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Comparative Study of Passive Methods for Reducing Cooling Load

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Abstract

It is predicted that 3.2% annual rise of energy consumption in developing countries. This means that there is a need to reduce energy consumption. One of the methods is through reducing cooling load in buildings since opportunities are present in it. This study aims to investigate the existing methods for cooling load reduction and to compare and recommend the most suitable method for Malaysian conditions. Several existing methods for cooling load reduction were researched and after applying parameters such as effectiveness, availability of material and practicality of method's application, three methods were selected. These methods were wall insulation by polystyrene, single low-emissivity window glazing and white painted roof. CFD analysis using ANSYS© Fluent was then performed to observe the effect of temperature and energy consumption reduction. The case study was done on Seminar Room 1 in Heriot-Watt University Malaysia (Seminar Room 1). It was found that application of all methods used together has the most temperature and energy consumption reduction (0.980C and 9.5% monthly energy reduction). However, in terms of cost effectiveness, wall insulation was discovered to be the most cost-effective method. It was concluded that wall insulation is the most suitable cooling reduction method since it has second highest temperature reduction and the most cost-effective method.

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Keywords: Passive method ; cooling load; computational fluid dynamics(CFD);

1. Introduction

An increase of 48% in global energy consumption is expected to occur from 2012-2040[1]. It is predicted that energy consumption in developing countries (Southeast Asia, Middle East, South America and Africa) rises annually by 3.2% [2]. The increase in energy consumption results in more carbon dioxide emissions which is one of the greenhouse gases. An increase in concentration of greenhouse gases resulted in increase of Earth's temperature by 2°-

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4° Celsius which also raised the sea level by 30-60 cm [3]. Hence there is a need to reduce energy consumption as increase in it has negative impact to the environment.

About 20-40% of total energy consumption in developed countries is accounted for buildings [2]. Figure 1 shows that buildings are the second highest sector that consume energy in South East Asia. It can be observed from figure 1 that there will be around 60 Mtoe (697800 kWh) increase from 2013 to 2040 in building energy consumption [4].

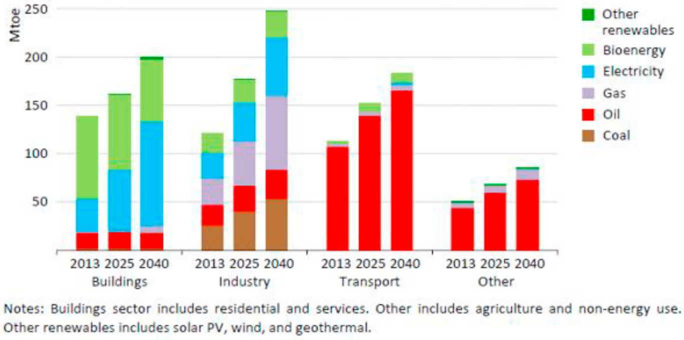

Fig. 1. Final Energy Consumption of Sectors in South East Asia [4]

About 64% of total energy consumed in a typical Malaysia office building is used for air-conditioning [5]. The use of air-conditioning is essential in the Malaysian environment as Malaysia is a tropical country with a constant average temperature of 28-32°C throughout the year [6].

Based on the statistics stated above, it could be observed that there are opportunities to save energy in the building sector. One of the methods is to reduce the cooling load in buildings. Cooling load is defined as the amount of heat that needs to be removed to achieve the designed temperature and humidity [7].

The main objective of this work is to study various methods of passive cooling in buildings and to compare and recommend passive cooling methods suitable for Malaysian conditions. Three methods selected out of various suggested ones are discussed in detail and compared in terms of efficiency in reducing cooling load and cost effectiveness.

2. Literature Review

Passive methods in cooling load reduction can be referred as alterations implemented to the building to reduce the cooling load. Meanwhile an active method is defined as improvements in the HVAC unit of the building [8]. In this work, only passive method would be discussed. The methods discussed here are segregated based on improvement brought about in various building entities.

2.1. Wall

The wall is one of the important parts of the building envelope. Thermal and acoustic comfort could be provided by wall and its thermal insulation value is crucial. The wall thermal insulation value is important as the building's energy consumption is heavily affected by it [9].

One of the research work depicts the use of polyethylene aluminum single bubble insulation to the wall of lecture hall and found out that this insulation reduces the inside temperature by 2.7°C and hence cooling load reduction was obtained [10]. Another researcher used polystyrene of 50 mm thick polystyrene on both external and internal wall of the apartment building in Hong Kong which resulted in 38% reduction of yearly space cooling load [11]. A 2cm thick polyurethane was installed on external walls of house in Qatar and up to 28% cooling load reduction is achieved [12]. All the methods mention above reduce both convective and conductive heat transfer coefficient which resulted in less heat moving into the room.

Installation of phase change material, material that stores latent heat,can be done in the interior wall of the building. Combination of phase change material along with night ventilation reduce cooling load. At afternoon, the phase change material absorbs the latent heat while it releases it back to the room at night. The night ventilation will then remove the heat out of the room. A simulation work showed that the use of phase change material along with night ventilation in Iran reduced 47% of cooling load [13]. However, the use of phase change material in Southeast Asia is uncommon as the temperature at night is constantly more than 20^{O}C. The heat released from phase change material might not be removed naturally and hence would require extra cooling [14].

2.2. Lighting

Minor adjustment to lighting system in a building could lead to cooling load reduction. A research in Korea showed that by simply replacing fluorescent light by LED light in a building would bring in a cooling load reduction of about 0.86% [15]. Although this is a very practical method of reducing cooling load (easy to implement and economic), the reduction achieved is insignificant compared to other methods.

2.3. Overhang

Another method to reduce heat gain from solar radiation is by installing overhang. Direct solar radiation is being prevented to enter window using overhang. The length of overhang affects the cooling load reduction.It could be observed that the longer the overhang, larger is the cooling load reduction [16]. Valladares-Rendón and Lo shows that the use of overhang could lead to cooling load reduction of 4.41% on 17th floor and 8.92% on 18th floor [17]. Meanwhile, Florides et.al analyzed that by using 1.5m overhang in a house resulted in 7% annual cooling load reduction [16]. Implementation of overhang however is not practical as additional construction is needed and might cause some parts of the building to be completely reworked.

2.4. Window

The properties of windowpanes that are usually taken into consideration are visible transmittance, U-factor and solar heat gain coefficient (SHGC) and should have low values for a reduced heat gain. The typical glazing that are applied in building is low emissivity glazing as it has good visible transmittance, low U-factor and low SHGC [18].

An analysis on the effect of using low emissivity glazing window and cooling load was done in buildings in Putrajaya, Malaysia by Nazi et al. and discovered that 3.1% cooling load reduction could be obtained [19]. Meanwhile Al-Tamimi and Fadzil discovered the usage of double glazing low emissivity glass ina high rise residential building located in Penang Malaysia reduced theannual cooling by 5.8% [20].On the other hand based on the study done in one of the high rise residential building in Turkey, usage of double glazed pyrolytic coated low emissivity window reduces 40.29% of annual energy consumption compared with usage of clear window [21].

2.5. Building Orientation

The building orientation is another factor which affects cooling load. The best orientation for a building is the one that would receive minimum amount of solar radiation in summer and maximum during winter. Countries located in equator such as Malaysia and Singapore receives strong solar radiation along east and west direction. A study by Wong and Li claimed that in Singapore, buildings facing north and south have 8.57%-11.54% less cooling load compared to the buildings facing east and west [22]. Research done by Gupta [23] in India supported the claim by Wong and Li. Meanwhile, Chenvidyakarn [24] suggested that by adjusting the shorter side of building against direction of strongest solar radiation and longer side of building to block the prevailing wind, cooling load can be reduced. The constraint faced with building orientation is that it needs to be applied before the building is built and any changes made to change the orientation after that is impractical.

2.6. Natural Ventilation

Applying cross ventilation to a building is one of the traditional method to provide thermal comfort as well as reducing indoor temperature. However, several limitations such as climate and wind direction prevent this method from being widely used [25]. The possibility of using natural ventilation is further eliminated by modern buildings which is mostly made up from glass as opening of windows are not allowed in these type of buildings [26].

2.7. Roof

Roof is a major part of building that receive/loss high amount of heat gain since it is very susceptible to solar radiation and environmental changes. Kotak et.al simulated that installation of roof top solar PV can decrease 73%-90% cooling load in urban areas in India. It is also suggested that at least 11.9 MWh of electricity can be generated annually from 90 m^2 PV roof [27]. The problem faced with it is that the installation cost is very high.

According to Alvarado et.al applying polyurethane as insulator and aluminum as reflector, reduces heat flux by 88% [28].

Light wavelength is reflected by white color so that less sunlight is absorbed and converted into heat [29]. By using the idea, simple adjustment on the roof to reduce cooling load is plausible by painting the roof with white paint. Applying white paint on roof has proven to bring in a drop of6.5°C on average in the room temperature as stated by Amer [30]. Evaporative cooling is a process that relied on the effect of water evaporation which acts as natural heat sink. One of the method to integrate evaporative cooling into building is porous roof. Raeissi and Taheri reported the use of shaded pond roof reduces 78.97% of cooling load in Iran [31]. The limitation of this method is that it is difficult to maintain the water level due to evaporation.

A few methods were to be selected out of the methods discussed above. The main parameters that needs to be considered to select the methods are the availability of the material in Malaysia, the practicality of applying the method in the existing condition and effectiveness of reducing the cooling load. However, it should be noted as the program used for simulation is ANSYS©, not all methods are plausible to be simulated (e.g. Venetian blind and overhang).

After reviewing the 3 main parameters, the methods selected were painting the roof white, low emissivity glazing window and polystyrene insulation on wall.

3. Methodology

The methodology followed for this work is discussed in brevity

3.1. Room modelling

One of the room in Heriot Watt University Malaysia is selected to be the case study room which is seminar room 1. It could be selected as the room has high window to wall ratio which is similar to modern office buildings in Malaysia. An optimal window to wall ratio for office building is estimated to be around 0.30-0.45.

A model of the room is generated using the software CREO 2.0 as 3D model is required. Input data for the room was measured by student as the university does not provide details for the room. The data were:

- Dimension of the room (Floor area of 83.31 m2 and wall height of 3.09 m)
- Dimension of the windows (1.34 m x 0.64 m)
- Number of window (25)
- Dimension of door (2.37 m x 1.47 m)
- Number of air conditioners (4)

Assumptions to the several data were also made. These assumptions were:

- Number of occupants in the room is set to be 20
- Air conditioning temperature is set to be 250C (ASHRAE Room comfort condition)
- All electronic appliances (computer, projector and lamps) and equipment are neglected
- Outdoor temperature data from meteorological department (310 C)
- Clear window is used

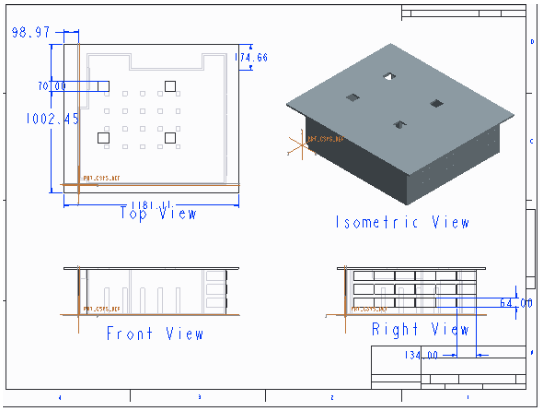

Figure 2 CAD Drawing of the Room

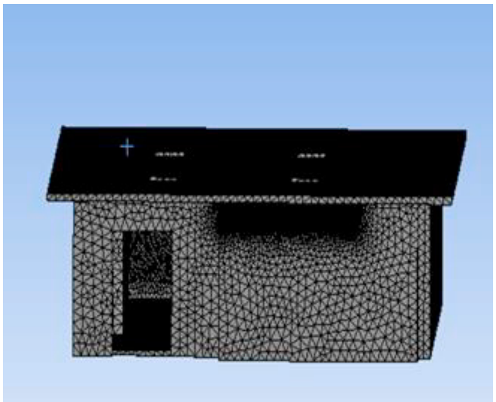

Figure 3 CAD drawing of ROOM meshed.

Next the boundary condition zone for the room was assigned. The 4 holes represent the air conditioner in the room and is also the inlet. Airflow of the air conditioner is set to be 0.34 m/s [9]. The door of the room is made into hollow so that it could serve as the outlet.

3.2. Temperature Analysis

After each simulation is done, the average temperature should be taken to analyse its effect to cooling load reduction. Assumptions were made before the formula for cooling load reduction could be determined. The assumptions were:

Steady-state heat transfer, Constant internal load and The fluids (air) property is independent of temperature

Following the assumptions, these equations can be used to determine the cooling load:

$$U_{Overall} = \frac{1}{h_1 A_1} + \frac{x}{kA} + \frac{1}{h_2 A_2} \quad (1)$$

Where U is overall heat transfer coefficient (W/m^{2}K), h is convective heat transfer coefficient (W/m^{2}K), A is area (m^2), x is wall thickness (m), k is thermal conductivity (W/mK).

$$Q_1 = U_{overall} A (T_2 - T_1) \quad (2)$$

Where Q_1 is heat due to convection and conduction in kW, T_2 is outside temperature in K, T1 is average temperature of room in K

$$Q_{radiative} = \varepsilon \, A \, \sigma \, (T_2^4 - T_1^4) \quad (3)$$

Where $Q_{radiative}$ is heat due to radiation in kW, ε is emissivity coefficient, σ is Stefan-Boltzmann constant (5.6703 10^{-8} W/m^{2}K^4).

$$Q_{total} = Q_{convective} + Q_{radiative} \quad (4)$$

Where Q_{Total} is the total cooling load of the room in kW

3.3. Energy and Cost Analysis

The total energy consumption can be calculated using the following formula:

$$E = Q_{Total} \; x \; Operating \; hours \quad (5)$$

Where E is energy consumption in kWh

The cost of energy consumption can be calculated by:

$$Electricity \; Cost = Total \; Energy \; Consumption \; x \; Electricity \; Price \quad (6)$$

The amount of money saved by implementation of the methods is then calculated using the formula:

$$Money \; saved = Initial \; power \; cost - power \; cost \; with \; methods \; applied \quad (7)$$

4. Results

Simulation studies were conducted like that done by Venkiteswaran et. al [32]. The results are depicted here in concise.

4.1. Temperature Contour of the Room

The three cases viz. Polystyrene-Insulated Room, White Painted Roof Room, Low-E Glazed Room were investigated separately. For brevity, only results of the combination of all methods is depicted and discussed.

The results are shown below are from the simulation using a combination of all the methods of passive cooling.

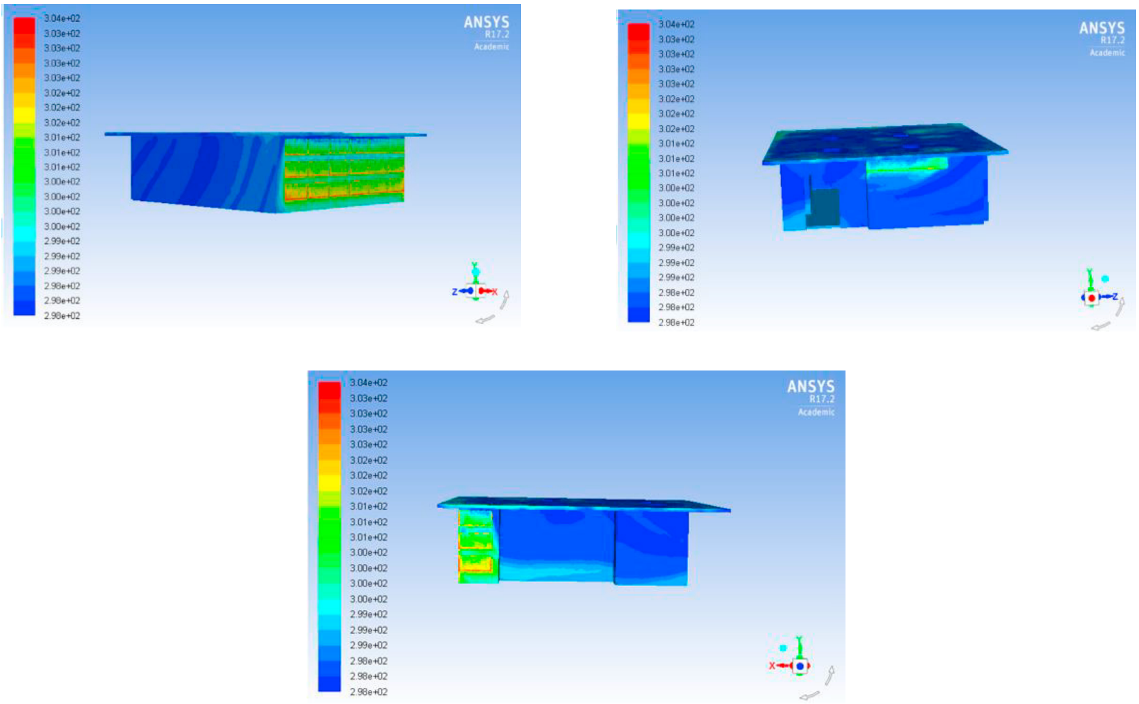

Figure 4 Temperature Contour of All Methods Applied, from three different angles.

It is observed that the air conditioners can cool the room efficiently as the temperature is evenly distributed. The temperature of the window and area of room near window is lowest compared with previous cases which could be observed from temperature contour. Average temperature for this case is 298.93 K which is also the lowest compared with all previous cases. This resulted in the lowest cooling load of the room.

The summarized results for each simulation are then shown in the table below:

Table 1 Table of Summarized Temperature Reduction for Each Method

Method	Average Temperature (K)	Temperature Reduction (^{0}C)
No Method	299.91	-
Wall Insulation	299.10	0.81
White Painted Roof	299.80	0.11
Low e-glass	299.55	0.36
All Methods	298.93	0.98

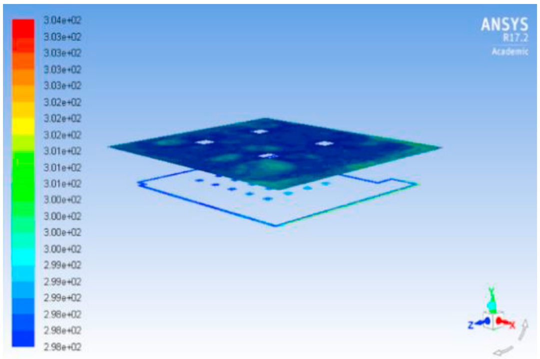

Figure 5 Temperature Contour of All Method's Iso-surface at normal human interaction level.

4.2. Energy Consumption Analysis

It is assumed that the air conditioners of the room operate for duration of 8 hours daily and there are 20 working days in a month. The room energy consumption for each method are then tabulated in the table below:

Table 2 Table of Energy Consumption

Method	Total Cooling Load (kW)	Monthly Energy Consumption (kWh)	Monthly Energy Reduction (kWh)	Percentage Energy Reduction (%)
No Method	4.95	792	-	-
Wall Insulation	4.63	740.8	51.2	6.5
Roof	4.87	779.2	12.8	1.6
Low-e Glass	4.74	758.4	33.6	4.2
All Methods	4.48	716.8	75.2	9.5

The result from table 3 shows that application of white paint give the least monthly energy reduction followed by single low-e glass glazing, wall insulation and all three methods applied and is further justified by the temperature reduction. Meanwhile by applying all three methods, highest temperature reduction is obtained and hence highest energy reduction is also obtained.

The electricity cost is then calculated based on the electricity tariff by Tenaga Nasional Berhad. The commercial tariff for the first 200 kWh is 43.5 cent per kWh and 50.9 cent per kWh for 201 kWh onwards [33]. The following table shows the monthly electricity cost for each method.

Table 3. Monthly Money Saving

Method	Monthly Energy Consumption (kWh)	Monthly Electricity Cost (RM)	Monthly Money Saving (RM)	Percentage Money Saved (%)
No Method	792	388.33	-	-
Wall Insulation	740.8	362.27	26.06	6.7
Roof	779.2	381.82	6.51	1.7
Low-e Glass	758.4	371.23	17.1	4.4
All Methods	716.8	350.05	38.28	9.9

From table 4, applying all methods to the room resulted in the most money saved monthly while painting the roof white resulted in the least money saved. This is due to applying all methods has highest energy reduction followed by wall insulation, single low e-glass glazing and lastly white painted roof.

4.3. Cost effectiveness

The cost of implementation of each method is then discussed. Application of single low emissivity glazing to clear windows costs about RM20 per square feet while purchasing of 50 mm polystyrene costs RM 7 per square meter. 5 litres of weatherproof white paint that could last until 5 year costs RM 190.

The total area of wall to be insulated is 93.8 m^2 and it cost around RM 656.6 for its implementation. Meanwhile the total area of window is 21.44 m^2 and this translate into RM 428.8 for its implementation. On the other hand, 1 litre of paint could cover an area of 12 m^2 and since the total area is 116 m^2, 2 buckets of 5 litres paint is needed. This cost about RM 380. The return of investment is then calculated as show in the table below:

Table 4. Cost Implementation and Return on Investment

Method	Monthly Money Saving (RM)	Cost of Implementation (RM)	Return on Investment (ROI) (months)
Wall Insulation	26.06	656.6	25
White-painted Roof	6.51	380	58
Low-e Glazing	17.1	428.8	25
All methods	38.28	1840.6	38

From table above, it is showed that the fastest return of investment is achieved by the implementation of white paint to the roof. However, it should be noted that the roof need to be repainted every 5 years (60 months). The ROI with application of all three methods together is about 3 years which is quite justified in terms of energy saving.

Therefore, based on current results, wall insulation is the most cost-effective method along with Low-e Glazing. Although it has longer return of investment compared with white-painted roof, the polystyrene does not need to be replaced every 5 years like the white paint.

5. Conclusions

Several existing methods of passive cooling load reduction were studied and compared based on some parameters. This resulted in selection of three methods out of all studied methods; wall insulation by polystyrene, white painted roof and single low emissivity window glazing. Computational fluids dynamics using ANSYS Fluent was then carried out to see the effect of implementation of each method to average temperature of the room and cooling load of the room. One of the room in Heriot-Watt University Malaysia (Seminar room 1) is chosen as the test room.

The results show that application of all three methods together produce highest reduction in temperature and cooling load (0.98^{0}C and 75.2 kWh) followed by wall insulation (0.81^{0}C and 51.2 kWh) then low emissivity glazing (0.36^{0}C and 33.6 kWh) and lastly white painted roof (0.11^{0}C and 12.8 kWh). However, in terms of implementation cost and return of investment wall insulation has the most economical effectiveness followed by white painted roof, application of all three methods and lastly low emissivity glazing. Therefore, the most suitable method in terms of effectiveness and economical reason is wall insulation by 50 mm thick polystyrene.

This research can be further developed by performing transient state of the model. This is mainly because outside temperature varies every minute. Hence by performing transient analysis of the model, wider range of results can be obtained.

In this research, direction of solar radiation is not considered. However, in reality, the direction of solar radiation keeps changing every hour. The solar radiation affects the temperature of the room as it is one source of heat gain for the room. Thus, hourly solar radiation direction should be considered for future research.

For this research, all furniture is neglected and all electronic equipment are turned off. For future research, both furniture and electronic equipment should be included in research as it might have effect to cooling load of the room

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