Modeling of Underground Heat Exchanger for Heat Pump and Air Conditioning Systems

Sarwo Edhy S
Department of Mechanical Engineering, Faculty of Engineering, Syiah Kuala University
Jl. Tgk. Syech Abdurrauf, No. 7, Darussalam, Banda Aceh 23111
Email: sarwo.edhy@unsyiah.ac.id

Abstract

Air conditioning and heat pump systems can use the ground as a medium to dump or absorb heat energy to increase efficiencies. As compared to the air, the ground has lower temperature in the summer and higher in the winter. In this research, the vertical U tube underground heat exchanger that can be used to harvest geothermal energy, has been modeled by using two dimensional finite difference methods. The model is not only able to estimate the water temperatures out of vertical U tube underground heat exchanger, but also capable of calculating the temperature profile change of surrounding soil under various water entering heat exchanger and weather conditions. The heat transfer process between the underground heat exchanger and soil has been investigated and profiles of soil and water temperatures are presented.

Keywords: Modeling, Underground heat exchanger, Heat transfer

Nomenclature

Cp	Specific heat of the pipe (kJ/kg.K)
Cs	Specific heat of the soil (kJ/kg.K)
C_w	Specific heat of water (kJ/kg.K)
Fo	Finite difference form of the Fourier number
h	Convective heat transfer coefficient ($W/m^2.K$)
Ks	Soil thermal conductivity (W/m.K)
mp	Mass of pipe at an increment length (kg)
ms	Mass of soil at an increment length (kg)
$Q\ (i)$	Heat loss of water in finite volume i (W)
Q'	Heat transfer in radial direction (W)
r	Copper tube radius (m)
ri	Inner radius of the pipe (m)
T	Soil Temperature (K)
Tp^t	Pipe temperature at time t (K)
$Tp^{t+\Delta t}$	Pipe temperature at time t+Δt (K)
$Ts^t(j+1)$	soil temperature at the soil radius increment (K)
$Tw(i)$	Water temperature at increment length i (K)
$Tw(i+1)$	Water temperature at increment length i+1 (K)
u	Water velocity (m/s)
Δr	Radius increment (m)
Δz	Distance increment (m)
Δt	Time increment (h)
α	Thermal diffusivity of the soil (m^2/h)
ρ	Water density (kg/m^3)

Subscripts

m	index for grid column
n	index for grid row

1. Introduction

Global warming and limitation of fossil fuel have forced the people to look for other energy resources. Renewable energy is an energy resource that is abundantly available in the world. However, this energy resource is not yet utilized properly. In past few years, the efforts to exploit the renewable energy have been continuous. One effort is by harvesting underground geothermal energy using underground heat exchanger for application of heat pump and air conditioning systems.

The geothermal heat pump (GHP) and air conditioning systems use the ground which has temperature between 5 and 30 °C to absorb and dump heat energy. During the cooling process, the indoor heat is transferred by an air conditioning system to the circulating fluid of underground heat exchanger system. A pump then circulates this fluid through an underground U tube heat exchanger. In the heat exchanger, the heat is transferred by circulating water to the ground. As a result, temperature of the ground around heat exchanger increases gradually. In the heating systems, the process is vice versa.

Various researches related to geothermal heat pump (GHP) system have been done since it was introduced by Robert Webber in the 1940s. Some people are interested in using the experimental work, while the others prefer to choose the modeling work.

A numerical modeling of borehole heat exchanger for application of geothermal heat pump had been carried out. An integral finite-difference method is used to model and simulate borehole heat exchanger (BHE). Both the temperature distribution in BHE and the economic profit of GHP are analyzed [1].

The link between the piping length of borehole heat exchanger and the operating parameter of heat pump also had been investigated through the mathematical modeling. The model is a single pipe configuration surrounded by the grout and the soil. The soil region was assumed had a constant ambient temperature. The effect of Taylor dispersion of the heat in the fluid with steady state and transient approach was used. The conduction between the two regions was modeled with a classical thermal resistance. It was found that when Taylor dispersion was considered, the approximated tubing length for the complete energy transport increases. However, the effect could be minimized with a suitable borehole radius choice [2].

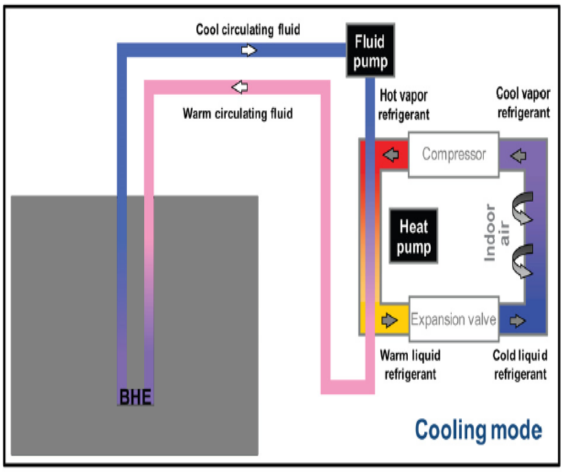

Figure 1: Schematic diagram of vertical U tube underground heat exchanger for pump and air conditioning systems [3]

In this research, the vertical configuration of single U tube underground heat exchanger is modeled by using two dimensional finite different methods.

The aim of this research is to develop a model that can be used to assess the capacity of vertical underground heat exchanger for cooling and heating purposes. Also, to investigate the impact of utilization underground heat exchanger on the surrounding soil temperature and the water temperature's profile into U tube heat exchanger.

2. Modeling

2.1 The governing equations

Heat transfer rate between U tube heat exchanger and soil is estimated using two dimensional conduction equations. The thermal properties of the soil are assumed isotropic and homogeneous.

A two dimensional conduction equation for cylindrical polar coordinates is given as [4].

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}=\frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (1)$$

The initial condition of soil temperature is considered uniform at t = 0. Using Baggs model, the Adelaide soil temperature can be calculated by using metrological data. From the calculation, it is obtained that the Adelaide soil temperature is stable at 3m depth. The temperature is 20^{o}C. While from 0 to 3m depth, the soil temperature fluctuates depend on the weather condition. Thus to simplify the simulation, the U tube heat exchanger is assumed thermally insulated from the soil surface to 3m depth. The insulated thermal area of the heat exchanger is shown in the grey color in figure 1.

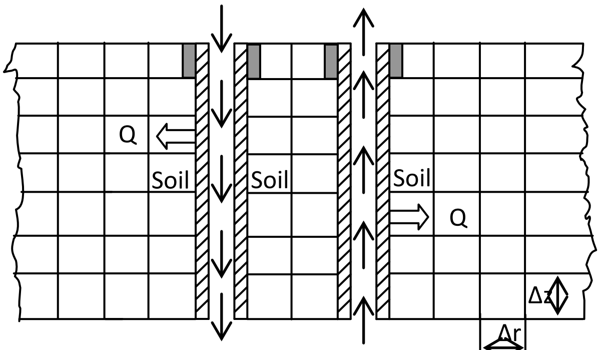

Figure 2: Soil discretization around U tube heat exchanger

In the figure 3, the water in the tube is divided into finite volumes with a finite incremental length Δz. If Δz is selected small enough according to the numerical approximation, the water temperature in each finite volume will be assumed identical. The horizontal surface of the tube to the soil surface is represented by Δr. According to Incropera and Dewiit (1990), the value of Δr can be evaluated using the equation $\Delta r \geq \sqrt{4\alpha\Delta t}$, where α is thermal diffusivity of the soil.

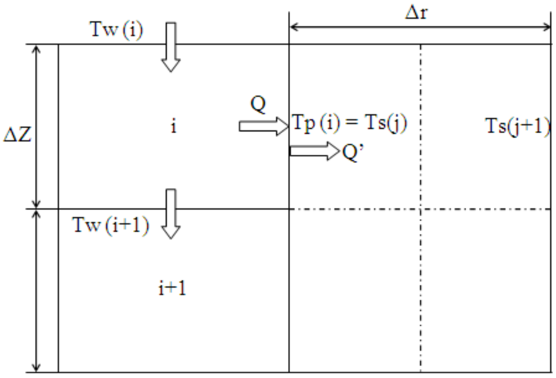

Figure 3: sketch of heat transfer process from the circulating water to the soil

The heat loss of water in finite volume i, $Q\ (i)$, can be determined from an energy conservation equation. The water heat loss is equal to the heat being transferred to the soil, within Δz.

$$Q = \left[\frac{Tw(i) + Tw(i+1)}{2} - \frac{Tp^{t} + Tp^{t+\Delta t}}{2}\right] * h.(2.\pi.ri.\Delta z) \qquad (2)$$

Applying the heat balance equation, the heat transfer from of the water in finite volume i to the outside surface of the tube also can be calculated as

$$Q\,(i) = u\rho C_w \Delta t.\pi.r_i^2 [T_w(i) - T_w(i+1)] \qquad (3)$$

The water temperatures at a next finite volume i +1 can be determined by rearrange the equation 2 and 3.

$$Tw(i+1) = \left[\left[\frac{u.\rho.Cw.ri}{h.\Delta z} - 1\right] Tw(i) + Tp^{t} + Tp^{t+\Delta t}\right] * \frac{1}{\left[1 + \dfrac{u.\rho.Cw.ri}{h.\Delta z}\right]} \qquad (4)$$

Assuming there is no contact resistant between the pipe and soil, the pipe temperature at the time t + Δt and an increment length i is expressed as

$$Tp^{t+\Delta t}(i) = Ts^{t+\Delta t}(j) \qquad (5)$$

The heat stored in the pipe and soil from the circulating water is described as

$$Q - Q' = \left[\frac{Cp.mp + Cs.ms}{\Delta t}\right].\left(Tp^{t+\Delta t} - Tp^{t}\right) \qquad (6)$$

Where Q' is calculated as

$$Q' = \left[Ts^{t+\Delta t}(j) - Ts^{t}(j+1)\right] \frac{Ks.2.\pi.ro.\Delta z}{\Delta r} \qquad (7)$$

Rearrange the equation 6,7,5 and 4, the pipe's temperature at the time t + Δt can be obtained as

$$Tp^{t+\Delta t} = \left(-c.Tw(i) + a.b.Tw(i) + a.Tp^{t} - d.Tp^{t} - e.Ts^{t}(j+1)\right) * \frac{1}{-e-d-a} \qquad (8)$$

Where

$$a = \frac{u.\rho.Cw.\pi.ri^2}{\left(1 + \dfrac{u.\rho.Cw.ri}{h.\Delta z}\right)} \qquad (9)$$

$$b = \left(\frac{u.\rho.Cw.ri}{h.\Delta z} - 1\right) \qquad (10)$$

$$c = u.\rho.Cw.\pi.ri^2 \qquad (11)$$

$$d = \frac{Cp.mp + Cs.ms}{\Delta t} \qquad (12)$$

$$e = \frac{2.Ks.\pi.ro.\Delta z}{\Delta r} \qquad (13)$$

Since the pipe temperature at the time increment t + Δt is obtained, then the water temperature for each length increment can be calculated like given in equation 4.

The soil temperature then can be calculated using numerical method for the various radiuses, length and time increment, based on its boundary condition. In this simulation, the boundary condition for the soil adjacent to the heat exchanger can be determined by applying all the governing equation to get the tube temperature at various length and time increment $Tp^{t+\Delta t}(i)$. The boundary condition for the other planes is the constant soil temperature, which is the initial temperature.

Thus the boundary condition can be summarized as

Boundary conditions

T(0,r,t) = Ts, T(Z,r,t) = Ts, T(z,R,t) = Ts, T(z,0,t) = f(z,t) = $Tp^{t+\Delta t}(i)$.

Some assumptions are used in order to keep the numerical simulation is manageable. The assumptions are summarized as follows:

1. The soil properties are assumed isotropic and homogeneous.
2. Contact resistance between U tube heat exchanger and the soil is ignored.
3. Heat transfer process between the heat exchanger legs is ignored.
4. The underground water flow is ignored
5. The U tube heat exchanger is assumed thermally insulated from the soil surface to 3m depth below the surface.

2.2 Numerical Method

The explicit method is one of a common method used to solve numerical solution of parabolic partial differential equation. This method used to estimate the later temperature of a system based on the previous time temperature. Therefore, the unknown temperature is calculated straightforward.

The two dimensional heat transfer equation 1 with constant properties and no internal heat generation then is reduced to an approximate algebraic equation. The explicit form of the finite difference equation for interior node m,n is

$$\frac{T^{t+\Delta t}_{m,n} - T^{t}_{m,n}}{\alpha.\Delta t} = \frac{T^{t}_{m+1,n} - 2T^{t}_{m,n} - T^{t}_{m-1,n}}{(\Delta r)^2} + \frac{1}{r} \tag{14}$$

Solving for the nodal temperature at new time step (t+Δt) and assuming that Δr = Δz, the equation 14 will lead to

$$T^{t+\Delta t}_{m,n} = Fo\left(T^{t}_{m-1,n} + T^{t}_{m+1,n} + T^{t}_{m,n-1} + T^{t}_{m,n+1}\right) + (1-4Fo)T^{t}_{m,n} + Fo.\Delta r\frac{\left(T^{t}_{m+1,n} - T^{t}_{m-1}\right)}{2.r_o(m)} \tag{15}$$

The equation 15 is only valid for middle interior point which is Δr = Δz like shown in figure 3.

Since the increment Δr and Δz is different for the top and down interior point, the interior top and down node's equation at time step t + Δt are respectively described as

$$T^{t+\Delta t}_{m,n} = Fo\left(T^{t}_{m-1,n} + T^{t}_{m+1,n} + 2T^{t}_{m,n-1} + T^{t}_{m,n+1}\right) + (1-5Fo)T^{t}_{m,n} + Fo.\Delta r\frac{\left(T^{t}_{m+1,n} - T^{t}_{m-1,n}\right)}{2.r_o(m)} \tag{16}$$

$$T^{t+\Delta t}_{m,n} = Fo\left(T^{t}_{m-1,n} + T^{t}_{m+1,n} + T^{t}_{m,n-1} + 2T^{t}_{m,n+1}\right) + (1-5Fo)T^{t}_{m,n} + Fo.\Delta r\frac{\left(T^{t}_{m+1,n} - T^{t}_{m-1}\right)}{2.r_o(m)} \tag{17}$$

$$Fo = \frac{\alpha.\Delta t}{(\Delta r)^2} \tag{18}$$

To improve the accuracy of the finite difference solution, the mesh quality of discretization's region should be fine enough. This can be done by decreasing the value of Δr and Δt. Indeed, decreasing Δr and Δt will increase the amount of interior nodal points and time interval respectively. As a result, the computational time increases with decreasing Δr and Δt.

To be well within the stability region limit, Δt must be selected as

$$\Delta t \le \frac{Fo.(\Delta r)^2}{\alpha} \tag{21}$$

Since the most restrictive stability criterion in associated with the interior top and down node's equation, the Fo is selected as $Fo \le 1/5$.

Then all the required equations are put in the Mat-Lab software in the compact way. Finally, the simulation is ready to execute.

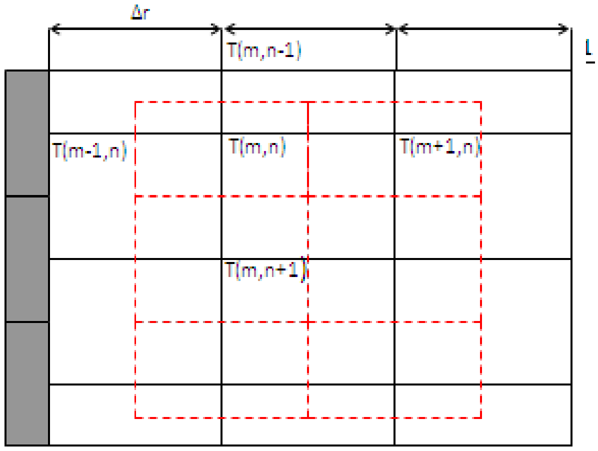

Figure 4: Nodal network of soil region around the heat exchanger

2.3 Simulation condition

The simulation condition for the underground heat exchanger for heating and cooling purposes can be summarized as

<u>U tube</u>
Material : Copper
Inner diameter : 35 mm
Outer diameter : 45 mm
Spacing : 100 mm
Thermal conductivity : 401 W/m.K
Density : 8960 kg/m^3
Specific heat : 390 J/kg.K
Depth : 20 m

<u>Geological conditions</u>
Soil type : Clay
Thermal conductivity : 1.27418 W/m.K
Thermal diffusivity : 0.8 x 10^{-6} m^2/s
Density : 1746 kg/m^3
Specific heat :912.2149 J/kg.K
Initial ground temperature : 20^{o}C

<u>Heat carrier</u>
Fluid : Water
Water inlet temperature : 30 ^{o}C,40 ^{o}C,50 ^{o}C (Cooling), 15 ^{o}C, 10 ^{o}C, 5 ^{o}C (Heating)
Flow rate : 9.61 x 10^{-5} m^3/s, 1.92 x 10^{-4} m^3/s and 2.88 x 10^{-4} m^3/s.

3. Results and discussion

3.1 Water temperature profiles

3.1.1. Cooling

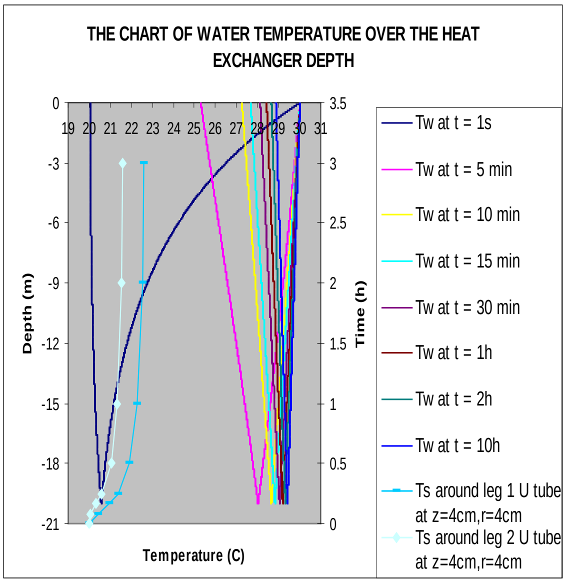

Figure 5: Water temperature profile over the heat exchanger depth at Tw in = 30 ^{o}C and V = 1.92 x 10^{-4} m^{3}/s

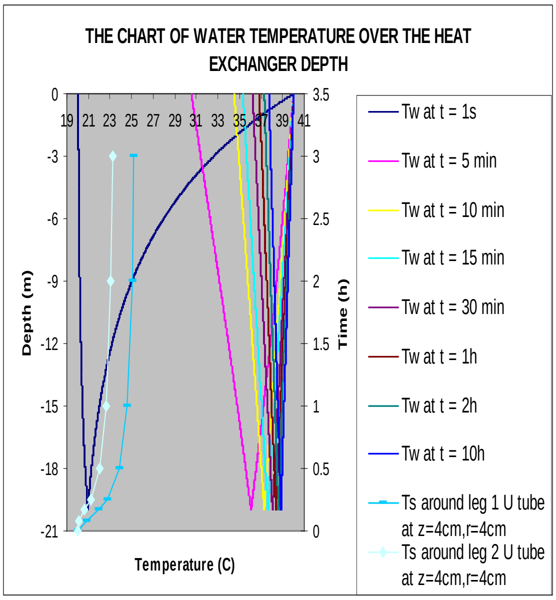

Figure 6: Water temperature profile over the heat exchanger depth at Tw in = 40 ^{o}C and V = 1.92 x 10^{-4} m^{3}/s

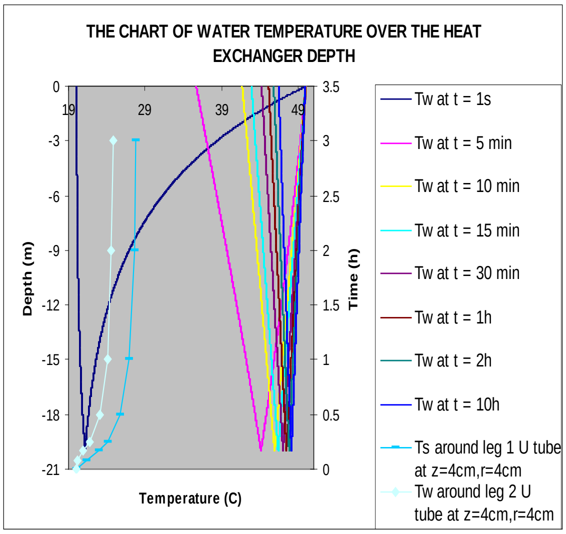

Figure 7: Water temperature profile over the heat exchanger depth at Tw in = 50 ^{o}C and V = 1.92 x 10^{-4} m^{3}/s

In the cooling system simulation, water inlet temperature entering the heat exchanger is varied to 30, 40 and 50 ^{o}C, with the flow rate is 1.92 m^{3}/s. The graphs of cooling system simulation show that the profile of water temperature distribution along the heat exchanger decreases over the time. At 1 s after the first water circulation, it shows that the water temperature nearly reach the initial soil temperature just at leg 1 U tube heat exchanger. While in the leg 2 the water temperature decreases insignificantly. This occurs because the difference of water temperature at the inlet of leg 2 U tube heat exchanger and soil is lower. As a result, small amount of heat can be release at the leg 2 U tube. After 5 minutes of water circulation, the profile of water temperature tends to decrease. This phenomenon occurs because the soil temperature around the U tube heat exchanger increases. As a result, the heat that can be dumped from the circulating water decreases significantly.

3.1.2. Heating

In the heating system simulation, the inlet temperature of water entering the U tube heat exchanger is varied to be 15,10 and 5 ^{o}C with the flow rate is 1.92E-4m^{3}/s. At 1 s of water flow into U tube heat exchanger, the amount of heat can be harvested from the ground is very high for three kind of water inlet temperature. This occurs because of the difference between soil and water temperature is relatively high. The water temperature difference between inlet and outlet at this time are 4.96, 9.92, and 14. 84 ^{o}C. By the time increases, the water temperature difference tends to decreases.

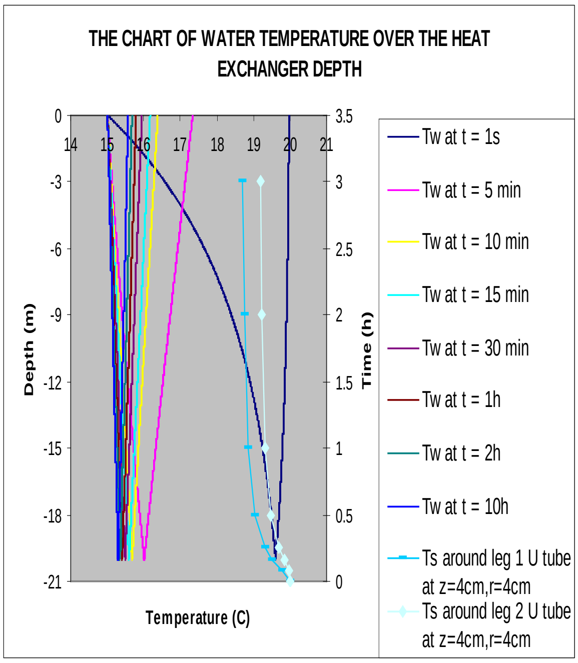

Figure 8: Water temperature profile over the heat exchanger depth at Tw in = 15 ^{o}C and V = 1.92 x 10^{-4} m^3/s

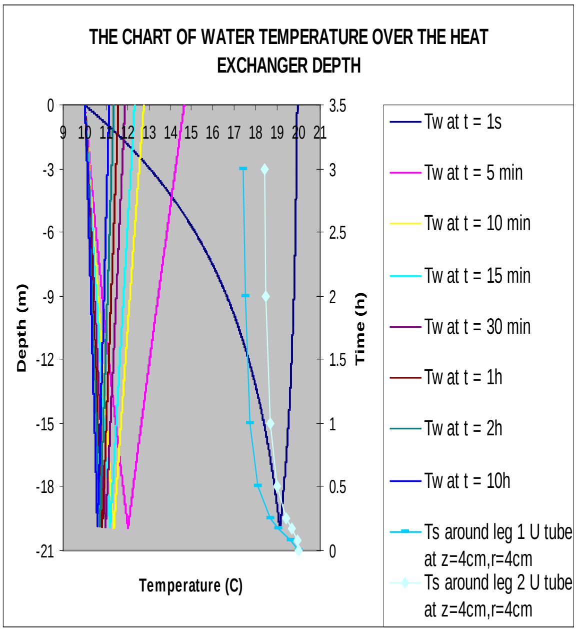

Figure 9: Water temperature profile over the heat exchanger depth at Tw in = 10 ^{o}C and V = 1.92 x 10^{-4} m^3/s

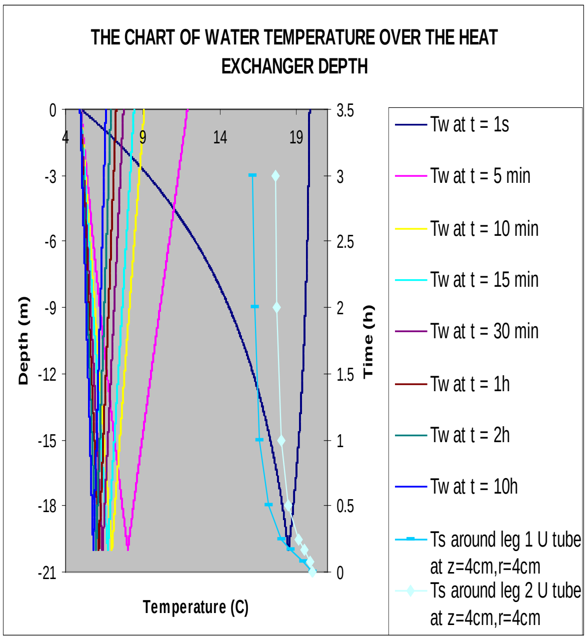

Figure 10: Water temperature profile over the heat exchanger depth at Tw in = 5 ^{o}C and V = 1.92 x 10^{-4} m^3/s

3.2 Soil Temperature

The graphs below show the soil temperature around U tube heat exchanger for both cooling and heating systems at various distances after 10 hours of water circulation. At the heating process, the soil temperature decreases because the heat exchanger absorbed the heat from the surrounding soil. The lowest soil temperature is at the distance zero from the pipe. The soil temperature around leg 1 is lower compared to leg 2 U tube heat exchanger. This phenomenon occurs because at the leg 1 the difference between the water and the soil temperature is relatively high. Thus, higher heat can be harvest. As a result, the soil temperature surrounding the heat exchanger is lower. From the figure, it describes that, the lower of water inlet temperature, the lower is soil temperature is achieved. The soil temperature change is relatively small at the distance more than 0.04 m. this could be happened because the soil is assumed as unsaturated. Thus, because the lower of water contains in the soil, the soil's heat transfer conductivity is small. As a result, it will need longer time for the temperature increased.

In the cooling process, the heat from the water circulation is dumped to the soil. Thus the soil temperature around the heat exchanger increases. The higher temperature of water inlet, the higher the soil temperature is reached. The soil temperature around leg 1 U tube heat exchanger is higher compared to the leg 2 U tube heat exchanger. This occurs because at the leg 1, the difference between water and soil temperature is relatively higher. So, the heat that can be transfer is higher, while in the leg 2 U tube heat exchanger, the difference between water and soil temperature is relatively lower. As a result, the heat that can be transfer to the soil is also relatively lower

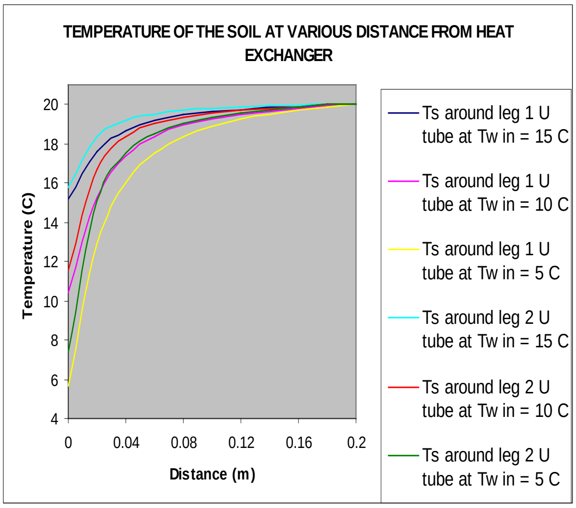

Figure 11: Temperature of the soil at various distances from heat exchanger for heating load

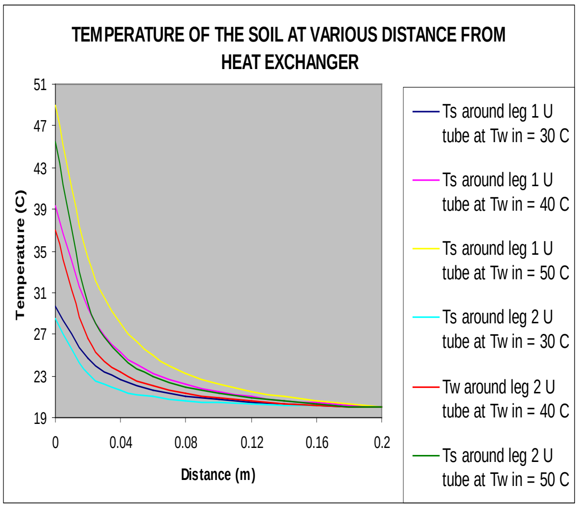

Figure 12: Temperature of the soil at various distances from heat exchanger for cooling load

4. Conclusion

In conclusion, the effect of water inlet temperature is investigated for heating and cooling systems.

The results of simulation for cooling purpose show that the water inlet temperature is not only affecting the water outlet and soil temperature, but also the number of heat that can be released to the soil. The higher water inlet temperature is fed into the underground heat exchanger, the higher water outlet and the soil temperature is attained. Also, the higher the number of heat can be released to the soil. While for the heating purpose, it shows that the lower water inlet temperature, the higher the heat can be harvested from the ground.

References

[1] Kim, SK, Bae, GO, Lee, KK, Song, Y, 2009, Field-scale evaluation of the design of borehole heat exchangers for the use of shallow geothermal energy , *Journal of Energy*, vol.35, no.2, pp.491-500.

[2] Ortan, O and Hepbasli, A 2007, 'Modeling and performance evaluation of ground source geothermal heat pump systems', *Energy and building*, vol.39, no.1, pp.66-75.

[3] Lee, CK, Lam, HN 2007, 'Computer simulation of borehole ground heat exchangers for geothermal heat pump systems' ,*Renewable energy*, vol.33, no.6, pp.1286-1296

[4] Croft, DR and Liley, DG 1977, *Heat transfer calculations using finite difference equations*, Applied Science Publishers LTD, London.

[5] Incropera, FP, Dewiit, DP 1990, *fundamentals of heat and mass transfer,* 3nd edn, John Willey and Son, USA.

[6] Lund, J, Sanner, B, Rybach, L, Curtis, R, Hellstrom, G, 2004, *Geothermal (ground-source) heat pumps a world overview*, GHC Bulletin, viewed 18 August 2010,<http://www.cres.gr/kape/pdf/geotherm/4.pdf>