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Numerical Modelling of Hybrid Vertical Earth Pipe Cooling System

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Abstract

Buildings consume a significant amount of energy and they are responsible for approximately 40% of the total world annual energy consumption. Most of this energy is for the provision of cooling and heating which can be reduced by adopting various energy efficient technologies. Passive air cooling of earth pipe cooling technology is one of them which assist to save energy in the dwellings and buildings for all subtropical zones. It is an approach for cooling specific area in a passive process without using any customary or habitual units such as fan, compressor etc. The paper reports a numerical model of hybrid vertical earth pipe cooling system by combining a vertical earth pipe cooling system with a green roof system. The numerical model was developed using ANSYS Fluent. Data were collected from three air conditioned modelled rooms one of which was connected to a vertical earth pipe cooling system, another to a green roof system and the other to a standard room (not connected to any earth pipe cooling or green roof system). Effect of air temperature, air velocity and relative humidity on the performance of hybrid vertical earth pipe cooling system was assessed in this study. A temperature reduction of 3.02°C was found for the vertical earth pipe cooling system when combined with the green roof system saving energy in the buildings.

Introduction

Energy has been the key part in the economic development, advancement as well as security of any country. Energy demand has increased worldwide significantly in recent years due to industrial development and population growth. The total world energy use was 524 quadrillion Btu in 2010, and that is expected to rise to 630 quadrillion Btu in 2020 and 820 quadrillion Btu in 2040 [1]. Among this energy usage, a significant amount is consumed by today's buildings. Almost all of the world population uses this energy at some point for own needs in their buildings for cooling, heating and lighting. Ventilation, cooling and heating can account for as much as 70% of this energy use [2].

Energy consumption has also been increasing in Australia with the world. Residential, commercial, agricultural and industrial sectors are using this energy. The energy consumption for the Australian residential sector in 1990 was about 299 petajoules (PJ) and that by 2008 had grown to about 402 PJ and is projected to increase to 467 PJ by 2020 under the current trends [3]. This represents 56% energy consumption increase in the residential sector over this period. The energy consumption is mainly due to space cooling and heating of the buildings. Australian houses account for 38% of their total energy consumption for heating and cooling purposes [4]. As per this projection, more energy will be required for maintaining thermal comfort. Therefore, it is essential to save energy in the Australian residential sector for a sustainable environment and economy. The residential energy consumption can be reduced by adopting either active or passive cooling techniques. The underground spaces used in this technique offer many additional advantages including protection from noise, dust, radiation and storms, limited air infiltration. Its effectiveness is largely influenced by temperature difference between ambient and soil temperature and thermal conductivity, followed by air flow inside the pipe, pipe length and diameter.

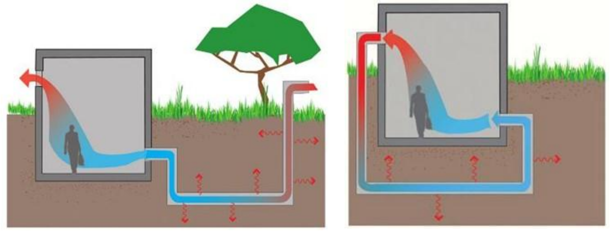
An estimation of thermal performance for earth pipe cooling technique is important to assess its cooling capacity. To measure the thermal performance, two thermal models were developed using two different piping systems for a subtropical climate in Queensland, Australia [5-7]. To assess the cooling capacity and thermal performance of this technology, a transient and implicit model was also developed based on numerical heat transfer and computational fluid dynamics [8]. The result revealed that a daily cooling capacity of up to 74.6 kWh can be obtained from the system. In some cases, the earth pipe cooling system is assisted with a heat pump as a heat exchanger located within the buried pipe. Al-Ajmi et al. [9] measured the cooling capacity of earth-air heat exchangers for domestic buildings in a desert climate. The result demonstrated that the earth-air heat exchanger have the potential to reduce 30% of cooling energy demand in a typical house in summer. The earth-air-heat exchangers were also used in cooling agricultural greenhouses [10-13].

The earth pipe cooling technique became increasingly popular in Europe and America after the oil crisis in 1973. There are many on-going researches on this technique using both simulation and experimental studies. However, no credible research is seen on the earth pipe cooling technique in combination with any other active or passive strategy (hybrid earth pipe cooling system). Therefore, this paper investigates the performance of a hybrid system - a vertical earth pipe cooling system combining with another energy efficient technology of green roof system as a passive cooling strategy.

Earth Pipe Cooling Technique

The technique utilizes the earth's near constant underground temperature to cool air for residential, agricultural or industrial uses. It works with a long buried pipe with one end for the ambient air intake and the other end for providing air cooled by the soil to the house. The pipe is buried underground at an optimum depth that could give most effective results. In winter, the soil temperature increases with increasing depth up to a certain depth and hence the use of earth as a heat source. Meanwhile, the soil temperature decreases in summer with increasing depth, which provides the use of earth as a heat sink. Adequate air flow is required into the buried pipe intake to generate cool air at the other pipe end to achieve thermal comfort. The earth pipe cooling system is of two strategies: direct earth contact and indirect earth contact. The direct contact involves partial or total placing of the building envelope in direct contact with the ground surface, and the indirect contact involves the use of an earth-to-air heat exchanger system through which air from indoor and outdoor of a building is circulated and then is brought into the building [14]. The direct earth-to-building contact ground cooling is a low maintenance passive cooling strategy with minimal heat gains and solar exposure. Considering the potential consequences of the direct earth contact ground cooling and the indirect earth contact ground cooling is less risky, the latter strategy has been adopted in this study.

Earth pipe cooling system can be organized into two ways: open loop and closed loop as shown in figure 1. In an open loop system the air comes through the buried pipes into the room and it passes through a ventilation system. In a closed loop system the air is constantly re-circulated from the buried pipes underground to the room.


(a)Open loop

(b)Closed loop

Figure1. Earth pipe cooling layout.

Green Roof Technology

Green roof is a rooftop garden, which is completely or partially covered with vegetation and a growing medium, positioned over a waterproofing membrane. It absorbs heat and acts as insulators for buildings, reducing energy required to provide cooling [15]. It may include extra layers such as a protection board, insulation, irrigation system, drainage and filter fabric. The green roof replaces traditional roofing materials with a lightweight, living arrangement of soil, compost, and plants. The plants can absorb significant amount of solar energy through their biological functions. It generates a wide range of social, economic and ecosystem benefits, for both public and private use.

Green roofs are categorized into two techniques: intensive and extensive, which are shown in figure 2. Intensive roofs utilize hardier plants that involve a growing medium of more than 300mm. Roofs of this system can support the different functions such as providing an outdoor garden space for food production. It includes a greater load of more than 150 kg/m^2 and requires maintenance in the form of weeding, fertilizing and watering [16].


(a) Extensive Green roof

(b) Intensive Green roof

(1) Waterproofing membrane (2) Drainage system (3) Filter fabric (4) Cellular confinement cells (5) Lightweight growing medium

(1) Drainage system (2) Waterproofing membrane (3) Filter fabric (4) Sand and (5) Lightweight growing medium

Figure 2. Green roof layout [17].

Extensive green roof is more common between the two techniques, which employs a shallow growing medium of less than 300mm. A well designed extensive green roof includes subsystems of drainage, plant nourishment and support, protection of underlying waterproofing system, water proofing system and an insulation system. The plants chosen for extensive roofs usually include succulents and moss. The design of extensive green roofs is geared towards low maintenance and limited irrigation. At most, maintenance occurs one to two times a year with limited access to the roof [18]. It can be distinguished by being low cost and light weight of 50-150 kg/m2. The extensive green roof technology has been adopted in this study due to these advantages.

Experimental Design and Measurement

Three shipping containers, each of dimension 5.63 m x 2.14 m x 2.26 m were refurbished and installed in the sustainable precinct at Central Queensland University, Rockhampton, Australia for the experimental measurement. They were connected to the vertical earth pipe cooling (VEPC) system, green roof system and standard room (without any of the systems). For the VEPC system, an excavation of dimension 8.1m x 1m was made for fitting the corrugated buried pipes vertically. The vertical pipe installation system shown in figure 3 consists of two Polyvinyl Chloride (PVC) pipes of outside diameter 0.125 m, also known as manifold. PVC pipes were set at the end points outside the container. The manifold contains 20 holes of 21mm diameter each to accept 20 tubes of 20mm each. 20 corrugated PVC tubes each with 6 meter length and 21 mm diameter were connected with the manifold. These corrugated PVC tubes with a wall thickness of 1mm were pressed (friction fitting) into the manifold in 5 rows, i.e, each row contains 4 corrugated PVC tubes. Each row is separated from one another by 100 mm and each tube in each row was separated from its neighbour by 20mm.

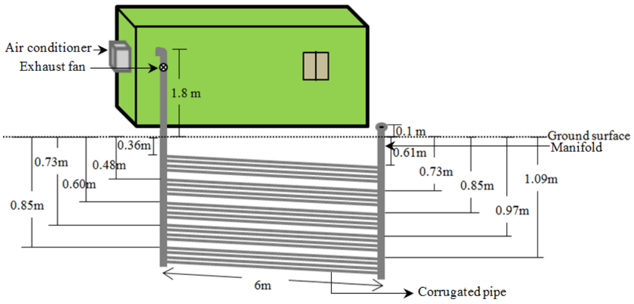


Figure 3. Vertical earth pipe cooling system

An exhaust fan was fitted in the manifold to suck intake air coming through another manifold. To increase the cooling effect of the system, small trees were planted to provide shade to the soil which also covered the pipes underground. Each roof of the containers of area 15m^2 was built by die-stamp corrugated steel sheets. A galvanized aluminium frame of 230mm was bolted onto the roof securely to hold the green roof materials. Waterproofing membrane, drainage system, filter fabric/geotextile, substrate and plants were used as the green roof materials for the experimental green roof system. The schematic diagram of the green roof system is shown in figure 4.

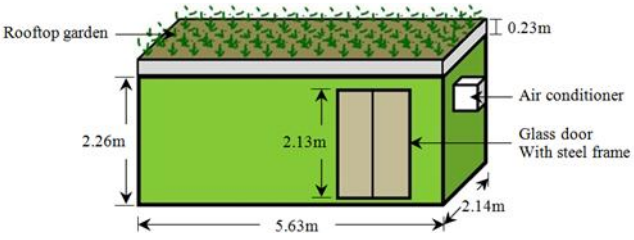


Figure 4. Diagram for green roof system.

A gutter was positioned on the south wall top for collecting excess water from the green roof. Elmich Versicell lightweight drainage module was used to capture high volume of water and protect the waterproofing membrane. Bioganic earth substrate of

Enviroganics was used for growing the plants. It has high water storage capacity, includes peat moss, composted sawdust, coco peat, washed sand, fertilizer and water retaining crystals. The plants selection for green roof must endure severe sun and hot temperatures, along with changes in humidity and moisture. Different types of local native plants were chosen to make the rooftop garden such as Rhoeo, Helichrysum Italicum, Callistenon Captain Cook, Dianella little jess, Eremophila Maculata and Grevillea Obtusifolia Gingin Gem. An auto-irrigation system was installed to water the plants.

Data Collection

The cooling performance of the vertical earth pipe cooling was assessed in combination with green roof (hybrid VEPC) system through a suite of experimental design, experimental tests and field investigation. Average room air temperature, air velocity and relative humidity were measured from all the modelled rooms to investigate their impact on room cooling performance. Average air temperature and velocity were collected at the pipe inlet of the VEPC modelled room. Data were collected in February, 2014 from 10:00 AM to 5:00 PM. The data for this time period was taken into consideration for this study as the maximum heat loads occurred in this period during a day. All data were logged at 5 minutes interval.

Modelling Approaches

RNG turbulence model was used to develop the model of this study. The modelling equations were described in the ANSYS Fluent theory guide [19]. A 2D geometry was created for this model and a typical mesh was generated using DesignModeler in ANSYS 15.0. A study was carried out to check the effect of the grid variation and to establish the optimum mesh size which ensures the consistent results for every mesh size. A 2D pressure-based-segregated solver was used for the modelling. The pressure implicit with splitting operators (PISO) pressure-velocity coupling scheme was adopted for numerical calculations. The PISO scheme allows for a rapid rate convergence without a significant loss of solution stability and accuracy [20]. Pressure was discretised with a PRESTO scheme because of its strong convergence capability [21]. Spatial discretization of second-order upwind scheme was used for momentum, turbulent kinetic energy and turbulent dissipation rate as the second-order discretization of the viscous terms is always accurate in Fluent.

Results and Discussion

Experimental results were obtained through a series of experimental tests and measurements. All the measurements were conducted in February of summer, 2014. The maximum temperature of 40.78^{o}C and minimum temperature of 23.98^{o}C was recorded outside the rooms as shown in figure 6. However, the outdoor temperature fell on 8 February, 2014 due to rainfall. The indoor room temperature varies from 24.70^{o}C to 26.38^{o}C for vertical earth pipe cooling, 24.45^{o}C to 26.88^{o}C for green roof system and 24.45^{o}C to 33.53^{o}C for standard room. Average indoor room temperatures of 25.23^{o}C, 25.01^{o}C and 26.63^{o}C were measured for VEPC, green roof and standard room. The VEPC and green roof technology reduced the temperature of 1.40^{o}C and 1.62^{o}C respectively in comparison with standard room.

An average air velocity of 2.72 m/s and air temperature of 24.31^{o}C were measured at the pipe inlet of VEPC modelled room. Relative humidity of the air has a noticeable impact on thermal comfort, especially in hot climates. The relative humidity of the rooms was measured to assess its impact inside the rooms, which is summarized in table 1. It was also found that the relative humidity of both VEPC and green roof system are higher than the standard room.

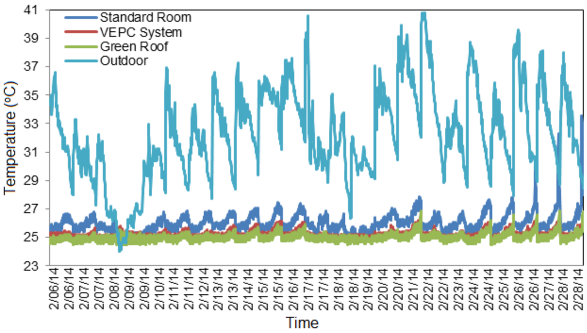


Figure 6. Performance of VEPC and green roof system.

	Indoor temperature			Outdoor temperature		
Modelled rooms	Min (^{o}C)	Max (^{o}C)	Avg (^{o}C)	Min (^{o}C)	Max (^{o}C)	Avg (^{o}C)
VEPC	24.70	26.38	25.23	23.98	40.78	32.32
Green Roof	24.45	26.88	25.01	--	--	--
Standard Room	24.45	33.53	26.63	--	--	--
	Relative humidity					
Modelled rooms	Min (%)		Max (%)		Avg (%)	
VEPC	57.43		92.44		75.43	
Green Roof	54.48		90.62		72.30	
Standard Room	39.89		87.9		67.39	

Table1. Experimental measurement for all the modelled rooms

The average room temperature and relative humidity range for both VEPC and green roof system were compared with ASHRAE standard 55-2010 in the centre for the built environment (CBE) thermal comfort tool using adaptive method. It was found that this level of temperature and relative humidity complies with the ASHRAE standard 55-2010 [22].

Performance of hybrid vertical earth pipe cooling (VEPC in combination with green roof) system was calculated numerically at different iterations. The solution was convergent at the iteration of 33,450. At this iteration, temperature and velocity profiles for hybrid VEPC system are shown in figure 7 and figure 8 respectively. The flow and thermal variables for the boundary and cell zone conditions were set on the boundaries of the model. Average air velocity of 2.72 m/s and air temperature of 24.31^{o}C collected from VEPC system were set at the pipe inlet of the boundary conditions. Average indoor room temperature of 26.63^{o}C measured from the standard room was put as the indoor room temperature and indoor roof temperature of 25.29^{o}C was set as the roof temperature of the model.

The predicted indoor room temperature of 297.60K (24.45^{o}C) was found at the midpoint of the room for hybrid VEPC system as shown in figure 7. This predicted temperature is 2.18^{o}C less than the measured standard room temperature of 299.78K (26.63^{o}C).

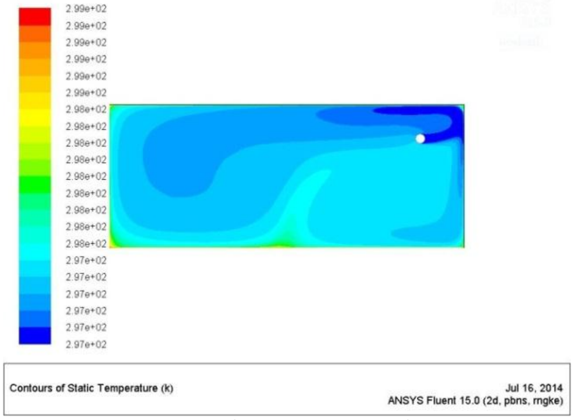


Figure 7. Temperature profile at the iteration of 33,450.

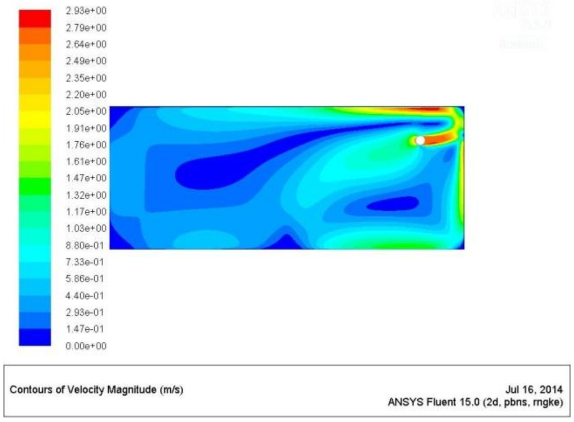


Figure 8. Velocity profile at the iteration of 33,450.

The numerical result shows a temperature reduction of 2.18^{o}C for hybrid VEPC system while the experimental result displays 3.02^{o}C using VEPC and green roof system together. There may be the main reasons behind this deviation: (i) there were no experimental shed involved both VEPC and green roof system together (ii) air pressure was dropped inside the pipe in VEPC system (iii) roof temperature measured from green roof system would be quite different, if the two systems are installed together with a single room.

Conclusion

Both earth pipe cooling and green roof system are well known as an energy efficient technology which uses geothermal energy to reduce cooling needs in buildings. Recent progresses on these technologies can help to enhance the indoor environmental quality of the buildings. The main purpose of this study was to measure the thermal performance of both these systems together. Hybrid vertical earth pipe cooling performance was evaluated by developing a thermal model for a subtropical climate in Queensland, Australia. RNG turbulence model was used to develop the thermal model. Impact of air temperature, air velocity and relative humidity were assessed on the room cooling performance using simulation in Fluent within ANSYS 15.0. Room temperature reduction of 2.18^{o}C was found in the simulation result for hybrid vertical earth pipe cooling system while 3.02^{o}C was observed in the experimental result for vertical earth pipe cooling and green roof system together. Manufacturers, industrialists and inhabitants will be benefitted to save energy in buildings using the hybrid vertical earth pipe cooling system. Further investigation is being undertaken in this study.

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