

Renewable Indoor Radiant Cooling And Earth Tube Heat Exchanger Hybrid For Thermal Comfort Improvement

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Keywords: Nocturnal cooling, radiant cooling, long wave radiation, sky temperature, regression model , energy efficiency, operative temperature, thermal comfort, Predicted Mean Vote

Abstract

This study investigates the applicability of radiant cooling system charged with night cooled water in combination with the ground as a heat sink source to cool down building in Sarawak particularly for low income building to a thermally acceptable level. An annual simulation using Energy Plus program for a low income home model retrofitted with radiant cooling system only charged with renewable night cooled water as cooling medium shows that 77% of the time the thermal condition could meet ASHRAE acceptable PMV thermal condition between -0.5 and + 0.5 . Simulation of radiant and earth tube system hybrid further improves the indoor thermal condition of the low income house significantly 100% of the time well below ASHRAE upper range of acceptable thermal condition. The hybrid system was able to improve the baseline uncomfortable operative temperature of 37°C to 28.5°C while meeting the average comfort zone upper limit for Malaysia of 30.1 °C. Simulation on energy spent shows that as much as 94% energy could be saved by using the hybrid system. This level of saving is not impossible as renewable night cooling of water was used to charge the indoor radiant cooling system.

Keywords: earth tube system, Energy Plus program, hybrid system, low energy, radiant cooling

1.0 INTRODUCTION

Building sector account for 40% of the total energy consumption and most of the energy is used to maintain an adequate thermal indoor climate condition by heating, cooling and ventilation (Nielsen, 2012). Typically 60% energy is used for building indoor air cooling in hot and humid region (Vangtook & Chirarattananon, 2007). High saving potential is possible with the current technology that optimizes the building envelope as well as the HVAC system. Radiant system integrated in building is able to provide such saving where 12% to 18% energy reduction is a minimum expectation for a radiant system in comparison to a convective system providing equivalent comfort (Watson & Chapman, 2002). Energy conservation of building using a radiant cooling system are on the order of 17% - 53% below the upper limit set by ASHRAE Standard 90.1-2010 (Uponor Inc, 2013). This is due to the efficient operating modes by allowing chiller to operate at a higher temperature and thus lower overall energy use. Temperature between 12.7°C to 17.2°C is the typical temperature for a radiant cooling system therefore allow mechanical chiller to operate in efficient range. However some researcher have restricted the temperature between 20°C to 25°C [5,6,7] due to dew point and condensation restriction in hot and humid climate and that lower temperature is advisable with the use of a desiccant dehumidification as a mean to improve the performance of radiant cooling panel in hot and humid climate. Ideal water temperature to be used in this region is in the range of 21°C to 25°C and in Malaysian climate the yearly minimum temperature could provide such cooling source. Due to the higher temperature operation range, there is potential alternative source for chilled water which may include fluid coolers, geothermal heat pumps or lake water (Uponor Inc, 2013). Combining radiant cooling system with a free cooling source can reduce energy consumption by 80-90% since traditional chillers can be eliminated and only electricity for circulation pumps is needed (Nielsen, 2012).

A high potential cool water source in this hot and humid region is the cooling of water via long wave radiation to the night sky. There are several ways or device that could be used to cool the water under the night sky to take advantage of the night radiation including evaporation and conduction heat loss effect. Literature survey have found studies done by others such as water flowing under flat plate collector [6,7], open tank experiment (Ali, 2007), water flowing openly over solar collector (Dan & Chinnappa, 1989), thermosyphon heat pipe radiator cooling (Chotivisarut, Nuntaphan, & Kiatsiriroat, 2012), roof pond experiment [10,11], converted flat plate solar collectors (Erell & Etzion, 2000), thermal absorber with water pipes numerical analysis (Sima, Sikula, Kosutova, & Plasek, 2014), hybrid nocturnal radiative cooling and direct evaporative cooling test (Heidarinejad, Farmahini, & Delfani, 2010), piped nocturnal radiator with phase change material (PCM) (Zhang & Niu, 2012), solar water heater absorber test (Dobson, 2005) and

others. Study by B.Azhaili et al. (Azhaili, Halipah, Omar, & Ooi, 2011) have showed that water temperature by morning after a night cooling process by trickling water over roof could reach lower than 25°C in Malaysian region. The process only requires minimum pumping energy therefore greatly reduce the energy consumption in comparison to a mechanical chiller. This night cooled water supply could be used as cooling medium for indoor radiant cooling system for building cooling.

Another method of building cooling that is rare in this region is the using the ground as a heat sink source. Studies have been done that showed building could be passively cooled by transferring the heat to the ground in several ways. The ground will act as a heat sink source to offset the peak temperature of the building indoor environment. Among other technology is the Ground Air Heat Exchanger (GAHE) which basically cools room air by forcing the ventilation air into the ground via pipes before entering the building. This method if building cooling have been showed to be a promising method outside of Malaysia as explained by Woodson et al. (Woodson, Coulibaly, & Traoré, 2012), Ascione et al. (Ascione, Bellia, & Minichiello, 2011), Florides and Kalogirou (Florides & Kalogirou, 2007), Leong et al. (Leong, Tarnawski, & Aittomaki, 1998), Man et al. (Man, Yang, Spitler, & Fang, 2011), Sharan and Jadhav (Sharan & Jadhav, 2003), Yu et al. (Yu, Li, Niu, & Yu, 2014), Yusof et al. (Yusof, Anuar, & Ibrahim, 2013) as well as Zimmermann and Andersson (Zimmermann & Andersson, 1998).

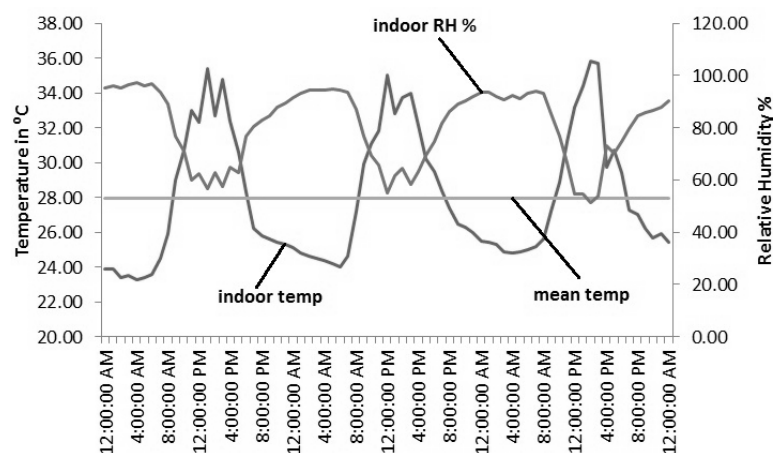
This technology were first tested by Reimann et al. (Reimann, Boswell, & Bacon, 2007) and Sanusi et al. (Sanusi, Shao, & Ibrahim, 2013) at the Peninsular region of Malaysia. Reimann et al. (Reimann et al., 2007) showed that forced ventilation air via ground pipes could deliver 27.2°C of air at the outlet when the outdoor air is about 30° C while Sanusi et al. (Sanusi et al., 2013) showed that ambient air between 35°C to 37°C pumped through earth tube could be reduced to as much as 6.4°C to 6.9°C as measured at the outlet of pipe buried at 1 m depth. While both studies focuses only the pipe outlet air temperature after travelling through earth tube in the ground, impact of earth tube application towards indoor thermal comfort of a full scale building was not demonstrated. Both studies was restricted to determine the outlet temperature of the earth tube system and there were no simulation or experiment conducted to find out the impact of earth tube installation on thermal comfort of any residential building in Malaysia. Ground cooling method has yet to capture the interest of local home builders where study and research on the application and performance of the technology in this region is still limited and still rare. Survey of the ground temperature for this purpose is also rare where 5m deep ground survey was done by Sanusi et al. (Sanusi et al., 2013) in the peninsular so far.

Both radiant cooling and earth tube system is designed to improve the indoor mean radiant temperature (MRT) as well as the mean air dry bulb temperature (DB). Both MRT and air DB temperature have the same influence on a thermal comfort of a person (Tang & Chin, 2013) therefore operative temperature (OT) which describe the average of MRT and air DB is normally used as an indicator of thermal comfort in a room. The room temperature in which occupants exchange heat by radiation and convection is expressed as the operative temperature (ANSI/ASHRAE, 2013). There are six factors that determine an acceptable thermal environment which are metabolic rate, clothing insulation, air temperature, radiant temperature, air speed and humidity. These factors are used as parameters to calculate the Predicted Mean Vote (PMV) which is another way to determine thermal comfort. PMV is an index that predicts the mean value of the votes of a large group of persons on the 7 point thermal sensation scale (ISO, 2005). The thermal sensation scale which spread between +3 and -3 indicates a person thermal sensation of hot (+3), warm (+2), slightly warm (+1) , neutral (0) , slightly cool (-1), cool (-2) or cold (-3). MRT and DB are the conditions of the thermal environment that is being addressed in this study to bring the room condition to certain comfort criteria preferably not higher than +1 on the thermal sensation scale.

Building developers nowadays construct residential homes with little regards to indoor thermal comfort and make assumption that the future owner of building will install a mechanical means of cooling the indoor environment. This is true for low income houses in the state of Sarawak where one can find single storey low cost terrace house and low rise low cost flat are the common type of low cost house being constructed in Sarawak. The single storey building is mainly for sale to lower income group whereas the low rise flats are normally used as transit house by the government of Sarawak to reduce squatters in the state. However the focus of this study is on single storey low cost house as this type of house is more widely constructed and made available by the government in a huge land reserve of Sarawak. A typical low cost house ranging from RM 50,000 to RM60,000 constructed by Sarawak Housing Development Corporation is available for low earners group with household income of less than RM5000 a month (HDC Sarawak, 2015). An example of a constructed low cost house in Sarawak and its measured indoor air temperature is shown in Figure 1. Measurement was taken in an occupied unit during clear weather to show the internal climate condition of the low cost house.



(a) Typical low cost house for low income earners in Sarawak (HDC Sarawak, 2015).



(b) Typical low income house indoor climate measure from 30/10/2014 to 1/11/2014.

Figure 1. Typical low cost housing indoor climate in Kuching Sarawak.

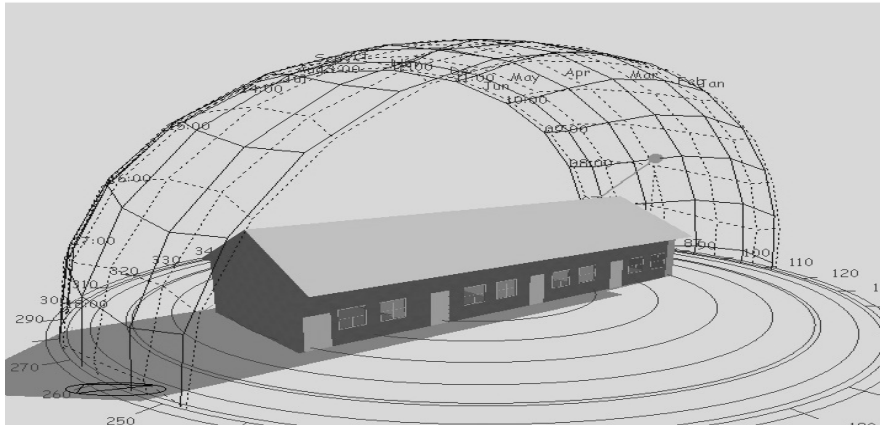
The peak temperature is somewhere between 34 to 36° C in the afternoon which is beyond the thermal comfort range of between 28 °C to 31 °C at air velocity of 0.8m/s in this climate condition as shown by Candido et al. (Cândido, de Dear, Lamberts, & Bittencourt, 2010) as well as beyond than what have been set by ASHRAE Standard 55 (ANSI/ASHRAE, 2013) and ISO 7730 (ISO, 2005). Investigation by other local researcher such as Halipah and Tinker (Ibrahim & Tinker, 2005), S.Rajeh (Rajeh, 1994), Nugroho (Nugroho, 2011), Kamar et al. (Kamar, Kamsah, Tap, & Salimin, 2012) as well as Normah et al. (Normah, Lau, & Mohd.Yusoff, 2012) have showed that typical Malaysian residential house including low income house failed to provide the minimum thermal comfort target. Study by Djamila et al. (Djamila, Chu, & Kumaresan, 2013) in a similar regional condition located in Sabah have showed from a survey that the thermal comfort temperature was at 30.2 °C. Another study by Hussein et al. (Hussein, Rahman, & Maria, 2009) have given an upper limit of 30.7 °C for an unconditioned building in Malaysia. Similarly study by Nguyen et al. (Nguyen, Singh, & Reiter, 2012) have put not more than 30°C as an upper limit for building in a hot and humid region. This strongly requires a strategy to allow for cheap and practical means to cool the low income house without passing over the burden of domestic cooling to lower income citizens.

The aim of this study is to give some insight on the applicability to utilise radiant cooling system charged with night cooled water combined with the ground as a heat sink source to cool down building in Sarawak particularly for low income building to a thermally acceptable level.

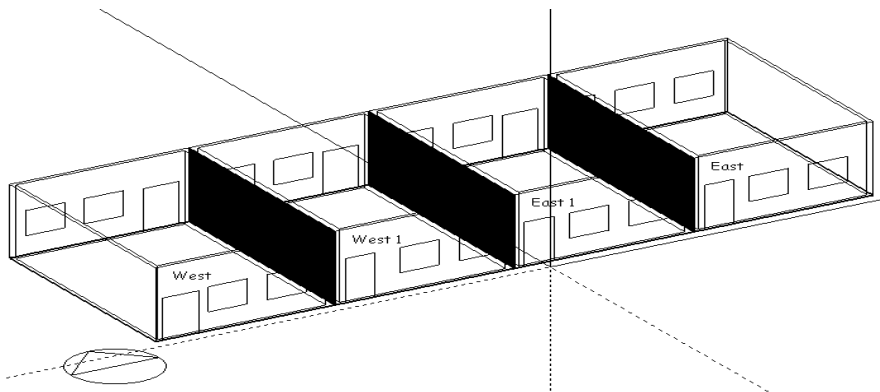
2.0 METHODOLOGY

2.1 Hydronic Radiant Panel and Earth Tube in Building Simulation using Energy Plus 8.1

Building energy simulation program or Energy Plus 8.1 program was used in this study to access the use of radiant surface cooling and earth tube system installed in a low income building model with 4 unit of houses as shown in Figure 2. Building shorter side was oriented to the east where the east wall is expected to receive the highest amount of solar radiation and therefore will experience the highest peak indoor air temperature. Each home unit was treated as a separate thermal zone as shown in Figure 2 with an area of 41.25m^2 for every home unit.



(a) 4 unit home building model with short side orientated to the east.



(b) 4 units home building with separate thermal zone for each unit.

Figure 2. Low income building model and its corresponding thermal zone.

For the purpose of this simulation the building thermal properties was set to a minimum requirement as per building energy standard of Malaysia (Standard Malaysia, 2007) as shown in Table 1 and was set as the base case model. The technical data for the radiant system and earth tube installation are shown in Table 2 and Table 3 respectively. The initial tank temperature was set to 24°C corresponding to the typical final water temperature from the night cooling process as describe in the introduction.

Table 1. Building envelope U value and Overall Thermal Transfer Value (OTTV) of model.

$\text{W/m}^2 \text{K}$

| | |
|---|------|
| Wall | 3.21 |
| Roof | 0.27 |
| Window | 5.89 |
| Door | 3.13 |
| Floor | 1.58 |
| Model OTTV, W/m ² | 30 |
| MS1525 recommended OTTV, W/m ² | 50 |

Table 2. Technical data for radiant system in building model.

| | |
|---|-----------------------|
| System Type as per ISO 11855-2 | Type A |
| No of Thermal Zone | 4 |
| Surface Name or Radiant Surface Group Name | Ceiling and wall |
| Hydronic Tubing Inside Diameter (m) | 0.012 |
| Hydronic Tubing Spacing (m) | 0.154 |
| Temperature Control Type | Operative temperature |
| Chill water tank volume per unit home (m ³) | 6.25 |

Table 3. Detail of earth tube installation in each unit of the building model.

| Field | Units | Model |
|---------------------------------|-------------------|---------------------|
| Earth tube type | | Exhaust |
| Pipe Material | | Clay/ concrete pipe |
| Pipe Radius | m | 0.04 |
| Pipe Thickness | m | 0.003 |
| Pipe Length | m | 150 |
| Pipe Thermal Conductivity | W/m.K | 1.8 |
| Pipe Depth Under Ground Surface | m | 1.5 |
| Design Flowrate | m ³ /s | 0.4 |
| Avg Soil SurfaceTemperature | °C | 28 |

Before the simulation run, the earth tube system was calibrated by comparing the simulated temperature of the air entering the thermal zone after passing through the earth tube with an actual experiment conducted by another study by Sanusi et al. (Sanusi et al., 2013). The ground interface temperature was set to 28°C based from the finding of the same study. Calibration result is shown in Table 4.

Table 4. Calibration of simulation model with an actual earth tube experiment by others.

| | Simulation Model | Study from (Sanusi et al., 2013) | Error |
|-------------------------------------|------------------|----------------------------------|-------|
| Outdoor Air DBT Peak Temperature °C | 33.8 | 34.1 | 0.9% |

| | | | |
|---|------|------|------|
| Earth Tube Zone Inlet Air Temperature °C* | 28.1 | 28.0 | 0.4% |
|---|------|------|------|

*Earth Tube Zone Inlet Air Temperature refers to the temperature of the air entering the zone after passing through the earth tube [C].

The first step in the simulation was to determine the indoor thermal comfort condition of the base case building. The simulation was then repeated to find out the thermal comfort condition of the same building fitted with radiant cooling surfaces as well as the earth tube system. The result is presented in term of indoor operative temperature as well as PMV index for both design day and annual simulation run.

2.2 Computer Programme: Validation against field data set

Discussion from energy modelling community Q&A website shows that field data to validate Energy Plus model is currently not abundant (<https://unmethours.com/question/10449/does-energyplus-need-to-be-validated-against-doe-22/>) According to Hong et al., (2013) empirical test for Energy Plus is still a growing area. However through DOE funding the Lawrence Berkeley National Laboratory (LBNL) is currently working to build flexible testbed facilities or Facility for Low Energy Experiments in Buildings (FLEXLAB). The Flexlab is primarily used to extract useful field performance data of wide range of building component such as lighting, controls, windows, façade and other building systems such as HVAC. Data collection from FLEXLAB may also be used to validate result predicted by Energy Plus while complying with Annex 58 quality procedures for dynamic full scale testing. Annex 58 is an ongoing project run by IEA under Energy in Building and Community programme that develops the necessary tools, knowledge and networks to achieve a high quality in situ dynamic testing and data analysis method. As validation of Energy Plus with FLEXLAB and Annex 58 is still in early stage and yet to have any software validation report, it is therefore proposed in this study to carry out a validation exercise of Energy Plus for increased confidence. Annex 58 have yet to publish any guideline of publication on the quality procedure involving full scale testing however reference will be made to other independent validation work of Energy Plus by other researchers addressing a few crucial thing such as accuracy of sensors, test environment etc.

The following describes the independent validation process of Energy Plus V8.1. Here a single storey semidetached house located in Kuching Sarawak was selected to be modelled in Energy Plus. The objective here is to compare the results provided by the Energy Plus with site measured data where in this case the result to be predicted and measured on site is the operative temperature of the building. The construction of the building uses typical material for construction such as brickwall, metal roofing with light insulation, concrete slab, glass window and timber door. Details of the building geometry, construction type with its thermos physical properties and building thermal load was surveyed and measured manually and included in the appendix. The building geometry was first created in Sketch Up as an open studio model and will be saved as an .osm file extension. Figure 3 shows the completed building geometry while Figure 4 shows the numbered internal spaces or thermal zones from TZ1 to TZ14.

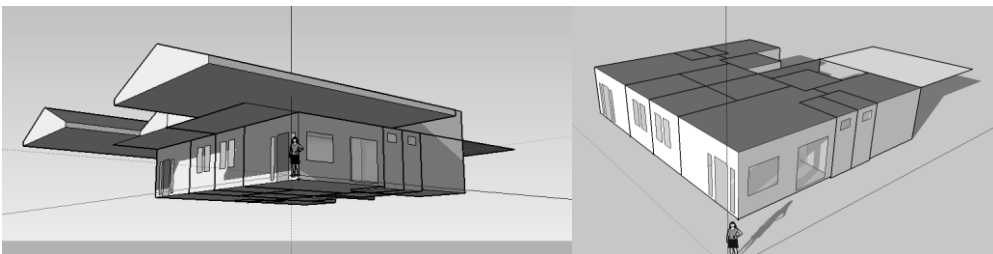


Figure 3. Building geometry constructed in SkectUp.

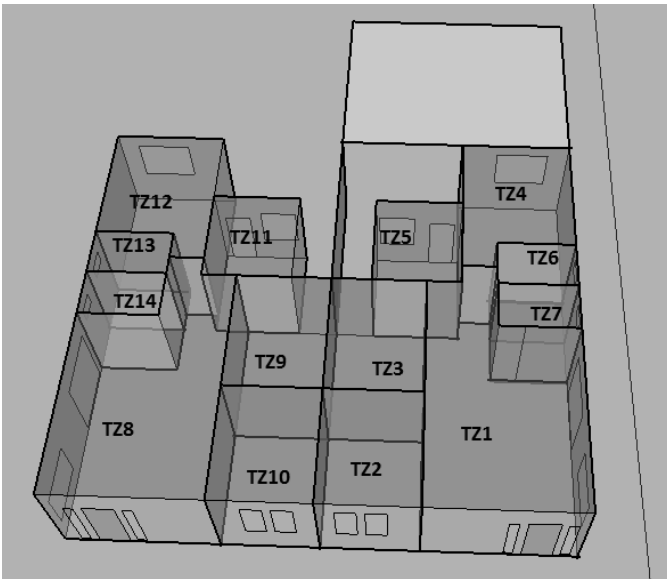


Figure 4. Building internal spaces.

The model was then loaded to Open Studio Application Suite a free interface to run Energy Plus, where amendments can be done on the construction material thermal physical properties, thermal loads including its schedules where necessary according to the required detail. Prior to running the simulation, the correct weather data or epw. extension file (Energy Plus weather format) was chosen so that simulation is run under the selected climatic region. Therefore the climatic information such as site wind speed, wind direction, site diffused and direct solar radiation rate, relative humidity and dry bulb temperature have to be corrected to reflect the actual climatic condition during which the site measurement is conducted. To complete the validation exercise, on site measurement was conducted between 11th and 13th October 2015. Thermal zone 6 was selected as subject of onsite measurement where hourly internal surface temperature of all 6 surfaces was recorded with a temperature data logger including the room air temperature and humidity level. At the same time measurement were also taken for the climatic condition such outdoor mean air temperature, outdoor air relative humidity, solar radiation rate as well as the outdoor wind speed. Other climatic info where needed could also be obtained from the local airport weather station. After completing the onsite measurement, the collected data was then analysed together with output from Energy Plus simulation. Given the uncertainty in the thermal physical properties of building construction material, several simulations were done using different set of input each time that was within the minimum and maximum value of the thermo physical properties of the building. A mean predicted value for room operative temperature (OT) was then established from this multi simulation run. Figure 5 shows that the in situ measurement closely compares to the mean predicted value by Energy Plus with a maximum error of 3.2% or $\pm 0.3^{\circ}\text{C}$.

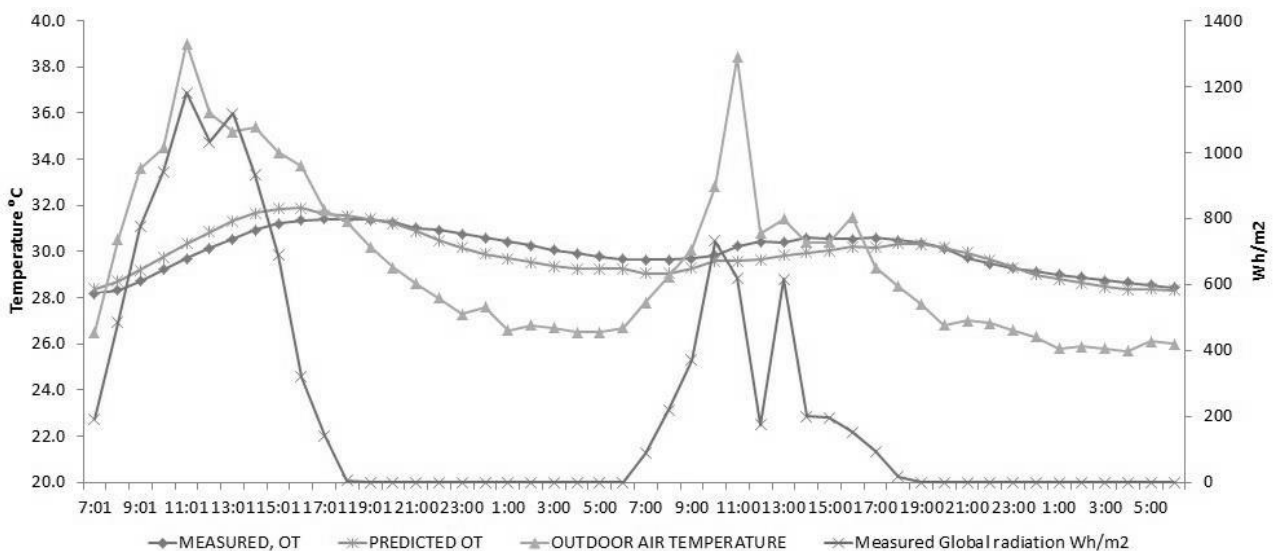


Figure 5. Comparison of predicted operative temperature of thermal zone 6 by Energy Plus and measured on site

3.0 RESULT

Annual simulation was conducted for building with radiant system only installed and the result of the simulation is shown in Figure 6. The annual operative temperature for the east facing home unit has been improved to 28°C most of the time and is within the acceptable range of 21°C to 28°C for condition spaces as specified by ASHRAE (ANSI/ASHRAE, 2013) with an air velocity of up to 0.2m/s. ASHRAE has specified that the upper limit could be increased to 31°C if the occupant control air velocity was elevated to 1.2 m/s. The average comfort zone upper limit in Malaysia is found to be 30.1 °C as shown by Sanusi et al. (Sanusi & Shao, n.d.). The radiant system therefore was capable of meeting both ASHRAE and Malaysian comfort zone upper limit. In term of heat balance, the radiant system which was charged with night cooled water of 24 °C have resulted in lower indoor ceiling and wall surface temperature. Radiation heat exchange takes place between the cool surfaces and short wave radiation of lights, transmitted solar as well as long wave radiation with other internal surfaces. Apart from the radiation heat exchange, convection heat exchange also take place between the cool surface and the zone indoor air. The low zone surface temperature as well as air temperature resulted in lower and acceptable operative temperature of 28 °C.

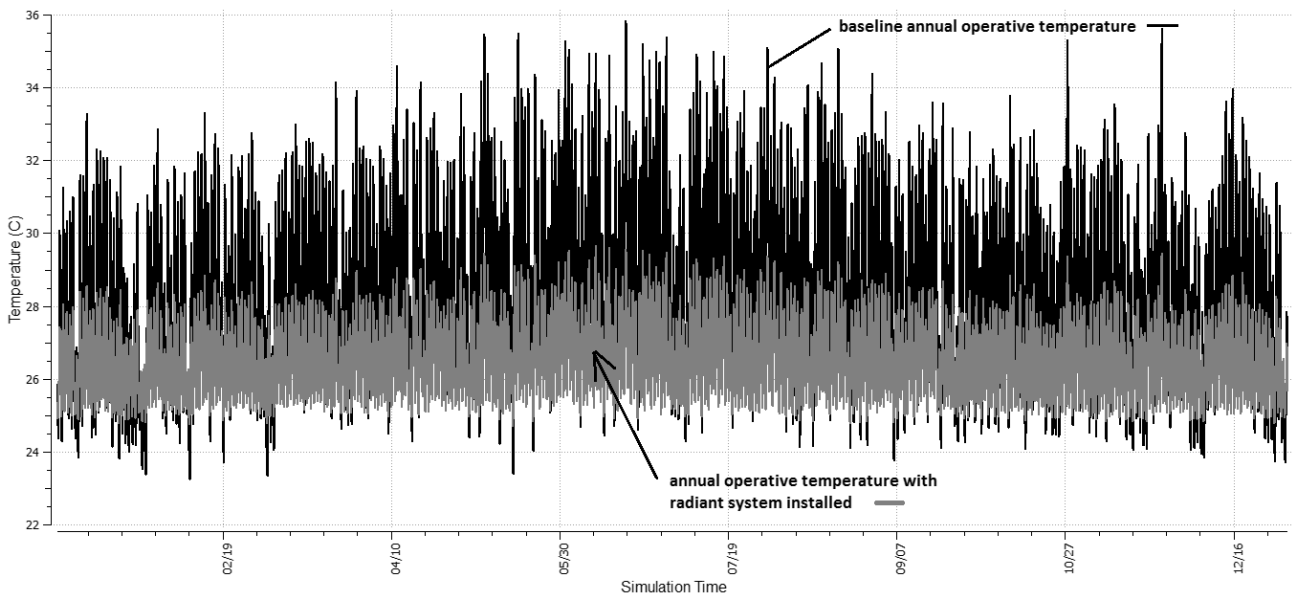


Figure 6. Annual operative temperature comparison of baseline model with radiant cooling system only.

On the other hand, Figure 7 presents the annual operative temperature for the same home unit with earth tube system only present to provide indoor cooling. The earth tube system was design to precool ventilation air before entering the zone thus providing a cooler air temperature. However the precool air was not sufficient to cool the zone surface through convective cooling. Air has a lower heat transfer capacity compare to water used in radiant system cooling. Radiant system using water circulator in place of a fan to move air use less energy and still give the same amount of heat transfer as well (Uponor Inc, 2013). The operative temperature was improved slightly however not able to meet the comfort zone upper limit as the mean radiant temperature was not addressed.

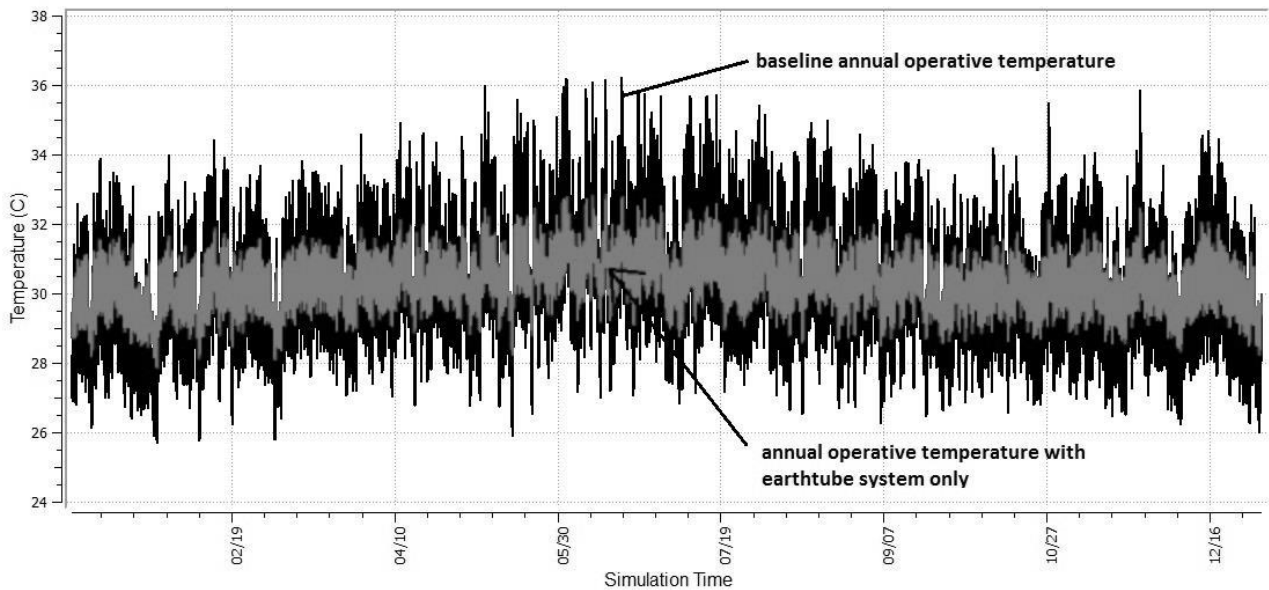


Figure 7. Annual operative temperature comparison of baseline model with earth tube cooling system only.

Figure 8 presents the annual operative temperature provided by the hybrid system which consist of both radiant system and eath tube system present in the building model. The presence of earth tube system in treating the ventilation air before entering the zone improves the operative temperature to about 1 °C lower. The hybrid system fitted in the building models provides significant cooling where building occupants could expect an indoor temperature of not more than 28 °C nearly 100% of the time all year. The hybrid system in this case was designed to improve both indoor surface temperature and mean air temperature therefore overall operative temperature.

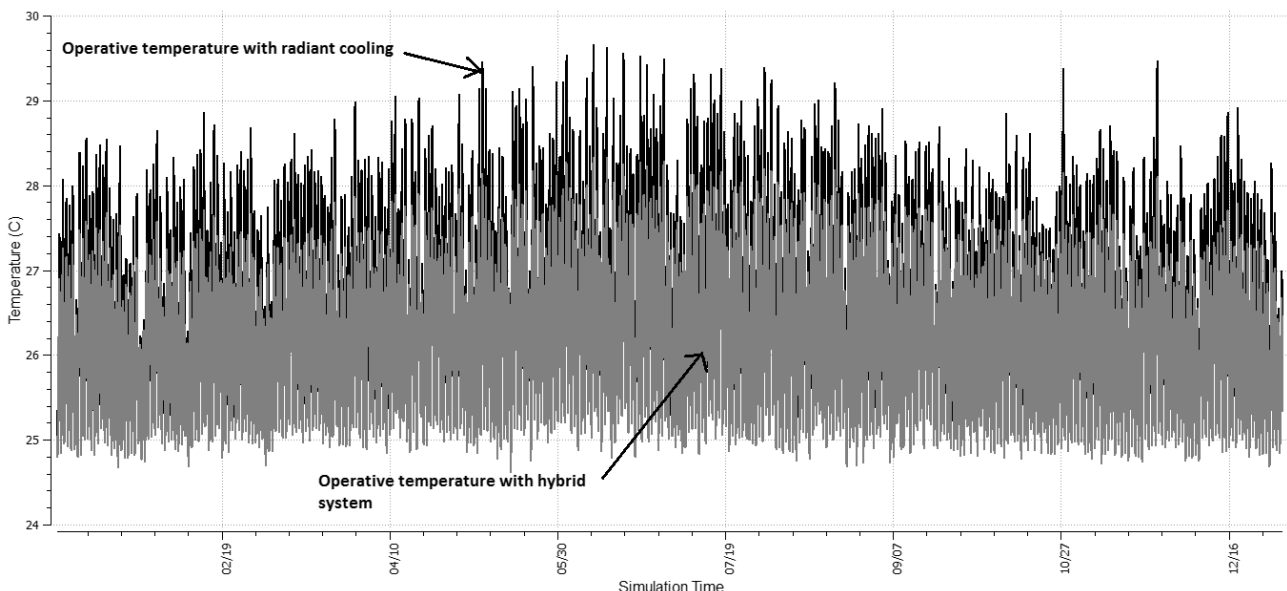


Figure 8. Annual operative temperature comparison for radiant system only model and hybrid system

For the same range of acceptable operative temperature, ASHRAE have specified the corresponding thermal comfort criteria expressed as Predicted Mean Vote (PMV) index of between - 0.5 and + 0.5 on the thermal sensation scale. Figure 9 shows the improved PMV after integrating radiant system into the building where about 77% of the time the PMV is within ASHRAE acceptable thermal condition. The calculated PMV was based on preset clothing insulation value of 0.7 clo, room air air velocity of 0.2 m/s, work efficiency of 0.3 as well as variable air humidity, air temperature and mean radiant temperature as

calculated by Energy Plus using Kuching Sarawak weather data file. ISO 7730 allows for extended acceptable environments such as category C PMV between -0.7 and + 0.7 that could be set as a criteria in design (ISO, 2005). Therefore about 99% of the time the low income house thermal comfort would have been met. ISO 7730 also specifies that the PMV can be allowed to be outside the selected range for certain time when considering the economic aspect of the cooling system operation. In order to save more on energy bills, it is up to the occupant to compromise on the thermal comfort by running the cooling system at shorter operation time.

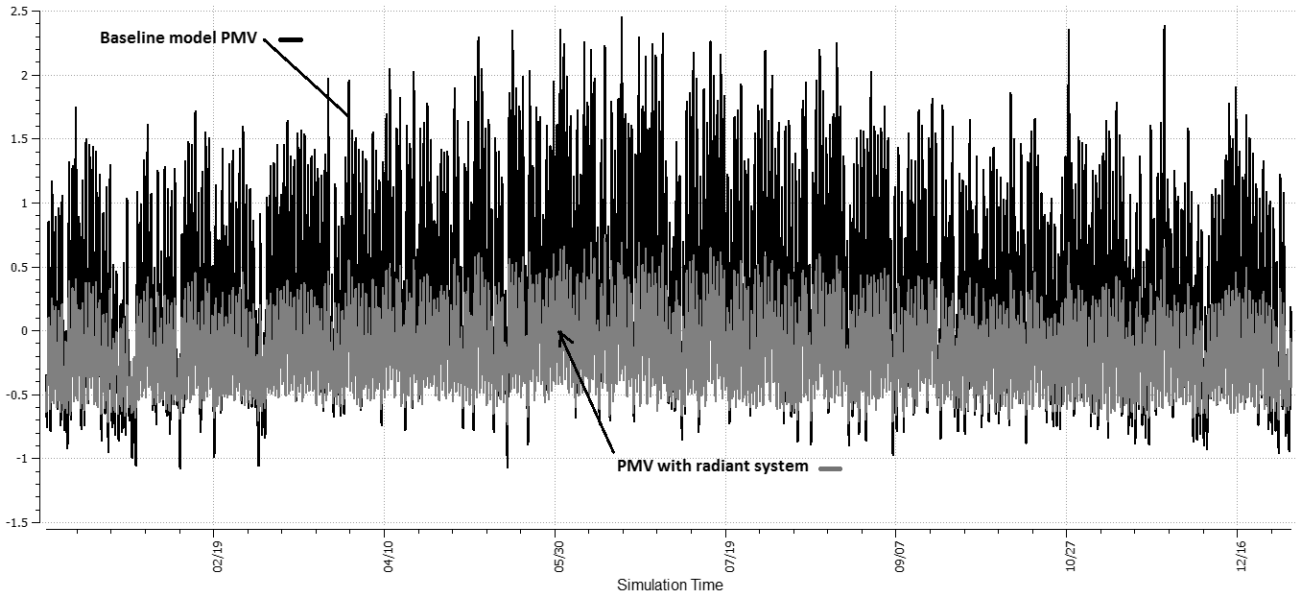


Figure 9. PMV comparison of baseline model and the radiant system model.

As for the hybrid system, the peak PMV was reduced significantly 100% of the time well below ASHRAE upper range of acceptable thermal condition of + 0.5 as shown in Figure. The cooler PMV value which takes place at night is not an issue as building occupant could adjust with higher clothing insulation value such as combination of underwear with outer garment such as long sleeve and legs with sweater and jacket which is equivalent to 1.3 clo (ISO, 2005). The operation time of the hybrid system could also be regulated by the occupant by early system shut off in the late afternoon to prevent overcooling.

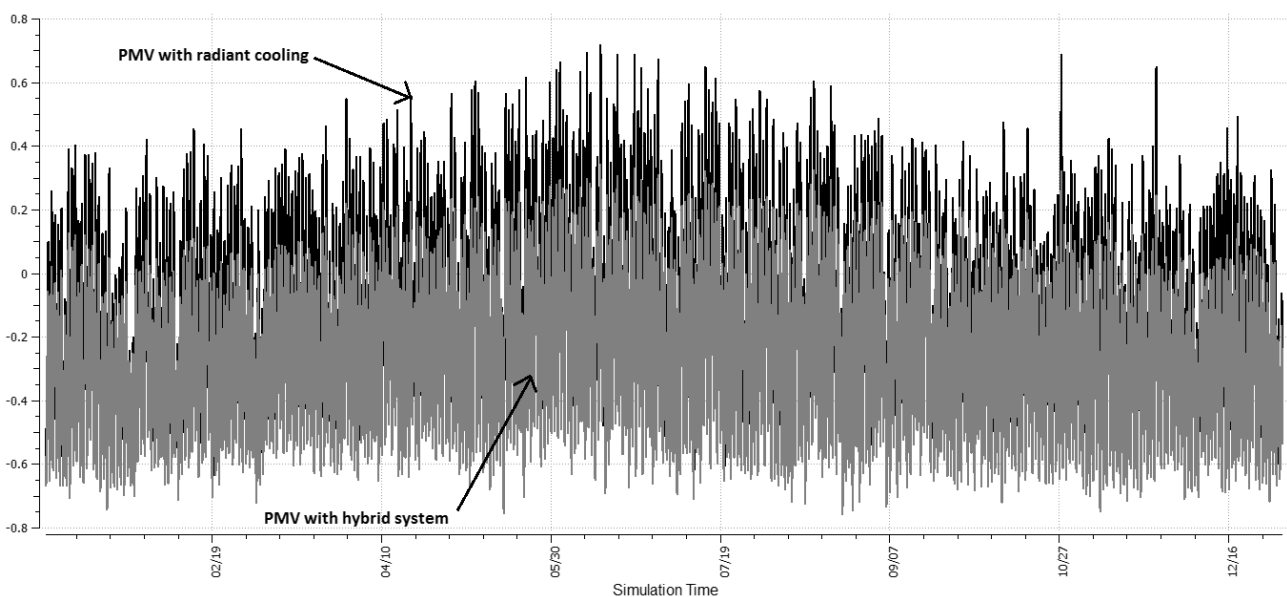


Figure 10. PMV comparison of radiant system only model and hybrid system.

The simulation was also conducted for a design day with a maximum dry bulb of 34 °C which correspond to 0.4% annual percentile of the design cooling condition for Kuching Sarawak as specified by ASHRAE (ASHRAE, 2014). In other word, for a 8760 hour in a year, on average 35 hr per year the maximum dry bulb of 34 °C is exceeded. Figure 11 shows the improvement in the operative temperature for east unit of the low income house where the extreme hottest peak operative temperature was reduced to about 30 °C or about 7 °C drops. This was possible with the usage of radiant system in place of a conventional air conditioning system. The radiant cooling system was integrated with a renewable source such as night cooling water which was kept in a 25m³ tank at a 24°C initial temperature. The water temperature in the tank had increased to about 26°C and by 7 pm the zone operative temperature begins to drop. It is also by this time the supply from the tank to the radiant system was cut off and recharging of the tank begins by night cooling process until early in the morning.

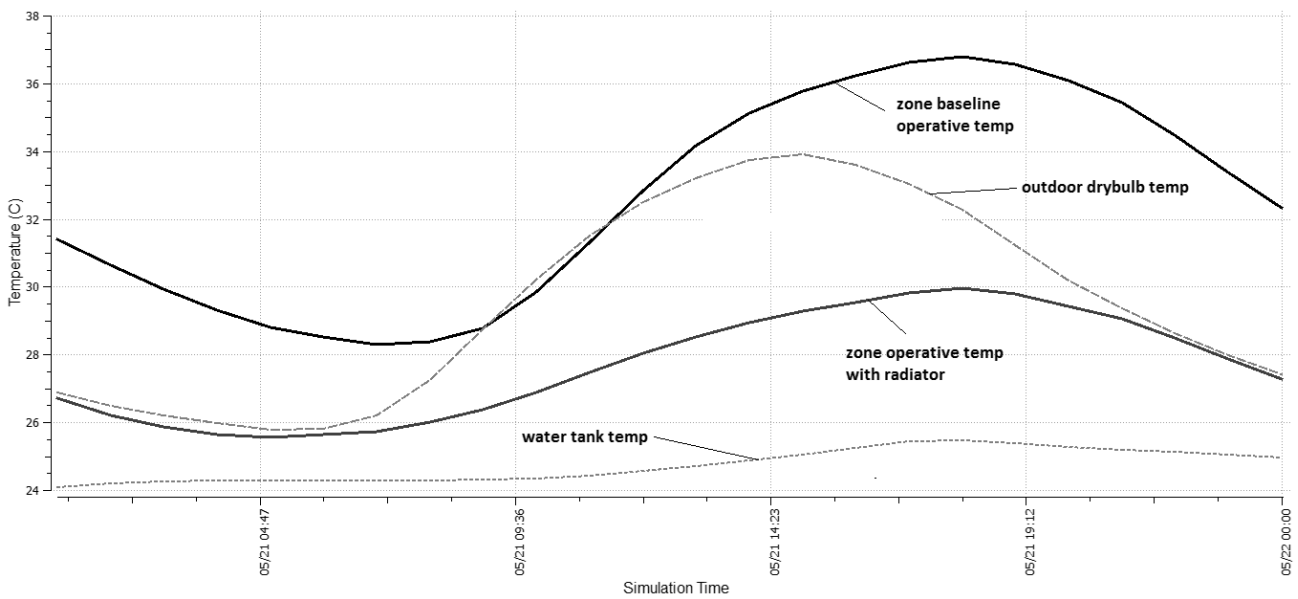


Figure 11. Baseline east unit zone operative temperature reduction by radiant cooling system with renewable water source.

With the introduction of earth tube system in combination with the radiant cooling system, almost 2 °C additional drop was provided as shown in Figure 12. This additional cooling was contributed by the earth tube system where the outdoor air was forced through the ground pipe first to be pre-cooled before it was circulated through the room or space. The earth tube was operated when the outdoor ambient temperature was above 30 °C.

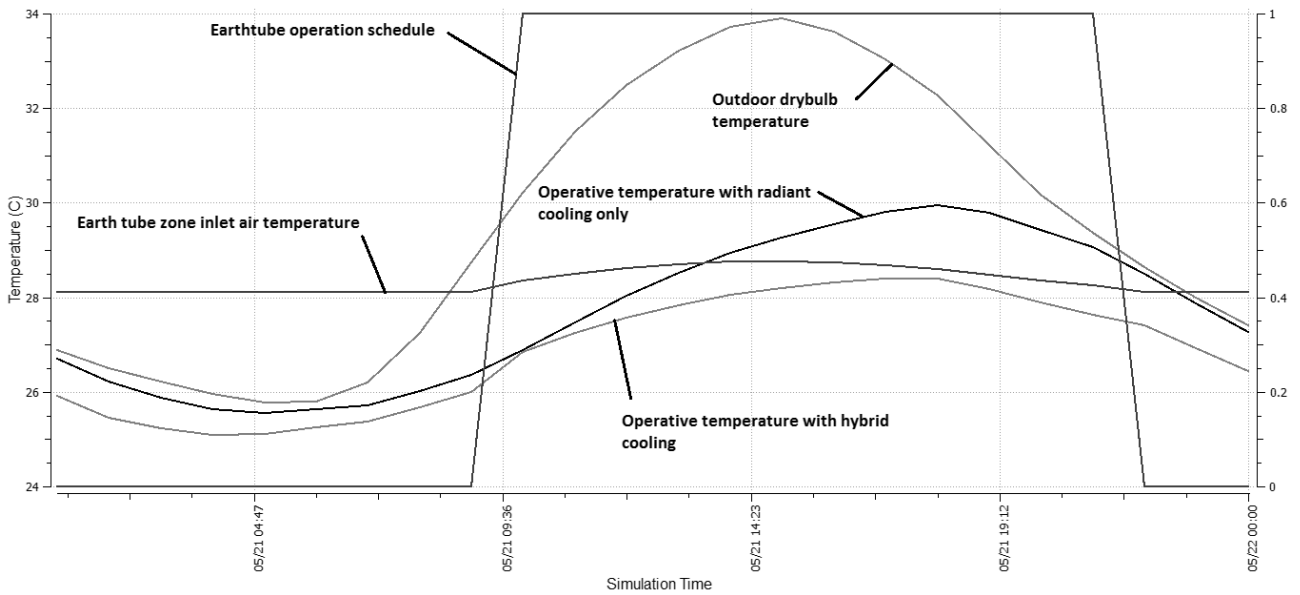


Figure 12. East unit zone operative temperature further reduction by hybrid system

Figure 13 presents the application and effect towards zone operative temperature of earth tube system, radiant system and hybrid system respectively. Application of each system independantly or as hybrid both deliver improvement to the zone baseline condition. However to meet the the comfort zone upper limit as set out by ASHRAE or ISO 7730 as well as Malaysian local comfort zone, application of radiant system independantly or hybrid with earth tube system is required particularly for this low income home unit.

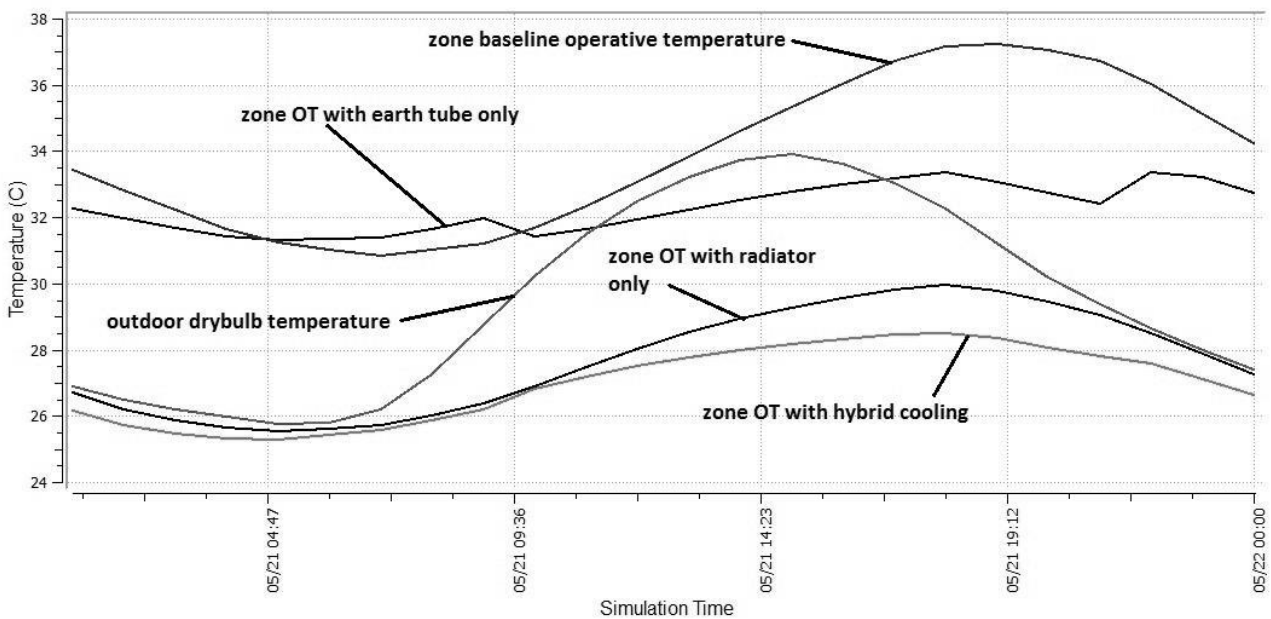


Figure 13 East unit zone operative temperature with the application of earth tube system, radiator system and hybrid system respectively

For this radiant system which has been integrated with a renewable energy source, energy was only required to run 2 units of pump for the demand loop and the supply loop of the radiant system. Additional power was also required to run the blowers associated with the earth tube system. Table 5 shows the saving in energy and money term that can be achieved by radiant cooling and earth tube hybrid in comparison to the conventional air conditioning system for every low income home unit. The simulation on the amount of energy spent shows that as much as 95% energy could be saved by using radiant system with night cooled water as cooling medium source. This particular system makes use of free chill water that was supplied from renewable night cooling system which only requires minimal pumping power. This level of

saving is not impossible as mentioned by radiant cooling industries expert (Nielsen, 2012) as Malaysian climatic condition still allows for night cooling of water to give final water temperature as low as 24 °C.

Table 5. Calculated energy savings for radiant system with free cooling source relative to conventional air cooling system

| Cooling system | Site energy GJ per annum | kWh | Yearly operation cost (RM) | Monthly operation cost (RM) | % of conventional air conditioning operating cost | Remark |
|---|--------------------------|-------|----------------------------|-----------------------------|---|---|
| Conventional air conditioning | 52.85 | 14681 | 4551 | 379 | 100 | 24 hrs air conditioning (mean air temperature set point of 24°C) |
| Radiant cooling with purchased district cooling supply or chiller | 25.11 | 6976 | 2162 | 180 | 48% | 24hrs operation |
| Radiant cooling with free night cooled water supply | 2.60 | 723 | 224 | 19 | 5% | |
| Radiant and earth tube hybrid | 3.32 | 923 | 286 | 24 | 6% | As above plus 9am to 9pm daily operation time for earth tube system |

4.0 CONCLUSION

The focus of this study is on single storey low income house as this type of house is more widely constructed and made available by the government in a huge land reserve of Sarawak. The indoor thermal condition is beyond the thermal comfort range that was set by related standards. Local researchers also have showed that typical Malaysian residential house including low income house failed to provide the minimum thermal comfort target. An annual simulation using Energy Plus program have showed that radiant and earth tube system hybrid improves the indoor thermal condition of the low income house significantly 100% of the time well below ASHRAE upper range of acceptable thermal condition as well as meeting the average comfort zone upper limit for Malaysia of 30.1 °C. Night cooled water has a great potential to be used as cooling medium for indoor hydronic radiant panel to provide thermal comfort. The amount of the energy spent to operate the hybrid system is at a small fraction of the conventional air system operating cost.

Acknowledgment

The authors would like to convey their thanks to the Centre of Renewable Energy consultants and technicians for their assistance in providing data as well as technical advice which was necessary to complete this paper.

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Appendix

Building geometry

| Parameter | Value |
|---|-----------------------|
| Total floor area (double unit home) | 164.00 m ² |
| Floor to ceiling height | 3.20m |
| Glazing sill height (bottom of window to floor) | 0.90m |
| Glazing head height (top of window to ceiling) | 0.85m |

Indoor thermal loads

| | | |
|-------------------|-------|-----------------------|
| Occupancy density | 0.028 | Person/m ² |
| Lighting (LPD) | 10.65 | W/m ² |
| Appliances | 3.88 | W/m ² |

Building all surfaces construction type

| Envelope | Construction type | Uncertainty in thermo physical properties | | | Source |
|------------------------------|---------------------------|---|-------|-------|---|
| | | Property | Min | Max | |
| Exterior wall /Interior wall | Cement mortar; | λ | 0.9 | 1.2 | (Roy & Roger, 2008) |
| | | ρ | 1700 | 1800 | |
| | | c | 840 | 1000 | |
| | Brick; | d | 0.01 | 0.014 | (Lomas & Eppel, 1992) |
| | | λ | 0.75 | 0.96 | |
| | | ρ | 1700 | 2000 | |
| | Paint | c | 650 | 840 | (Farzaneh-Gord, Rasekh, Nabati, & Saadat, 2010) |
| | | d | 0.105 | 0.115 | |
| | | λ | 0.05 | 0.2 | |
| Roof | Concrete Tiles; | λ | 1.25 | 1.75 | (Lomas & Eppel, 1992) |
| | | ρ | 2000 | 2300 | |
| | | c | 950 | 1100 | |
| | Fibre plaster ceiling; | d | 0.01 | 0.014 | (Santamouris, Synnefa, & Karlessi, 2011) |
| | | λ | 0.14 | 0.22 | |
| | | ρ | 760 | 1300 | |
| | Reflective Foil Laminate; | c | 800 | 1140 | (NZS, 2006) |
| | | d | 0.007 | 0.009 | |
| | Air space; | R value | 0.15 | 0.65 | generic R value |
| | Paint | R value | 0.15 | 0.21 | |
| | λ | 0.05 | 0.2 | | |
| | R | 0.4 | 0.6 | | |
| Suspended Slab | Concrete slab reinforced; | λ | 1.3 | 2.5 | (ISO, 2007) |
| | | ρ | 2300 | 2400 | |
| | | c | 800 | 1000 | |
| | Ceramic tiles; | d | 0.10 | 0.15 | (Lomas & Eppel, 1992) |
| | | λ | 1.2 | 1.4 | |
| | | ρ | 2200 | 2400 | |

| | | | | | |
|--------------|---|--|--|--|---|
| | Hardcore; Ground temp | c d λ ρ c d °C | 900 0.004 1.79 1800 612 0.04 26 | 1100 0.006 1.87 2600 812 0.06 29 | |
| Fenestration | Hardwood door; Green Tinted glass; | λ ρ c d λ ST SR | 0.17 650 2400 0.03 0.75 0.5 0.05 | 0.19 750 2600 0.04 1.2 0.7 0.2 | (Roy & Roger, 2008) Manufacturer specification |