Application of Earth Tube Heat Exchanger and Solar Chimney for Natural Cooling System in Basrah City

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Abstract- **Solar chimney (SC) together with earth to air heat exchanger (EAHE) is being employed as a low-energy consuming technique to remove undesirable interior heat from a building in the hot seasons. A numerical program "FLUENT 6.3 code" of an earth to air heat exchanger (EAHE) is studied for predicting the outlet air temperature and cooling potential of these devices in Basrah climate. Theoretical analyses have been conducted in order to investigate the ventilation in a solar chimney. The investigation into the viability of Low Energy Earth Pipe Cooling Technology in providing thermal comfort in Basrah. The demand for air-conditioning in buildings in Basrah affects the country escalating energy consumption. Therefore, this investigation was intended to seek for an alternative passive cooling to air-conditioning. The passive technology, where the ground was used as a heat sink to produce cooler air, has not been investigated systematically in hot and humid countries. A sub-soil temperature model adapted for the specific conditions in Basrah is presented and its output compared with CFD modeling. The results have shown that the potential of Earth Pipe is providing lower output temperature of air inlet to the room. We found that the resulting temperature at the buried pipe outlet decreases with increasing pipe length, decreasing pipe diameter, decreasing mass flow rate of flowing air in the pipe and increasing depths up to 4m.**

Keywords:
Passive cooling, earth to air heat exchanger, solar chimney, soil temperature, FLUENT code.

1. Introduction

Earth-air heat exchanger is an underground cooling system that utilizes
ground temperature for pre-cooling or pre-heating ventilation air in summer and winter
respectively. The subsurface soil temperature is lower than ambient air temperature in summer and higher than ambient air temperature in winter, this is as a result of high soil thermal mass that store high percentage of the heat gain on daily basis to less than 30cm under the surface. Temperature difference between air and soil can be utilized to pre-cool or pre-heat ventilation air supply using earth-air heat exchanger, which consists of pipes buried under ground surface through which ventilation air is circulated. Potential of earth-air heat exchanger has been established in moderate climates of Europe, however not much research has been carried out in hot climates because of the claim that the potential is low due to higher soil temperature in summer. Potential of the system in hot climates may however be improved using various soil cooling strategies to lower the natural subsurface soil temperature such as shading, irrigation and so on. Natural ventilation is usually employed in a region with mild climate and in spaces where a little variation in indoor climate is tolerable. A solar chimney on the other hand, is a good configuration to implement natural ventilation in buildings where solar energy is available[1].

Environmental comfort, economy, and energy conservation are some of the major functional considerations in the buildings. So far as institutional, commercial, and residential buildings are concerned, electrical air-conditioning systems are mainly employed for the health and comfort of the occupants. As matter of fact, the demand for air-conditioners is growing yearly. However, with the increasing cost, diminishing supply of nonrenewable energy and environmental reasons there began a tremendous surge of interest and research in solar and passive systems since the 1970s. The use of passive cooling techniques combined with a reduced cooling load may not only result in a good thermal summer comfort but they save cooling energy consumption, too. Here, the two interesting and promising passive cooling techniques are: natural day ventilation and earth to air heat exchangers. Natural ventilation is usually employed in a region with mild climate and in spaces where a little variation in indoor climate is tolerable. A solar chimney on the other hand, is a good configuration to implement natural ventilation in buildings where solar energy is available.

The Earth Pipe Cooling system works with a long buried pipe with one end for the ambient air intake and the other end for providing cooled air to the desired space. The pipe is buried underground at the ultimate depth that could give most efficient results, but with the two pipe ends above ground. This technology uses the ground as a heat sink for cooling purposes in warm countries where the channelled ambient air, via the buried pipe, transfers excess heat to the ground by convection. There should be adequate air flow into the buried pipe intake to produce cool air at the other pipe end for occupants thermal comfort.

The performance of Earth Pipe Cooling are affected by four main parameters and they are:

i. pipe length.
ii. pipe radius or diameter.
iii. depth of the pipe inserted into the ground.
iv. air flow rate inside the pipe.

a) Effect of pipe length

Commonly, the results from various researchers in the past had shown that Earth Pipe Cooling systems with different pipe lengths perform differently. The findings have proven that a longer pipe provides lower air temperature at the buried pipe outlet. Mihalakakou et al. [2] compared Earth Pipes of 30m, 50m and 70m long and found that the pipe exit temperature reduces when the pipe length increases. Santamouris et al. [3] carried out Earth Pipe Cooling study to cool a 1000m2 agricultural greenhouse in Athens, Greece, comparing two different pipe lengths; 10m and 50m. The result has shown that the air temperature at 50m pipe outlet is 2oC lower than at the 10m pipe outlet. Similar results were found in a study carried out by Ghosal and Tiwari [4] also at a greenhouse but in Delhi, India. The rationale behind the better performance of a longer pipe was due to the longer pipe allowing the air to circulate underground for a longer time and hence transfer more excess heat into the earth. Meanwhile, pipe lengths are sometimes limited by economic matters. To have the cooling system efficient, it should not be costly and longer pipes tend to cost higher.

Hanby et al.[5] approached the Earth Pipe Cooling study in a slightly different way. He has combined the system performance with the cost by calculating a payback time to find the efficiency economical. In his study in hot, arid Kuwait, . have found that the optimum pipe length is 56.97m alongside pipe diameter of 0.35m buried at 5.47m deep underground, gives a payback time of 7.24 years to cover the cost of building the Earth Pipe Cooling system.

b) Effect of pipe radius or diameter

Another parameter listed as the main factor of Earth Pipe Cooling system performance is the buried pipe radius. Mihalakakou et al. [2] tested the performance of three buried pipes of different radius; 0.125m, 0.180m and 0.250m. The result found that the increasing pipe radius result in higher air temperature range at the buried pipe outlet, the author concluded the reason for this is because a bigger pipe radius reduces the convective heat-transfer coefficient and hence the higher temperature at the buried pipe outlet. Santamouris et al. [3] has stated that the pipe with the smallest radius performs best. In his opinion, based on his test results, when the radius is small, the center point of the pipe gets closer to the soil outside, allowing a faster transfer of excess heat from the air to the soil. Ghosal and Tiwari [4], agreeing with the previous studies, have stated that pipe outlet temperature can be reduced with decreasing pipe diameter.

In a published paper by Krarti and Kreider [6], they have explained an equation that shows the relationship of heat transfer coefficient, Us and the buried structure radius ro:

$$U_s = k_s / r_o \qquad (1)$$

Where k_s = ground conductivity.

r_o = radius of the buried structure.

From the equation, They concluded that when the buried structure is small, the heat transfer coefficient increases. Therefore, according to the developed Equation (1), smaller structure transfers heat more easily into the ground. They carried out a study on the effect of pipe diameter towards the buried pipe outlet temperature using a developed numerical model, which was validated against an experimental data set. The various diameters were 0.1m, 0.2m, 0.4m and 0.8m and the result shows the lowest temperature range at buried pipe outlet were from the 0.1m diameter pipe.

However, when the radius is small, the air pressure inside the pipe increases and hence provides faster air flow. If the air flow inside the pipe is too fast, the channelled air would not have adequate time underground to dissipate the excess heat onto the earth, unless the pipe is long enough. Again, there has to be balance between these parameters to achieve efficient passive cooling.

c) Effect of pipe depth buried underground

Increasing soil depths equals to decreasing amplitude of daily or diurnal soil temperature due to the distance of soil from the soil surface and ambient air. This then influences the temperature of air circulating in the buried pipe. Therefore, the air temperature at the pipe outlet has decreasing amplitude throughout the day or a year with increasing depth it is buried.

Mihalakakou et al. [2] carried out a study on Earth Pipe Cooling with three different soil depths; 1.2m, 2m, and 3m and has found that pipe buried at 3m provide the lowest temperature range and the pipe outlet. They carried out another study on buried pipes at different depths; 2.5m, 4m and lower than 4m. The finding shows that the pipe outlet temperature decreases as the depth increases. The pipe outlet temperature stops decreasing when the pipe was buried beyond 4m deep because the ground temperature became stable .

d) Effect of air flow rate inside the pipe

Similar to other parameters, several researches has found that it does affect the Earth Pipe Cooling performance. Mihalakakou et al.[2] also performs investigation on the effect of air flow rate in the buried pipe. They compared three air velocities, namely 5m/s, 10m/s and 20m/s. The findings have shown that increasing air velocity result in increasing air temperature at the buried pipe outlet. The reason given was due to the increased mass flow rate.

Krarti and Kreider [6] also did a parametric study using a developed numerical model on the effect of air flow rate within the buried pipe towards the temperature at the buried pipe outlet. They compared four different air velocities; 3.5m/s, 14m/s, 31.5m/s and 56m/s and 3.5m/s air velocity produce the lowest outlet temperature range. However, the various selected air velocity were unusual.

Another study on the effect of air flow to the performance of Earth Pipe Cooling system was carried out by Bansal et al. [7]. They have tested air velocity ranges from 2m/s to 5m/s. The result agrees with previous researches that when the air velocity is increased, the out temperature in summer increases. This lead to the reduction of temperature difference between pipe inlet and outlet, which then makes the coefficient of performance (COP) reduced.

2. Methlodogy

2.1 Analytical modeling of EAHE

The first equation calculates the ground temperature in the vicinity of the buried pipe. This equation is developed from the work by Kusuda & Achenbach [8], but arranged to fit the attributes of this particular model:

$$T(z,t)=T_m-A_s*e^{-(Z*\sqrt{\pi/365*\alpha})}*\cos[2\pi/365*(t-t_o \quad -z/2 \quad * \sqrt{\pi/365*\alpha})] \qquad (2)$$

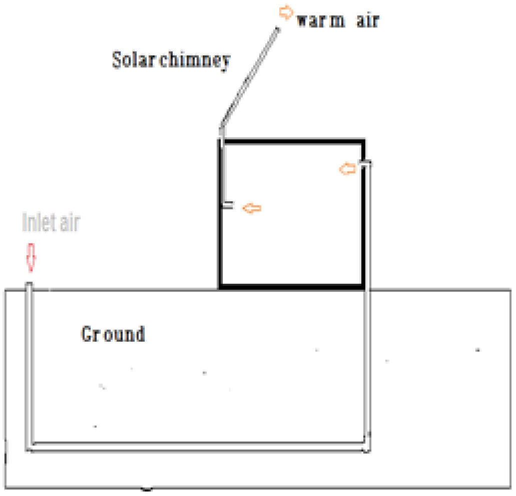

Fig. 1 Schematic diagram of integrated systems

The soil data, pipe data, and fluid data have now all been initialized and steps can be taken to compute the exiting fluid temperature. First, the thermal resistances of each material and interface are calculated, then the total resistance, and therefore the total conductance, can be calculated with the following equations.

Convection resistance:

$R_c=1/2\pi r_1 h$ (3)

Pipe wall Resistance:

$R_p=1/2\pi k_p * \ln(r_1+r_2)/r_1)$ (4)

Soil resistance :

$R_s=1/2\pi k_s * \ln(r_1+r_2+r_3/r_1+r_2)$ (5)

Total resistance :

$R_t = R_c + R_p + R_s$ (6)

air heat exchanger and solar chimney.

Total conductance $U_t=1/R_t$ (7)

the convection heat transfer coefficient inside the pipe is defined by:

$h=Nu*k_{air}/d$ (8)

$Nu = 0.023\ Re^{0.8}\ Pr^{0.3}$ for cooling (9)

$Nu = 0.023\ Re^{0.8}\ Pr^{0.4}$ for heating (10)

Where

$Re = u\ d/\upsilon$ (11)

To calculate the exit value of air temperature:

For $T_{a,i} > T_{z,t}$

$T_{a,ex} = T_{z,t} + e^A$ (12)

For $T_{a,i} = T_{z,t}$

$T_{a,ex} = T_{z,t}$ (13)

For $T_{a,i} < T_{z,t}$

$T_{a,ex} = T_{z,t} - e^A$ (14)

Where

$A = \frac{\dot{m}aCa * \ln|Ta,i - Tgnd|\ \_Ut*L}{\dot{m}a\ Ca}$ (15)

Total hourly cooling has been calculated

$Qc = 3600\ \dot{m}\ c_p\ C_d(T_{a,i} - T_{a,ex})$ (16)

Where

$\dot{m} = \frac{\pi}{4} d^2 \rho\ u$ (17)

The energy balance for dx, a differential length of EAHE can be expressed in the following form:

$T_{a,p} - T_{gnd} = dQ\frac{Rt}{dx}$ (18)

The energy balance of the circulating fluid is given by:

$dQ = -mC_a \frac{dTa,p}{dx} dx$ (19)

Eqs. (18) and (19) give the differential overall energy balance equation in the form:

$\frac{dTa,p}{dx} + \frac{Ta,p}{mCaRt} = 0$ (20)

$T_{a,p} = T_a$ at x=0

The solution of equation (20) can be expressed as:

$T_{a,p}(x)=T_{gnd} + (T_a - T_{gnd}) \exp[-\frac{x}{mCaRt}]$ (21)

2.2 Analytical modeling of Solar Chimney

The solar chimney is the driving element to naturally create a breeze inside a space. The glass and absorber temperatures significantly affect the flowing air temperature, and accordingly velocity. Hence, an energy balance on the chimney is carried out. This balance considers the main elements of the chimney: the glazing, the absorber, and the air in between. Some assumptions are adopted to enable solving the mathematical model. Flow through the chimney was considered: laminar, and steady-state. Energy exchange through glass, air, and absorber was treated as one-dimensional. Air entering the chimney was considered to have the same room temperature. Energy exchange between other walls in the room and the surrounding was neglected, and chimney inlet and exit areas are equal. Applying the energy balance concept on the 1 m^2 glass wall under the aforementioned assumptions yields the following[9]:

$\alpha_g I\ A_g + hr_{abs\text{-}g}\ A_{abs}\ (T_{abs} - T_g) = h_g\ A_g\ (T_g - T_{fsc}) + U_{g\text{-}a}\ A_g\ (T_g T_a)$ (22)

The energy balance equation for air flow in the chimney is [8]:

$$h_{abs} A_{abs} (T_{abs} - T_{fsc}) + h_g A_g (T_g - T_{fsc}) = - \dot{m} C_{fsc} (T_{fsc} - T_r)/\gamma \quad (23)$$

Value of the constant g is taken as 0.74.
The energy balance equation for the absorber plate is written as:

$$\alpha_{abs} I A_{abs} = h_{abs} A_{abs} (T_{abs} - T_{fsc}) + hr_{abs-g} A_{abs} (T_{abs} - T_g) + U_{abs-r} A_{abs} (T_{fsc} - T_r) \quad (24)$$

For glass cover:
The overall top heat loss coefficient from glass cover to ambient air U_{g-a} ,can be written as

$$U_{g-a} = h_{wind} + hr_{g-sky} + h_{g-a} \quad (25)$$

The convective heat transfer coefficient due to the wind is

$$h_{wind} = 2.8 + 3.0\, u_{wind} \text{ Then } hr_{g-sky} = \sigma\varepsilon (T_g + T_{sky}) (T_g^2 + T_{sky}^2) (T_g - T_{sky})/(T_g - T_a) \quad (26)$$

$$hr_{sky-g} = \sigma (T_g^2 + T_{abs}^2) (T_g + T_{abs}) / (1/\varepsilon_g + 1/\varepsilon_{abs} - 1) \quad (27)$$

where $T_{sky} = 0.0552\, T_a^{1.5}$ (28)

and $h = Nu\, k_{fsc}/L$ (29)

For the air flow in the chimney

$$T_{fsc} = \gamma T_{fsco} + (1-\gamma) T_{fsci} \quad (30)$$

For the absorber plate

$$U_{abs-r} = 1/(1/h_r + t_{ins} / k_{ins}) \quad (31)$$

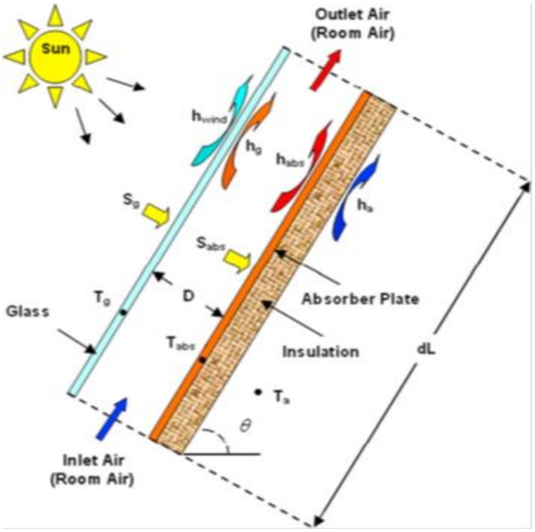

Fig. 2. Schematic diagram of the heat transfer in the solar chimney[10]

2.3 Room ventilation and temperature

The chimney heated by solar energy can be used to drive the chimney effect without increasing room temperature. Chimney effect causes the movement of air into and out of buildings and is driven by buoyancy. Buoyancy occurs due to a difference in indoor-to-outdoor air density resulting from temperature and moisture differences. The driving potential for the air flow through the solar house is function of the pressure difference between the inlet of the EAHE and the SC outlet. The buoyancy pressure due to increasing air temperature in SC, sucks the cooled and heavy air through the EAHE. The friction losses due to fluid flow through the channels and across the fittings, refrain from the fluid flow. If the buoyancy pressure overcomes the sum of all flow pressure losses, the natural ventilation may take place.

The main criteria for thermal comfort condition is the Air change per hour "ACH" which is calculate under steady-state conditions by the following equation [11]:

$$ACH = \frac{3600\, \dot{m}}{\rho a\, V} \quad (32)$$

The air mass flow rate at the chimney and EAHE are the same if there is no air infiltration

$$\dot{m} = \rho A u \quad (33)$$

the air velocity in the SC can be obtained as:

$$u_{sc} = \sqrt{\frac{\text{Bouyancy terms}}{\text{Friction terms}}} \quad (34)$$

Then

$$u_{sc} = \sqrt{\frac{2gH(\rho a - \rho a.r)}{\rho a.r}} = \sqrt{\frac{2gH\,(Ta.r - Ta)}{Ta.r}} \quad (35)$$

3. CFD model

The CFD program is structured around the numerical algorithms that can tackle fluid flow problems. It provides numerical solutions of partial differential equations governing airflow and heat transfer in a discretized form. Complicated fluid flow and heat transfer processes involved in any heat exchanger can be examined by CFD software, FLUENT 6.3. FLUENT 6.3 packages include sophisticated user interfaces to input problem parameters and to examine the results. CFD codes in FLUENT contain three main elements:

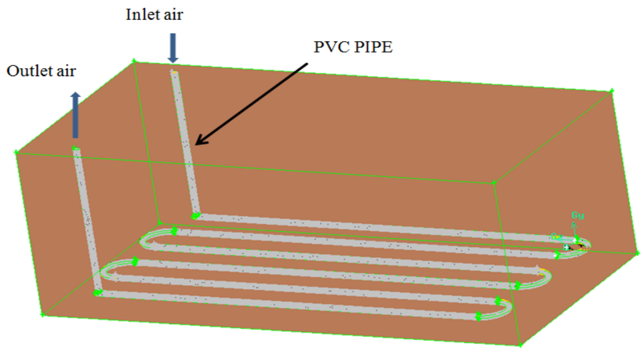

Figure 2. Earth air tube Heat exchanger system

(i) a pre-processor, (ii) a solver and (iii) a post-processor. Pre-processing consists of the input of a flow problem to a CFD program by means of definition of the geometry of the region of interest: the computational domain, grid generation—the subdivision of the domain into a number of smaller, non-overlapping sub-domains: a grid (or mesh) of cells (or control volumes or elements), selection of the physical and chemical phenomena that need to be modelled, definition of fluid properties, specification of appropriate boundary conditions at cells which coincide with or touch the domain boundary. Solver uses the finite control volume method for solving the governing equations of fluid flow and heat transfer. Post-processor shows the results of the simulations using vector plots, contour plots, graphs, animations, etc. Thermal modelling of the Earth–pipe–air heat exchanger (EAHE system shown in Fig. 2 is done using FLUENT 6.3. The model was developed inside the FLUENT simulation program using GAMBIT. The CFD simulations were performed considering 3D transient turbulent flow (standard k–ε model) with heat transfer enabled. In this transient analysis time step is taken as 100 s with 20 iterations in each step.

total numbers of the control volume used for the CFD analysis were about 1.7 million. CFD analysis is carried out for PVC pipe. The main objective of the CFD study was to investigate the effect of air velocity ,pipe length and pipe diameter on the performance of the ETHE system. In the study it was assumed that air is incompressible and subsoil temperature remains constant since the penetration of the heat from the surface of the soil is very slow. It was also assumed that engineering materials used are isotropic and homogeneous.

4. Analysis

Two computer programs were written in MATLAB software to solve the mathematical model for ETEH and Solar chimney. So, the calculation has been carried out for SC and ETEH separately under the conditions which are the size of the room 4.0 m x4.0 m x 3.125 without air infiltration. The heating demand is assumed to change within the range of 0.0-

1000 (W) in the calculations. A solar chimney with the length of 3.125 (m), width of 4.0 (m) and air gap depth of 0.2 (m) is considered. The thickness and thermal conductivity of the insulation located in south wall of the room are 0.2 (m) and 0.046 ($Wm^{-1}K^{-1}$),respectively. The transmissivity of the glass wall is 0.84, absorptivity of glass is 0.06, emissivity of the glass is 0.90 and the absorber wall has an emissivity and absorptivity equal to 0.95 A detailed study on a south facing solar chimney in Basrah. The heating pipe of EAHE is a PVC pipe with 70.0 (m) length, 0.01 (m) thickness, and inside diameter of (0.2,0.3and 0.4m) and is buried 4.0 (m) below the soil surface.

5. Results and discussion

5.1 soil temperature

The annual sub-surface soil temperature based on heat conduction theory applied to a semi-infinite homogenous solid have been mathematically modelled. Predictions of soil temperature exhibit a sinusoidal pattern due to the annual temperature fluctuation above. The prediction accuracy of the undisturbed soil temperature is very sensitive to the values of the input parameters in the equation (2) ,the sub-surface soil temperature in Basrah was predicted with input parameters, for the annual mean ground temperature (T_m), annual surface temperature amplitude (A_s), soil thermal diffusivity (a), and phase constant (t_0) were 24.4°C, 12 °C, 0.0038m^2/h and 552 h, respectively Substituting these values into Eq. (2), the Basrah sub-surface soil temperature can be predicted. The prediction and measured soil temperatures at depths 1 ,2,3,4 and 5 m are presented in (Fig. 3) .It has been shown that the suitable depth for the installation of the earth to air heat exchanger system is 3m.At this level ,the predicted sub soil temperatures range from 24.4°C .

5.2 pipe length

The thermal exchange between the ground and the air crossing the tube increases with the length of the buried tubes (Fig. 4-7). In Fig. 4, the velocity of air effected on the output temperature at diameter 0.2m ,when reduced the velocity the output temperature is reduced and we can using smaller length of pipe. Lengths of about 10 m are unsatisfactory, while significant advantages do not occur for lengths over 70 m. Fig. 5&6 show the effect of diameter in air velocity equal to 1m/s &2m/s, for medium diameter equal to (0.1 m,0.2m and 0.3 m), increasing pipe radius, result in higher air temperature range at the buried pipe outlet, the reason for this is because a bigger pipe radius reduces the convective heat-transfer coefficient and hence the higher temperature at the buried pipe outlet , the pipe with the smallest radius performs best. When the radius is small, the center point of the pipe gets closer to the soil outside, allowing a faster transfer of excess heat from the air to the soil. For higher diameter equal to 0.4& 0.5m with slow air velocity the outlet temperature reduced in faster an low length. In Fig. 7 shown the outlet temperature for different depth, the best depth is at 3m.

5.3 CFD Result

Simulation of the problem by fluent code, the depth is 4m and the length of pipe 70 m , the diameter is 0.2 m and the air velocity is 2 m/s, Fig. (8-11) shown the reduction in air temperature with the length of pipe, the figures explain the heat transfer between air and soil temperature. Fig. 12 show the comparison between analytical modeling and CFD simulation.

6. Conclusion

1.Soil temperature is the main factor affecting the performance of Earth Pipe Cooling system. This research has taken that into account and managed to obtain soil temperature data of Basrah for various depths up to 5m underground. The first key finding is that soil temperature measured on Basrah is found to change little beyond the depth of 4m, which ranges from. Beyond 4m depths, the soil temperature became stable and increases slowly as it gets deeper into the Earth core.

2.The results have shown significant temperature reductions at the buried pipe outlets from their inlets. maximum temperature drop through the buried pipe was found to be 11ºC. In both seasons, the maximum temperature drop occurred in the buried pipe at 1m depth underground.

3The study on the Earth Pipe Cooling Technology was explored using computer simulation program" FLUENT code". The input data used obtained from analytical investigation and sets of buried pipe outlet temperature were recorded. The results were then compared with analytical investigation data .The research concludes

FLUENT code to be a suitable results simulation for further investigation.

4.It was shown that the performance of the buried pipe increases with increasing pipe length. However, when the pipe length was set up beyond 70m, the buried pipe outlet temperatures remain the same, with no influence from the increasing pipe length.

5.The parametric study concerning effective pipe diameter shows that Earth Pipe Cooling system performs more temperature reduction within the buried pipe when using a smaller size pipe. Small pipe diameter enables more efficient heat transfer and hence closer temperature range to the surrounding soil temperature. The rationale behind this is when the pipe diameter is small, air in the center of the pipe gets closer to the surrounding soil.

6.In terms of air flow, the best velocity is 1 m/s . When the air velocities are higher than this range, the temperature reduction between the buried pipe inlet and outlet became less

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Nomenclature

A: area
A_s : annual surface temperature amplitude (°C)
ACH air change per hour h^{-1}
C_a: specific heat of air (J/kg K)
D: gap between absorber wall and glass (m)
d: pipe diameter (m)
h: convective heat transfer coefficient (W/m^2 K)
hr: radiative heat transfer coefficient (W/m^2 K)
I : total solar radiation on surface (W/m^2)
k: thermal conductivity (W/m K)
L : pipe length (m) $\dot{m}$: mass flow rate of air (kg/s)
Q: heat transfer to air stream (W/m2)
Q_c Hourly cooling (W)
R: thermal resistance (m^2 K/W)
r: radius (m)
r_1 inner pipe radius(m)
r_2 outer pipe radius
r_3 radius of cylinder thickness of soil surrounding pipe (m)
S: solar radiation heat flux absorbed by plate (W/m2)
T: temperature (K)
T_a ambient air temperature (°C)
$T_{a,i}$ Entering air temperature (°C)
$T_{a,p}$ Air temperature inside pipe (°C)
$T_{a,ex}$ exit air temperature from pipe outlet (°C)
$T_{(z,t)}$ undisturbed soil temperature (°C)
T_m mean annual ground temperature (°C)
t time of the year (hours)
t_0 phase constant, hours
u: air velocity (m/s)
V: volume of room (m3)

Greek symbols

α thermal diffusivity of the soil (m^2/h)
α_g absorption coefficient of glass
ε: emissivity
μ: Dynamic viscosity (kg/s m)
υ: Kinematic viscosity (m2/s)
ρ: density (kg/m3)
σ: Steffane Boltzmann constant (W/m^2 K^4)

Subscripts

a: ambient
abs: absorber wall
c: convective
f: air flow
g: glass
i: internal
in: inlet
ins: insulation
o: outlet
p: pipe
r: radius, room
s: soil
sc: solar chimney
su: undisturbed soil
W: width of chimney (m)
x,y: coordinate system (m)
Z depth below ground (m)
U: overall heat transfer coefficient (W/m2 K)
Dimensionless terms
Nu: Nusselt number [h L/μ]
Pr: Prandtl number [C μ /k]
Re: Reynolds number [u d/υ]

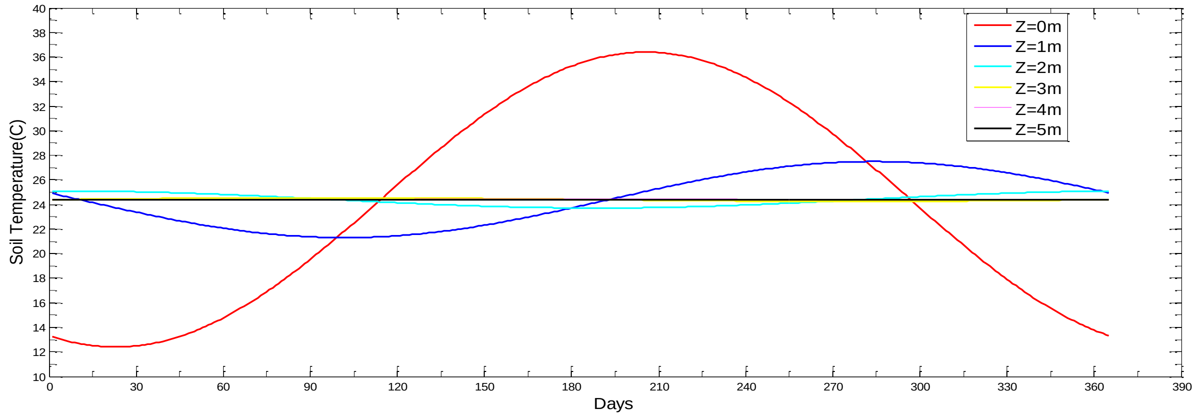

Fig. 3. Sub- Soil Temperature for different depths

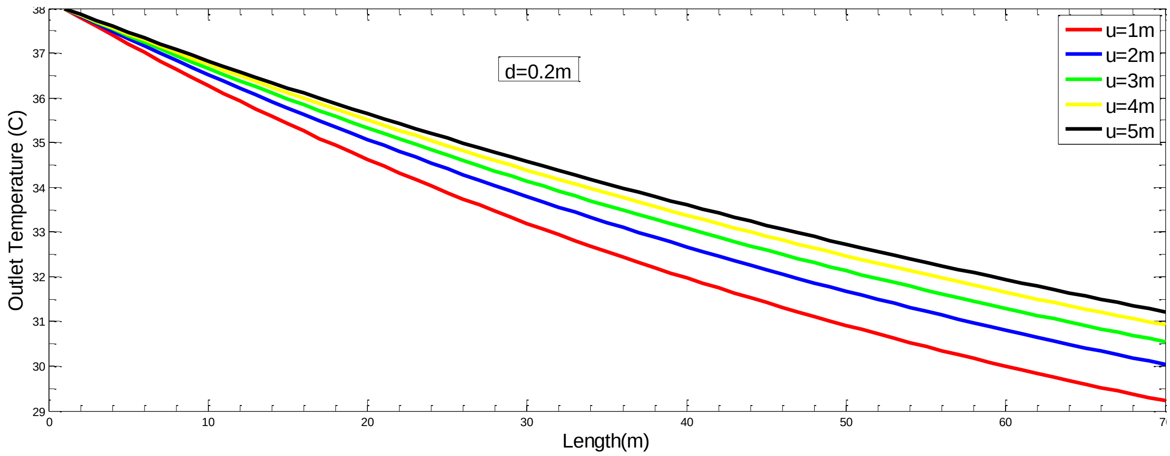

Fig. 4. The outlet air temperature of diameter 0.2 m for various velocities.

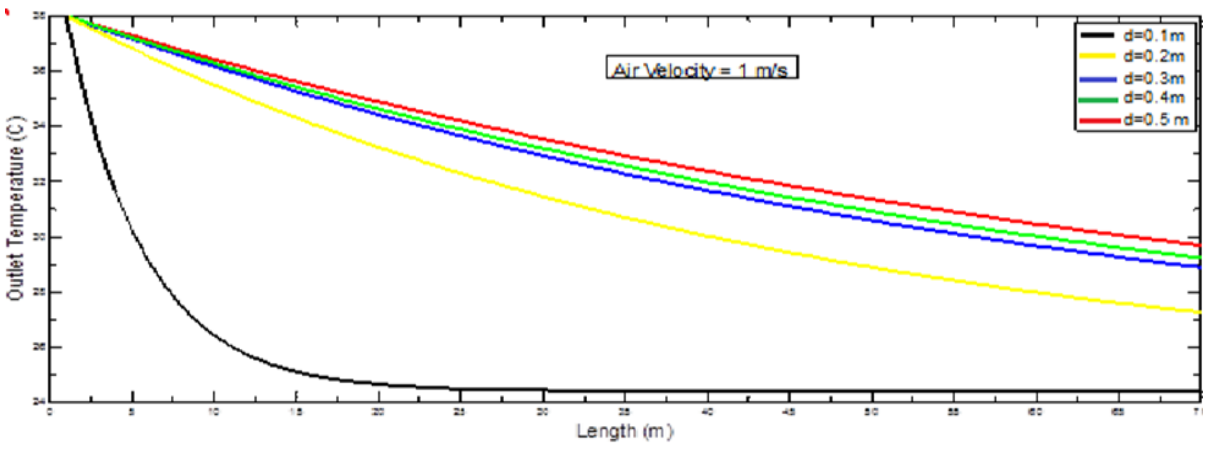

Fig. 5. The outlet air temperature of air velocity=1m/s m for various diameters.

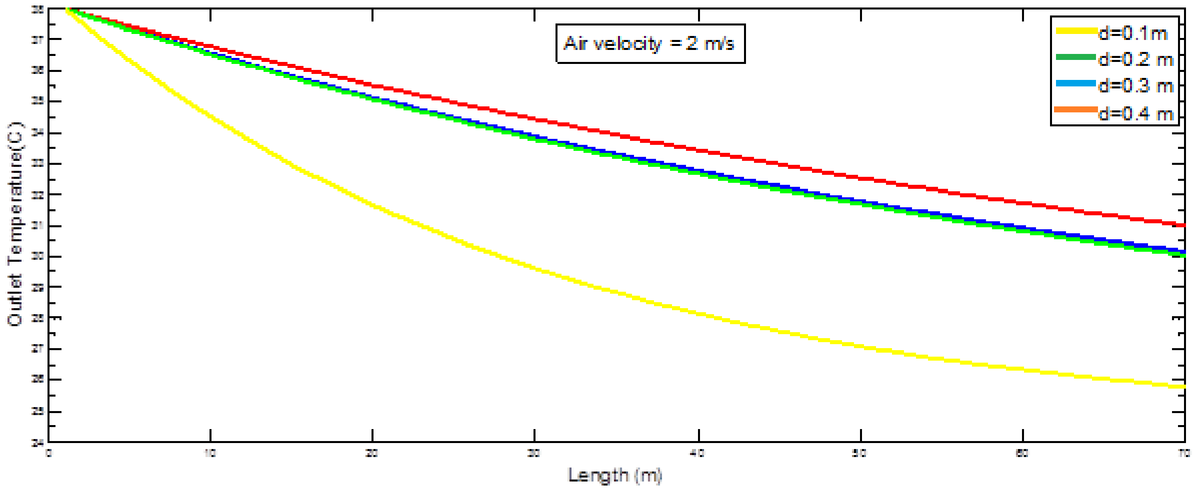

Fig. 6. The outlet air temperature of air velocity=2m/s m for various diameters.

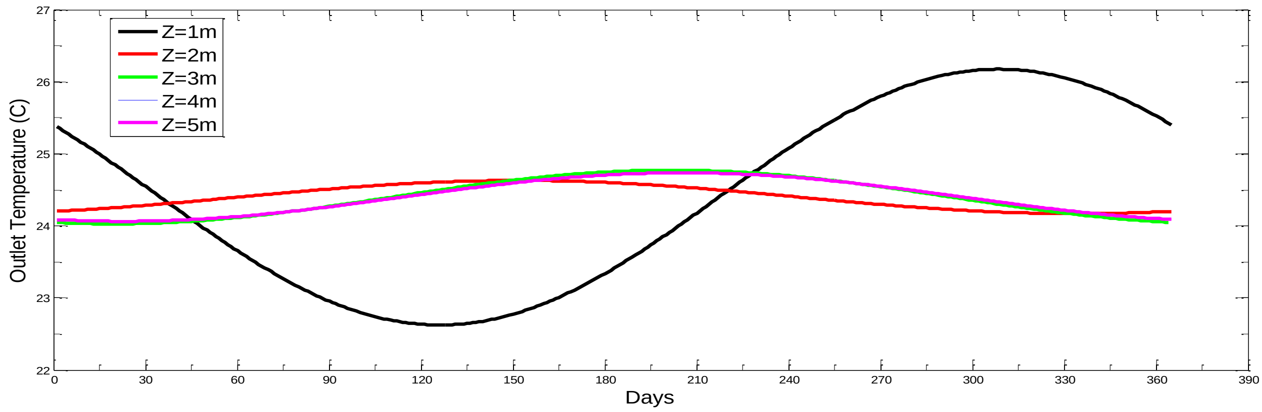

Fig. 7. The outlet air temperature of air velocity=2m/s m for various depths

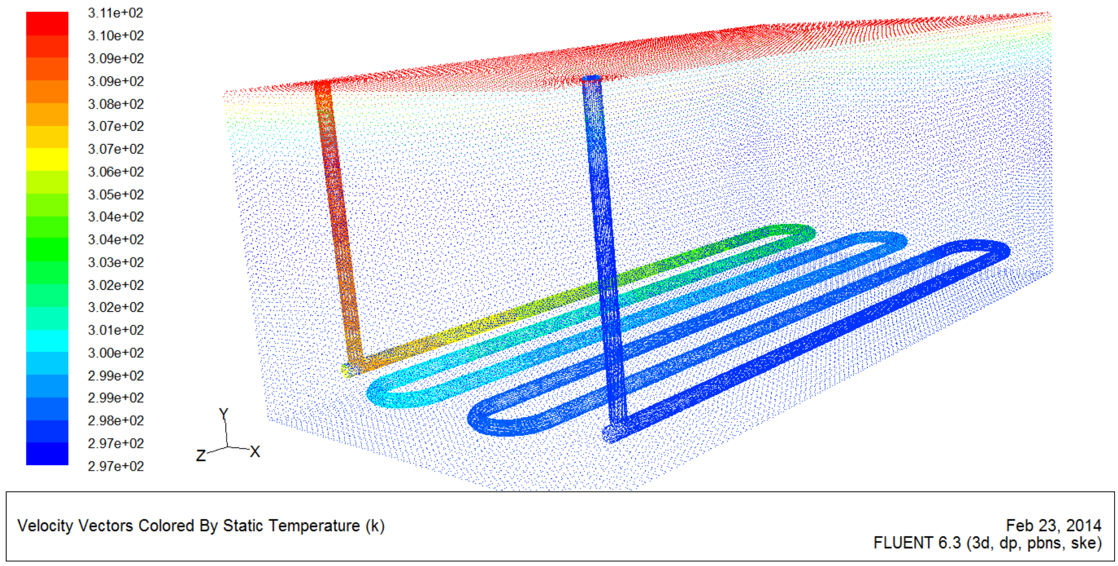

Fig. 8. Velocity vectors colored by static temperature for heat exchanger under ground

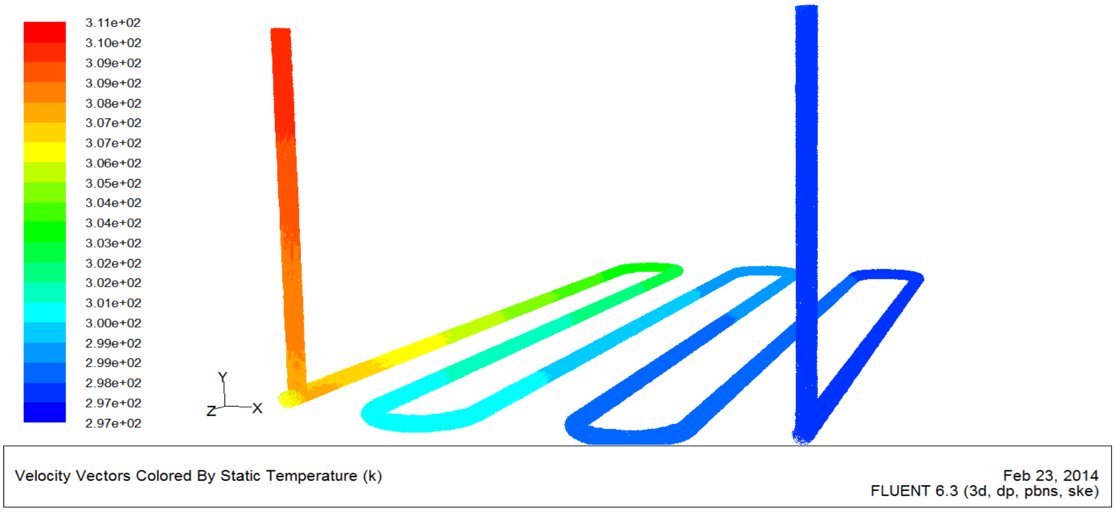

Fig. 9. Velocity vectors colored by static temperature for heat exchanger under ground

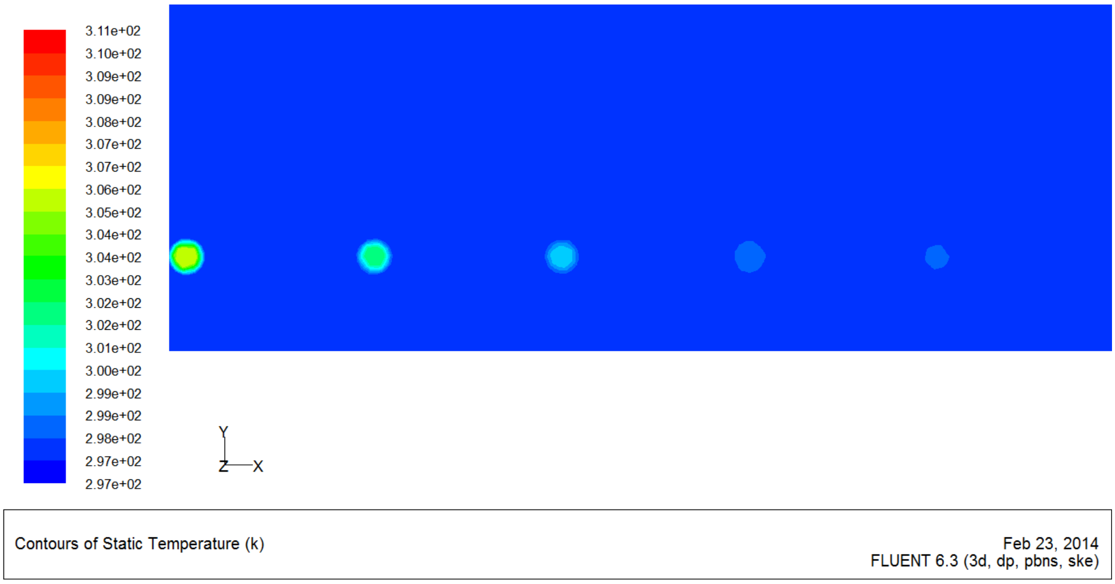

Fig. 10. Vertical section Velocity vectors colored by static temperature for heat exchanger under ground

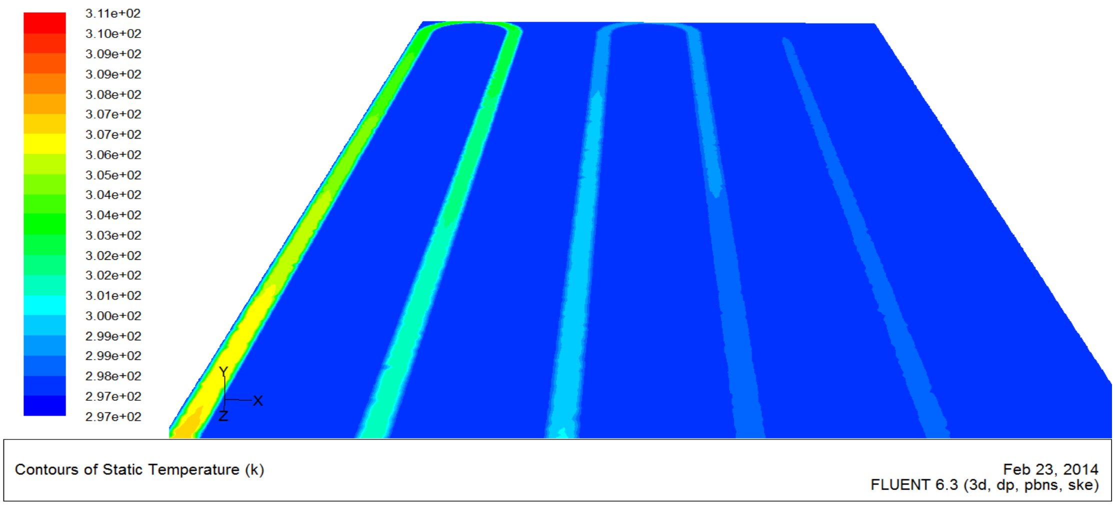

Fig. 11. Horizontal section Velocity vectors colored by static temperature for heat exchanger under ground

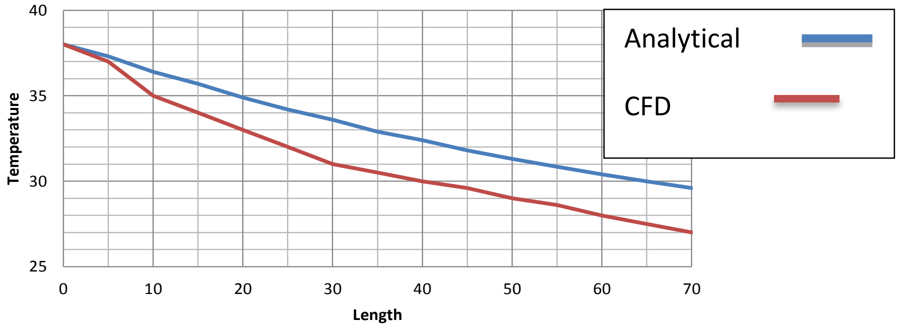

Fig. 12. The comparison between analytical modeling and CFD simulation