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Construction and Performance Analysis of an Earth-Air-Pipe Cooling System

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Abstract

The urge to develop new technologies that allow the use of sustainable renewable sources of energy is escalating evidently. This research introduces a developmental model of the earth-air-pipe cooling system that ushers a new side to the refrigeration cycle. This cooling system can be used for passive cooling of buildings and also for reducing the cooling load. A 7-feet deep and 30-feet long trench was dug for the experiment. The lowest temperature at that depth was recorded to be 26.27 °C. HDPE pipes - buried in the trench - were used as duct and a 1400 RPM, 2.13 CFS centrifugal blower was used to maintain a constant flow of air. The system had a COP of 1.78, 0.888, 0.267 at full, half and quarter load respectively. The results showed the validity and effectiveness of the experimental model. This can also be further developed and used in future researches and projects.

Keywords: Renewable source of energy, earth-air-pipe cooling system, passive cooling, COP.

1. Introduction

Nowadays, air conditioning is widely employed in industrial productions and for the comfort of occupants. It can be achieved efficiently by vapor compression systems but due to the depletion of the ozone layer and global warming by chlorofluorocarbons (CFCs) and to reduce energy consumption; numerous alternative techniques are currently being explored. One such method is the earth–pipe–air heat exchanger system, in which hot outdoor air passes through pipes that are buried underground.
Bangladesh is currently experiencing scalding summers with an average temperature of 30 *°C*. As the temperature increases, so do the energy consumption due to the use of air-conditioning system. A need for alternative studies for the cooling of buildings is pertinent to save energy and to reduce the detrimental effects on the environment. Therefore, this thesis aimed to enact a developmental project for a passive cooling system.
In an earth-air-pipe cooling system, outdoor air flows through underground pipes buried a few meters deep; using the soil as a heat sink where the heat of air is dissipated. As a result, the air becomes much cooler than the surroundings. The outlet air from the earth-air-pipe cooling system can directly be used for space cooling if its temperature is low enough with sufficient air flow to provide thermal comfort. Alternatively, the outlet air may be cooled further by the building's HVAC system. Since the climate of Bangladesh is hot and humid with an average temperature of 30 *°C* and relative humidity (RH) more than 75%, comfort for occupants is hard to achieve naturally. According to ASHRAE 55-2004, around 22 *°C* to 27 *°C* temperature and 40% to 60% relative humidity is appropriate for human comfort.
In this thesis, our main contention was to evaluate the feasibility of this type of system in the cooling of air in our country. The soil temperature was tested at 5 *ft*, 7 *ft*, and 10 *ft* depth using an Arduino system. The temperature at 7 *ft* underneath the soil was 26.27 *°C*. As the temperature remained almost the same at 7 *ft* and 10 *ft*, a trench was cut with a depth of 7 *ft* and a length of 30 *ft*. HDPE pipes were used for economical purposes, although steel pipes could have done a better job. For supplying air to the pipeline at a constant rate, a blower was used. An Arduino system measured the inlet and outlet temperatures.

2. Literature Review

Sodha et al. [1] constructed an Earth-Air tunnel system for heating and cooling of a building complex of a hospital in India. They found that an 80 *m* long tunnel having a cross-sectional area of 0.528 m^2 had a cooling capacity of 512 *kWh* whereas heating capacity was 269 *kWh*. The heating capacity was found to be not adequate for thermal comfort.

Kumar et al. [2] developed a numerical model to predict the cooling as well as the heating potential of an earth-air-tunnel heat exchanger. They also considered various factors namely ground temperature gradient, moisture content of air, surface conditions and various other design parameters. They also validated it against the experimental results of an earth-air-tunnel heat exchanger constructed in Mathura, India. Only the earth-air-tunnel heat exchanger alone was enough for having a comfortable temperature in the outlet in summer. But in winter, auxiliary energy load was needed to achieve a comfortable temperature.

Ghosal et al. [3] did a comparative study of Ground-Air collector and Earth Air Heat Exchanger for heating of a greenhouse located in the Indian Institute of Technology, Delhi, India. The heating system works in the same principle. For the heating system, pipe and so air in pipe absorbs heat from the soil whereas, for a cooling system, ground soil receives heat from the pipe. The ground-air collector system works like solar heaters. In their ground-air collector setup, they made a sand bed for solar radiation. The air in the pipe received heat from the sand bed. In the earth-air heat exchanger, the pipes were buried underground. So in this case, the heat transfer was between ground soil and pipe surface. They found that the ground-air collector could heat the greenhouse about 2-3 *°C* more than the earth-air heat exchanger.

Bansal et al. [4] did a performance analysis of an earth-air-pipe heat exchanger for a CFD model developed in the FLUENT simulation program and the results were validated against the results of the experimental setup in Ajmer, Western India. They varied the pipe material and air velocity inside the pipes. The pipe length was 23.42 *m*, buried 2.7 *m* under dry soil and materials used for the pipe was PVC and steel. Air velocity was varied from 2-5 ms^{-1}. They found that with increasing air velocity the fall in temperature decreases, but pipe material has little impact on the performance of the cooling system.

Vaz et al. [5] made an experimental setup of the Earth-Air Heat Exchanger in Viamão city of Brazil. They made three PVC pipes, two at a depth of 2.0 *m* and one at a depth of 0.5 *m* under the soil. They observed the variation of temperature of the air inside the pipes for an annual cycle. They also made a numerical analysis of the problem based on the Finite Volume Method in the FLUENT simulation program. They visualized the thermal field behavior of soil. They also found that for depth more than 2.0 *m*, the heating potential is 8.0 *°C* and the cooling potential is 4.0 *°C*.

3. Experimental Procedure

General Procedure

The Earth's surface is heated by the sunlight but under a few feet of it, heat is not transmitted. So the temperature underneath the Earth's surface is lower than the atmospheric temperature which is more or less constant. Heat can be transferred from the hot body to a cold body in the presence of a temperature gradient. So, if the hot air can pass through some tubing buried under the Earth's surface, it can transmit heat to the cooler pipe surface. As there was no study of this phenomenon in Bangladesh, we had to test the underground soil temperature first. The testing was done at Chamurkandi village of Narayanganj District, Bangladesh. After conducting some tests, we found out that the soil temperature is constant underneath the surface.

After that, pipe material was selected followed by determination of the pipe length. A trench of 30 *ft* long, 2 *ft* wide and 7 *ft* deep was cut on the same place where soil temperature was tested. Then the pipe was placed and buried under the soil. After a few days, when the soil was compact again, a blower was attached to the pipe inlet. The temperature reading was taken at the inlet and the outlet.

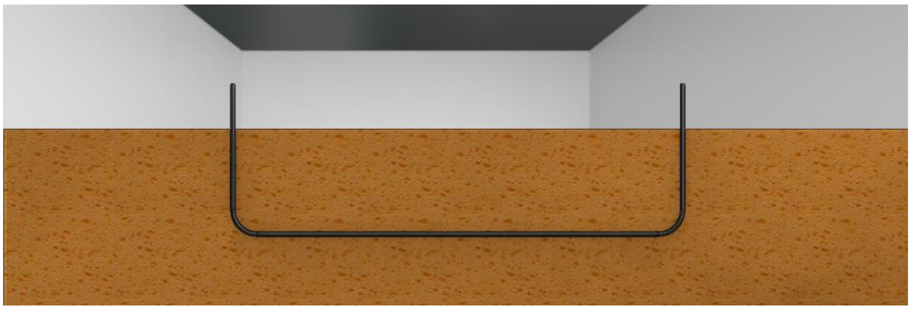

Fig. 1. Simplified design of the system

Testing Soil Temperature

For testing the soil temperature at various depths below the Earth's surface, a 10 *ft* hole was dug at the test area. Four temperature sensors were used among them three were below the surface at 5 *ft*, 7 *ft*, and 10 *ft* respectively and one of them was in the air. No sensor was placed at a depth above 5 *ft* because previous works found that optimum depth for preferable underground temperature was at 2 *m* (approx. 6.6 *ft*). An Arduino system was constructed for taking the temperature readings.

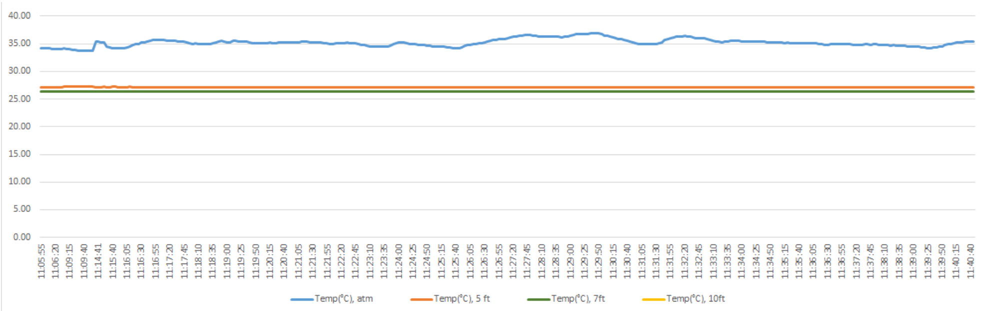

Fig. 2. Temperature Data-set-1

Depth underneath the surface

From the data observed, it was seen that the minimum soil temperature was found at 10 *ft* under the soil. But as the temperature variation between 7 *ft* and 10 *ft* was not that significant and also considering economical factor, the optimum soil depth for placing the pipe was chosen 7 *ft* under the Earth surface.

Pipe

The various factors regarding the pipe which was considered for designing this system are:
1. Pipe material, 2. Pipe Length, 3. Pipe diameter.

Pipe material

Considering various properties, steel is the best option. But due to economic factors, the HDPE-PN10 pipe was selected as it shows properties close to steel and much better than PVC. HDPE-PN10 can endure pressure up to 10 *MPa*. The comparative analysis of thermal properties among steel, PVC, and HDPE is given below.

Table 1. Thermal Properties of various pipe materials

Material	Specific Heat Capacity ($JK^{-1}kg^{-1}$)	Thermal Conductivity ($Wm^{-1}K^{-1}$)
Steel, Stainless	470	16
PVC	1000	0.19
HDPE	1900	0.45-0.52

Pipe Length

For determining pipe length, at first air flow rate was assumed. Maximum air temperature recorded for Dhaka (from the meteorological data set of Bangladesh Meteorological Department) was taken as the pipe inlet temperature. Pipe outlet temperature was taken from the range of maximum and minimum soil temperature. Then the required heat transfer between air and pipe surface was calculated for that inlet and desired outlet temperature. It was assumed that pipe surface temperature and temperature of soil around the pipe was the same. Then assuming the pipe and soil as a cross-flow heat exchanger, for the same heat transfer, pipe length was calculated. Pipe diameter was taken as 4 *inches* and air velocity was taken 5 *fps*. The volumetric flow rate was calculated as follows:

$$\dot{V} = v \times A \tag{1}$$

The volumetric flow rate was converted to the mass flow rate by:

$$\dot{m} = \dot{V} \times \rho \tag{2}$$

Heat transfer between pipe inlet and outlet:

$$\dot{Q} = \dot{m}C_p(T_i - T_o) \tag{3}$$

For finding heat transfer co-efficient, the Nusselt number was calculated first. It was calculated using three co-relations. One of them considers friction factor but the other two do not.

Dittus and Boelter [9] proposed an expression for calculating Nusselt number for a fully developed turbulent flow in a smooth wall tube which is:

$$Nu = 0.023\,Re^{0.8}Pr^n \tag{4}$$

$$n = \begin{cases} 0.3: for\ cooling \\ 0.4: for\ heating \end{cases}$$

HDPE has an absolute roughness of 0.000005 *ft*. Although this roughness is considered to be smooth, it was taken into consideration. *W. Nunner* [10] derived an expression for finding Nusselt number with the consideration of friction factor. Although his empirical formula does not suit well with fluids other than air, it was used in this thesis as the working fluid was air. Nunner's equation is:

$$\boldsymbol{Nu} = \frac{\frac{f}{8}RePr}{1+1.5Re^{-\frac{1}{8}}Pr^{-\frac{1}{6}}\left[Pr\frac{f}{f_o}-1\right]} \tag{5}$$

Here, *Colebrook-White* equation gives the value of f and *Karman-Nikuradse* equation gives the value of f_o. The best formula to find the Nusselt number is to use the *Petukhov's Equation* [11] where μ_b and μ_s are calculated at bulk temperature and surface temperature respectively. It is expressed as:

$$\boldsymbol{Nu} = \frac{\frac{f}{8}RePr}{1.07+12.7\left[\frac{f}{8}\right]^{\frac{1}{2}}\left[Pr^{\frac{2}{3}}-1\right]\left[\frac{\mu_b}{\mu_s}\right]n} \tag{6}$$

$$n = \begin{cases} 0.11 & for\ T_s > T_b \\ 0.25 & for\ T_s < T_b \\ 0 & for\ constant\ heat\ flux \end{cases}$$

After finding Nusselt number, heat transfer co-efficient was found from the equation:

$$\boldsymbol{Nu} = \frac{h\ \overbrace{d}^{hydraulic\ diameter}}{k} \tag{7}$$

Newton's Law of Cooling was used for finding the pipe surface area. The equation is:

$$\boldsymbol{Q_{conv}} = \boldsymbol{hA_s\Delta T_{lm}} \tag{8}$$

The equation used for finding the log-mean temperature of the system, which was assumed as a cross-flow heat exchanger is:

$$\Delta\boldsymbol{T_{lm}} = \frac{\Delta T_e - \Delta T_i}{ln\frac{\Delta T_e}{\Delta T_i}} \tag{9}$$

Where,

$$\Delta T_e = T_e - T_s$$
$$\Delta T_i = T_i - T_s$$

And then pipe length was found from:

$$\boldsymbol{A_s} = \boldsymbol{\pi dL} \tag{10}$$

The pipe length for different cases was found to be 28.9 *ft*, 28.6 *ft*, and 30.33 *ft*. 30.33 *ft* was chosen for the experimental pipe length.

Pipe diameter

The outside diameter of the pipe was taken 90 *mm*. The thickness of the pipe surface was 4.30 *mm*. The inner diameter of the pipe was 81.4 *mm*.

Blower

A 1400 *RPM*, 2.13 *CFS*, 200 *W* centrifugal blower was chosen for forcing outside air at pipe inlet. The airflow rate was varied manually to change the air velocity at the outlet.

Construction of the system

The construction was done at various phases namely, cutting the trench, construction of the pipe, burying the pipe, and setting the blower. A 30 *ft* long HDPE pipe section was buried horizontally at the desired soil depth. Two vertical pipes were attached on both sides of the section. One of these vertical pipes was used as inlet and the other was the outlet. Then, the trench was covered with soil again. 3 *ft* of both of the inlet and outlet pipe were above the Earth's surface. Finally, the blower was set at the pipe inlet.

Fig. 3. Experimental setup

4. Experimental Results and Observations

To do the performance analysis of the cooling system, an experiment was done. As it was in winter, the atmospheric temperature was lower than our initial assumed temperature used to determine pipe length. Two temperature sensors, one at the pipe inlet and the other at the outlet was set to read the temperature. The instrumentation process was the same as the soil temperature data experiment done before. Data was taken in three stages that are, 1. at full load, 2. at half load, and 3. at quarter load. Load variation (flow rate variation to be precise) was done manually by blocking the air intake path of the centrifugal blower. The average difference between inlet and outlet temperature was used to determine COP for load variations. The equation follows:

$$COP = \frac{\dot{m}C_p(T_i - T_e)}{Blower\ Power} \quad (11)$$

The Temperature variations with load variations followed as:

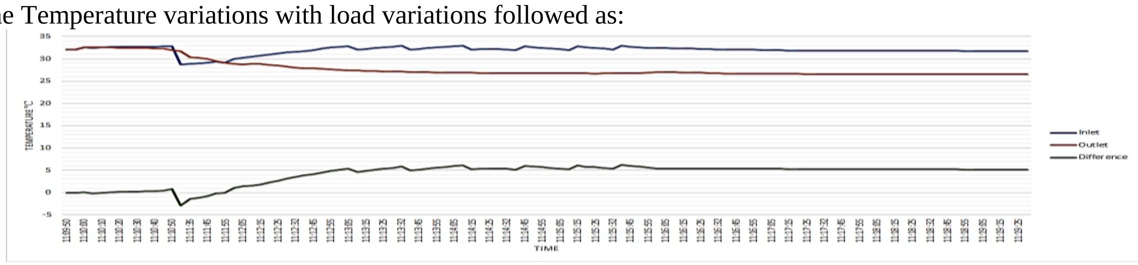

Fig. 4. Data taken at full load

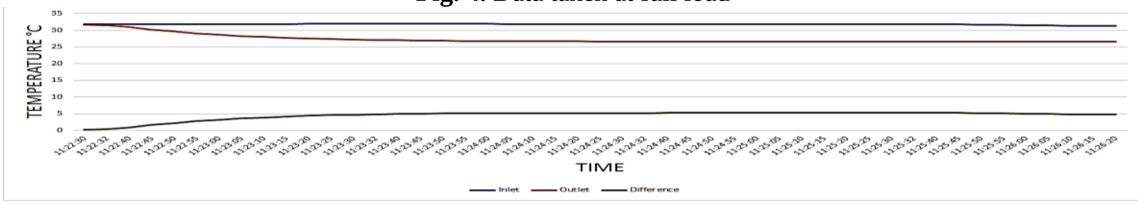

Fig.5. Data taken at half load

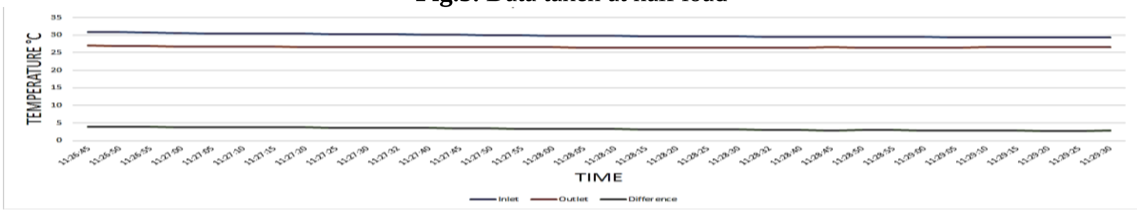

Fig. 6. Data taken at Quarter load

The average temperature difference of inlet and outlet air temperature and variation in COP for load variation found in the experiment was:

Table 2. Variation in average temperature difference and COP

Load	Average T_i *(°C)*	Average T_o *(°C)*	Average *ΔT (K)*	Cooling Capacity *(kWh)*	COP
Full	31	26	5	1281.6	1.78
Half	31	26	5	639.36	0.888
Quarter	29	26	3	192.24	0.267

One should not reach the verdict that COP decreases with decreasing load. As we varied the load manually, the input power used by the blower did not change. But as the load was decreased, the output cooling effect decreased. It was found that the minimum outlet air temperature achieved was 26.50 *°C*. It was close to the minimum temperature we found at the soil temperature test. So, the system could cool the air to a more or less constant outlet temperature. When the inlet temperature decreased, the outlet temperature did not fall drastically. Again, when the inlet temperature increased, the outlet temperature was quite the same.

5. Discussions on Results and Relevance

From this study, it is evident that underground soil can be used as a heat sink. It was also found that the soil temperature remains almost constant at a specified depth under the soil. If the pipe design can be done properly, the system is capable to cool the outside air near to the soil temperature around the pipe. In our study, the design of the system was such that the outside air could release heat to the soil and gain almost the same temperature as the soil. Whether the outside air temperature was maximum or minimum, the outlet air temperature was almost the same.

It was observed that, after starting the blower, the temperature of outlet temperature fluctuated at first. Then it started to lower down the temperature. Then it came to a constant temperature and remained almost the same. But one phenomenon that we could not observe was when it would come to saturation. Soil can be a great heat sink, but after receiving heat for a long period, its temperature may increase. So, its heat receiving capacity may

decrease. In our experiment, we could not observe when the outlet temperature would start to rise again. After a long period, it may start to rise again.
The cooling capacity and the COP of the system decreased when the flow rate or load was decreased. As the flow rate was less, the mass flow rate was less and so the heat transfer. But if the revolution of the centrifugal blower could be varied, the phenomena could be different. As we experimented only by changing the flow rate, we only could observe the effect of flow rate on COP and cooling capacity.
In our study, we considered only the underground horizontal pipe length. All the calculations were done based on the horizontal length. It was done to simplify the calculation. The temperature decreases gradually when the depth under the soil increases. When the air entered through the pipe inlet and deeper into the soil, it released heat but in different rates at different layers of the soil. Again after being cooled, when it started to come up to the atmosphere, it may face reverse effect. It would make the study more complex, so we did not consider the vertical pipe lengths at the inlet and outlet pipe.
In the first soil temperature test, we wanted to test the temperature for atmosphere and soil at a depth of 5 *ft*, 7 *ft* and 10 *ft* under the Earth surface. But as the setup was done by hand and it was fragile. The sensor which was at 10 *ft* depth, could only transmit two sample data.

6. Conclusion

This study was done to find a non-conventional way of cooling using an earth-air-pipe combination. The temperature of the earth below the surface is lower than the surface and it is quite constant. Our objective was to harness this temperature difference for the space cooling. Thus not only to reduce the load of cooling on the conventional cooling system but also the cost of cooling.
The system was run under three load condition and in three cases we got slightly different results. But in all cases, the outlet air temperature became constant at a certain point. During the full load and half load conditions, the temperature difference between the average inlet and outlet was around 4-5 *°C*. Whereas for the quarter load condition the difference between inlet and outlet was around 3 *°C*. As the mass flow rate was less and so was the heat transfer.
Soil can be a great heat sink, but after receiving heat for a long period, its temperature may increase. So, its heat receiving capacity may decrease. In our experiment, we could not observe when the outlet temperature would start to rise again. After a long period, it may start to rise again. Further research or experiment could be done on this to find out the saturation point.
So from this study, we conclude that the method can be applied for the cooling purpose of households. It can also be added with conventional cooling systems. It would reduce the cooling load of the cooling system. With some further development, it can be also used for commercial purposes.

7. References

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