Journal of Natural Sciences Research www.iiste.org
ISSN 2224-3186 (Paper) ISSN 2225-0921 (Online)
Vol.8, Special Issue for ICNST 2018

Earth Pipe Cooling Strategy in Buildings: A Sustainable Approach

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Abstract

Abundant energy supply is one of the preconditions of economic growth, however, the economic growth in turn leads to higher energy consumption to support higher living standard. The energy demand is increasing at an alarming rate throughout the world, which may lead to scarcity of energy in near future. Most of this energy is used in buildings for heating and cooling. Therefore, it is important to adopt a system to save energy in buildings without using any habitual mechanical devices. Passive air cooling is such a system assists us to save energy in passive process. Earth pipe cooling strategy is one of them, which can cool a space with minimal energy. In this strategy, air comes through a pipe inlet and passes underground via buried pipes, transfers heat to the earth (soil), gets cooler and goes to the room through pipe outlet. This paper reviews the earth pipe cooling performance in different climates by an intensive literature survey. The performance was also compared with other common passive air cooling strategies used in buildings. The findings of the study recommend an optimum passive air cooling guidelines, and passive air cooling products to the occupants of the buildings.

Keywords: Cooling Performance; Passive Air Cooling; Energy Consumption.

1. Introduction

The energy and economic growth are potentially linked with each other. In one way, the sustainability of the economic growth greatly depends on the efficient use of energy. On the other way, the economic growth results in higher living standards, which ultimately leads to higher energy consumption [1]. According to the International Energy Outlook 2016 (IEO2016) report, it is projected that the total energy demand will increase by more than 48% from 2012 to 2040, as shown in Table 1. The table shows a slow rise in energy consumption in the OCED (the Organization for Economic Cooperation and Development) countries, which is only about 18%, due to the developed infrastructure and slower-growing economies. On the contrary, this demand is increasing fast among the non-OECD countries (outside the Organization for Economic Cooperation and Development), which is expected to rise by 71% from 2012 to 2040, where economic development and growing population lead to the higher energy demand. For example, an ever growing energy demand is observed in Bangladesh due to the high density of population and rapid urbanization [2].

About 40% of the total global energy is consumed in building sector [3], especially for the purpose of heating and cooling of the building envelopes. Conventional air cooling systems are accountable for consuming enormous energy as well as it creates considerable negative impacts on environment. In Bangladesh, the residential and commercial buildings are accountable for consuming 20% of the total energy used in cooling, heating and ventilating. It is projected that the reserve of the natural gas of Bangladesh will deplete in the near future [4]. The energy consumption and hazardous impacts on the environment can be reduced by adopting different strategies in buildings. The passive air cooling (PAC) system is one of them which can save energy in the passive process without using any habitual mechanical units. However, the efficiencies of PAC systems depend on various parameters such as local climates, building orientations, geographical location and so on. Therefore, it is very important to learn about the comparison of PAC systems considering different parameters for choosing the right PAC systems to achieve the highest performance as well as to avoid system losses.

Table 1. World energy consumption by country grouping, 2012–2040 (quadrillion Btu)

	2012	2020	2025	2030	2035	2040	2012–40 (change in percentage)
OECD	238	254	261	267	274	282	18.5
Americas	118	126	128	131	134	138	16.9
Europe	81	85	87	90	93	96	18.5
Asia	39	43	45	46	47	48	23.1
OECD with U.S. CPP	238	252	258	265	272	280	17.6
OECD Americas with U.S. CPP	118	124	125	128	132	136	15.3
Non-OECD	311	375	413	451	491	533	71.4
Europe/Eurasia	51	52	55	56	58	58	13.7
Asia	176	223	246	270	295	322	83.0
Middle East	32	41	45	51	57	62	93.8
Africa	22	26	30	34	38	44	100
Americas	31	33	37	40	43	47	51.6
Total World	549	629	674	718	766	815	48.5

The earth pipe cooling (EPC) technique is one of the PAC systems, which is a viable option to reduce the energy consumption. This technology involves long buried pipes in which outdoor air goes through one end, passes through underground pipes, and finally the air cooled by the soil comes into the building through the outlet end. It offers various additional advantages such as protection from noise, dust, limited air infiltration, radiation, storms and so on. To cool air in buildings, it utilizes the Earth's near constant underground temperature. As no comprehensive and/or comparative study is seen for this system, it is necessary to find the most efficient strategy among the commonly used PAC systems. Therefore, this study aims to investigate the EPC performance in comparison to other cooling technologies, and to recommend an optimum passive air cooling guideline which is expected to help in choosing the appropriate PAC strategies for the climate condition taken under consideration.

The remaining part of the paper is organized as follows. Section 2 introduces the different type of PAC strategies. An extensive comparison between these PAC strategies has been made in Section 3. Section 4 summarizes the key findings obtained through a comprehensive literature survey. Finally, Section 5 provides the conclusion of this work.

2. Passive Air Cooling Strategies

The passive air cooling has long been used technique to control the temperature of the buildings in hot and humid subtropical climate. This system is designed based on the building envelops which need to cool and the surrounding nature from where the system takes the benefit of natural resources. The PAC system delivers cooling in a passive manner where the conventional mechanical structure for example compressor, condenser are not used, suggesting that this system is the least expensive means of cooling a room with minimal environmental impact [5].

Different passive cooling strategies, namely, ventilation, wind tower, high thermal mass, high thermal mass with nocturnal ventilation, radiant cooling, phase change materials, evaporative cooling and earth pipe cooling are used in buildings. Among these strategies, natural ventilation, wind tower and evaporated cooling are found most commonly used strategies [5]. There is another passive cooling strategy called earth pipe cooling, which has been brought into focus by many researchers around the world in recent years. In the following section, we discuss these widely used strategies along with the EPC.

2.1. Natural Ventilation

Natural ventilation strategy is used for cooling the building without using the mechanical systems, where the natural forces induce the air flow inside the building and remove air from envelop of the building. This strategy is historically proven to have many benefits such as improving the indoor environment quality, reducing the power consumption of air-conditioning systems and low-cost maintenance [5]. There are two types of natural ventilation techniques used in buildings, namely single-sided ventilation and cross ventilation, as shown in Figure 1. The single-sided ventilation system is designed with one external façade, whereas, the cross ventilation is designed with at least two external facades placed on different walls within a room. Among these two techniques, the cross ventilation system is more efficient and widely used [5].

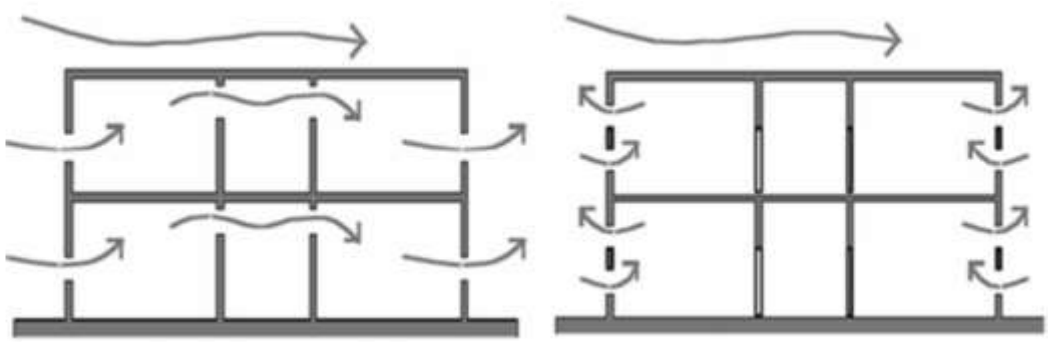

Figure 1. Schematic diagram showing cross ventilation (on the left)
and single-sided ventilation (on the right).

2.2. Wind tower

Wind tower or wind catcher is another passive cooling system for providing thermal comfort to the building occupants. It works on the principal of natural ventilation by engaging both wind driven and stack effect ventilation. Air enters via windward side which has a positive pressure coefficient and goes into the tower through the openings. The air then becomes cooled and noticeably heavier causing it to sinks down [6]. Subsequently, the cool air from wind tower passes toward envelops of the buildings and cools the atmosphere in the living spaces. Used air will disperse through the building and exit wherever negative pressure coefficients exist in respect to where the air entered (see **Figure 2**). The walls of the tower absorb the heat during daytime as the air exchanges for the whole day, and it discharges heat during night time which helps to heat the cool air inside the tower. The inclusion of the wind towers in the building envelop in the Middle East were in practice for more than three thousand years [7]. Conventional wind towers are still used in some countries in Middle East, for example Egypt, United Arab Emirates, Iran, Pakistan and Afghanistan [8].

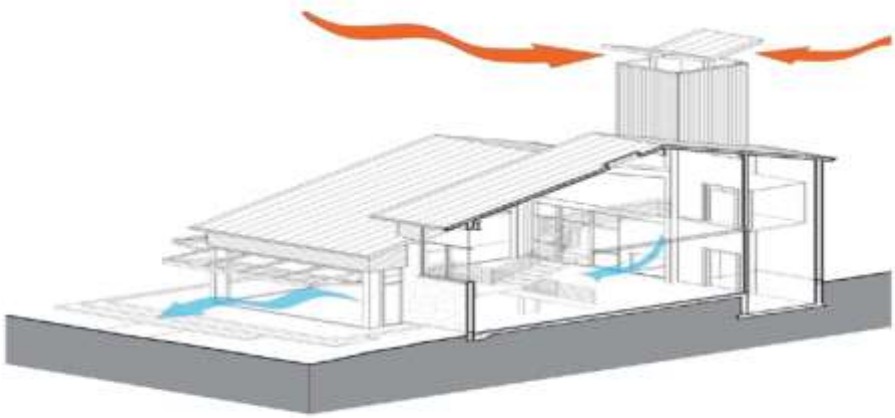

Figure 2. Schematic diagram demonstrating the wind tower system.

2.3. Evaporative cooling

Evaporative cooling is the process where the air temperature is decreased through the evaporation of water using fresh airstream from outside, as shown in **Figure 3**. During evaporation process of the water, the energy is lost from the air, and the temperature is decreased as the sensible heat in the in the airstream is exchanged for the latent heat of the water droplets [6].

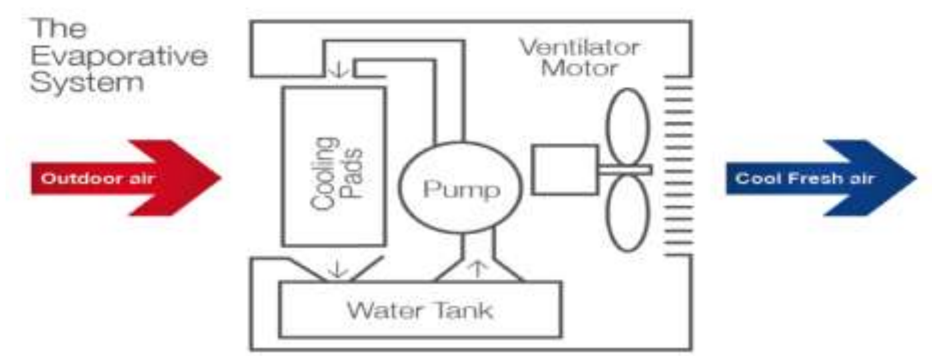

Figure 3. Schematic diagram demonstrating the wind tower system.

Fresh airstream from outside is drawn through humidified channels that cool the air through water evaporation. The cool air is then disseminated all over the room by a blower wheel. The four key elements that impact the dissipation rate are relative humidity, air temperature, airflow and surface area. Evaporative cooling can be characterized mainly in two ways which are indirect evaporative cooling system and direct evaporative cooling system. In the indirect evaporative cooling system, one side of the plate keeps wet using water continuously and this side of the plate is non-porous so that the other side of the plate remains dry. When the airstream passes on the wet side of the plate, the heat transfer occurs between air and the water and the evaporation of the water take place. This operation results in the sensibly cool air by transferring heat from outside air to the plate.

2.4. Earth pipe cooling

The earth pipe cooling (EPC) system takes the advantages of the consistent underground soil temperature for cooling air of the buildings in residential, agricultural and industrial sectors. The system works with a long-buried pipe in soil with one end of the pipe for the air intake, and the other end of the pipe is exposed inside the building for giving air cooled by soil. The buried pipe may be installed in the soil as vertical or horizontal or spiral shape. In summer, the soil temperature decreases in proportion to the increasing depth at a certain point of the earth, which permits the use of earth as a heat sink for the earth pipe cooling system [9]. On the contrary, in winter the soil temperature increase in the proportion to the increasing depth of the earth, which enables the system to use earth as heat source. The cooling tube systems are mainly two types: closed and open loops, as shown in **Figure 4**. The closed loop system is more efficient than the closed one because it does not exchange air with outside as opposed to the open loop.

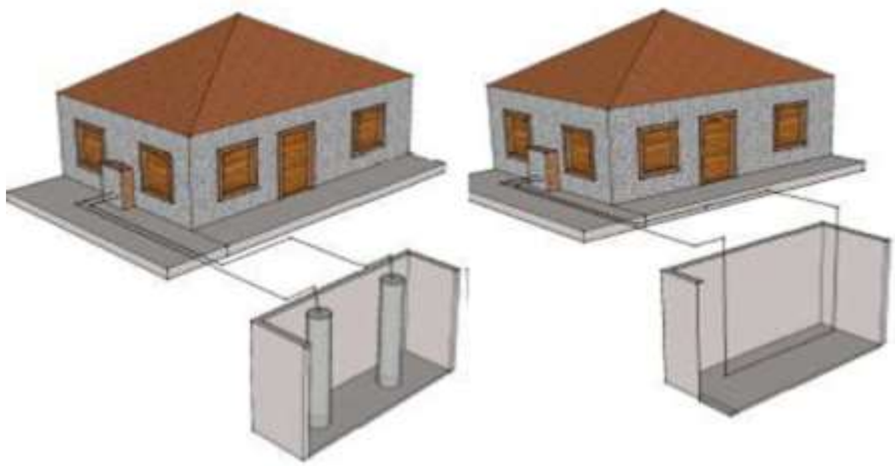

Figure 4. Diagram showing open loop (on the left) and closed loop (on the right) earth pipe cooling systems.

3. Performance of Different PAC Strategies

The performance of different PAC strategies depends on the local climates, building orientation, building materials and many more factors. Therefore, the utilization of appropriate passive cooling strategy is an incredibly preferred perspective with the raising concerns in regards to the cost-benefit impact of energy use. In the following, we investigate the advantages and shortcomings of different strategies depending on the local conditions.

The study conducted by Bhatia [10] suggests that the natural ventilation system is capable of reducing up to 40% of the total energy that is consumed by the conventional air-conditioned equivalent. In another study, Huang et al. [11] conducted an experiment on natural ventilation in an exhibition hall with a capacity of 350 persons. The lower seats in the hall were under the influence of natural ventilation where the temperature was recorded in a range of 23°C to 26°C. In contrast, the temperature in the upper seats of the hall was 27.5°C and higher where the natural ventilation was absent. Besides reducing the temperature, other profound benefits of natural ventilation include capital cost savings and increased fresh air supply. However, the performance of the natural ventilation may vary depending on many factors such as the exposure of the building to the wind and the outdoor temperature. For example, if the building is surrounded by other high raised buildings or the outside temperature is very high, the natural ventilation system would not be as efficient as expected. Other shortcomings of this system include free entry of dust, pollen, insects as well as the security limitations of the building. The natural ventilation system may cause adverse situations in hot arid and cold regions, hence has limited use based on the geographical locations.

On the other hand, the wind tower works well in the hot arid regions. For example, Khani et al. [8] found that the modular wind tower with wetted surfaces can diminish the air temperature and raise the humidity, respectively, by an average of approximately 10°C and 40%. Although the wind tower is inconvenient to use during the rainy season, its performance is less dependent on the wind speed as suggest by Bahadori et al. [12]. In addition, the wind tower with wetted surface has better control on dust compared to the natural ventilation system. However, the wind tower is useful only for a single unit while the natural ventilation may be used in multiple units in the high raised buildings [13]. It is worth noting that both these systems are ineffective in the absence of wind flow.

In contrast, the evaporative cooling system can work with the available air in the room and not necessarily require wind flow from outside. This system is usable in areas with various climatic conditions, for example, in areas with hot and dry atmosphere as well as in areas with the moderate atmosphere [14]. Experiment studies reveal that the evaporated cooling can reduce the indoor temperature up to 3 to 4℃ and save a substantial amount of energy consumed by the refrigerated air conditioner [5, 15]. However, it has relatively less cooling effect in hot and humid climates due to the high moisture content of the surrounding air. Also, the evaporated cooling can cause health hazard due to the development of bacteria, namely Legionella within the airstream supply [14], which may also be present on the wetted surface of the wind tower. Besides, evaporative cooling may cause an uncontrolled humidity resulting in discomfort so does by the wind tower.

The earth pipe cooling is less affected by the parameters which are found to downgrade the performance of other three systems since it takes the advantages of the consistent underground soil temperature. The EPC is an attractive choice for reducing the energy consumption of the building in most of the warm regions notably subtropical climates. This system is capable of reducing the temperature up to 3 to 4℃. The performance of EPC system is profound in summer, yet it helps to increase the temperature by 2 to 3℃ in winter [16], which is an added advantage in comparison to other passive strategies. Although the system requires a blower to move air through the piped system into the room, it does not need any other heavy mechanical units; for example, compressors. Thus this system does not cause much use of extra energy. Other advantages of EPC system include the protection from noise, dust, radiation, partial air infiltration etc.

However, there are some shortcomings of the cooling tube system, for example, the health hazard in a closed loop system. The open loop system does not have this health issue though. The installation cost of the cooling tube system is relatively high compared to other passive cooling systems, which is another disadvantage of this system. It is worth mentioning that this system does not require often repair and can function adequately for about 10 years or more without any further expense. Apart from this, as mentioned earlier, the EPC takes the advantages of the consistent underground soil temperature, and its cooling effect is regardless of the climate conditions. However, in some climates, for example, hot and arid, the EPC may not be able to produce a satisfactory outcome. In such climates, for an expected output, the EPC can be used as an additive alongside other passive cooling. Bansal et al. [17] suggests that by adding an evaporative cooler at the opening of the simple earth pipe heat exchanger, the performance of EPC can be improved. In another study, Bansal et al. [18] reveal that the performance of an EPC gets almost double once it is integrated with an evaporative cooling. Table 2 summaries the rationale, strengths and weakness of the above discussed passive cooling strategies.

Table 2. Comparison between the passive cooling strategies.

Strategies	Installation & maintenance costs	Results	Suitable climate conditions	Disadvantages
Natural ventilation	Very low	i. Can reduce up to 3°C ii. Lower 40% energy cost used by the air-conditioning systems	Low temperature region with available natural air flow	Free entry of dust, pollen, insects & security limitations
Evaporative cooling	Relatively high	i. Can reduce up to up to 3 to 4°C ii. May lower 50% of energy cost used by the air-conditioning systems	Hot & dry atmosphere	May cause an uncontrolled humidity & health hazard due to the development of bacteria
Wind tower	Relatively high	i. Can reduce up to 10°C ii. May lower around 60% of energy cost used by the air-conditioning systems	Hot & arid or humid areas	Not useful for high rise building
Earth pipe cooling	Installation cost is high but maintenance cost is low	i. Can reduce up to up to 3 to 4°C ii. May lower around 40% of energy cost used by the air-conditioning systems iii. Can be used as an additive with other PAC system in any climate conditions	Less dependent on local climate conditions	i. May cause health hazard in a closed loop system ii. May not work well in the high rise buildings.

4. Findings and Recommendations

The following findings were noticed through a comprehensive literature survey:

- Wind tower works best in hot arid climate which, however, is not an ideal type of climate for the natural ventilation.
- Evaporative cooling works efficiently in hot and dry climate, but it is less efficient in the hot and humid region.
- EPC also depends on climate conditions like the other three strategies mentioned above. However, it has minimal cooling effect in all climates since it takes advantages of consistent underground soil temperature.
- The EPC can be integrated with other PAC system to produce a satisfactory outcome when it fails to produce by itself in a particular climate condition.

5. Conclusion

Cooling capacity of several popular passive cooling strategies in different climate conditions were reviewed in this study. The review suggests that the cooling effect of these strategies depend greatly on the climate conditions as well as on the orientation of the building. Similar to other PAC strategies, the EPC system also found dependent on the climate conditions. A satisfactory outcome in such climate conditions can be produced by coupling two or more PAC strategies, for example, the EPC and evaporated cooling.

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