NUMERICAL ANALYSIS FOR DIFFERENT CONFIGURATIONS OF U-SHAPED BOREHOLE HEAT EXCHANGER

Shaimaa H.Hefny*, Medhat M.Sorour**, Osama A.El-Masry***
*Instructor at Mechanical Engineering Department-Faculty of Engineering-Pharos University in Alexandria-Egypt
**Professor of Power Station, Mechaincal Engineering Department-Faculty of Engineeriegn-Alexandria University-Egypt
***Professor of Energy and Environment, Mechanical Engineering Department, Pharos University in Alexandria-Egypt

Abstract— Vertical U-shaped borehole heat-exchangers (UBHE) use the earth as a heat sink or heat source, respectively, to dissipate and absorb thermal energy into/from the ground. The ground temperature depends on the seasons at a certain depth (about 30 meters in the ground) the cold and warm temperatures of the ground are represented for cooling and heating of buildings that happens in summer and winter respectively. Various model's Configurations have been investigated by changing the diameters of borehole and U-tube, the shank spacing between U-tube. The simulation of the dynamic and thermal behavior of the geothermal vertical U-tube borehole heat exchanger (UBHE) was carried out under Fluent –ANSYS 14.0 software, using three-dimensional implicit finite difference method. The simulation of UBHE assumes heat transfer within the circulating fluid and grout to be in a Transient. The governing equations, based on the k–ε model used to describe the turbulence phenomena, are solved by using finite volume method. CFD calculations were performed for different of diameters borehole and U-tube and U-tube shank spacing results.

Index Terms— Keywords: 1) Geothermal/Ground Heat Pump (GHP), 2) Geothermal/Ground Heat Exchanger (GHE), 3) Borehole Heat Exchanger (BHE), 4) U-shaped Borehole Heat Exchanger (UBHE), 5) Thermal Response Test (TRT), 6) 3D Numerical Model, 7) Fluent-ANSYS.

◆

1 INTRODUCTION

Geothermal energy is the thermal energy stored in the Earth body, it is an inexhaustible source of thermal (cooling and heating) and electrical energy on a human time scale. Its utilization is friendly to the environment and supplies base-load energy "[1, 2]" .There are three basic types of ground loop systems. There are horizontal, vertical, and pond/lake are closed-loop systems. Which one of these is best depends on the climate, soil conditions, available land, and local installation costs at the site. All of these approaches can be used for residential and commercial building applications. borehole heat exchangers are designed as U-tube exchangers, in which the heat transfer medium flows in a tube branch from the surface to the base of the ground heat exchanger hole; i.e., from top to bottom. In the other tube branch, the circulating heated heat transfer medium flows from the borehole base to the surface; i.e., from bottom to top. When rising, the heat transfer medium always releases a portion of the accumulated heat energy to the heat transfer medium circulating downward in the adjacent tube branch and to the surrounding colder soil "[3, 4]". Vertical Borehole Heat Exchangers (BHEs) have a low space requirement and make use of a constant temperature level. The exchangers are typically implemented as vertical boreholes in which plastic (HDPE) tubing is installed. Within the tubes, a heat transfer fluid circulates that absorbs heat from the surrounding ground and feeds it to the heat pump. Thermal response tests (TRTs) are routinely used to determine subsurface and borehole thermal properties, which are needed to size ground heat exchangers for commercial or institutional ground-coupled heat pump systems. Raymond, J., R. Therrien, and L. Gosselin "[5]"investigated 2-D numerical simulations of the borehole temperature evolution during thermal response tests (TRT). The measurement of temperature inside a borehole at specified depths happens during TRT. Numerical simulations also indicate that the borehole thermal resistance. Borinaga-Treviño, R., et al. "[6]", studied borehole thermal response and thermal resistance of four different grouting materials measured with a TRT in vertical geothermal closed-loop heat systems which exchange heat with the ground through a closed buried pipe system, sealed with a grouting material that ensures the stability and thermal transmission of the borehole. They were showed the results that all mixes fulfill the minimum consistency and strength requirements. There are many methods which were investigated in almost science papers for calculation of thermal resistances for vertical ground heat exchangers in geothermal heat-pump systems that are designed. For instance, Sharqawy, M.H., E.M. Mokheimer, and H.M. Badr "[7]"investigated numerically effective pipe-to-borehole thermal resistance for vertical ground heat exchangers. An analysis is carried out to determine the dimensionless geometrical parameters affecting such resistance. The heat transfer rates between the U-shaped pipes and the borehole are determined numerically and compared with some well-known limiting analytical solutions. The temperatures distributions of fluid inside U-tube along UBHE are the most important calculation for designing geothermal systems, so there are some researches for that point. The results of temperatures distributions are different for various areas of ground because there are many dependent variables. Beier, R.A., et al "[8]"developed an analytical model of the vertical temperature profiles of the undisturbed ground and studied the values of ground thermal conductivity and borehole resistance in a U-tube borehole heat exchanger.

2 THE AIM OF STUDY

The present study is 3D- numerical solution by using Fluent-Ansys 14.0 to study the thermal behavior of the circulating fluid temperature inside U-tube borehole heat exchanger (30 m deep underground) to cooling water in summer season, by changing some thermal parameters (velocities of fluid- time size of transient heat transfer) with depth and diameters of U-tube and BHE. After this study it is found the best velocity with typical depth to leave the system more time size of transient heat transfer.

Nomenclature

T: Temperature (K)

D_b:The borehole diameter (m)

D_p: The pipe diameter (m)

S_u: The Spacing between the centers of two legs (m)

D_h:The hydraulic diameter (m)

m^o: The Mass Flow Rate (kg/sec)

Q: The Heat Transfer Rate (Watt)

L or H: Length (m)

Z: Depth (m)

k: The Thermal Conductivity Coefficient (W/m.K)

Greek symbols

ρ: Density of the fluid [Kg/m^3]

μ: Viscosity of the fluid [m^2/s]

Abbreviations

GHP: Geothermal/Ground Heat Pump

GHE: Geothermal/Ground Heat Exchanger

BHE: Borehole Heat Exchanger

UBHE: U-tube Borehole Heat Exchanger

DLP: Downward Leg of Pipe

ULP: Upward Leg of Pipe

TRT: Thermal Response Test

HDPE: High Density Polyethylene

FVM: Finite Volume Method

CFD: Computational Fluid Dynamics

Subscripts

b: borehole

p: pipe

f: fluid

w: water

g: grout

s: soil

i: inside

o: outside

in: inlet

out: outlet

3 SIMPLIFIED U-TUBE BHE

Usually, the borehole diameter is about 0.11–0.2 m, and the pipe diameter is about 0.02–0.05 m. The properties needed mainly the ground temperature, the thermal load, and soil Table (1), grout Table (2) and pipes thermo-physical properties Table (3). The U-tube geometry, however, provides more of a challenge, because simple radial heat transfer does not apply within the borehole. In addition, the thermal conductivity of the grout material and the pipe walls are different from that of the soil. At a given depth the temperatures of the circulating fluid Table (4) in the two pipes differ. Thus, the pipes do not only exchange heat with the soil, but the pipes also exchange heat with each other.

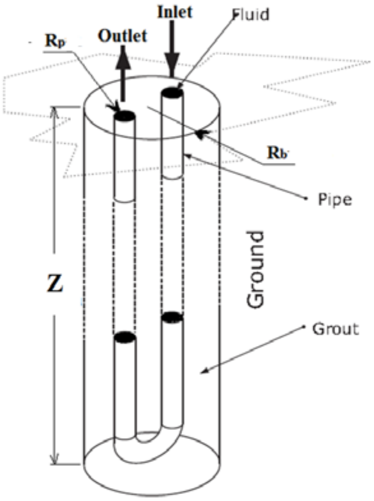

Figure (1) Schematic diagram of the 3D UBHE

Table (1) Properties of Ground (Soil):

Ground - Soil			
Thermal Conductivity of Soil	Ks	3.49	W/m. °c
Density of Soil	ρs	3197	kg/m3
Soil Specific Heat Capacity	Cp	1550	J/kg.K
Soil Thermal Capacity	ρCp	4.95535	$MJ/m^3.K$
Convection Coefficient	h	1690	$W/m^2.K$

Table (2) Properties of Grout:

Grout			
Thermal Conductivity of Grout	K_g	2.6	W/m. °c
Density of Grout	ρg	1600	kg/m^3
Grout Specific Heat Capacity	C_p	1250	J/kg.K
Grout Thermal Capacity	ρC_p	2	$MJ/m^3.K$

Table (3) Properties of HDPE:

High Density Polyethylene (HDPE) - Plastic			
Thermal Conductivity of U-Tube Material	K_U	0.46	W/m. °c
Density of U-Tube Material	ρ_U	940	kg/m^3
Specific Heat Capacity of U-Tube Material	C_p	1800	J/kg.K
Ground Thermal Capacity	ρC_p	1.692	$MJ/m^3.K$

Table (4) Properties of Fluid inside U-Tube:

Fluid - Water			
Mean Initial Water Temperature	T_{wi}	17	°c
Thermal Conductivity of Water	K_w	0.5926	W/m. °c
Density of Water	ρ_w	998.66	kg/m^3
Water Specific Heat Capacity	C_p	4183.8	J/kg.K
Dynamic Viscosity	μ	1.086*10^-3	kg/m.s
Kinematic Viscosity	ν	1.085*10^-6	m^2/s
Thermal Diffusivity	α	1.417*10^-7	m^2/s
Prandtl Number	Pr	7.658	____
Volume Expansion Coefficient	β	0.1608*10^-3	1/K

4 RANGE OF CONTROL PARAMETERS

Two dimensionless geometrical parameters or variables were adapted to control the size of borehole, pipe, thermal resistance and the arrangement of DLP-ULP of BHE.;i.e. the borehole-to-pipe diameter ratio (D_b/D_P) and the shank spacing to-borehole diameter ratio (S_u/ D_b). Generally in vertical ground heat exchangers the borehole diameter (D_b) is between 11 and 20 cm, and the diameter of the pipes between 3.2 and 6.0 cm. Therefore the minimum value of (D_b / D_P) is 2 and the maximum is 6.6.(S_u / D_b) depends on (D_b / D_P) the minimum and maximum values of the shank spacing, Su are investigated in following equations from (1) to (5)"[9]"

$Su_{min}=D_p$ (1)

$Su_{max}=D_b- D_p$ (2)

Therefore, the minimum and maximum values of (S_u / D_b) are,

$(S_u/D_b)_{min}=(1/(D_b/D_p))$
(3)

$(S_u/D_b)_{min}=1-(1/ \quad (Db/Dp) \quad)$
(4)

5 GOVERNING EQUATIONS:

The governing equations of problem are solved by the finite volume method (FVM), based on the algorithm SIMPLEC and PISO, for the coupling pressure–velocity. The iterative solution is continued until the residuals for all cells of calculation have become <10−5 for all dependent variables"[10]". The general transport equation that describe the principle of conservation of mass, momentum and energy can be expressed in the following conservative form"[11]":

$$\partial u/\partial x+\partial v/\partial y+\partial w/\partial z=0 \quad (5)$$

$$\rho\, Du/Dt=(\partial(-p+\tau_{xx}))/\partial x+(\partial\tau_{yx})/\partial y+(\partial\tau_{zx})/\partial z+S_{Mx} \quad (6)$$

$$\rho\, D_v/Dt=(\partial\tau_{xy})/\partial x+(\partial(-p+\tau_{xy}))/\partial y+(\partial\tau_{zy})/\partial z+S_{My} \quad (7)$$

$$\rho\, D_w/Dt=(\partial\tau_{xz})/\partial x+(\partial\tau_{yz})/\partial y+(\partial(-p+\tau_{zz}))/\partial z+S_{Mz} \quad (8)$$

$$\rho DE/Dt=-div(pu)+[\partial(\llbracket u\tau\rrbracket_{xx})/\partial x+\partial(\llbracket u\tau\rrbracket_{yx})/\partial y + \partial(\llbracket u\tau\rrbracket_{zx})/\partial z +\partial(\llbracket v\tau\rrbracket_{xy})/\partial x+ \partial(\llbracket v\tau\rrbracket_{yy})/\partial y + \partial(\llbracket v\tau\rrbracket_{zy})/\partial z + \partial(\llbracket w\tau\rrbracket_{xz})/\partial x + \partial(\llbracket w\tau\rrbracket_{yz})/\partial y + \partial(\llbracket w\tau\rrbracket_{zz})/\partial z]+div(k\ grad\ T)+S_E \quad (9)$$

Table (5) CFD - k-ε Model constants

Constant	Value
C_μ	0.09
C_1	1.44
C_2	1.92
SCTK -(σ_k)	1
SCTD -(σ_ε)	1.2

6 BOUNDARY CONDITIONS:

A 3D, unsteady-state model were built and simulated twice in the CFD-software Fluent for this study. The thermal–physical proprieties (C_p, μ, K, ρ and T_{in}) of the fluid and solids are considered constant.

i. For inlet boundary, the velocity considered for inlet flow.
ii. Mass flow boundary condition is set for outlet.
iii. Velocity inlet is uniform.
iv. The flow is fully developed.
v. Pressures of inlet and outlet are atmospheric pressure.
vi. Wall temperature of BHE is constant.
vii. Wall temperature of U-tube is coupled.
viii. Surface of BHE is equal zero heat flux (adiabatic).

7 RESULTS AND DISCUSSION

7.1 CASE STUDY-1: The Effect of changing spacing between two legs of U-tube BHE on Temperatures Distributions of water inside U-tube:

The system consists of a section of 5 m of a geothermal vertical heat exchanger in U-tube configuration, with 0.110 m borehole diameter;the U-tube is 40 mm of diameter and the distance between its two legs is changed by using equation from(1)to (4). These dimensions were previously used to design UBHE as shown in Table (6).

Table (6) Geometry Parameters for U-Tube:

Case 1				Case 2				Case 3			
Min. (S/D_b) = 0.4				Average (S/D_b) = 0.5				Max. (S/D_b) = 0.6			
H	1, 5, 10, 15, 20m			H	1, 5, 10, 15, 20m			H	1, 5, 10, 15, 20m		
D_b	0.11	R_b	0.055	D_b	0.11	R_b	0.055	D_b	0.11	R_b	0.055
D_p	0.04	R_p	0.02	D_p	0.04	R_p	0.02	D_p	0.04	R_p	0.02
S_u	0.066	S_c	0.033	S_u	0.055	S_c	0.0275	S_u	0.044	S_c	0.022

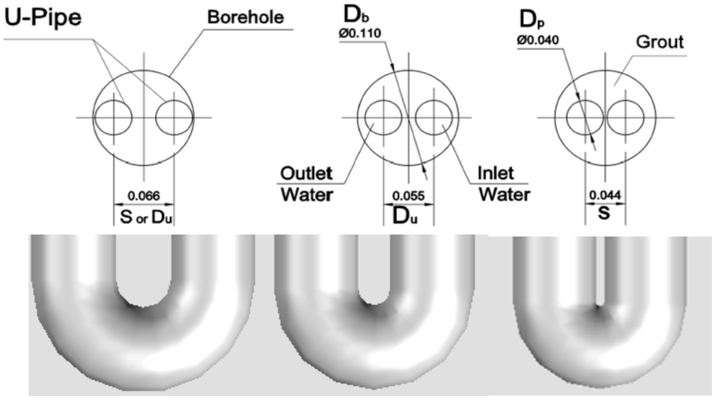

Figure (2) Schematic Diagram of BHE configurations of Vertical U-Tube

Table (7) Some Results from three cases for different configurations

Cases	Case 1	Case 2	Case 3
T-out (˚c)	12.4	12.6	12.9
Thermal Power (W)	4553.76	4458.66	4423.45

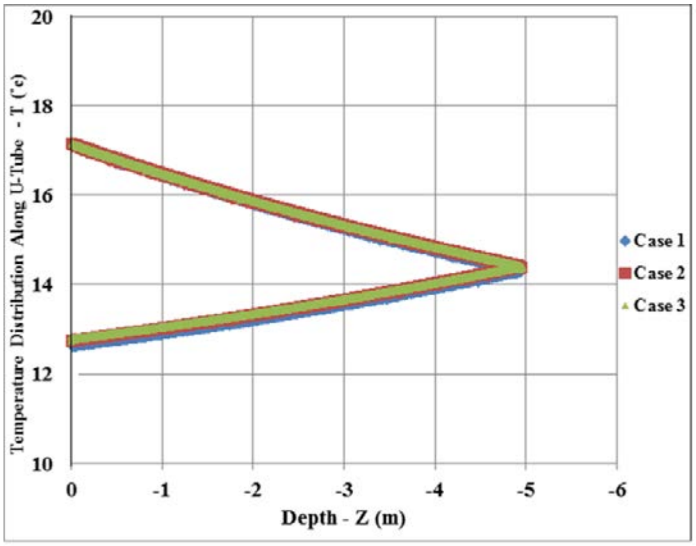

Figure (3) Temperature Distribution T with Depth Z for difference configurations in Table (6)

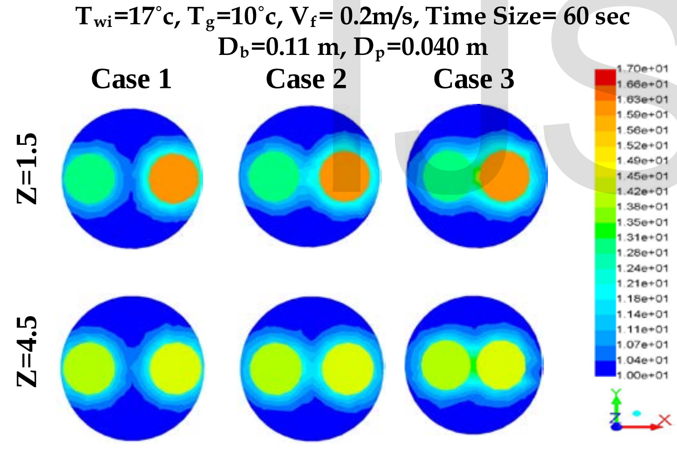

Figure (4) Cross sections in U-Tube BHE at different depth Z to show temperature distribution inside and around U-Tube BHE for difference configurations in Table (6)

Figure (3) displays temperature distribution around and along U-tube at different spacing between two legs for three cases that match. This spacing distance should not be chosen by any value, it is a ratio of diameters of borehole and U-tube and should be calculated from equations from (1) to (4) which have different spacing (minimum, average, maximum). Figure (4) shows cross section profile for different depth to display temperatures distributions around U-tube for three cases, the temperatures change less than 0.5 ˚c as shown in Table (6).

7.2 CASE STUDY (2): The Effect of changing of diameters of borehole and U-tube on Temperature Distribution of water inside U-tube:
From practical part of view the borehole diameter (Db) is from 0.11 m to 0.2 m, and the pipe diameter (Dp) is from 0.02m to 0.06 m. Consequently, three different diameters of borehole (0.11-0.13-0.16) and U-tube (0.032-0.040-0.052) are presented. Tables from (5.3) to (5.5) present the outlet temperature and heat transfer rate for three cases. It can be seen that have is no significant change in these output parameters at inlet water temperature Tin = 17 ˚c.

Table (8) Some Results from three cases for Case (1)

	Case (1)		
	D_b=0.11 m		
Pipe Diameter – D_p (m)	0.032	0.040	0.052
T_{out} (˚c)	12.5	12.6	13.7
Heat Transfer Rate(W)	2851.0763	4460.291	7539.9147

Table (9) Some Results from three cases for Case (2)

	Case (2)		
	D_b=0.13 m		
Pipe Diameter – Dp (m)	0.032	0.040	0.052
T_{out} (˚c)	12.6	12.7	12.8
Heat Transfer Rate(W)	2862.1223	4457.1733	7431.4007

Table (10) Some Results from three cases for Case (3)

	Case (3)		
	D_b=0.16 m		
Pipe Diameter – Dp (m)	0.032	0.040	0.052
T_{out} (˚c)	12.4	12.6	12.7
Heat Transfer Rate(W)	2864.1271	4460.623	7416.4621

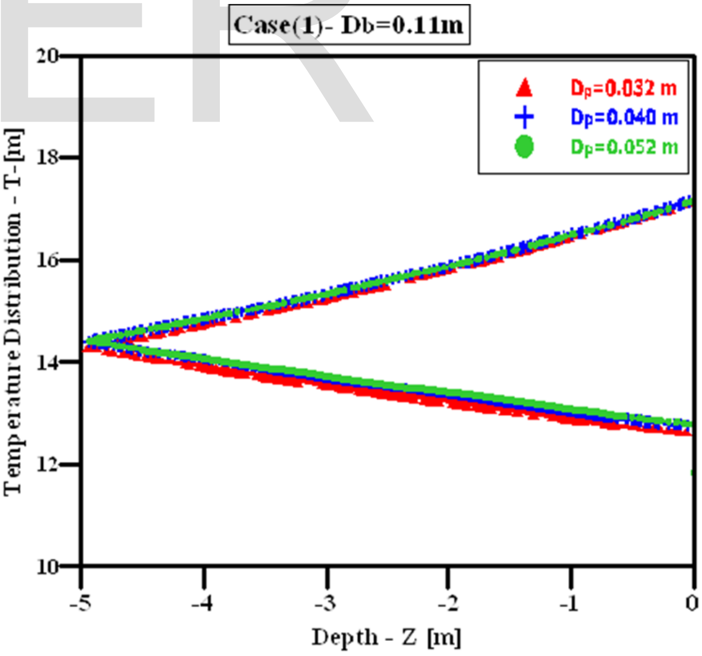

Figure 5 Temperature Distribution T with Depth Z of Case (1)-D_b=0.11 m at [Z=5m,T_g=10˚c, T_{wi} =17˚c, V_f=0.2m/s, Time Size=60 sec

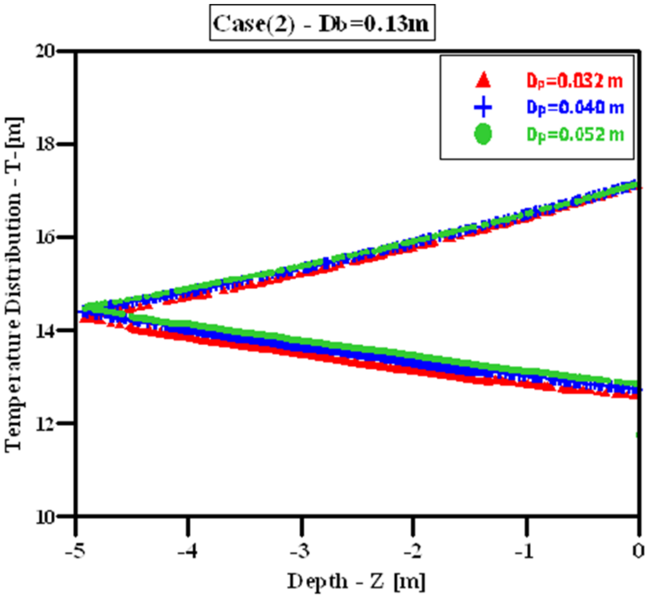

Figure 6 Temperature Distribution T with Depth Z of Case (2)-D_b=0.13 m at [Z=5m,T_g=10˚c, T_{wi} =17˚c, V_f=0.2m/s, Time Size=60 sec]

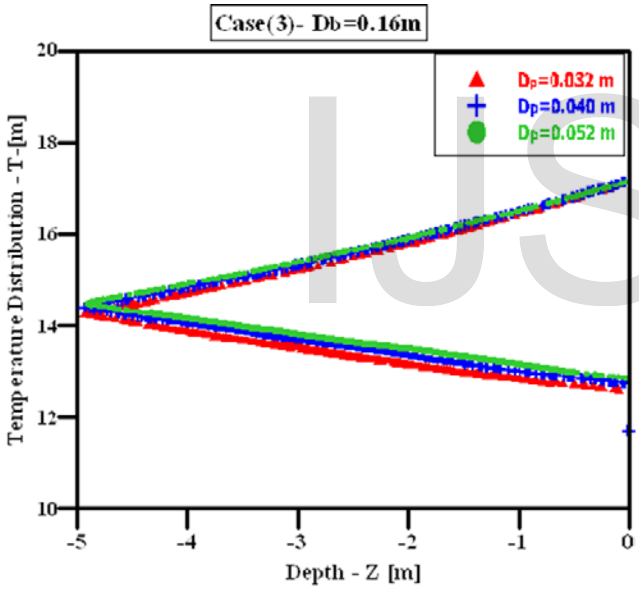

Figure 7 Temperature Distribution T with Depth Z of Case (3)-D_b=0.16 m at [Z=5m,T_g=10˚c, T_{wi} =17˚c, V_f=0.2m/s, Time Size=60 sec]

As shown in Figures from (5) to (7) show a temperature distribution of water inside U-tube BHE to cooling water which enters at 17˚c, for the selected cases of the borehole heat exchanger and U-tube. In this cases the depth is 5m, the grout temperature is 10˚c and the water velocity is 0.2m/s for a transient period 60 seconds. These figures indicate temperatures distributions at these various cases. It can be seen that increasing or reducing of the diameters of borehole and U-tube are not making any significantly change in temperature distribution of water. This may be attributed to the high thermal conductivity of grout. It is to be noted that because of constant velocity and changing the diameters of U-tube. The mass flow rates change as indicated in Figure (8).

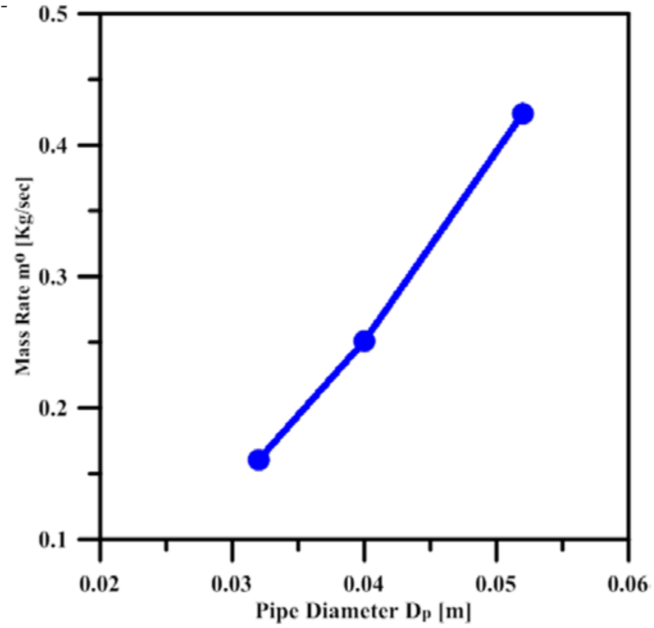

Figure (8) Mass Rate changing various with different diameters of U-tube BHE at [Z=5m,Tg=10˚c, Twi =17˚c, Vf=0.2m/s, Time Size=60 sec]

Figure 9 displays the results for Net Heat Transfer Rate Q_{io} at different diameters of borehole D_b and pipes D_p. As shown at constant diameter of pipe D_p and different diameters of borehole D_b, there are not any changes in Q_{io}. But there are dramatically changes in Q_{io} at different diameters of pipe D_p.

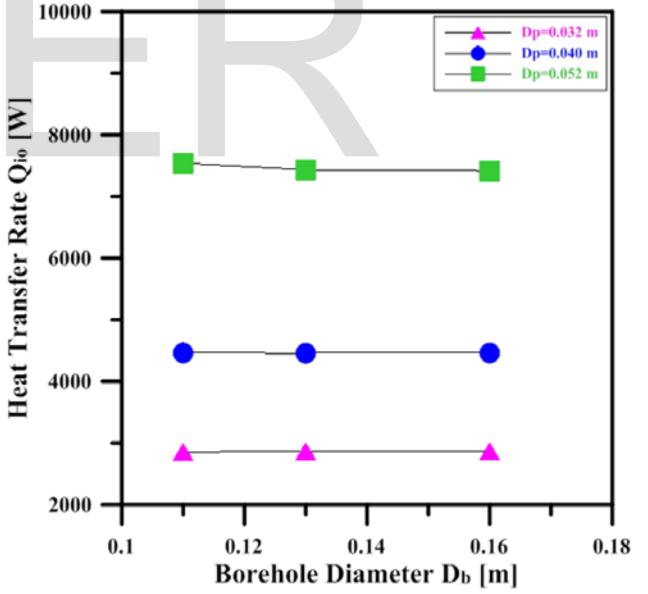

Figure (9) Net Heat Transfer between changing with different diameters of UBHE at [Z=5m,T_g=10˚c, T_{wi} =17˚c, V_f=0.2m/s, Time Size=60 sec]

8 CONCLUSION

In this study, a three dimensional numerical model for vertical UBHE simulation is developed using a commercially available finite volume simulation by using ANSYS-FLUENT 14.0. The proposed numerical model uses 3D physics; such that, the flow and heat transfer inside the pipes are simulated using 3D element sand heat transfers in the grout and soil/rock mediums is represented in a 3D geometry. Calculation of the circulating fluid transport and diffusion processes with a high degree of accuracy likely requires the pipe to be fully discretized and the application of CFD methods (SIMPLIC and PISO) for unsteady flow in ANSYS-FLUENT 14.0 software. The results of the study show that for a single well under cooling condition. Because of the small size of borehole diameter and the temperatures difference between the legs, the DLP and ULP not only exchanges heat with the soil and grout, but also exchanges heat each other. If the DLP and ULP are closely, the effect on temperature less than 0.5˚c.It is prefer to let space between two legs to increase heat transfer inside U-tube. There are no large changes in temperature distribution along U-tube, when U-tube diameter increases. Consequently, it can be increased U-tube diameter to increase mass flow rate and heat transfer rate.

REFERENCES

[1] Arnold Watson, “Geothermal Engineering, Fundamentals and Applications” Springer Science and Business Media London and New York 2013.

[2] Ingrid Stober, Kurt Bucher, “Geothermal Energy, From Theoretical Models to Exploration and Development”, Springer-Verlag Berlin Heidelberg 2013.

[3] German Energy Agency ‘dena’, “Energy Supply with renewables-Made in Germany- Information on Technologies, supplies, products and services Conference”, 8^th December 2015.

[4] European Energy Manager ‘EUREM’ Licensed for Egypt, “German-Arab Chamber of Industry and Commerce Conference”, Geothermal Energy, Federation of Egyptian Industries, 15 th December 2015.

[5] Raymond, J., R. Therrien, and L. Gosselin, Borehole temperature evolution during thermal response tests. Geothermics, 2011. 40(1): p. 69-78.

[6] Borinaga-Treviño, R., et al., Borehole thermal response and thermal resistance of four different grouting materials measured with a TRT. Applied Thermal Engineering, 2013. 53(1): p. 13-20.

[7] Sharqawy, M.H., E.M. Mokheimer, and H.M. Badr, “Effective pipe-to-borehole thermal resistance for vertical ground heat exchangers”. Geothermics, 2009. 38(2): p. 271-277.

[8] Beier, R.A., et al., “Vertical temperature profiles and borehole resistance in a U-tube borehole heat exchanger”. Geothermics, 2012. 44: p. 23-32.

[9] Sharqawy, M.H., E.M. Mokheimer, and H.M. Badr, “Effective pipe-to-borehole thermal resistance for vertical ground heat exchangers”. Geothermics, 2009. 38(2): p. 271-277.

[10] ANSYS, Inc. , “ Fluent Theory Guide”, 2009.

[11] H. K. Versteeg and W. Malalasekera, “Introduction to computational fluid dynamics - Finite Volume Method” 1995.