Aubrey, 2010). Under the same condition, a cool roof color records a temperature of 28 °C, which is lower than a dark roof color's temperature of 66 °C or higher (Urban and Roth, 2010). A white cool roof helps minimize the indoor temperature in hot climate areas and especially reduce the temperature up to 2.3 °C (Mohamed and Ahmad, 2012).

Repainting a dark color with a light one on the roof surface increases the number of solar reflectance from 0.10 to 0.35, thereby significantly reducing the heat absorption and the electricity consumption by 7%–15% (Urban and Roth, 2010). A light color reflects up to 80% of invisible solar rays, while a dark color reflects up to 20%. Givoni (1994) showed that the maximum difference of the temperature of external surfaces between white and black roof colors in the desert during summer ranges between 30 °C and 40 °C. Typically, a cool roof is colored white and has higher solar reflectance values. Based on the US Green Building Council, a standard white color and a standard black color has an initial solar reflectance value of 0.80 and 0.05, respectively. The first generation of cool roof recorded a higher albedo (reflective coefficient) value of 0.75 or more (Doulos et al., 2004); the second generation of white colored cool roof with artificial materials noted a solar reflectance value of more than 0.85 (Santamouris et al., 2008; Kolokotsa et al., 2012).

The effectiveness or the performance of reflective roof application can be improved along with the adoption of the optimum roof pitch. It is essential to focus on the energy-efficient methods through the proposed strategies to reduce the amount of transmitted heat into the house and minimize the usage of electricity for powering up the conditioning units.

Table 2 shows the requirements for a minimum cool roof. These ensure that the low or steep slope roof meet or exceed both minimum solar reflectance and thermal emittance values. These allow some roofs to have a low thermal emittance with high solar reflectance value or vice versa to qualify as a cool roof (US Department of Energy, 2011).

In recent years, modern low-cost houses in Malaysia are designed with a lower roof pitch. It is important to take the color aspect of the roof surface into account while designing the roof angle. Ramly and Hussain (2012) indicated that the increase of roof angle from 0° to 60° could reduce the indoor climate by 1.5 °C. Air movement under the roof slope of 30° is faster when compared with a 15° roof pitch (Tashoo et al., 2014). The 30° optimum roof pitch is recommended for easy maintenance purposes in the future.

A higher roof pitch absorbs a small amount of heat during peak hours because solar radiation mostly falls on a bigger surface area (Abdul Rahman et al., 2009). The morning sun is perpendicular to the roof surface of a high pitch, but the heat insolation or the absorption of the solar radiation is weak at that time. Al-Obaidi et al. (2014c) showed that a higher roof pitch records the lowest indoor temperature compared with a flat roof. A white aluminum sheet with the same roof pitch indicates a low indoor temperature than other colors (Al-Obaidi et al., 2014c). The study also revealed that a black aluminum sheet with a higher pitch of 45° records the lowest temperature compared with a white aluminum sheet. It also discovered the relationship of the roof color against the roof pitch.

Since Malaysia is experiencing a tropical climate, a flat roof is not recommended for modern houses. A cool roof shall be highlighted and implemented in the current or future practice of passive design. From these findings, the recommended cool color, such as white, is suitable for a roof pitch of 10°. Meanwhile, a steeper roof pitch is highly recommended for a black colored roof.

3.2. Ventilated roof approach

Ventilation should be treated as a design option instead of a universal requirement (Rose and TenWolde, 2002; Rudd and Lstiburek, 1998). Therefore, it is natural to expect that an unvented roofing system would affect the energy consumption of a house. Research efforts focus on implementing natural ventilation as an alternative source of energy saving (Puangsombut et al., 2007). Ciampi et al. (2005) concluded that a well-designed ventilated roof improves the overheating condition at the attic, particularly in buildings with moderate height and wide area.

Natural ventilation provides free cooling systems to its surrounding space and creates a comfortable condition for the occupants. It is widely known for its remarkable reduction of overheating due to solar radiation (Ciampi et al., 2005). A study discovered that roof ventilation plays an important role in controlling the roof surface temperature (Ismail et al., 2012). The indoor temperature could be reduced from up to 8 °C by providing an opening on the roof surface (Ibrahim et al., 2014b). The ventilated roof approach focuses on the natural method of air circulation. There are two types of natural ventilation, which are wind-driven ventilation and stack ventilation. Natural forces of the wind cause wind-driven ventilation, while stack ventilation results from the existence of temperature differences.

Table 2 Minimum cool roof requirements.
Source: Urban and Roth (2010).

Roof type	Solar reflectance [3-year aged]	AND	Thermal emittance [new or aged]	OR	Solar reflectance index (SRI) [3-year aged]
Low slope	0.55		0.75		64
Steep slope	0.20		0.75		16

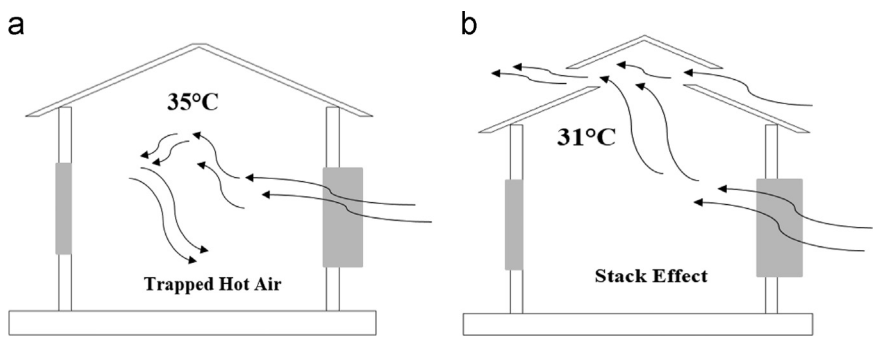

Fig. 3 Condition of air movement with and without stack effect.
Source: Towards a low-energy building design for tropical Malaysia (Abdul Rahman et al., 2009).

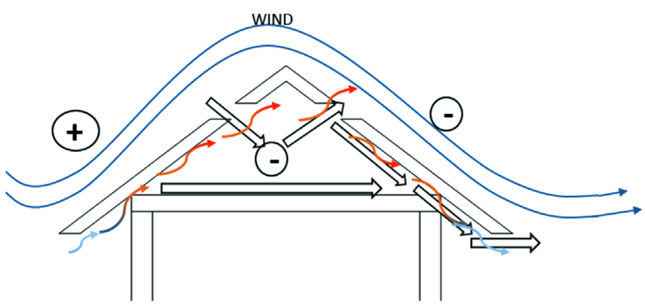

Fig. 4 Air flow in and out through windward and leeward openings.
Source: Attic Ventilation (US Department of Energy, 2011).

Natural ventilation is always a good choice since it depends on the natural air movement and it is a cost-effective approach in designing a house. The ventilated air gap on the roof surface should be adequate to allow natural air movement (Endriukaityte et al., 2005). The optimal height of the opening could maximize the effectiveness of the ventilated roof. However, it depends on the wind speed at that particular location.

Al-Obaidi et al. (2014c) concluded that a ventilated roof would perform well during the increase of air velocity as the height or thickness of the air gap also rises. Furthermore, the air gap on the roof surface at an optimum roof angle could help in reducing heat transfer (Trinuruk et al., 2007). Qasim et al. (2010) showed that the increase of air gap spacing could lessen the amount of heat transferred from the roof surface. Air gap thickness of 20 mm significantly reduces the heat gained through the roof. The ventilated roof approach allows the house to experience the condition of both stacks and wind pressure effects.

3.2.1. Stack effect

Although all openings are closed in a traditional Malay house, the indoor air temperature is cooler than the outdoor climate, with a 1.5 °C difference and airspeeds remaining above 0.2 m/s, due to the ventilation from the louvers (Tinker et al., 2004). The stack effect occurs because of the hot air traveling from an area with low pressure to an area with high pressure. The efficiency of the stack effect depends on the ease of air movement inside the building (Abdul Rahman et al., 2009). Fig. 3 explains how natural ventilation, such as openings, and stack effect could help in reducing the indoor temperature.

Fig. 3(a) shows that hot air will be trapped if only one opening allows the air to move inside. However, no stack effect occurs in this condition. Fig. 3(b) illustrates the effectiveness of the stack effect in easing air movement that enters the house and throughout it. Fig. 3(b) also demonstrates the condition of the opening at the upper part of the house, which reduces the indoor temperature by providing space for air to move from inside to outside through the opening on the roof surface. The opening allows the stack effect to occur; hence, the opening at the upper part of a house should be included in passive design. It is important to allow the trapped air inside the house to flow out to the atmosphere via the opening at the roof surface. Shaded areas generally contain cooler air compared with those exposed to direct sunlight. The air flow increases similarly with the amount of solar radiation (Mathur et al., 2006). Thus, building orientation is important in enhancing the stack effect. A bigger area should be positioned at the shaded area. The cool air could help speed up the air movement to the upper part of the house. The rising of warm air lessens the pressure at the lower part of the house.

3.2.2. Wind effect

The wind effect could help extract the trapped heat inside the attic space through the Bernoulli principle, which usually occurs on the low slope roof. This phenomenon occurs due to the pressure difference. Wind flows over to the flat roof surface and exerts positive pressure on the windward wall; while negative pressure or suction takes place on the leeward wall and the walls parallel to the flow direction. A flat roof and a lower slope are likely to experience high local suction pressure along the roof (Baskaran, 2002). Fig. 4 shows the airflow through windward and leeward opening.

The negative pressure or suction occurs mostly on the roof surface. The suction pressure generates at any part on the roof, where it depends on the wind speed and direction, turbulence, building topography and geometry, architectural features, and so forth. Fig. 4 shows that air flows in and out through windward and leeward vents. The air flow helps in extracting the heat at the attic area by flowing in the air through the openings on the windward side and out through the opening of the leeward vents (US Department of Energy, 2011). Since pressure difference plays an essential role in carrying in and removing the air, this concept should be considered in passive design.

Researchers agreed on the capability of a ventilated roof approach to reduce the indoor temperature and minimize the amount of heat transfer (Endriukaityte et al., 2005; Trinuruk et al., 2007; Qasim et al., 2010; Al-Obaidi et al., 2014a; Ibrahim et al., 2014b). Proper design of a ventilated roof could also help in maintaining the indoor temperature within the thermal comfort zone, thereby reducing electricity consumption. In addition, the need to power up the mechanical cooling system becomes less necessary.

4. Conclusions

Implementing reflective cooling with optimum roof pitch and ventilated roof approaches in the current passive design of the roofing system could assist in the reduction and removal of heat gained at the upper part area, thereby reducing indoor temperature. These recommendations could lessen energy demands, which minimize the cost of generating electricity for cooling purposes. However, the traditional Malay house is the best instance that uses both stack effect and wind-driven concept in its construction. It is important to consider the adaptation of these perceptions into the current and future modern passive design of a house.

A reflective cool roof with an optimum pitch should be combined with the application of a ventilated roof in the improvement of the current passive design for modern houses, specifically for low-cost houses. However, the effectiveness of these recommendations also depends on the building orientation and type, climatic condition and weather, and topography. Designers should be aware in selecting the best approach to avoid inappropriate or unsuitable techniques that stimulate the overheating of indoor temperature and expend energy demands.

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