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Performance Analysis of Rectangular Earth-Air Tunnel System used for Air-Conditioning of the College Classroom

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Abstract

The present paper discusses the designing of metallic earth-air tunnel system taking under consideration all the variables like cooling load, heating load of the classroom, optimum underground temperature, and weight of the soil acting on the underground duct. Duct is of Zigzag pattern and its cross-section is of square shape. The zigzag pattern resulted in less area occupied and shorter length of the duct required for proper air-conditioning effect. Part of the duct leading to the classroom is insulated in order to stop the temperature change of the conditioned air after coming in contact with atmospheric conditions. The results showed a 13^{o}C reduction in temperature during summers. Heating effect in winters was relatively less, with just 5^{o}C increase in temperature.

Keywords: Ground Temperature Estimation, Metallic Duct, Heating and cooling Load, Pressure Drop in the Duct, Year Average C.O.P.

1. Introduction

Gurdaspur district lies in the state of Punjab in the republic of India. The geographical conditions makes it a place with variable temperature all round the year, with average day temperature ranging from maximum 42^{o} C in June, to minimum 18^{o} C in January. Air conditioners are used in summers and heaters in the winter. With rising electricity cost in the state, it was thought to implement such air conditioning equipments which would consume less electricity and give the thermal comfort to the occupants. Thus, implementation of the earth air heat exchanger system in one of the college's classroom was done. The use of passive cooling technique for air conditioning of the air has been known for past few years. There has been a lot of research going on in this field to implement and optimize the passive cooling equipments for future use. Houghton *et al.* [1] made an attempt of reducing heat flux entering in the room by using the concept of open roof pond and spraying water over the roof. Tiwari *et al.* [2] gave a review on the evaporative cooling by spraying water over the roof. Sodha *et al.* [3] analyzed the ways of heat reduction by evaporation of water film over the roof and, by the flow of water over the roof. Mathematical model of the earth-air tunnel was proposed by Dhariwal and Goswami [4]. Goswami and Biseli [5] used a 12 inch diameter, 100 feet long corrugated pipe for air conditioning of residential building and compared the effects of open loop and closed loop systems along with the pipe material. Sharan and Jadhav [6] made use of metallic pipe to condition the air in Ahmadabad city in India. Al-Ajmi et al. [7] studied the model for employing it in desert conditions. Sehli et al. [8] tried to find out the potential of earth-air tunnel system in South Algeria. Further studies have been carried out and are still in progress in the field of earth-air tunnel system [9-18].

2. Methodology

First of all, temperature gradient of the earth along its depth was recorded throughout. Then cooling and heating loads of the classroom was calculated and duct was designed subsequently.

2.1 Temperature variation of the Earth with depth

Though there have been many approximated relationships for finding the optimum temperature inside the earth's surface [19-26], it was decided not to follow the generalized equations as their application is not viable at all the locations. Hence, a separate apparatus was made by attaching T-type thermocouples to a long stick at an interval of every 2 feet. A total of 6 thermocouples were attached on the wooden stick and each one's wire extended to the instrument called temperature indicator. The ground was dug 10 feet deep and thermocouple apparatus was inserted. After inserting the apparatus, the hole was filled with soil again in order to get correct readings. The experiment continued for 1 year and the variation of soil temperature at various depths were noted for all seasons. The depth at which temperature remained nearly constant all round the year was at 10 feet. There were slight changes in the optimum temperature throughout the year, but it was ignored as the changes were in few decimals.

A plot between atmospheric temperature and optimum underground temperature is made. The ambient temperature in Figure 1 is the maximum day temperature recorded, and averaged over whole month. The underground temperature depicts the optimum temperature recorded at 10 feet depth, and then averaged over whole month.

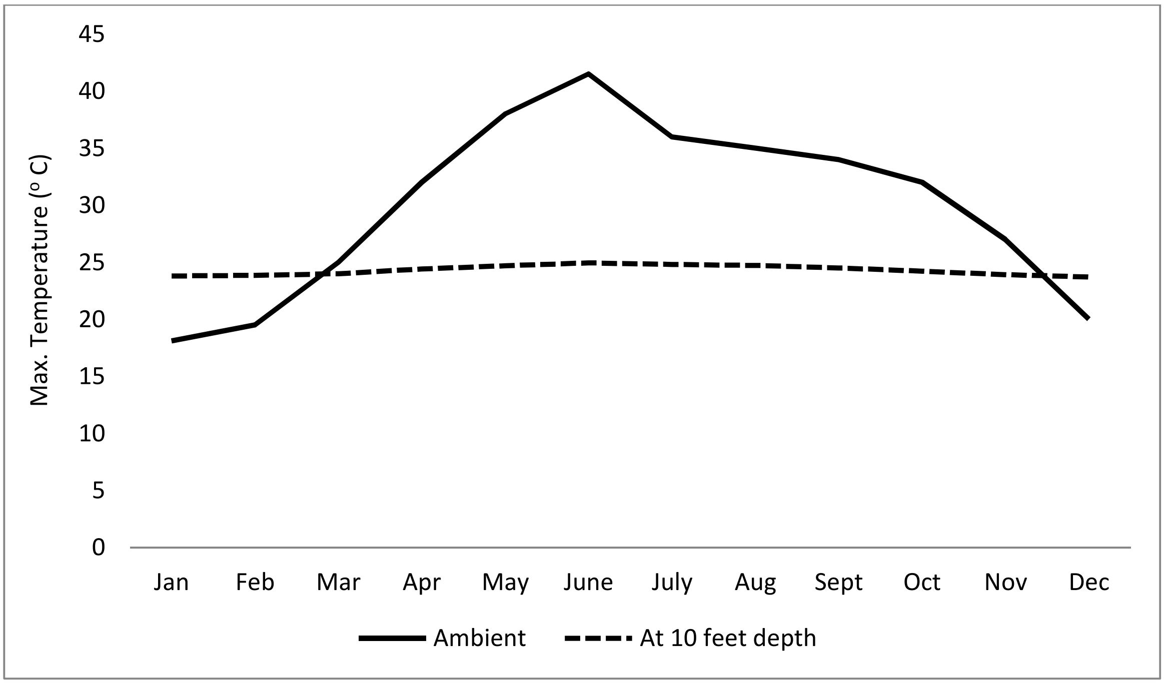


Figure 1. Variation of underground temperature with ambient air temperature throughout the year

The temperature at a particular depth in Figure 2 is the average temperature for the whole season. Summer or winter has been categorized on the basis whether the average temperature of the month is more or less than the optimum underground temperature (24.3° C) respectively. As evident, the ambient temperature is above the underground temperature for almost seven months in a year. So, implementing the prototype in this area could be advantageous from cooling point of view.

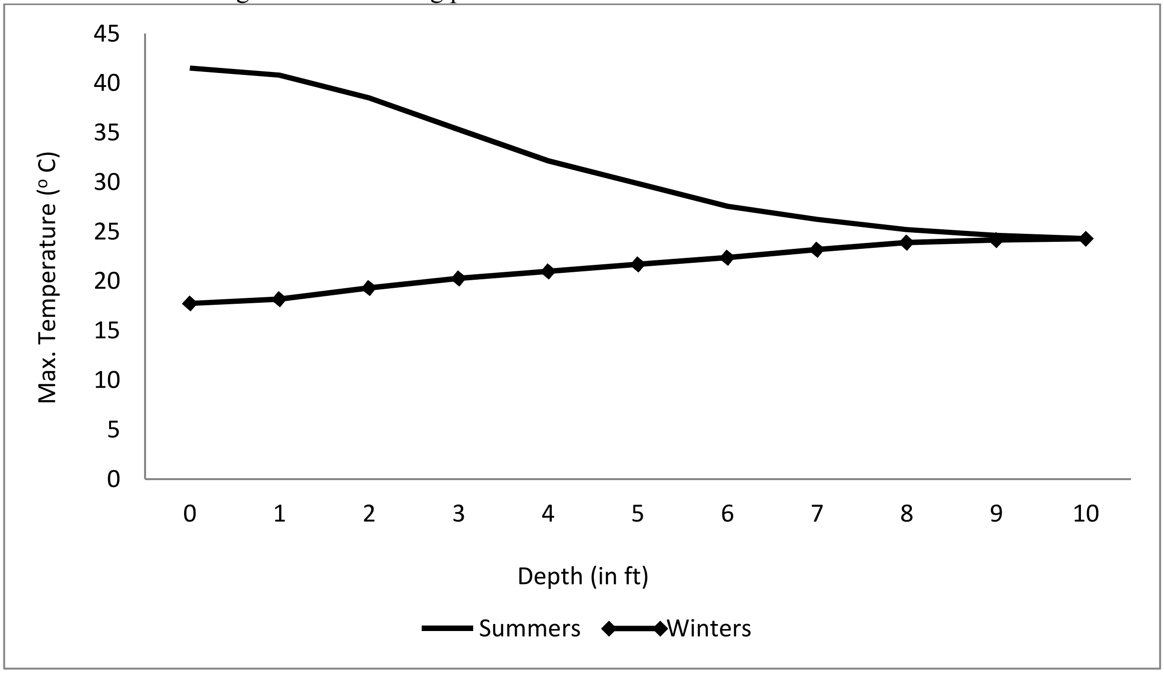


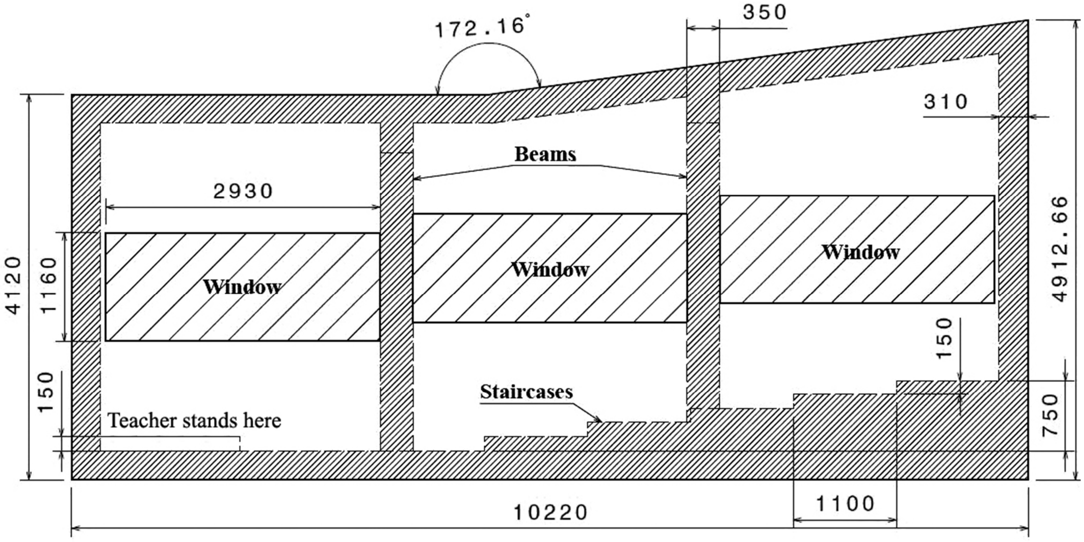
Figure 2. Temperature gradient of earth along its depth

2.2 Designing phase

Various variables were taken into consideration before designing the duct. These variables were cooling and heating load of the classroom, relative humidity of the area throughout the year, temperature gradient of the soil, and weight of the soil acting on the surface of the duct. The weight of the soil was considered in order to design the duct in such a way so that it does not collapse during backfill and thereafter.

2.2.1 Cooling/Heating Load

The dimensions of the room are 10.22 m by length, 7.38 m by width, and 4.12 m by height. It contains 3 windows, 1 door, and 1 ventilator. The roof of the room is slanting in order to accommodate the stairs on the ground of the room where benches are fixed. All the rules specified by ASHRAE 2013 Fundamentals handbook [27] were followed to find out the loads. CLTD method for calculations of the cooling load was followed. Solar Heat Gain Factor was used for heat coming through windows. While doing the calculations for internal sensible and latent loads of occupants, the maximum occupant capacity of the room was taken as 50. In heating load calculation, heat released by occupants (which was to be subtracted from the total value) is ignored as we have designed the prototype at peak load. The cooling load and heating load came out to be 6.1 KW and 2.4 KW respectively. So, in accordance with the ASHRAE fundamentals [27], the mass flow rate of air required to condition the room is 0.31 kg/s. conversion of mass flow rate into velocity is done which tells us that the velocity of inlet required at fan is 16.7 m/s.



Side view (all dimensions in mm)

Figure 3. Side view of the room to be conditioned

Table 1. Cooling and Heating load of the room calculated

Source	*Cooling Load (W)*		*Heating Load (W)*	
	Sensible	*Latent*	*Sensible*	*Latent*
Walls, floor, and roof	1157	0	1423	0
Glass panes	366	0	564	0
Infiltration	610	0	407	0
Occupants	2285	2500	0	0
Lights & fans	1153	0	1153	0
Total	**5571**	**2500**	**3547**	**0**

2.2.2 Duct Layout

It is already in the literature that for duct fabrication, PVC ducts are usually preferred over Galvanized Iron as there is not much difference in the thermal conductivity of two materials. But this small difference can also be a major factor on the performance of the prototype. So, it was decided to make duct in three parts. The main part would be square in cross section. It would be made of Galvanized Iron and placed at 10 feet depth. The GI duct would be connected with PVC round pipes at both ends. The fan would be installed at the first PVC part and the second PVC part would lead the air to the room. This is done because as the air flows from surface to underground at 10 feet, it does not go much conduction because the optimum ground temperature required for conditioning of the air is at 10 feet depth only. At any other depth, the temperature is not of the optimum value. Plus, employing PVC pipes at less conducting areas would reduce the cost of the prototype. The second part of the PVC pipe was insulated in order to prevent the temperature loss of the conditioned air after coming in contact with the ambient temperature. Now, the whole responsibility of heat transfer was on metallic duct lying underground. The pattern of the metallic part was designed through ANSYS. Various patterns were designed and analysis was run on each pattern in order to get an idea about the output temperature that it would give. The final pattern of the metallic part was finalized as zigzag shape and its cross section was of square shape, with side of square being 215 mm for proper convection of the air at design flow rate.

2.2.3 Analysis

For a readymade PVC pipe of diameter 152.4 mm, and knowing the design flow rate of 0.31 kg/s, the velocity of air flow through the pipe comes out to be around 16.7 m/s, which reduce to 6.39 m/s in the metallic part. For getting less error in the calculations, the square cross section of the duct is always first considered to be of circular shape with equivalent circular diameter [27]. As the side of the square cross section of metallic part is 216mm, its equivalent circular diameter is 246 mm and all the calculations are done by considering the metallic part as circular pipe of 246mm. inputting a speed of 6.39m/s, the metallic duct was again test run in ANSYS and checked for solution at the output. The visual solution is shown in the Fig. 4 and 5.

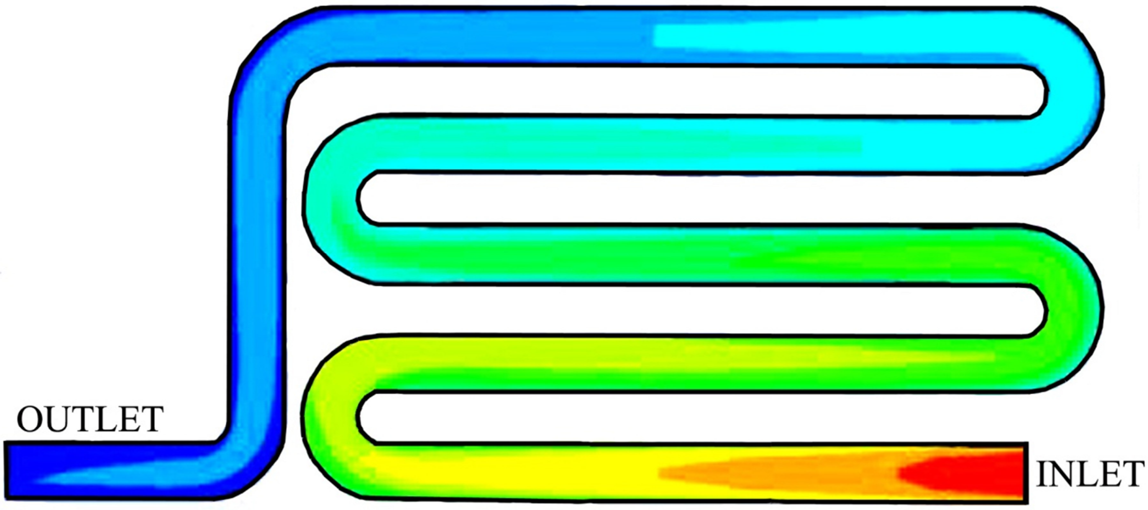


Figure 1. Variation of air temperature along its way in the metallic part of the duct

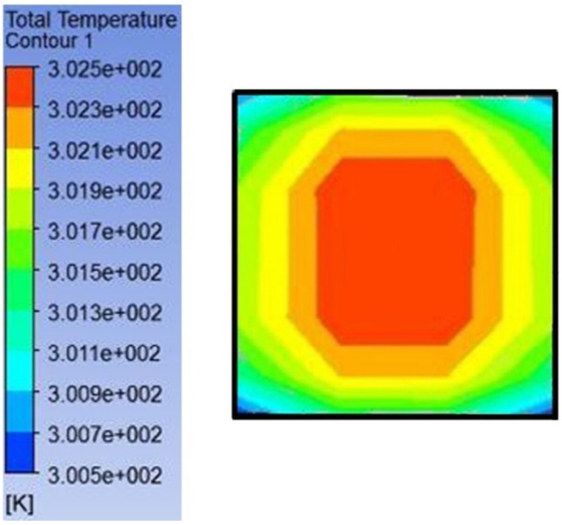


Figure 1. Temperature profile at the outlet cross-section of metallic part

At the outlet of the metallic part, the software shows a change in temperature profile. The central part of the air is hotter than the air near the boundary layer by 2^{o}C. This is because of the fact that the air at the innermost part goes less convection than the air near the boundary layer. So, average of the temperature over the whole cross sectional area is taken which comes out to be around 302.3 K. so, the results showed a decrease in temperature of the air by 17.7^{o}C (the value of inlet air temperature of 320 K was inputted.) The assumptions that were made in the software were the flow was considered frictionless, and there was no pressure loss (static and dynamic) of the air.

2.2.4 Weight of the soil

The metallic duct placed underground faces certain amount of weight of the soil form top. In order to prevent the collapsing of the duct due to the soil weight, its thickness is designed by using flexural formula [28]. For calculations, the duct surface is considered as simply supported beam with uniform distributed load of soil acting on it. Considering soil density of 1200 kg/m^3, the weight of soil on the duct is 7.86 kg/m. Inputting 140 MPa as the ultimate tensile strength of GI (Galvanized Iron), the minimum thickness of the duct sheet comes out to be 1.02 mm. After all the variables were taken into account, final layout of the earth-air tunnel was made through CATIA software. Fig. 6 elaborates the dimensions of the metallic part of the duct.

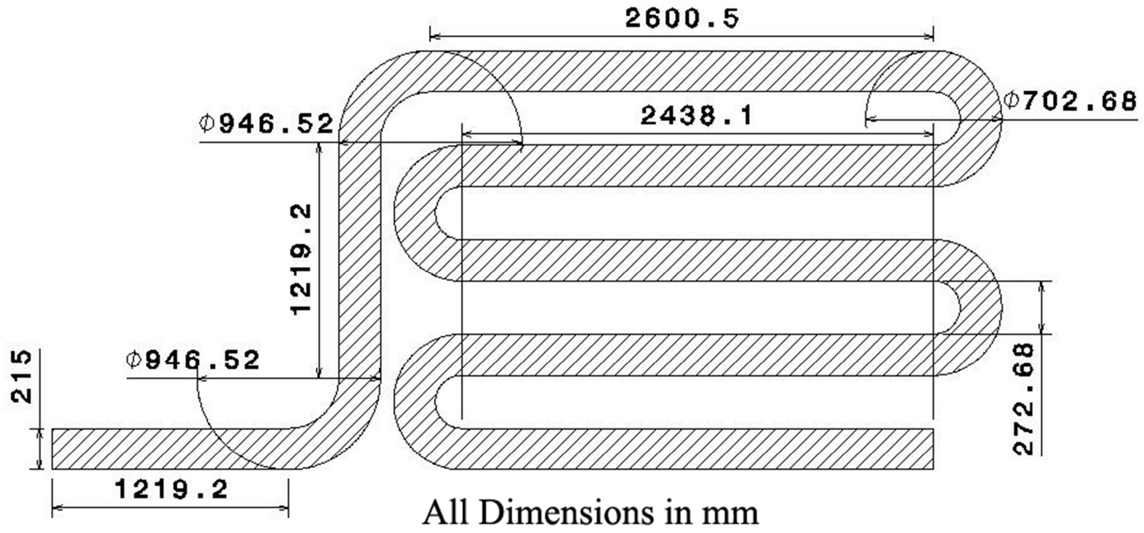


Figure 1. Finalized pattern of the metallic part

2.2.5 Designing of the fan

Relative roughness of Galvanized Iron and PVC was found and the pressure drop of the air along its way is calculated [27]. The pressure drop (static and dynamic) came out to be 583 Pa (2.34 inch WC). In order to overcome this pressure loss, the fan power required is about 720 Watts (assuming suitable values of fan belt and motor efficiency). So, centrifugal fan with radial blades was bought. The rated power on the motor was 1 hp (747 watts approximately).

2.2.6 Prototype assembling

The prototype was assembled in different parts. The earth was dug with the help of excavator and metallic part was laid inside at 10 feet depth. The PVC parts were then connected with the metallic part with the help of adhesive. The openings of the metallic part were made round and of the same size as that of the PVC parts diameter. This ensured the proper joining of the parts which helped in preventing soil penetration in the duct during the backfill. It might be seen in Fig. 7 that there is slight difference in the proposed design and the actual fabricated part. This is due to the fact that it was relatively tough to round the 1 mm GI sheet at such a small radius of curvature. So, compromise is done at the area where duct is curved.

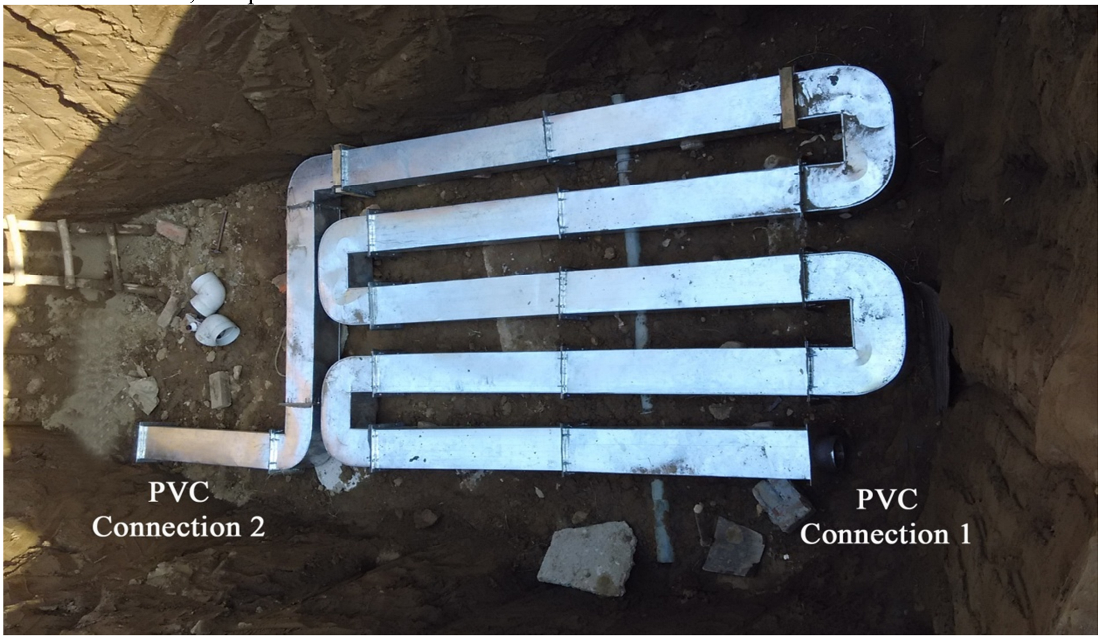


Figure 1. Fabricated metallic part at 10 feet depth

Figure 1. Prototype after being installed at the site

3. Results

3.1 Input and output speed of the duct

The prototype was test run in different weather conditions. Tests were carried out for different input speeds and related output speeds were noted. The equation of the trend line shows a slope of approximately 26° between outlet and inlet velocity.

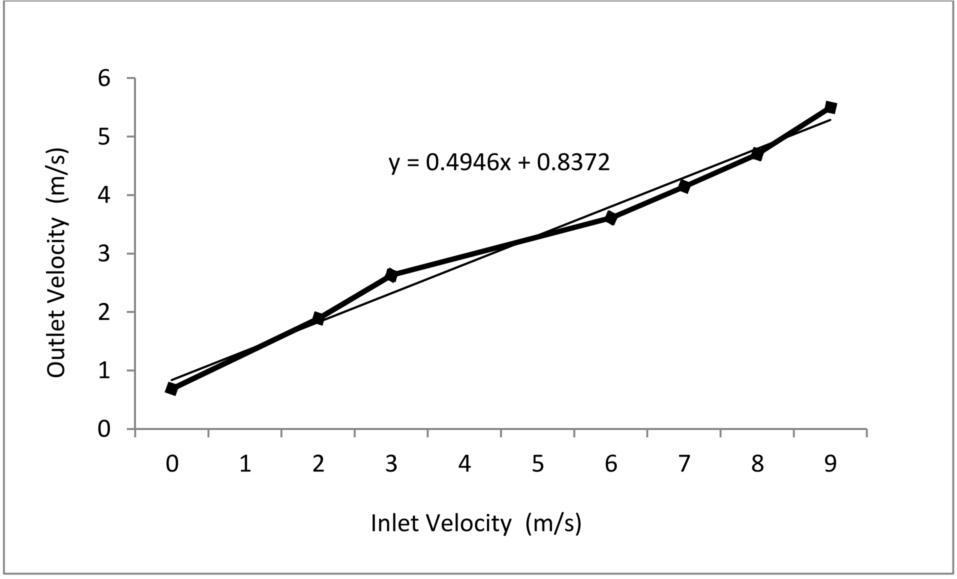


Figure 1. Relationship between inlet and outlet velocity of the duct

3.2 Coefficient of performance

The prototype showed maximum C.O.P of 3.9 in peak summer conditions. The monthly average value of C.O.P. is changing due to the changing ambient temperature every month. The year average C.O.P. value of 1.97 is obtained. Also, in peak winter conditions, the maximum C.O.P of 1.2 is obtained. Fig. 6 shows the variation of C.O.P of the prototype with changing months.

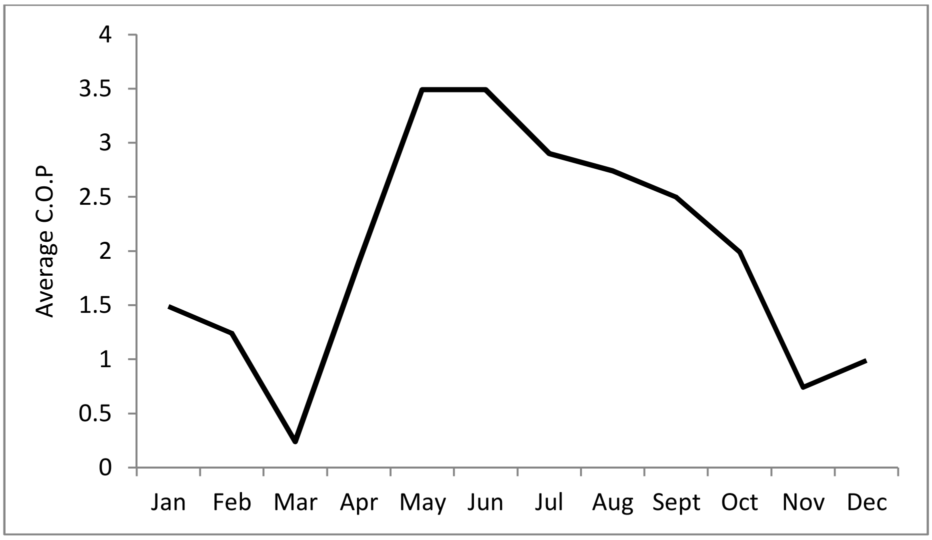


Figure 1. Variation of Monthly Average C.O.P. with time

3.3 Cooling/ heating effect

The maximum cooling effect the prototype has given is 2.6 KW. Like C.O.P value, the cooling and heating value is also variable due to the variation of monthly average ambient temperature. The year average cooling and heating provided by the prototype was 1.87 KW and 0.92 KW respectively. Table 1 shows the variation of heating/cooling effect with time.

Table 1. Cooling/ Heating capacity of the prototype in a year

Month	**Cooling/ Heating (KW)**	***Month***	***Cooling/ Heating (KW)***
Jan	1.11	Jul	2.23
Feb	0.93	Aug	2.04
Mar	0.18	Sept	1.8
Apr	1.48	Oct	1.48
May	2.6	Nov	0.55
Jun	2.6	Dec	0.74

4. Conclusions

So far, there are mixed views in the context of earth-air tunnel system. While some advantages favor it commercially, some of the restrictions hamper its use.

4.1 Advantages

The C.O.P and cooling effect of the prototype is best in the months of May and June, when the summer is on its peak. Though the C.O.P. is reduced drastically in winters in the months of November, December, February, and March, it can be increased by employing a small heating coil at the duct outlet. The system can only be used for sensible cooling and heating, i.e. it cannot be used for changing humidity directly. However, some independent equipment can be employed to maintain humidity within the limits of human comfort. The system consumes very less electricity as compared to Air Conditioners. It is also eco friendly, so there is no harm to the environment. The initial investment is a little more than the Air Conditioners but its maintenance is very less.

4.2 Restrictions

The only restriction that is there in case of earth-air tunnel system is ground availability. The system requires digging of the large ground area, which can be a problem at some places.

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