NUMERICAL ANALYSIS OF EFFECT OF GROUNDWATER VELOCITY ON EFFICIENCY OF GROUND SOURCE HEAT EXCHANGER

A DISSERTATION

Submitted in partial fulfilment of the

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By

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DEPARTMENT OF HYDROLOGY

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CANDIDATE’S DECLARATION

I hereby declare that the work which is being presented in the dissertation entitled ‘Numerical analysis of effect of Groundwater velocity on efficiency of ground source heat exchanger’ towards the partial fulfilment of the requirement for the award of the degree of **Master of Technology** in **Hydrology** submitted in the Department of hydrology, Indian Institute of Technology Roorkee, Roorkee (India) is an authentic record of my own work carried out under the guidance of **Dr. Brijesh K. Yadav** (Associate Professor), Department of hydrology, Indian Institute of Technology Roorkee.

The matter presented in this dissertation has not been submitted by me for the award of any other degree of this or any other institute.

Place: Roorkee **(JOGENDRA PAL)**

Date: **Enrolment No. – 14537008**

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of our knowledge and belief.

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Date: May 2016 (**JOGENDRA PAL)**

Place: Roorkee

ABSTRACT

Geothermal heat pumps are used for various purposes as a green energy source. These pumps are used as an alternative of conventional heating/cooling devices in heat ventilation and air conditioning (HVAC) systems and in binary cycle steam power plants. In this study, the effect of groundwater movement on the heat exchanging efficiency of the heat pump is investigated by numerical experiments. A two-dimensional model representing heat transport in porous media is used to study the heat transfer mechanism of geothermal heat pumps in subsurface system. A single borehole heat pump is considered for the heat transfer at a constant heat flux of 10W/m to the subsurface for a simulation period of 200 days under different groundwater velocities. The region inside the borehole is studied considering a steady state condition by taking a constant heat flux at borehole wall. Temperature condition of the region outside the borehole is taken transient state throughout the simulation period. The results show that a temperature drop of 0.71-2.7% is achieved in mean fluid temperature at outlet by changing the groundwater velocity ranging from 1-10m/year. With increasing groundwater velocity the thermal affected zone is shifted to downstream direction meaning faster travel of thermal plume which ultimately increases the heat exchange between bore well and subsurface. This phenomenon of heat transfer is governed by the Peclet number which is defined as ratio of thermal fluxes by advection to the diffusion in the same direction. Therefore a parameter variation test is done to see the most influencing parameters amongst those constituting the Peclet number. The parameters are varied from -20% to +20% for getting the set of isothermal contours. The results show that variation in thermal conductivity of groundwater does not affect the thermal affected zone. While variation in porosity of the subsurface and thermal conductivity of soil, has a little impact on the thermal affected zone. The variation in specific heat of soil has comparatively more impact on thermal affected zone while variation in groundwater velocity and specific heat of groundwater has highest impact on thermal affected zone. The mean fluid temperature is also insensitive to the variation in groundwater thermal conductivity. Since there are various hydrogeological sites having different characteristics, therefore, a better estimation of subsurface water can help in reduced dimensions of borehole and finally the cost of project while designing the ground source heat exchanger. Thus, a precise range of Peclet

number for a certain temperature drop in mean fluid temperature can help in precise estimation of groundwater flow effect in better designing of heat exchangers.

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Chapter 1: Introduction

1.1 Project background:

Geothermal energy- geothermal energy is the energy stored in earth. It is renewable and green energy leaving no negative impact on the atmosphere. It is available in a wide range from shallow ground subsurface, to subsurface hot water and also to hot rocks found very deep, in form of hot steam trapped in fractured zones.

This energy can be utilized depending on the availability in several ways-

- Direct use- when a source of potential of heating water above 20˚c is available, it can be direct used for bathing purpose, maintaining greenhouse and aquaculture.
- Binary cycle- when a source of potential of heating water above 75˚c is available it can be used in binary cycles for electricity generation
- Flash steam generation- when a potential source above 175˚c is available. It can be directly used to obtain the steam which can be used in steam power plant directly [Lund and Chiasson, 2007].
- Geothermal heat pumps- as heat source and sink

Ground coupled heat exchangers (GCHE) are hydro mechanical devices which utilize the heat absorbing and releasing capacity of subsurface hydro-geological conditions (earth, ground water as a heat source and/or sink, resource 4 to 40˚c). The conventional systems used for heating and cooling, generally use atmospheric air for exchanging the heat. But the properties of this air are vulnerable to the change in weather. For example during the summer temperature of air in atmosphere rises up to 40 to 50 ˚c, therefore for cooling purpose it is not possible to transfer the heat from the condensing fluid which is below this temperature. Thus the minimum temperature limit is raised and hence efficiency of system is degraded. Similarly during winter if we are working on heating system, we use outside air for heating source. But during extreme winter the temperature of the sir falls below freezing point and then using these systems are appropriate. In such cases geothermal heat exchangers are used in which the temperature of the subsurface at a several depths remains almost constant throughout the year.

GCHE works on binary cycle which consists of three loops or cycles. The first cycle consist of exchanging heat on load using fluid (water/air or both). Here heat exchanging fluid is selected based on the application of cycle.

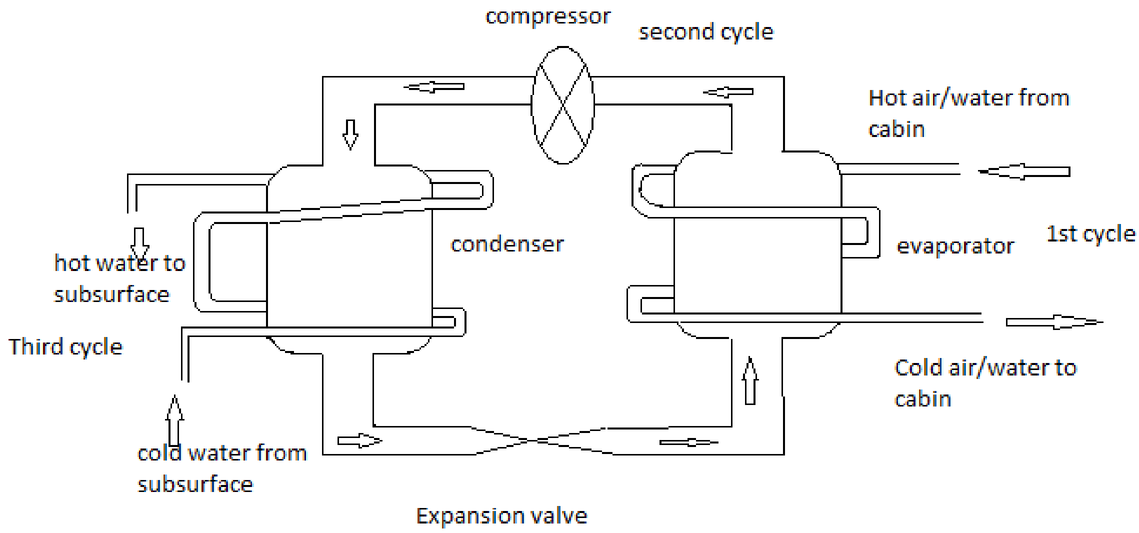


Fig. 1.1 Schematic diagram showing different loops of heat transfer mechanisms of a typical geothermal heat exchanger

The second cycle is on the pump system in which a suitable refrigerant used to exchange the heat with the water which is flowing through the third cycle and finally exchanging the heat with the ground and/or ground water. GSHP works on the second law of thermodynamics. Thermodynamically we find no difference b/w GSHP cycle and the refrigeration cycle based on vapour-compression cycle. Only difference between two is of their objectives. While vapour-compression cycle is used for obtaining refrigeration effect in the evaporator, on the other hand GSHP can be used for obtaining heating as well as cooling effects. Same cycle can be used for cooling as well as heating purpose; we have to interchange only first and third cycle. The vapour compression cycle functions in same way only condenser heat exchanger and evaporator heat exchanger cycles are interchanged. GSHP can be classified as opened loop heat exchanger devices and closed loop heat exchanger devices. In opened loop heat exchanger a water reservoir is required at subsurface with which water is exchanged. But these cycles face the difficulty of erosion due to silt. Therefore closed loop cycles are mostly preferred.

Now for better performance of GSHP it is important to analyse all parts of the project separately. In this study I have studied the ground source heat exchanger which is the third loop cycle of the system. If the pipe carrying fluid is buried to sufficient depth then it may encounter the presence of water contained in the voids and fractured zone. A sufficient quantity of this groundwater is a matter of concern while analysing the capacity of heat pump because water has a high value of heat capacity and it can work to transport the heat to and from the borehole that can affect the efficiency of heat pump. Also with variation of hydrogeological properties of the site the thermal plume transport may be affected, therefore it is necessary to analyse the effect of parameter variation on thermal affected zone.

Geothermal energy usage has experienced continuous and expeditious development within the last several decades. The use of this energy source has become attractive due to intrinsic savings of fossil fuels and relatively low CO2 emissions. While many parts of the country experience seasonal temperature extremes from blazing heat in the summer to sub-zero cold in the winter a few feet below the earth’s surface the ground remains a relatively constant temperature. A geothermal heat pump simply takes advantage of this low temperature energy source and pumps it up to a usable level to cool/heat the building. Geothermal Heat Pumps draw energy out of the ground which stays relatively constant year round. According to the Environmental Protection Agency, geothermal heat pumps can reduce energy consumption and corresponding emissions up to 44% compared to air driven heat pumps and up to 70% compared to electric resistance heating.

1.2 Physical model

The basic setup of ground source heat pump (GSHP) includes a vapour compression cycle which includes a compressor, expansion valve, refrigerant, condenser and evaporator. The evaporator and condenser are attached to the load side and ground source heat exchanger as per the requirement.

Compressor is used to compress the vapour refrigerant in the vapour compression cycle. It is an electromechanical device which is run by electric power. Expansion valve is used to expand the fluid so that its temperature and pressure drops isentropicaly. It is generally an orifice type device through which liquid refrigerant is passed after condensation so that it can reduce it to the evaporator working pressure and temperature. A suitable refrigerant whose boiling point and freezing point is low is used in pump cycle.

Heat exchanging fluid in load cycle- in load cycle a heat exchanging fluid (water/air) is used which can suitably transfer heat from the load cycle to/from the vapour compression cycle. Heat exchanging fluid in ground source heat exchanger-heat exchanging fluid in the ground source/sink heat exchanger is generally water. In case of open system it leaves the cycle and then fresh water is added. But in case of closed system water never leaves the cycle and therefore anti-freezing substance (such as ethanol or glycol) is added in it so that in case temperature falls too below it does not reach the freezing point of fluid.

The ground source heat exchanger consists of fluid as heat transporter, a fluid carrying conduit, grout material and soil zone. Properties of the above are explained in details: 1) the fluid carrying conduit- a u-bent pipe generally made of polyethylene is used as fluid carrying conduit. The material of pipe should be corrosive resistant to all mineral acids as it will come in contact with different types of mineral rocks. It should also have enough thermal strength and pressure bearing resistance so that it can work under the required temperature and pressure range without formation of cracks. The heat capacity of the pipe material should be low and conductivity should be high so that it can work as a good heat conducting material. It should be light in weight and flexible so that it can be easily inserted in the borehole. 2) Heat carrying fluid: Water is used as heat exchanging fluid. It is mixed with anti-freezing substance. 3) Grout material: grout material plays a very precise role in heat transfer phenomenon in subsurface. It is used to fill the gap between pipe and the soil zone to make the thermal contact between them. So here it is necessary that the grout material have enough conductivity to maintain heat transfer rate optimum and it should have enough porosity so that flow is interrupted as low as possible, also convection due to groundwater takes place at better rate. Solid bentonite slurry (clay generated) is generally used as grouting material [Yu and Huang (2015)]. 4) Soil zone: it is the heat source/sink zone which is used as heat sink during summer and heat source during winter. Generally there are found several different geological layers. These may vary in physical and thermal behaviour to the heat exchanging phenomenon. Therefore it is necessary a proper assessment of the subsurface geology.

Ground water in porous zone- in the porous zone if ground water is present it is important to consider the effect of heat convected by it. And if group of boreholes to be arranged then it is important to consider the direction of groundwater flow direction along with velocity magnitude.

A GSHP can utilise the ground water as the sources of heat in the winter, and as the sink for heat removed from the home in the summer. To utilize this there should be a robust system to meet the required energy load. Therefore designing of heat exchanger is very important and hence effects of all parameters on heat transfer mechanism should be considered so that size of the elements used is optimized. There are many numerical methods and software used to design pipe heat exchanger, but all of these soft-wares are based upon the principle of heat transfer only through conductivity, specific heat capacity of rock and soil. But while designing the heat exchanger on should consider-

- When most of the pipe is located in the saturated rock and soil zone, below the underground water the impact of groundwater flow is particularly important. The effect becomes stronger and stronger with increase of the porosity, an also permeability coefficient in aquifer. The infiltration and groundwater flow will affect the entire underground heat transfer coefficient of heat exchangers, thereby affecting the drilling depth, pumping required etc. that leads to affect the initial investment costs.
- To identify the difference in value of thermal conductivity of rock and soil in two experiments with (no groundwater flow) and (groundwater flow).
- Also a fundamental aspect in GWHP plant design is early assessment of the thermally affected zone (TAZ) that develops around the injection well. This is extremely important to avoid interference with already existing groundwater network (wells) and subsurface underground structures [Russo et al., 2012].
- It is equally important to determine the effect that variation of each parameter will have on development of the thermally affected zone (TAZ) around the injection well.

Therefore, it is very necessary to consider the effect of groundwater flow on heat exchanger efficiency and thermal conductivity of rock and soil and the effect of different parameters on thermally affected zone.

1.3 Types of geothermal system installations.

- **Closed loop**

  Closed loop geothermal pumps are those in which circulating fluid do not leave the cycle [Vibhute et al. 2013]. Water mixed with anti-freezing substance goes down the subsurface through inlet pipe and after exchanging heat with the subsurface comes out in pump cycle.

  This type of arrangement can be both horizontal loop as well as vertical loop. In horizontal type of loop the fluid conduit can be buried at a several depth of subsurface in garden or in courtyard. For more heat exchange the fluid should get more time to spend in flow, therefore it should pass through sufficient length of pipe. That is why coiled shape of pipe is buried under bed.

- **Open loop**

  On the other hand open loop type arrangement are used when the fluid circulating in the heat exchanger. These can provide large source/sink but can be constructed where large amount of water can be extracted.

1.4 Geothermal vs conventional air conditioner:

Comparisons between Geothermal and conventional air source units are clear because the efficiency of air source equipment is a function of outside air temperature and decreases with increase in it. A typical example of a 2.5-ton air source unit shows manufacturer's energy efficiency ratio (EER) as 13.0. However, a closer look at performance values yields a calculated EER value of 10, at rated conditions. This would represent a daytime temperature of about 34° C. When the outside temperature rises to 38°C, the air source EER drops to 8.8, which represents a reduction in efficiency of around 12%. If outside temperature rises to 43.3° C, the air source EER drops even further to 7.7, which represents a reduction in efficiency of 27% [Vibhute et al. 2013]. This means that the unit is requiring 27% more electricity to yield the same cooling. Geothermal systems for air conditioning are considerably more efficient than the conventional air source units. Simple calculations show that energy costs for a Geothermal are nominally 40% less than air source.

1.5 Advantages and disadvantages of GSHP:

When geothermal heat pumps are properly designed, the liquid temperatures in the loops ensure that the equipment will operate with much higher efficiency and economy than conventional air source and fossil fuel equipment.

Advantages:

- Unlike burning oil, gas, LPG or biomass, a heat pump produces no carbon emissions on site Simple controls and Equipment.
- Low Maintenance Cost.
- Heat pumps are much cheaper to run than direct electric heating

Disadvantages:

- More expensive to install than air source heat pumps because of the need to install a ground heat exchanger.
- The design and installation of an effective ground source system depends on a thorough understanding of the movement of heat in the ground.
- Thermal and Ground Water Flow Modelling is require to get good efficiency in any installation of a ground source heat pump.

Table.2. CO2 emissions for different energy sources [Sarbu and Calin, 2014]

System	**Efficiency/cop**	**Co2 Emission per KWh of fuel [Kg CO2/KWh]**	**C02 emission per KWh of useful heat [Kg CO2/KWh]**
Coal boiler	0.78	0.34	0.49
Gas-oil boiler	0.80	0.28	0.35
LPG boiler	0.80	0.25	0.31
Natural gas-boiler	0.80	0.19	0.24
Air to Air heat pump	2.50	0.47	0.19
Geothermal heat mump	3.2	0.47	0.15

1.6 Objectives

The main aim of this study is to analyze the impact of groundwater velocity on heat transfer efficiency of geothermal heat exchanger. The specific objectives are

- To study the geothermal heat pumps setup and its working principles
- To understand the mechanism of heat transfer in subsurface
- To estimate the percentage drop in mean fluid temperature with different groundwater velocities
- To analyze the effect of simulation parameters on heat transfer efficiency

Chapter 2: Literature review

This chapter represents a literature review of study done in field of borehole heat exchanger. Borehole heat exchangers commonly use single u-bent tubes and concentric tube. The tubes are generally made of high density polythene which is efficient of heat transfer. Generally water mixed anti-freezing substance is used as circulating fluid to extract/reject heat with subsurface. The gap between the tubes and borehole is filled with grout to enhance the thermal conductivity. Borehole heat exchangers are generally 100-200mm in diameter and 50-200m in depth. Peclet number is used to see the effect of groundwater velocity on thermal plume movement and this Peclet number is varied depending on what is the characteristic length is used to calculate it.

Andrews et al. (1978) explain the impact of use of GSHP on groundwater temperature that was obtained by a mathematical model that couples the groundwater flow equation with the heat transfer. In a radius of forty meter from the well effect is considered and results indicated that in a period of ten years the temperature of the aquifer changed by single degree centigrade. Also due to presence of groundwater flow this effect is reduced significantly. It concluded that the groundwater temperature altered slightly, but as the groundwater temperature is function of the incident solar radiation this impact will be negligible.

Claesson and Eskilson (1988) gave improved line source theory. They included the effect of groundwater velocity in Kelvin’s line source model (1882). They suggested three main parameters to be considered during designing GSHE namely thermal resistance of borehole, mean fluid at outlet and ground thermal conductivity. They concluded that effect of groundwater flow on heat exchanger performance is negligible if Peclet number is less than one and hence to have effect on GSHE efficiency the groundwater velocity should be very high. Characteristic length for calculating Peclet number is taken as half of depth of borehole.

Gu and O’Neal (1998) developed equivalent pipe diameter model to calculate thermal resistance of borehole under steady state. They considered the thermal interaction between two legs of pipe and gave a single pipe diameter to calculate the thermal resistance of borehole. There are also other methods of calculating the steady thermal resistance like Paul model (1996) and multipole method (Bennet, et al. 1987) but they are too much complicated.

Chiasson et al. (2000) have done preliminary investigation on the effect of ground water flow on vertical GSHP. Numerical simulation of FE was used for solving transient 2d model for various geological conditions. The model accounted for several environmental heat transfer mechanism plus convective heat transfer mechanism from a closed-loop heat exchanger. Average temperature of the borehole is calculated and variation in it is seen with the change in Peclet number. For calculating Peclet number they used borehole spacing as characteristic length and gave the values of peclet number for various geological sites. He concluded that the significant groundwater flow can lower mean fluid temperature in coarse sand region.

Diao et al. (2004) considered the effect of presence of ground water flow in subsurface domain on the performance of ground source heat pumps. By his analytical solution based on the assumptions of saturated water stream, he has shown that if velocity of subsurface flow is sufficient it can affect the thermal response of subsurface domain. Explicit expression for thermal response obtained which give correlation among the influencing parameters. He compared this with analytic solution of Kelvin's line source model and found that groundwater can influence the thermal response around source. Actual impact of flow however depends on magnitude of groundwater velocity. By his analytical solution he provided a theoretical basis for design and performance simulation of GSHE.

Razdan et al. (2008) analysed the Geothermal Energy Resources and its Potential in India. Almost 300 thermally anomalous areas have been examined. 31 areas have been studied in details, out of which, shallow drilling has been done only in 16 areas. Exploratory boreholes drilled are in Puga (385m), Chhumathang (220m), Manikaran (700m), Tapoban (728m), Tattapani (620m) and West Coast (500m). Thermal discharges are at temperatures of 90°C to 140°C in the promising areas. On the basis of thermal potential these sites are divided into two categories-one is medium enthalpy potential site having temperature range from hundred to two hundred degree Celsius. Another is low enthalpy potential site having temperature less than hundred degrees Celsius. Thermal springs in the Uttrakhand, Himanchal Pradesh and Jammu Kashmir at altitudes 4000 to 4000m AMSL, give low enthalpy thermal resources. In Puga geothermal (J&K) field very low resistivity (2-10ohmm) is observed indicative of presence of thermal water in subsurface.

Wang et al. (2012) assessed the impact of groundwater heat pumps on urban shallow groundwater quality in Shenyang China. The results show that in heating season pH and the concentrations of total dissolved solid (TDS), chloride (Cl), total hardness , zinc (Zn), petroleum-related (Hydrocarbons) pollutants and ferrous (Fe) in pumping water were lower than that in recharging water, while the turbidity, SO4 and fluoride showed crosscurrent. There were no changes in Mn, Cu, nitrite nitrogen and total coliforms. The sampling of urban groundwater quality is higher than Chinese groundwater quality standard grade III. The GSHP little impacts on urban shallow water quality during the heating season.

Russo and Loretta (2012): thermal affected zone is analyzed in open loop borehole heat exchanger. Above study was done under the assumption that discharge rate and cooling/heating load are constant throughout the study no matter it is day time or night or summer or winter. But the actual flow rate and temperature of the injected fluid are highly variable and follow changes in requirements of building energy. For predicting the Thermal affected zone accurately, it is necessary to consider this time variability. They inserted discharge flow and temperature data on hourly basis, and then recalculated the TAZ using average daily, monthly, and seasonal energetic equivalents.

Choi et al. (2012) performed numerical simulation on borehole heat exchanger to study the effect of Groundwater-velocity on heat exchanger behavior. They modelled the system in cosmol and used finite element method coupled with conduction-advection equation to simulate the problem. For calculating thermal resistance they used Claesson and Dunand (1983) model. They used 2d model to see the effect of Groundwater-velocity and direction on different configuration of borehole groups in terms of thermal plume travel. They concluded that direction of groundwater flow affect the TAZ when group of boreholes are arranged in different configuration. Single line array was most influenced by direction of flow however rectangular arrangement of heat exchanger groups is insensitive to direction of flow. When Peclet number is greater than 0.05 it may have impact on heat transfer irrespective of heat exchanger configuration.

Nield and Bejan (2006) explains the energy equations of heat transfer through porous medium. For the conjugate heat transfer they gave the energy balance equation for the porous media as well carrying fluid. They considered the different cases for calculating effective thermal conductivity of porous domain and gave the most effective solution to calculate it. They also gave the solution for the both cases of local thermal equilibrium as well as non-equilibrium situations for the porous domain.

Capozza et al. (2013) used a model to extract heat from ground source and effect of subsurface flow on thermal plume movement is seen. Infinite line source model is used for borehole and implemented in a software name LENGTH. The results show that the temperature variation of the soil zone around the borehole is sensitive to the variation of subsurface water flow.

Kapil et al. (2015) put a light on scope and Implementation of Ground Source Heat Extraction Technology in India for Multiple Energy Saving Applications and gave a brief overview for implementation of the project on ground source heat pump based spaced heating system at SASE, Manali (HP). So the first GSHP system has been installed in India of 100 KW capacity by DRDO R&D establishment for space heating that was initially being done by oil resources. Before designing the gshp for the site they carried out a geothermal investigation of the site and found that the geothermal heat flux at the site is higher compared to the global average value due to passage of tectonic fault line over it. They evaluated performance of the system in energy saving terms. In which COP was achieved approx. 3.1 for peak loading, showing an energy saving about 67%. During winter for the existing heating plant they found that GHG emission reduced significantly.

A lot of work has been done in the field of geothermal heat-exchanger but still effect of groundwater velocity on GSHP requires more precise evaluation. The Peclet number used to represent effect of groundwater impact does not have a common acceptable value. Therefore objective of this study is to give a precise range of groundwater velocity to have certain drop in mean fluid temperature at outlet. A parameter variation test is done to see the impact of parameters influencing the heat transfer mechanism in subsurface so that for a certain drop in mean fluid temperature a range of the Peclet number can be defined.

Chapter 3: Methodology

3.1Numerical model formation- it is not always possible to construct the physical model as it is in numerical formulation. Always there are some difficulties associated while we are converting it into mathematical model and it is not possible to give mathematical solution to every aspect of the model. Therefore it is necessary that we introduce certain assumptions to simplify our numerical model. But one should keep in mind that while introducing the assumptions one should not make model so simplified that it get lost from its main objective. Since our objective is to study the effect of ground water flow on the performance of ground water heat exchanger and we are studying the behaviour of the thermal plume travelling in the soil zone. Therefore it will be convenient that we give stress on the heat transfer phenomenon in the soil zone.

3.1.1 Assumptions-

There are several assumptions used in this model –

- The ground is homogeneous in composition and in its thermal and geological properties
- Initial temperature of ground is uniform
- Heat transfer takes place in a radial direction from the borehole
- The thermal contact resistance b/w grout and soil zone is negligible
- Whole of the borehole is under steady state condition
- The groundwater zone is fully saturated and there is no phase change in the soil-water zone

Therefore it will be convenient to use a cylindrical model. Also a 2-d model will be sufficient to study the movement of the thermal plume in the soil zone.

The equation of the heat transfer in cylindrical model is given as-

$$\frac{\partial 2\mathrm{T}}{\partial \mathrm{r}2}+\frac{1}{\mathrm{r}}\frac{\partial \mathrm{T}}{\partial \mathrm{r}}+\frac{1}{\mathrm{r}2}\frac{\partial 2\mathrm{T}}{\partial \emptyset 2}+\frac{\partial 2\mathrm{T}}{\partial \mathrm{Z}2}+\frac{\dot{\mathrm{q}}}{\mathrm{K}}=\frac{1}{\propto}\frac{\partial \mathrm{T}}{\partial \mathrm{t}} \qquad (4.1)$$

This is a generalized equation of heat transfer equation from a cylinder via conduction governed by Fourier’s law. Where T is symbol for Temperature, r symbolize radial coordinate, Z is vertical coordinate and Φ is polar angle. α is thermal diffusivity which is defined as rate of heat diffusion given in m^2/s. K is thermal conductivity of the medium and $\dot{q}$ is heat generated per unit volume in the cylinder. Based on our assumptions as there is no heat transfer in vertical direction and also heat is only transferred in radial direction, the equation reduced to steady state is given by-

$$\frac{\partial 2T}{\partial r2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\dot{q}}{K} = 0 \qquad (4.2)$$

Applying boundary condition as heat generated inside the cylindrical borehole is totally transferred to the soil zone at borehole –soil zone interface-

$$q^{\cdot} * \pi R^2 * L = K * 2\pi RL * \frac{dT}{dr} \qquad (4.4)$$

That gives the amount of flux at borehole with the heat disposal rate to borehole-

$$\frac{\partial T}{\partial r} = \frac{\dot{q}R}{2K} \qquad (4.5)$$

Also from the heat conduction rate :

$$Q = K \times 2\pi RL \times \frac{dT}{dr}$$

And if we are using a 2-d model then heat supplied per unit length is applied and equation for heat supplied per unit length is given by-

$$\frac{Q}{L} = K \times 2\pi R \times \frac{dT}{dr} \qquad (4.6)$$

From eqn. (5) and (6) we can get heat generation rate to be applied in 2-D model from the heat transfer of a 3-d model.

Now if we want to apply a heat transfer rate of 2000W and the length of borehole is 200m. So boundary condition we can apply at the borehole wall in 2-d model is-

$$q_l = \frac{Q}{L} = 10W/m$$

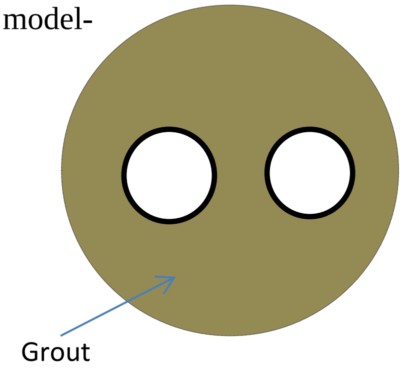
And from eqn. 1 and 2 we will get-

$$\frac{q_l}{2\pi RK} = \frac{\dot{q}R}{2K} \qquad (4.7)$$

Therefore if the radius of the borehole is 0.070m and heat generation to be applied is 649.61W/m3.

3.1.2. Thermal resistance

The thermal resistance of the borehole is calculated on basis of equivalent pipe diameter model-



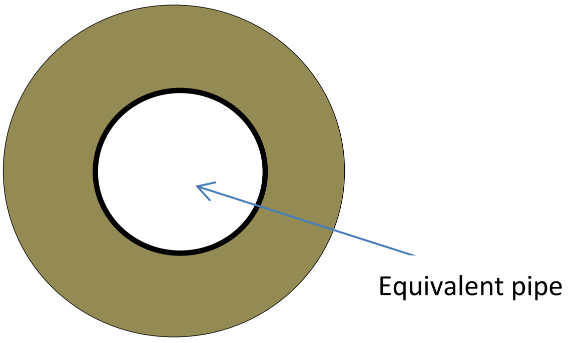


Fig.3.1 (a) U-tube borehole model

Fig.3.1 (b) Equivalent pipe model

Equivalent borehole resistance is given by-

$R_b=R_f+R_P+R_g$

Where R_f and R_p are resistance of single pipe and R_g is resistance of equivalent grout size. Here equivalent diameter is given by Gu and O'Neal (1998) :

$D_{eq}=\sqrt{(2 \times D \times S)}$

This gives grout resistance:

$$R_g = \frac{1}{2\pi K_g} \ln(\frac{r_b}{r_{eq}})$$

D is pipe outer diameter and S is spacing between centers of both pipes. Fluid convective resistance is obtained by-

$$R_f = \frac{1}{2\pi r_{pi} h}$$

Here h is fluid convective resistance in u-tube calculated Dittus-Boelter equation-

$$Nu = \frac{hd_p}{K} = 0.023Re^{0.8}Pr^{0.3} \qquad (4.8)$$

It gives equivalent convective heat transfer coefficient as-

$$h_b = \frac{1}{2\pi r R_b} \qquad (4.9)$$

Therefore the outlet temperature can be calculated on basis of equation-

$$T_f - T_b = q_l R_b \qquad (4.10)$$

The calculated value of R_b is 0.162.

Equation for the thermal plume movement in the soil zone is studied under transient behaviour. Since we are studying system under finite volume method, taking a finite control volume of soil-water system through which heat transfer mechanism takes place. Since effect of heat advected via groundwater is considered therefore equation turns as-

Heat conducted into element+ heat generated into element= heat conducted out of element+ heat convected out+ rate of change of internal energy

This can be further simplified as-

Net heat conduction in element – heat convection out of element = rate of change of internal energy

The partial derivative of any scalar of unit mass can be written as-

$$\frac{d\phi}{dt} = \frac{\partial\phi}{\partial t} + \frac{\partial\phi}{\partial x}\frac{\partial x}{\partial t} + \frac{\partial\phi}{\partial y}\frac{\partial y}{\partial t} + \frac{\partial\phi}{\partial z}\frac{\partial z}{\partial t} \qquad (4.11)$$

This can be further simplified as-

$$\frac{d\phi}{dt} = \frac{\partial\phi}{\partial t} + u\frac{\partial\phi}{\partial x} + v\frac{\partial\phi}{\partial y} + w\frac{\partial\phi}{\partial z} = \frac{\partial\phi}{\partial t} + U.\nabla\phi$$

For having equation per unit volume –

$$\rho\frac{d\phi}{dt} = \rho\left(\frac{\partial\phi}{\partial t} + U.\nabla\phi\right)$$

Or it can be further illustrated as-

$$\frac{d\rho\phi}{dt} = \left(\frac{\partial\rho\phi}{\partial t} + \nabla.\rho u\phi\right)$$

By conservational law in form of continuity-

$$\frac{d\rho\phi}{dt} = \left(\frac{\partial\rho\phi}{\partial t} + \nabla.\rho u\phi\right) = 0 \qquad (4.12)$$

This is the continuity equation for the scalar transport through a control volume. Therefore temperature distribution for the control volume for conjugate heat transfer [Diao et al. 2004] is given by-

$$\nabla.k(\nabla T) - \rho_g C_g u\nabla T = \rho_g C_g \frac{dT}{dt} \qquad (4.13)$$

Where $\rho_g C_g$ is the heat capacity of the soil-water zone and $\rho_w C_w$ is the heat capacity of the ground water, u is the groundwater flow velocity; k is the mean thermal conductivity of the soil-water system. The mean effective thermal conductivity [Woodside et al. 1961] is given by weighted geometric mean model as-

$$\ln k = (1-n)\ln k_s + n\ln k_w \qquad (4.14)$$

On the other hand volumetric heat capacity of the soil-water zone [Woodside et al. 1961] is given by parallel sum model as-

$$\rho_g C_g = (1-n)\rho_s C_s + n\rho_w C_w \tag{4.15}$$

Where n is porosity of the soil zone, K_s is the thermal conductivity of soil, K_w is the thermal conductivity of the groundwater.

3.2 Software used

The simulation of the problem is done with the help of computational fluid dynamics code in Ansys Fluent which works on finite volume method. CFD approach is the application of computer resources for the solving the fluid flow and heat exchanging phenomenon by creating mathematical algorithm in any computer languages. These CFD codes are formed on the basis of robust numerical algorithm that can handle the typical mathematical calculations. Each CFD code consists of three main elements-

- Pre-processor
- Solver
- Post-processor

Pre-processor consists of defining of the flow field system and associated properties of the system. In pre-processor we define the geometric dimensions of the system. Then we divide the whole system in smaller parts on the basis of the material properties and functionality in the system. Dividing the system into subparts helps in recognising the parts as solids and liquids, which in turns helps in meshing the parts into small grids as per requirements. Also this reflects during the defining the material properties. In pre-processing the phenomenon occurring in the flow domain is selected. And then problem is defined by applying the boundary conditions. The values given to properties are assigned to the nodes of the cells in which the parts are divided. Also the solutions are obtained on these nodes. Therefore it is important to generate mesh of the parts accurately. Generally larger the number of cells, more accurate is solution; therefore we should try to keep mesh size finer. But one should keep in mind that for handling large solution points, one should have enough computational resources.

First of all a 2-D model is created in the ICEM. The dimensions of the soil-zone to be studied are taken as 10m*10m. A rectangular box is generated of each side 10m. And then at the center of the rectangular box a circle of radius 0.07m is created. It is considered that groundwater is entering at the left side of the soil zone and exiting from the right side of the soil zone. The circle at the center defines the outer wall of the borehole. Thus the circle becomes the interface between the grout zone and the soil zone. Then different parts are defined of the system. The zone inside the circle is defined the grout zone/ borehole zone. Outside the borehole it is defined as soil zone.

Inlet of groundwater is defined at the left wall of the square soil zone while at the right side outlet of the groundwater is defined. All entities are grouped to respective parts. An entity can belong only one part. Once parts are created body is defined to material type. Once all the parts are defined now it is time to convert all parts into small grids. The meshing of parts is done in ICEM because it gives most accurate meshing. Meshing is generally of two types structural and un-structural. In structural meshing nodes of the grids are assigned values in i, j, k, form, while in unstructured meshing it is randomly assigned values. Hexahedron is used in structural meshing. Structural meshes are useful where geometry of the problem is simple, in complex geometry unstructured meshes are useful. Structural meshes do faster and accurate node calculations but unstructured mesh is useful for very complex geometries. Generally tetragonal meshes are preferred in unstructured meshing. Different type of grid shapes used for meshing are-

Quad mesh- it is quadrilateral having for nodes and four faces. It is used for meshing in 2-D geometry and gives good calculations at nodes in flow field. Tri mesh- it is triangle having three nodes and three faces. It is used in 2-D meshing and generally less preferred in the contact region as do not give good results for boundary layer phenomenon. Tetra mesh- it is used in 3-D meshing. It is prism of base triangle having four faces. Hex mesh- it is used in 3-D meshing. It is prism of base quadrilateral having six faces.

Whenever two neighbor parts of different material are meshed, if both the parts lie on common face there is nod to nod connectivity. And this type of meshing is called conformal mesh. But if both parts do not lie on the same face, there is not nod-nod connectivity and there is interface created between two and linear interpolation is done. Before generating mesh for the geometry blocking of the geometry can help in faster and accurate mesh generation. Blocking is important for mesh generation in complex geometries. Blocking is helpful in capturing the shape of the geometry so that better mesh finishing is generated at the edges. It is helpful in mesh checking tools, cells having undesirable skew-ness and/or angle can be easily identified in blocks and that block can be re-meshed separately. Refinement or coarsening of the mesh may be for any block region to allow a coarser or finer mesh definition in areas of high or low flow gradients respectively.

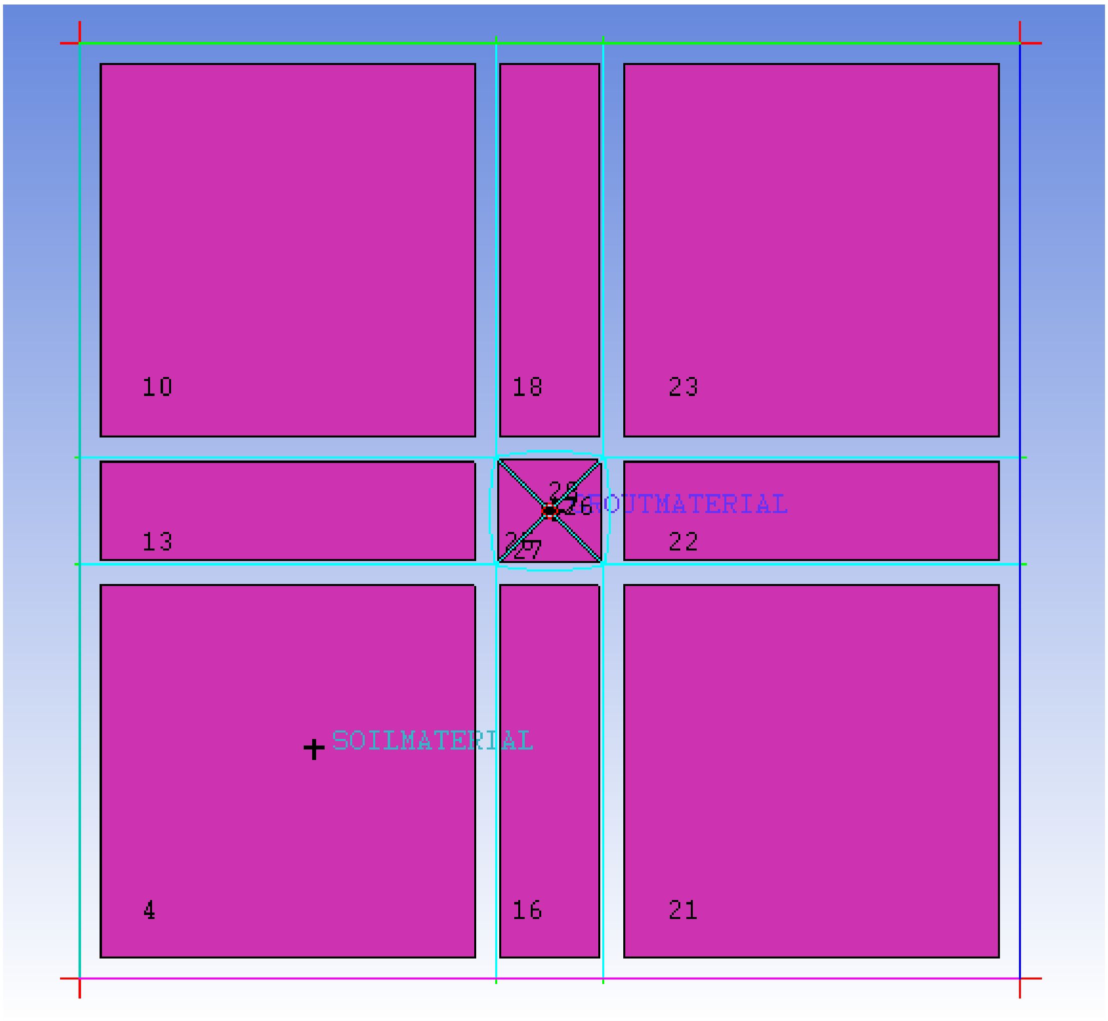


Fig.3.2. Blocking of the borehole-soil zone

Here I have done o-grid blocking for my geometry. Whole of the region is split into several blocks and blocks are associated to particular parts. Meshing is initiated after that by giving minimum grid size 2mm in grout zone and 40 mm in soil zone. Quality and size check is done before going to solver. More cells can give higher accuracy. The downside is increased memory and CPU time. For fluent solver the minimum orthogonal quality is 0.20 and the maximum aspect ratio should be<10. The minimum value of the cell should not be negative.

- For the same cell counts the quad mesh will give more accurate results especially if the grid lines are aligned with flow.
- The mesh density should be high enough to capture all relevant flow features.

- The cells adjacent to wall should be fine enough to resolve the boundary layer flow. In boundary layers, quad and hex cells are preferred over tri and tetra.

  Skew-ness- it is defined as measure of deviation of cell size from optimum size. In tri cells it is measured with reference to equilateral triangle size, while in case of quad it is measured with reference to 90° angle.

  Aspect ratio is ratio of longest edge length to shortest edge length. Poor quality grid may cause inaccurate solutions and/or slow convergence.

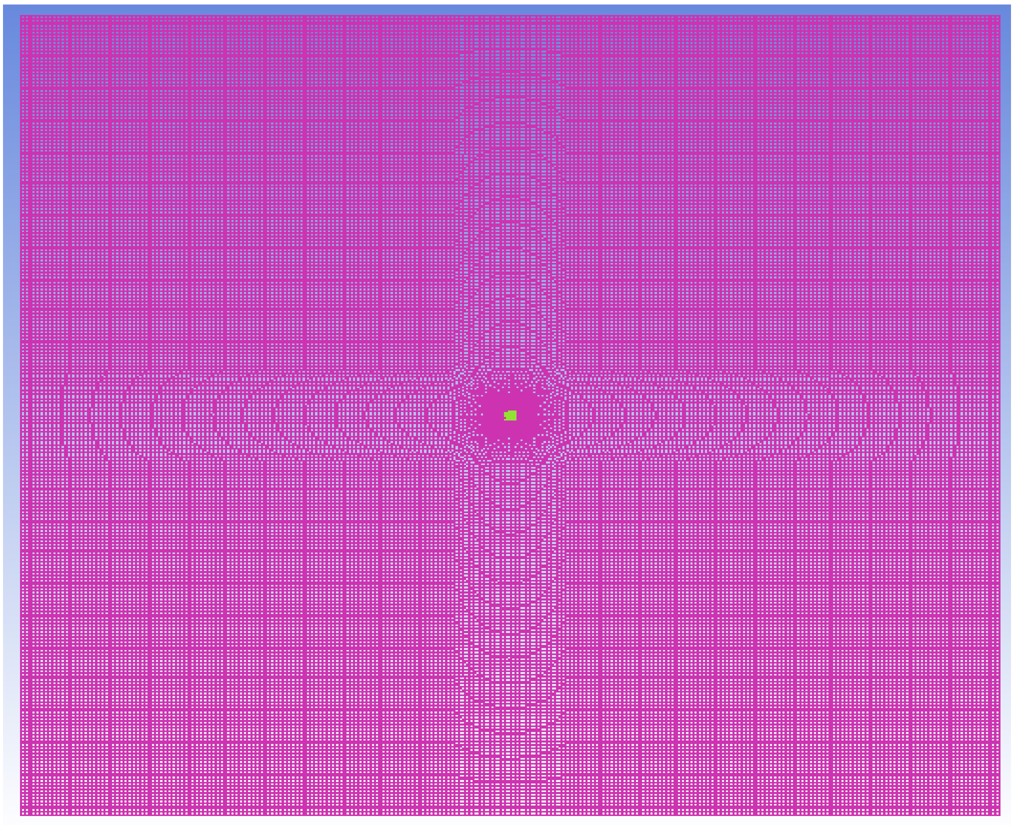


Fig.3.3. Meshing of the borehole-soil zone

Once the meshing is done, fluent is launched. The mesh is imported into the fluent and all aspects of the grids are checked in fluent before starting solver. Materials properties are defined and materials are selected for their respective application. Further boundary conditions are selected for the application domain. Here I imported mesh into fluent and checked the properties of mesh.

There are 59272 cells, 119112 faces, 59841 nodes. All the cells are quadrilateral meshed. The minimum orthogonal quality is 0.35 and max aspect ratio is 9.73.

Solver- after pre-processing the problem, now it is time of integrating the mathematical and physical models by selecting the appropriate model equations in solver. The mainly consideration in fluid flow problem during selecting a model is recognition of the flow characteristics. Since Darcy's law recognize subsurface flow as laminar flow in most cases since it has Reynolds number less than 10. And laminar flows are the cases of viscous momentum transfer between the adjacent layers. Therefore it is necessary to consider this viscous momentum transfer and Naiver-stokes equation holds good for that. In my model since flow in the subsurface is laminar, therefore viscous model for laminar flow is on. Then with the flow mechanism, heat transfer in the domain is the main mechanism. Therefore energy equation is on. The cell zones are defined and materials properties are assigned to them. In the soil zone, fluid zone is defined in the soil material with porosity 0.10.This is the porosity against the average sedimentary limestone. The viscous resistance is taken as inverse of the permeability in that direction. A uniform heat source of 649.61w/m^3 is applied to generate a constant heat flux of 10w/m at the borehole wall. The zone is selected as soil and material is applied grout.

3.3 Discretization

The discretization of the momentum and heat transfer equation in FVM is done by compass method (Versteeg et al, 2007). For general scalar ϕ transport equation is written as

$$\frac{\partial(\rho\emptyset)}{\partial t} + \nabla.(\rho\vec{v}\emptyset) = \nabla.(\Gamma\nabla\emptyset) + S \qquad (4.16)$$

Where ϕ is scalar, Γ is diffusion coefficient ($\Gamma=\frac{k}{c}$). S is source term if present. Here $\rho\vec{v}$ term is mass flow rate hence is advection strength.

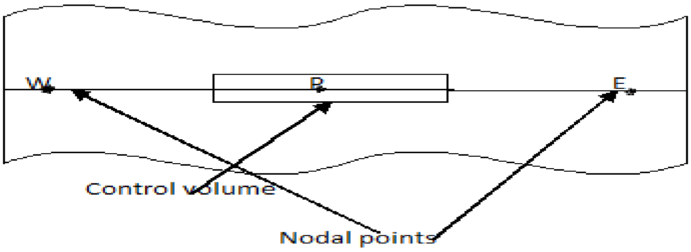


Fig.3.4. Schematic diagram showing selection of control volume

Here P is the node at which equations are solved and W is the west node and E is the east node to the P. a control volume is selected to the node P at mid-distance from east and west nodes.

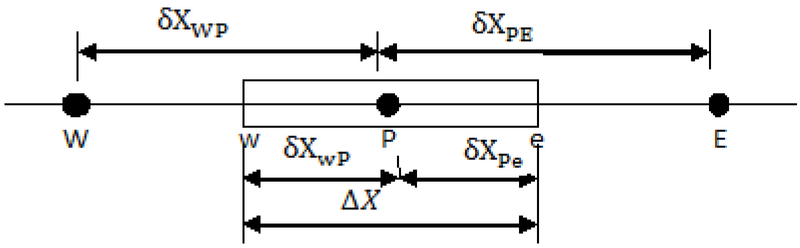


Fig.3.5 schematic diagram showing compass method for discretizing control volume

Here Δx is the grid size. w and e are the west and east faces of the control volume. Gauss-divergence is the basic equation governing conservation of scalar through a control volume. It states that a vector field's outward flux through an enclosed surface is equal to volume integral of the divergence over the region inside the surface. Directly saying it states that sum of all sources and sinks give flow through the region. It can be represented as-

$$\iiint (\nabla.\mathrm{F})\ \mathrm{dv} = \oiint (\mathrm{F.n})\ \mathrm{ds} \qquad (4.17)$$

Excluding the source and time term the equation can be simplified by Gauss-divergence law-

$$\nabla.(\rho\vec{\mathrm{v}}\emptyset) = \nabla.(\Gamma\nabla\emptyset) \Longmapsto \oiint_{\mathrm{A}} \mathrm{n}.(\rho \mathrm{v}\emptyset)\ \mathrm{dA} = \oiint_{\mathrm{A}} \mathrm{n}.(\Gamma\nabla\emptyset)\ \mathrm{dA} \qquad (4.18)$$

Now diffusion flux balance through the control volume is given by the expression-

$$(\Gamma \mathrm{A}\frac{\mathrm{d}\emptyset}{\mathrm{dx}})_{\mathrm{e}} - (\Gamma \mathrm{A}\frac{\mathrm{d}\emptyset}{\mathrm{dx}})_{\mathrm{w}}$$

The characteristic of FVM is that here we have to choose or assume the profile of parameters, for scalar diffusion assuming linear profile. Also FVM is a special case of FDM and thus coefficients at face of control volume are calculated by finite difference scheme. Therefore the values of coefficients at east and west faces of control volume are given by-

$$\Gamma_{\mathrm{w}} = \frac{\Gamma_{\mathrm{W}} + \Gamma_{\mathrm{P}}}{2} \qquad \text{and} \quad \Gamma_{\mathrm{e}} = \frac{\Gamma_{\mathrm{P}} + \Gamma_{\mathrm{E}}}{2}$$

Diffusion flux at east and west faces can be written as-

$$(\Gamma A\frac{d\emptyset}{dx})_e = \Gamma_e A_e(\frac{\emptyset_E - \emptyset_p}{\delta X_{PE}})_e$$

$$(\Gamma A\frac{d\emptyset}{dx})_w = \Gamma_w A_w(\frac{\emptyset_P - \emptyset_W}{\delta X_{WP}})_w$$

Similarly the convective heat flux through the control volume can be written as-

$$(\rho vA\emptyset)_e - (\rho vA\emptyset)_w$$

We can write the steady-state convection-diffusion with help of gauss divergence theorem as-

$$(\rho vA\emptyset)_e - (\rho vA\emptyset)_w = \Gamma_e A_e\left(\frac{\emptyset_E - \emptyset_p}{\delta X_{PE}}\right)_e - \Gamma_w A_w\left(\frac{\emptyset_P - \emptyset_W}{\delta X_{WP}}\right)_w \qquad (4.19)$$

The term ρv is mass flux term thus it is convective strength coefficient and represent it by term F. On the other hand the term $\frac{\Gamma}{\delta x} = \frac{K}{C\delta x}$ is the diffusion strength and is represented by D. Area of the faces are equal i.e. $A=A_e=A_w$

The equation then turns into-

$$F_e\emptyset_e - F_w\emptyset_w = D_e(\emptyset_E - \emptyset_P) - D_w(\emptyset_P - \emptyset_W)$$

Getting scalar value at faces by finite difference technique-

$$\emptyset_e = \frac{\emptyset_E + \emptyset_P}{2}$$

$$\emptyset_w = \frac{\emptyset_P + \emptyset_W}{2}$$

By putting these values in above equation, we get

$$F_e\left(\frac{\emptyset_E + \emptyset_P}{2}\right) - F_w\left(\frac{\emptyset_P + \emptyset_W}{2}\right) = D_e(\emptyset_E - \emptyset_P) - D_w(\emptyset_P - \emptyset_W)$$

$$\emptyset_E\left[D_e - \frac{F_e}{2}\right] + \emptyset_W\left[D_w + \frac{F_w}{2}\right] = \emptyset_P\left[D_e + D_w + \frac{F_e}{2} - \frac{F_w}{2}\right]$$

$$\emptyset_E\left[D_e - \frac{F_e}{2}\right] + \emptyset_W\left[D_w + \frac{F_w}{2}\right] = \emptyset_P\left[D_w + \frac{F_w}{2} - \frac{F_w}{2} + D_e - \frac{F_e}{2} + \frac{F_e}{2} + \frac{F_e}{2} - \frac{F_w}{2}\right]$$

Now taking $\left[D_e - \frac{F_e}{2}\right]$ asa_E, and $\left[D_w + \frac{F_w}{2}\right]$ as a_W.

Then coefficient of $\emptyset_P$ is $[a_E + a_W + (F_e - F_w)]$, which is termed as a_P. When the flow satisfies the continuity equation: $F_e - F_w = 0$ and $a_P = a_E + a_W$

So final expression for finite volume discretization of the cell is given as-

$$a_P\emptyset_P = a_w\emptyset_w + a_e\emptyset_e \qquad (4.20)$$

But there are several restrictions on the values of $\emptyset_P$ as it should be between $\emptyset_e$ and $\emptyset_w$. In certain cases such as when $\mathrm{D_e} = \mathrm{D_w} = 1$ and $\mathrm{F_e} = \mathrm{F_w} = 2$ the value of $\emptyset_P$ falls beyond the limits and that is violation of boundedness property of numerical scheme. Now we have to deal with the unsteady term of the equation. That is given by-

$$\int_{\mathrm{CV}}[\int_{\mathrm{t}}^{\mathrm{t+\Delta t}} \rho\frac{\partial\emptyset}{\partial \mathrm{t}}].\mathrm{dv} = \rho(\emptyset_\mathrm{p} - \emptyset^\circ{}_\mathrm{p})\Delta \mathrm{v} \qquad (4.21)$$

Let us consider the unsteady state heat transfer by conduction in 1-d. this can be discretized as-

$$\rho\mathrm{c}(\mathrm{T_p} - \mathrm{T^\circ{}_p})\Delta\mathrm{v} = \int_t^{t+\Delta t}[\mathrm{K_e A_e}\left(\frac{\mathrm{T_E} - \mathrm{T_p}}{\delta \mathrm{X_{PE}}}\right)_\mathrm{e} - \mathrm{K_w A_w}\left(\frac{\mathrm{T_P} - \mathrm{T_W}}{\delta \mathrm{X_{WP}}}\right)_\mathrm{w}].\mathrm{dt} \qquad (4.22)$$

Here $\mathrm{T_E}, \mathrm{T_W}, \mathrm{T_p}$ are temperatures at east, west and central nods. Generalizing the approach by introducing the weightage parameter θ ranging from 0 to 1, the temperature integral at point P can be written as-

$$\int_\mathrm{t}^{\mathrm{t+\Delta t}}\mathrm{T\,dt} = [\theta \mathrm{T_P} + (1-\theta)\mathrm{T^\circ{}_P}].\Delta \mathrm{t} \qquad (4.23)$$

Where at initial time t $\mathrm{T^\circ{}_P}$ is temperature at P and $\mathrm{T_P}$ is temperature at P after $\Delta\mathrm{t}$ time. Thus unsteady conduction heat transfer equation can be rearranged in terms of weightage parameter as follows (divided both sides by A.Δt)-

$$\rho c\frac{(T_p - T^\circ{}_p)}{\Delta t} = \theta[\mathrm{K_e}\left(\frac{\mathrm{T_E} - \mathrm{T_p}}{\delta \mathrm{X_{PE}}}\right)_\mathrm{e} - \mathrm{K_w}\left(\frac{\mathrm{T_P} - \mathrm{T_W}}{\delta \mathrm{X_{WP}}}\right)_\mathrm{w}] + (1-\theta)[\mathrm{K_e}\left(\frac{\mathrm{T^\circ{}_E} - \mathrm{T^\circ{}_p}}{\delta \mathrm{X_{PE}}}\right)_\mathrm{e} - \mathrm{K_w}\left(\frac{\mathrm{T^\circ{}_P} - \mathrm{T^\circ{}_W}}{\delta \mathrm{X_{WP}}}\right)_\mathrm{w}]$$

This can be rearranged in terms of coefficients of temperature-

$$T_p\left[\rho c\frac{\Delta x}{\Delta t}+\theta\frac{K_e}{\delta X_{PE}}+\theta\frac{K_w}{\delta X_{wP}}\right]$$
$$+T°_P\left[-\rho c\frac{\Delta x}{\Delta t}+(1-\theta)\frac{K_e}{\delta X_{PE}}+(1-\theta)\frac{K_w}{\delta X_{wP}}\right]$$
$$=T_W\left(\theta\frac{K_w}{\delta X_{wP}}\right)+T°_W\left((1-\theta)\frac{K_w}{\delta X_{wP}}\right)+T_E\left(\theta\frac{K_E}{\delta X_{PE}}\right)$$
$$+T°_E\left((1-\theta)\frac{K_E}{\delta X_{PE}}\right)$$

Now replace $\rho c\frac{\Delta x}{\Delta t}$ by $a°_p$, $\frac{K_w}{\delta X_{wP}}$ by a_w, $\frac{K_E}{\delta X_{PE}}$ by a_E and rewrite the equation.

$$T_P\left[a°_p+\theta(a_E+a_W)\right]$$
$$=a_W[\theta T_W+(1-\theta)T°_W]+a_E[\theta T_E+(1-\theta)T°_E]$$
$$+T°_P\left[a°_p-(1-\theta)a_E-(1-\theta)a_W\right]$$

With fully implicit method$\theta=1$, i.e. temperature is calculated at new time t+Δt and equation is reduced to-

$$T_P\left[a°_p+(a_E+a_W)\right]=a_WT_W+a_ET_E+a°_PT°_P$$

Further if we replace the term $a°_p+(a_E+a_W)$by a_P. We get

$$T_Pa_P=a_WT_W+a_ET_E+a°_PT°_P \qquad (4.24)$$

Since all the coefficients of the equation are positive this makes the implicit method unconditionally stable. For 2-D heat transfer process the equation will be represented as-

$$T_Pa_P=a_WT_W+a_ET_E+a_NT_N+a_ST_S+a°_PT°_P \qquad (4.25)$$

Where $a_P=a°_p+(a_E+a_W+a_N+a_S)$

And $a°_p=\rho c\frac{\Delta v}{\Delta t}$

Now we are in the direction of giving discretized convection diffusion equation in 2-dimensional form. But before that we will discuss the basic properties of discretization scheme-

1. Conservativeness: the property of numerical scheme in which the laws of conservation are implemented. For conservation of flux in a domain region, flux entering in the control volume should be equal to flux leaving the control volume.
2. Bound-ness: a property of numerical scheme in which the predicted values are limited to the certain physical realistic bounds. All coefficients of the discretized equation should have same sign (usually positive).
3. Transportive-ness: a property of numerical scheme that accounts for the direction in which the relative strengths of convection and diffusion influence the flow.

We had earlier seen that the central difference scheme fails in boundedness property during the conduction-convection discretization that also leads to violation of the transportiveness if coefficients become negative in certain cases. Hence there is need to consider the direction of to flow. And thus the unsteady conduction-convection heat transfer equation in discretized form is given by-

$$T_P a_P = a_W T_W + a_E T_E + a_N T_N + a_S T_S + a°_P T°_P \qquad (4.26)$$

Where

$$a_P = a°_p + (a_E + a_W + a_N + a_S) + \Delta F \text{ and } a°_p = \rho°_p c \frac{\Delta v}{\Delta t}$$

And –

$$a_W = \mathrm{Max}[F_w, \left(D_w + \frac{F_w}{2}\right), 0]$$

$$a_E = \mathrm{Max}[-F_e, \left(D_e - \frac{F_e}{2}\right), 0]$$

$$a_S = \mathrm{Max}[F_s, \left(D_s + \frac{F_s}{2}\right), 0]$$

$$a_N = \mathrm{Max}[-F_n, \left(D_n + \frac{F_n}{2}\right), 0]$$

And $\Delta F = F_e - F_w + F_n - F_s$

Upward differencing scheme: when $\left[D_e - \frac{F_e}{2}\right] = a_E$, the convective coefficient to east face is negative if the convective flux dominates. For it to be positive it must satisfy the following condition-

$$F_e/D_e = Pe_e < 2 \qquad (4.27)$$

If Pe>2, it will be negative which violates the boundedness condition.
Then we use upward differencing scheme which is based on the principle that the west face of control volume must receive much convective influence from the W node than from node P.

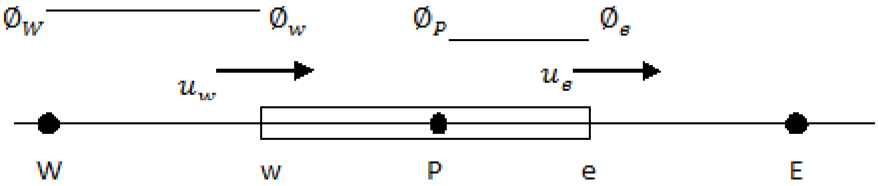


Fig.3.6. Schematic diagram showing directional potential of scalar

Therefore value of scalar ϕ at face of control volume is taken as to be equal to that at the upstream node. When the flow is taken in the positive direction i.e. from west to east, values of scalar at the faces is taken as-

$\emptyset_w = \emptyset_W$ and $\emptyset_e = \emptyset_P$

Then discretised form of steady advection-diffusion eqn. becomes as-

$$F_e\emptyset_p - F_w\emptyset_W = D_e(\emptyset_E - \emptyset_P) - D_w(\emptyset_P - \emptyset_W)$$

This can be further written as-

$$(D_w + D_e + F_e)\emptyset_p = (D_w + F_w)\emptyset_W + D_e\emptyset_E$$

Or

$$(D_w + D_e + F_e + F_w - F_w)\emptyset_p = (D_w + F_w)\emptyset_W + D_e\emptyset_E$$

It can be generalised as-

$$a_P\emptyset_P = a_w\emptyset_w + a_e\emptyset_e \qquad (4.25)$$

Where $a_w = D_w + F_w$ and $a_E = D_e$

And $a_P = a_W + a_E + (F_e - F_w)$

Therefore a combination scheme is used in which central difference scheme is used when $P_e < 2$ and upward differencing scheme is used when $P_e > 2$.

3.4 Solver setting

Therefore following settings are used in solver for the iterations –

For unsteady convection-diffusion: fully implicit method is unconditionally stable, first order accurate and all coefficients are always positive. Therefore while selecting the solver we select fully implicit method for the discretization of the convection-diffusion equation.

PRESTO: Since flow is through porous zone therefore presto (pressure staggering option) is used for interpolation of the pressure. It utilizes the discrete continuity balance equation for unsteady control volume about the face to compute the staggered pressure at face.

Pressure-Velocity Coupling: A velocity –momentum diffusion scheme is required to calculate the pressure from the continuity equation. In case of unsteady flow and porous media (Pressure-Implicit with Splitting of Operators) PISO is used for pressure-velocity conversion.

Laminar Model: Since flow through the subsurface is laminar therefore laminar model is selected for the viscous dissipation

First order upwind scheme: it is used for momentum and turbulent kinetic energy and dissipation rate. Once solution is conserved second order upwind scheme is applied which is more accurate.

There are two forces that retard the flow through the porous zone termed as viscous force and inertia force respectively governed by Reynold equation and Navier-Stoke equation. Since flow rate is low therefore viscous resistance forces dominates. In our problem we can neglect inertial resistance due to low flow rate. Now these resistances are responsible for the pressure drop which is calculated by Ergun's equation [Macdonald et al. 1979] which says total pressure drop in porous zone is given by-

$$\frac{\Delta P}{\Delta L} = \frac{150\mu(1-n)^2}{\emptyset^2 D^2 n^2}.v + \frac{1.75\rho(1-n)}{\emptyset D n^3}.v^2 \qquad (4.26)$$

In fluent this equation is taken as momentum sink equation as-

$$\frac{\Delta P}{\Delta L} = R_v.\mu.v + \frac{R_i}{2}.\rho v^2 \qquad (4.27)$$

Where

$$R_v = \frac{150(1-n)^2}{\emptyset^2 D^2 n^2}$$

and

$$R_i = \frac{2 \times 1.75(1-n)}{\emptyset D n^3}$$

Here n is porosity, D is diameter of particle size and $\emptyset$ is sphericity of particle.

Since flow velocity is very low having low Reynold number and therefore viscous force dominates the inertia force. Thus inertial resistance force is neglected and we need only viscosity resistance. Thus the momentum sink equation is reduced to Blake-Kozeny equation in which viscous resistance can be calculated as-

$$R_v = \frac{1}{a}$$

Here a is permeability of porous media in that direction. Ansys fluent use Blake-Kozney equation for viscous resistance.

3.5 Post processing

After simulating the model in fluent case is uploaded in CFD-POST and results are obtained. Here is a brief description of data used in simulation. As result of cylindrical source, a constant heat flux of 10 W/m is applied at the borehole wall. The borehole is under steady state and continuously transfers heat to the soil zone. This heat is transferred away from the borehole wall via conduction through soil and conduction-advection through water flowing through porous zone. Therefore thermal gradient is created weakening away from the borehole wall. This thermal gradient can be seen in the form of temperature contour generated in the domain after simulating it for a time period.

During simulation all the energy and momentum equations were conserved and there were no divergence found in the simulation. The geological site is assumed to be sedimentary limestone having porosity 0.10; hydraulic conductivity of sedimentary limestone varies 10^{-7} to 10^{-4} m/s. Properties of groundwater were selected as ρ=1000 kg/m^3, heat capacity c= 4180J/Kg-K, Thermal conductivity as 0.6W/m-K, and viscosity of ground water was taken as 0.001421Kg/m-s. While for ground density is taken as 2190.5 kg/m^3, heat capacity is taken as 1050 J/kg-k and thermal conductivity of ground is taken as 3.0 W/m-k.

Table.3 Input properties of borehole (source: Choi et al. 2012)

Parameter	Value	Parameter	Value
Borehole radius	0.07m	Ground thermal conductivity	3w/mk
Pipe outer radius	25mm	Ground density	2190.5kg/m^3
Pipe thickness	2.9mm	Ground specific heat	1050J/kg-k
Distance between centers	70mm	GW thermal conductivity	0.6W/mk
Pipe thermal conductivity	0.48w/mk	Groundwater density	1000kg/m^3
Grout thermal conductivity	1w/mk	GW specific heat	4180J/kg-k
Fluid thermal conductivity	0.453w/mk	Fluid specific heat	3568J/kg-k
Fluid density	1068kg/m^3	Fluid volumetric flow	0.0007m^3/s

Chapter 4: Results

In this chapter results obtained from the numerical experiments are described in details. This chapter includes comparison of the results obtained with analytical solution available. Then results of parameter variation test are compared. Finally impact of range of ground water velocity is calculated for a certain temperature drop in mean fluid temperature at outlet.

4.1 Comparison with analytical solution

Since velocity applied was superficial velocity therefore actual velocity will be more than that. Also due to viscous resistance velocity is dropped around the borehole. The effect of viscous resistance is more near the borehole wall and it is the region where momentum and thermal diffusion in ground water is highest.

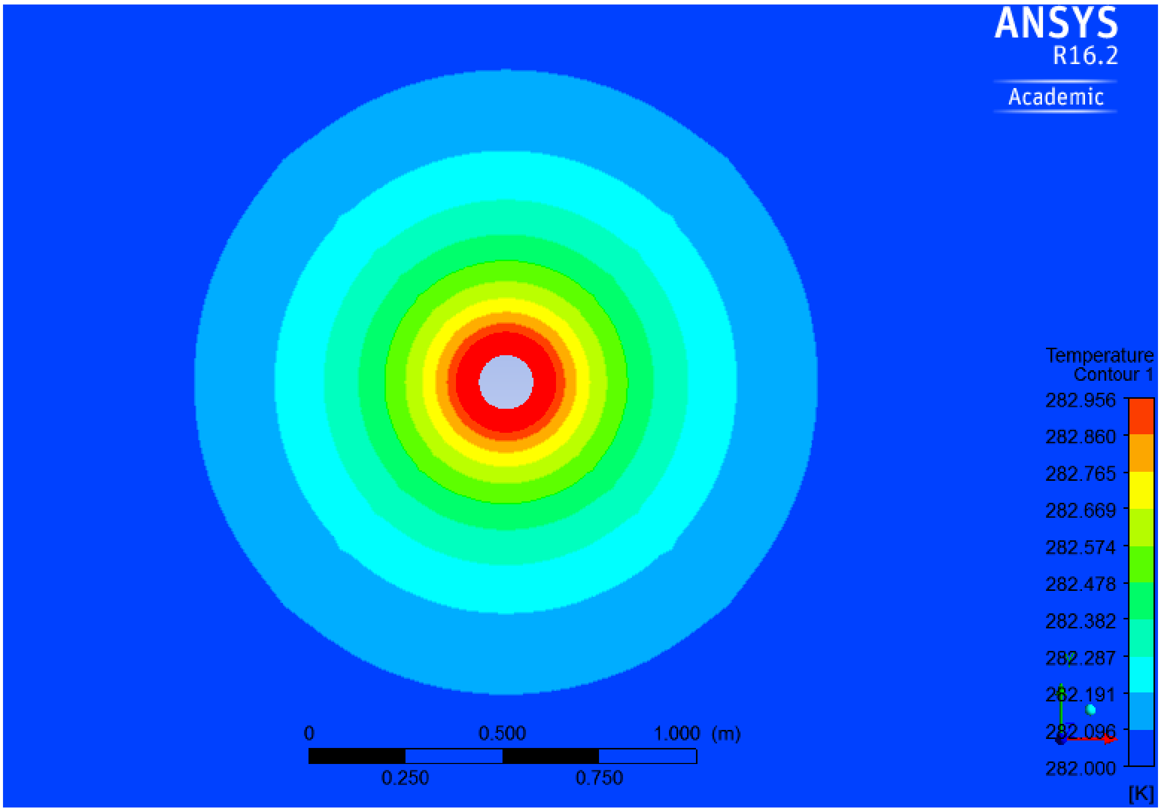


Fig.4.1. Temperature contours after 50 hours in absence of groundwater

The temperature contours are generated around the borehole showing the plume movement in subsurface weakening the temperature magnitude away from the borehole. When the groundwater has no movement the temperature contours are symmetric around the borehole showing that heat transfer is taking place only via conduction mechanism.

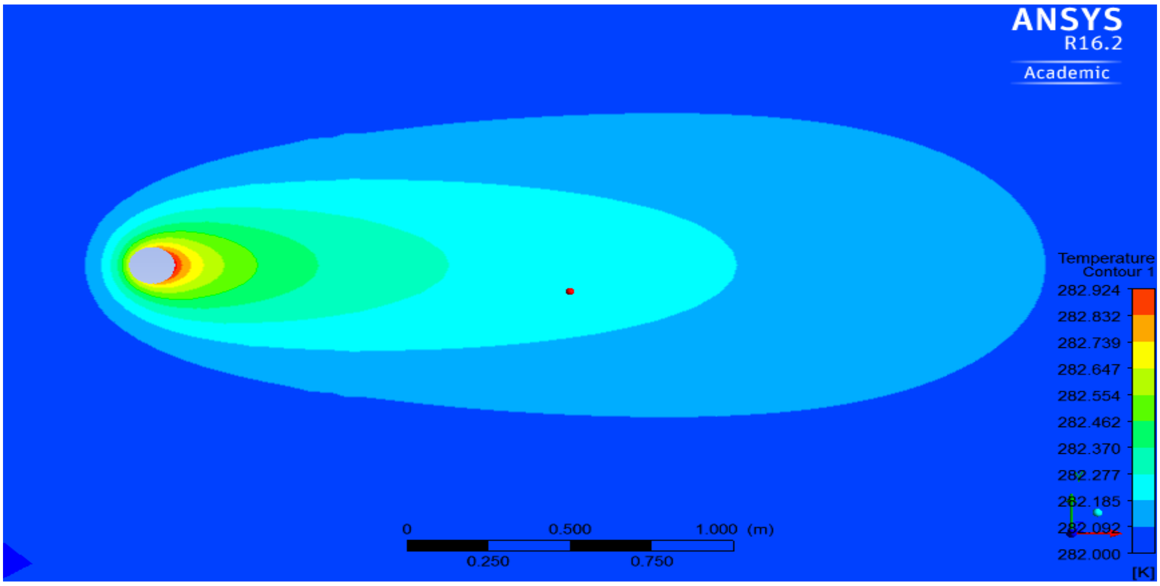


Fig.4.2.Temperature contours after 50hrs in presence of groundwater

When the boundary condition is changed to groundwater velocity of $1*10^{-5}$m/s the temperature contours are shifted in downstream direction indicating that heat is transported via conduction as well via convection.

The results of simulation for 50 hours are compared with the solutions given by Choi et al. 2012. The equation for temperature distribution in subsurface is given by-

$$\Delta T(x,y,t) = \frac{q_l}{4\pi k}\int_0^t \frac{1}{t-t'} \times \exp\left[-\frac{[x-u(t-t')]^2+y^2}{4a(t-t')}\right]dt' \tag{5.1}$$

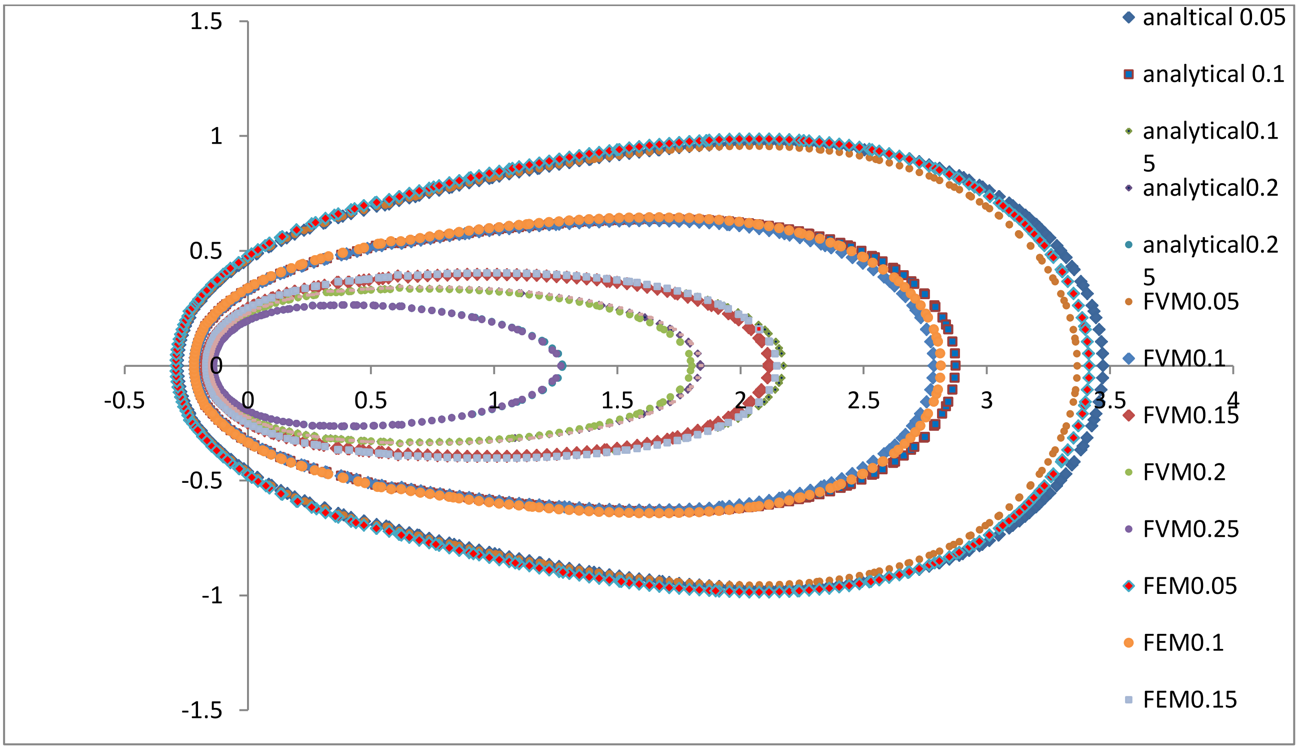


Fig.4.3. Change in temperature from initial temperature

Here x and y coordinates represents distances from borehole and is measured in meter. Isothermal contours of 282.05, 282.10, 282.15 and 282.20k are plotted in CFD-POST and these are compared with solutions available for the same. As we can see temperature plume is travelling downstream and therefore isothermal contours are mostly sifted downstream characterizing the advection phenomenon with the conduction. As the heat is transferred from the borehole to the neighbour soil zone by conduction mechanism, it is advected away by the groundwater in downstream side. Thus effect of groundwater is to moderate the temperature around borehole, which helps to increase the heat transfer mechanism and hence efficiency of the ground source heat exchanger is increased. The results show good matching. If there was no ground water present in the soil zone then heat transfer mechanism was only conduction and that would produce symmetric isothermal circles around the borehole as contours. That means heat is equally transported in all directions. Defining groundwater in porous zone with zero groundwater velocity also leads to only conduction although water is present in porous zone instead of air, which enhances conductivity of the subsurface domain.

4.2 Peclet number

This phenomenon is governed by Peclet number which is defined as ratio of strength of advection heat transfer to the strength of conduction heat transfer.

$$\mathrm{Pe} = \frac{\mathrm{F}}{\mathrm{D}} = \frac{\rho \mathrm{V}}{\Gamma / \delta \mathrm{x}}$$

Where F is ρv, which is mass flux rate and hence represents the strength of advection of heat, higher this value more heat advection takes place. On the other hand D is diffusion coefficient which is$K/_{C\delta x}$, lower the heat capacity and higher the thermal conductivity, higher is diffusion rate. Thus it represents the conduction heat transfer strength. When groundwater velocity is zero the value of Peclet number is zero and only conduction mechanism of heat transfer dominates. Then contours will show the circular plot.

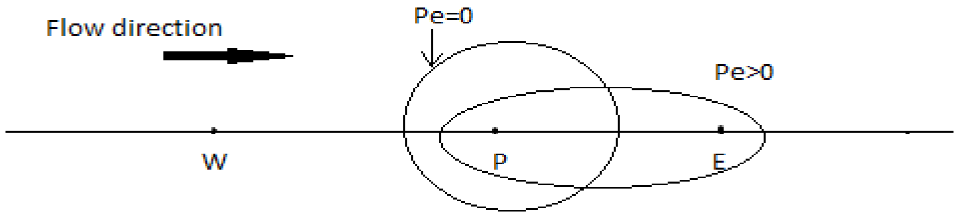


Fig.4.4.Schematic diagram showing impact of Peclet number on TAZ

When conductivity of soil-water zone is zero or the heat capacity is infinite then Peclet number reach to infinite and only advection phenomenon dominates. Thus isothermal-surface will show the elliptical plot. But Peclet number depends on the geological characteristics of the site and thus there can be found a lot of variation in Peclet number from site to site. It can also be represented as product of Reynolds number and Prandtl number.

$$\mathrm{Pe} = \mathrm{Re} \times \mathrm{Pr}$$

Here Reynold number represents the viscous resistance of the flow while Prandtl number represents the ratio of momentum diffusion to the thermal diffusion.

$$\mathrm{Pe} = \frac{\rho L v}{\mu} \times \frac{\mu C_p}{K}$$

4.3. Parameter variation test

Physical significance of peclet number comes from Bejan et al. (2006) which defines it as ratio of thermal flux by advection to the ratio of thermal flux by diffusion.

$$\mathrm{Pe} = \frac{A_x^H}{D_x^H} = \frac{\rho u c_p \Delta t}{k_{eff} \frac{\Delta t}{\Delta x}}$$

In groundwater system Peclet number used by authors is given by Domenico and Schwartz (1990)-

$$\mathrm{Pe} = \frac{q.\, l.\, \rho_f C_f}{K_{eff}} \qquad (5.2)$$

Here l is characteristic length of flow. Thus Peclet number depends on porosity of soil zone, velocity of groundwater, characteristic length of flow, density of the ground water, and water, thermal conductivity of soil and groundwater. Therefore a parameter variation test is done 50 hours to see that if certain percentage deviation occurs in any property of the domain, how much change in the isothermal contours occurs. Also impact of variation of soil heat capacity is seen on heat transfer mechanism. Thus we can find out which parameter has more impact on Peclet number and thus on heat transfer mechanism.

(1)Porosity: porosity is defined as volume of voids to the total volume of the soil zone. It is the volume which reflects the water content in soil domain when it is saturated. For a given hydraulic gradient if porosity is less then velocity of groundwater flow is more. Since we have taken case of sedimentary limestone and we have taken its average porosity as 0.10. Now in further study we will take n- 20%, n-10%, n, n+10%, n+20% and keep the other parameters constant.

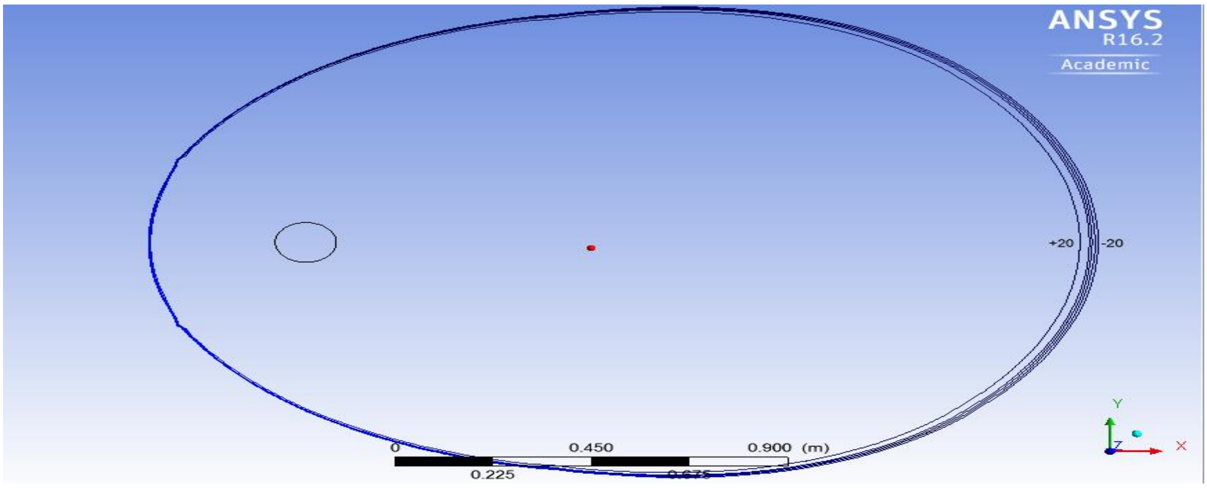


Fig.4.5 The isothermal-contours on variation in porosity from -20% to +20%

From the plot of isothermal contour of 282.2k it is indicated that with increase in porosity the size of isothermal contour decrease and it also travels in the upstream direction of flow and it increase or travels downstream direction with decrease in porosity. That may be due to fact that with increase in porosity groundwater velocity decreases that retards plume movement and vice-versa. But overall effect of porosity variation is not too much.

(2) Groundwater velocity: groundwater velocity is a function of hydraulic conductivity and hydraulic gradient. Higher hydraulic conductivity and gradient indicates higher groundwater velocity. Since we have taken velocity of groundwater in my study as 1×10^{-5} m/s or 0.864m/day, in further study we took five cases in which velocity is taken as v-20%, v-10%, v, v+10% and v+20%.

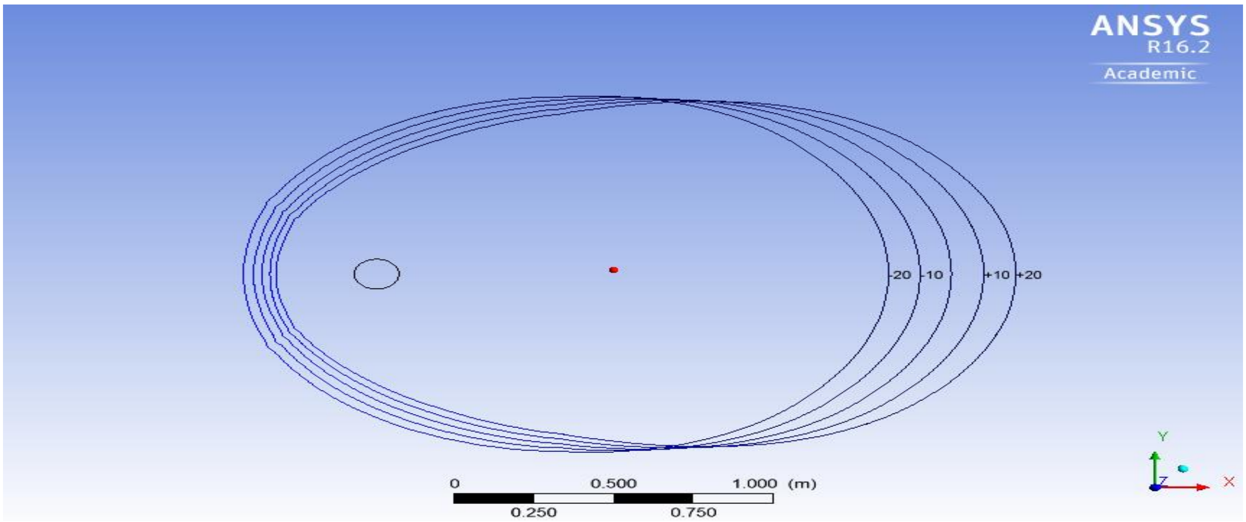


Fig.4.6 The isothermal contours variation in velocity from -20% to +20%

From the isothermal contour of 282.2k we can conclude that with increase in velocity the temperature contour is shifted in the downstream direction which indicates that the rate of convection heat transfer is increased compared to rate of conduction heat transfer. With the decrease in groundwater velocity the temperature contour is shifted in the upstream direction that means advection heat transfer is reduced compared to the conduction heat transfer.

(3) Specific heat of groundwater: it is the amount of heat stored by unit mass of fluid when a unit temperature is gained. It reflects the heat capacity of the fluid. Generally higher heat capacity indicates higher heat is absorbed by fluid which means more heat is transported by advection. So here we took five cases in which fluid heat capacity is taken as C_f-20%, C_f-10%,C_f, C_f+10% and C_f+20% respectively. Isothermal contours of 282.2k are compared for all cases.

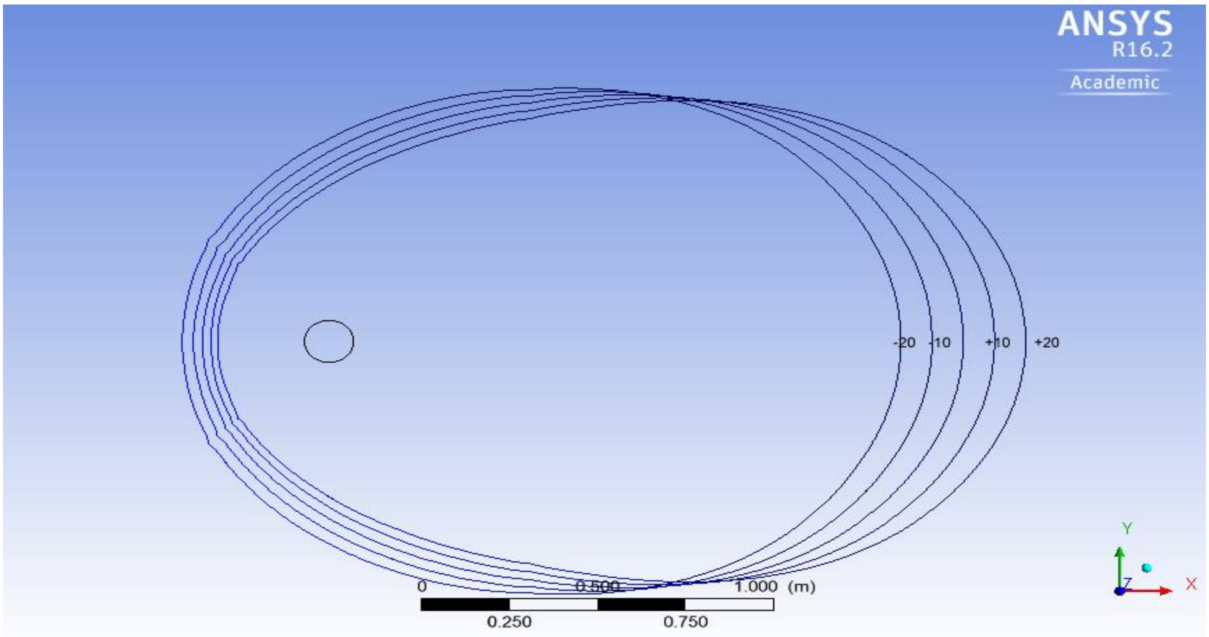


Fig.4.7. The isothermal-contours on variation in Groundwater specific heat from -20% to +20%

From the analysis of above results we can conclude that with increase of specific heat of groundwater the isothermal contour is increased and shifted more in the downstream direction that indicates that advection heat transfer is enhanced compared to conduction heat transfer. While with decrease in specific heat the isothermal contour is decrease in size and shifted in upstream side, that means advection heat transfer is decreased compared to the conduction heat transfer.

(4) Specific heat of soil: it is the amount of heat stored by unit mass of soil when temperature is gained by one unit. It reflects heat capacity of the soil. It indicated how much heat soil particle can store before transmitting it to next particle. Lower heat capacity of soil means higher thermal conductivity. In further study we have taken five cases having heat capacity C_s-20%, C_s-10%, C_s, C_s+10% and C_s+20% respectively. Isothermal contours of 282.2k of all cases are compared.

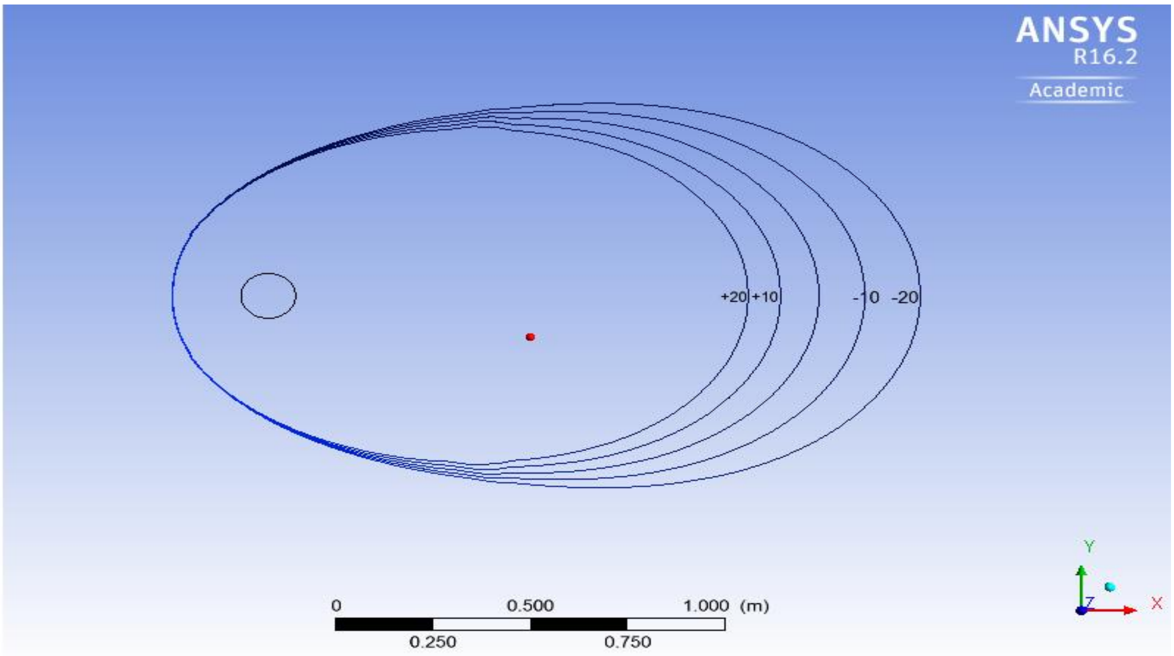


Fig.4.8. Isothermal-contours on variation of specific heat of soil from -20% to +20%

Here from the plots of isothermal contours we can assume that with the increase of thermal specific heat of the soil the heat transport phenomenon is retarded and hence contours are smaller in size, while with decrease in specific heat of the soil the heat transfer process is enhanced and hence isothermal contours are larger in size.

(5) Thermal conductivity of soil: it is the property of substance by virtue of which it transfer heat from higher temperature to lower temperature which is directly proportional to the thermal gradient between two points. Higher the value of thermal conductivity higher is coefficient of diffusion and hence conductance heat transfer rate is high. In this study we have taken five cases having thermal conductivity of soil K_s-20%, K_s-10%, K_s, K_s+10% and K_s+20% respectively. Isothermal contours of 282.2k all the cases are compared in CFD-POST.

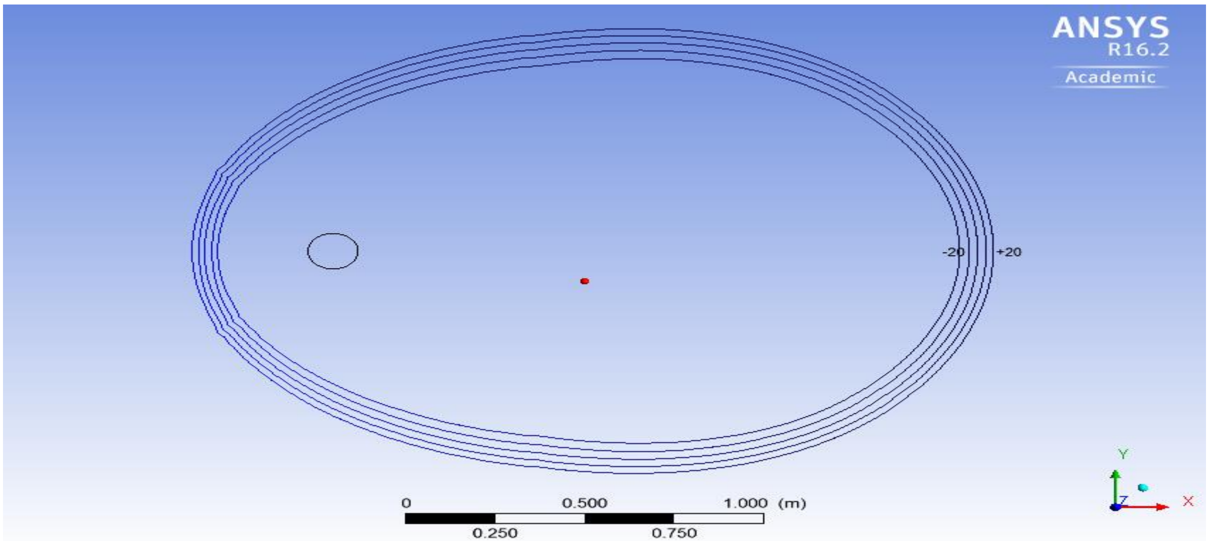


Fig. 4.9 The isothermal contours with variation in soil thermal conductivity from -20% to +20%

From the above plots we can easily get that with the increase in thermal conductivity of the soil isothermal contour expands outwards and also enhance in flow direction. That clearly indicates that both advection and conduction heat transfer mechanism is enhance although conduction phenomenon dominates. On the other hand if we decrease thermal conductivity of the soil, the conduction and advection both phenomenon retards.

(6) Thermal conductivity of Groundwater: Generally thermal conductivity of fluids is very less compared to solids. But it can play a very important role while studying the dominance of diffusion vs advection phenomenon. So in this study we have taken five cases having thermal conductivity of GW K_f-20%, K_f-10%, K_f, K_f+10% and K_f+20% respectively. Isothermal contours of 282.2k for all cases are compared in CFD-POST.

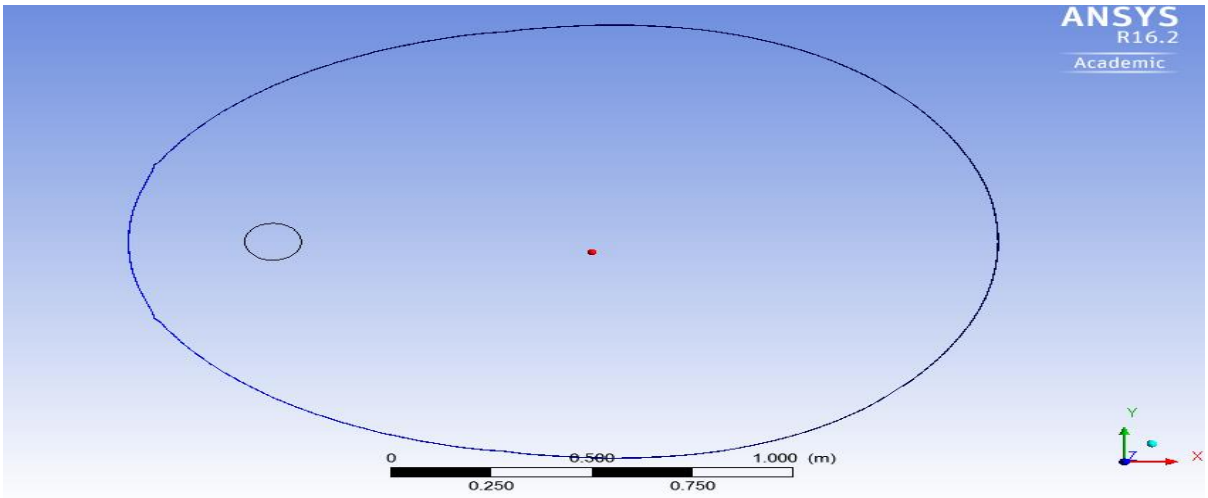


Fig.4.10. The isothermal contours with variation in groundwater thermal conductivity from -20% to +20%

From above plots we are not even able to differentiate the isothermal contour lines at different conductivity of the GW. It indicated that the thermal conductivity variation of the GW does not impact on the conduction-advection heat transfer mechanism.

The results obtained from the comparison contours are tabulated below. Two different tables are created one for deviation of TAZ by variation in properties and second for deviation of mean fluid temperature by variation in mean fluid temperature.

Table.3 Change in thermal affected zone with -10% variations of properties is given in tabular form below

Properties	Initial values	Plume area(mm^2)	-10% variation	plume area(mm^2)	proportion to TAZ	%change in area
Porosity	0.10	39546.5	0.09	39621	1.00188	0.188
Specific heat of groundwater(J/Kg-K)	4180	39546.5	3716	39400.8	0.9963	-0.368
specific heat of soil(J/Kg-k)	1050	39546.5	945	40087.4	1.0136	1.36
Soil conductivity(W/m-k)	3	39546.5	2.7	39408.08	0.996	-0.35
Velocity(m/s)	10^{-5}	39546.5	$0.9*10^{-5}$	39479.9	0.998	-0.168

Change in thermal affected zone with -20% variations of properties

Properties	Initial values	Plume area(mm^2)	-20% variation	plume area(mm^2)	proportion to TAZ	%change in area
Porosity	0.10	39546.5	0.08	39695.4	1.0037	0.376
Specific heat of groundwater(J/Kg-K)	4180	39546.5	3344	39362.4	0.9953	-0.46
specific heat of soil(J/Kg-k)	1050	39546.5	840	40223.1	1.017	1.71
Soil conductivity(W/m-k)	3	39546.5	2.4	39280.07	0.9933	-0.67
GW Velocity(m/s)	10^{-5}	39546.5	$0.8*10^{-5}$	39390.71	0.996	-0.39

Change in thermal affected zone with +10% variations of properties

Properties	Initial values	Plume area(mm^2)	+10% variation	plume area (mm^2)	Proportion to TAZ	%change in area
Porosity	0.10	39546.5	0.11	39470.8	0.998	-0.19
Specific heat of GW(J/Kg-K)	4180	39546.5	4598	39649.1	1.002594	0.259
specific heat of soil(J/Kg-k)	1050	39546.5	1155	39316.5	0.99418	-0.581
Soil conductivity(W/m-k)	3	39546.5	3.3	39700.6	1.003896	+0.38
GW Velocity(m/s)	10^{-5}	39546.5	$1.1*10^{-5}$	39609.1	1.0016	0.158

Change in thermal affected zone with +20% variations of properties

Properties	Initial values	Plume area(mm^2)	+20% variation	plume area (mm^2)	Proportion to TAZ	%change in area
Porosity	0.10	39546.5	0.12	39366.8	0.995	-0.45
Specific heat of GW(J/Kg-K)	4180	39546.5	5016	39748.32	1.0051	0.51
specific heat of soil(J/Kg-k)	1050	39546.5	1260	39078.8	0.9882	-1.1826
Soil conductivity(W/m-k)	3	39546.5	3.6	39925.2	1.0096	+0.95
GW Velocity(m/s)	10^{-5}	39546.5	$1.2*10^{-5}$	39679.24	1.0033	0.335

Table.4. Mean fluid temperature at outlet with variation of properties is given as-

Properties	Default values	Mean fluid temp(K)	+20% variation	Mean fluid temp(k)	Variation
Porosity	0.10	284.544	0.12	284.548	0.004
Specific heat of groundwater(J/Kg-K)	4180	284.544	5016	284.493	-0.051
specific heat of soil(J/Kg-k)	1050	284.544	1260	284.541	-0.003
Soil conductivity(W/m-k)	3	284.544	3.6	284.44	-0.104
GW conductivity(W/m-k)	0.6	284.544	0.72	284.544	0
GW Velocity(m/s)	10^{-5}	284.544	$1.2*10^{-5}$	284.497	-0.047

Properties	Default values	Outlet temp(k)	+10% variation	New outlet temp(k)	Variation
Porosity	0.10	284.544	0.11	284.546	0.002
Specific heat of groundwater(J/Kg-K)	4180	284.544	4598	284.517	-0.027
specific heat of soil(J/Kg-k)	1050	284.544	1155	284.543	-0.001
Soil conductivity(W/m-k)	3	284.544	3.3	284.488	-0.056
GW conductivity	0.6	284.544	0.66	284.544	0
GW Velocity(m/s)	10^{-5}	284.544	$1.1*10^{-5}$	284.52	-0.024

Properties	Default values	Outlet temp(K)	-10% variation	New outlet temp(K)	Variation
Porosity	0.10	284.544	0.09	284.541	-0.003
Specific heat of groundwater(J/Kg-K)	4180	284.544	3762	284.574	0.030
specific heat of soil(J/Kg-k)	1050	284.544	945	284.545	0.001
Soil conductivity(W/m-k)	3	284.544	2.7	284.608	0.054
GW conductivity(W/m-k)	0.6	284.544	0.54	284.544	0
GW Velocity(m/s)	10^{-5}	284.544	$0.9*10^{-5}$	284.574	0.030

Properties	Default values	Outlet temp(K)	-20% variation	New outlet temp (K)	Variation
Porosity	0.10	284.544	0.08	284.539	-0.005
Specific heat of groundwater(J/Kg-K)	4180	284.544	3344	284.609	0.065
specific heat of soil(J/Kg-k)	1050	284.544	840	284.546	0.002
Soil conductivity(W/m-k)	3	284.544	2.4	284.685	0.141
GW conductivity(W/m-k)	0.6	284.544	0.48	284.544	0
GW Velocity(m/s)	10^{-5}	284.544	$0.8*10^{-5}$	284.589	0.045

4.4. Impact of ground water velocity on heat transfer mechanism

Different velocities 0, 1.58*10^{-8}, 3.17*10^{-8}, 3.17*10^{-7}, 0.5×10^{-5}, 1×10^{-5} and 2×10^{-5}m/s are applied as boundary condition and simulated for 200 days. The results in thermal contours form show that how advection phenomenon dominates conduction at higher velocities.

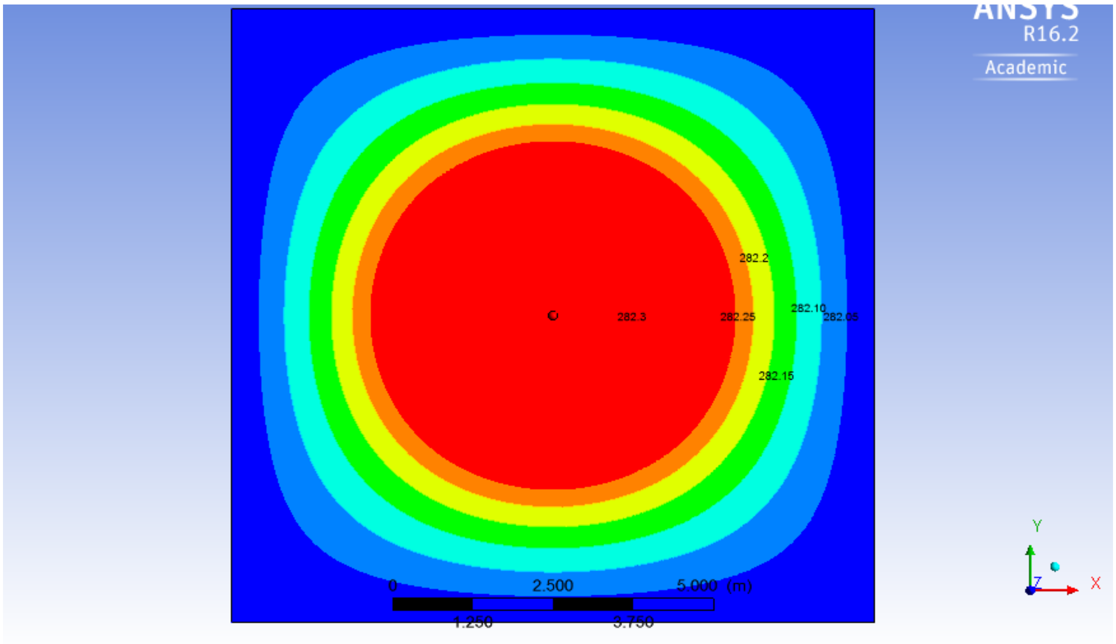


Fig4.11. Temperature contours after around borehole 200 days with conduction only

In the above plots it can be easily seen that when only conduction takes place around borehole in absence of ground water, heat is diffused equally around borehole and more temperature is accumulated around borehole which retards heat transfer.

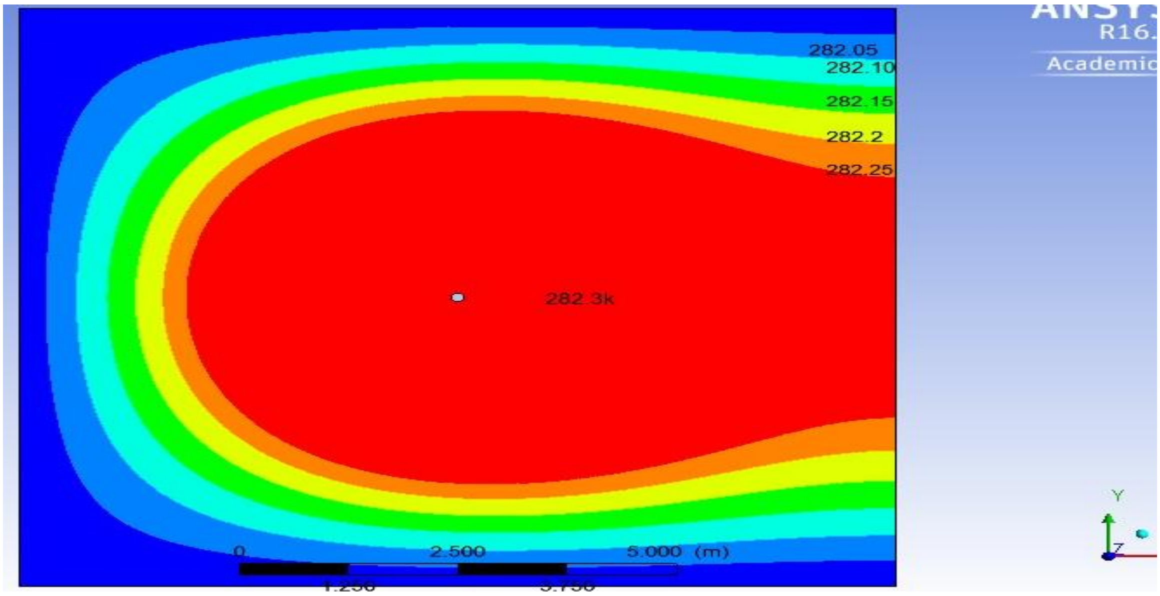


Fig.4.12 Temperature contours after 200 days with GW velocity 0.5m/year

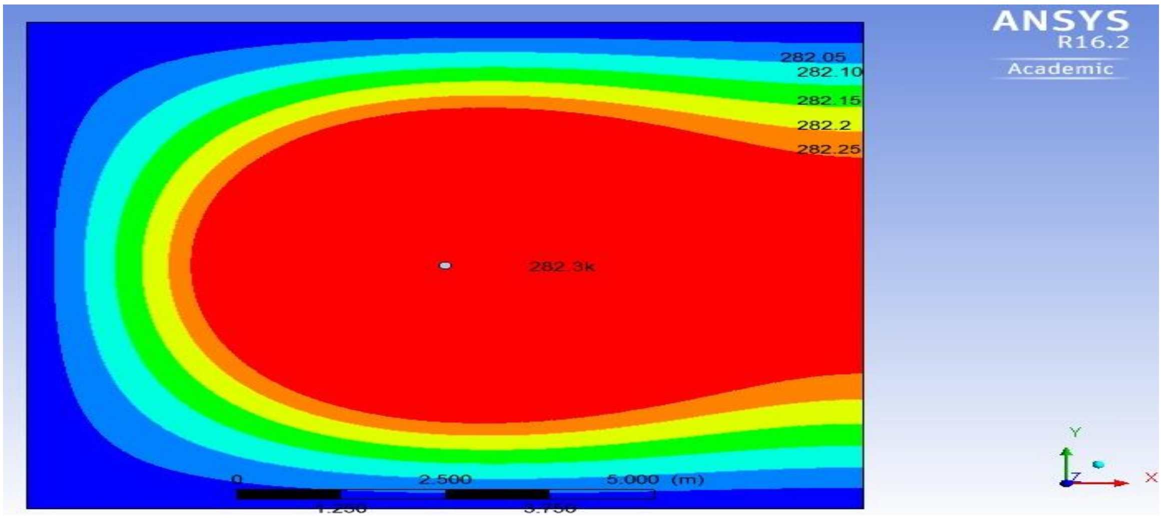


Fig.4.13 Temperature contours after 200 days with GW velocity 1m/year

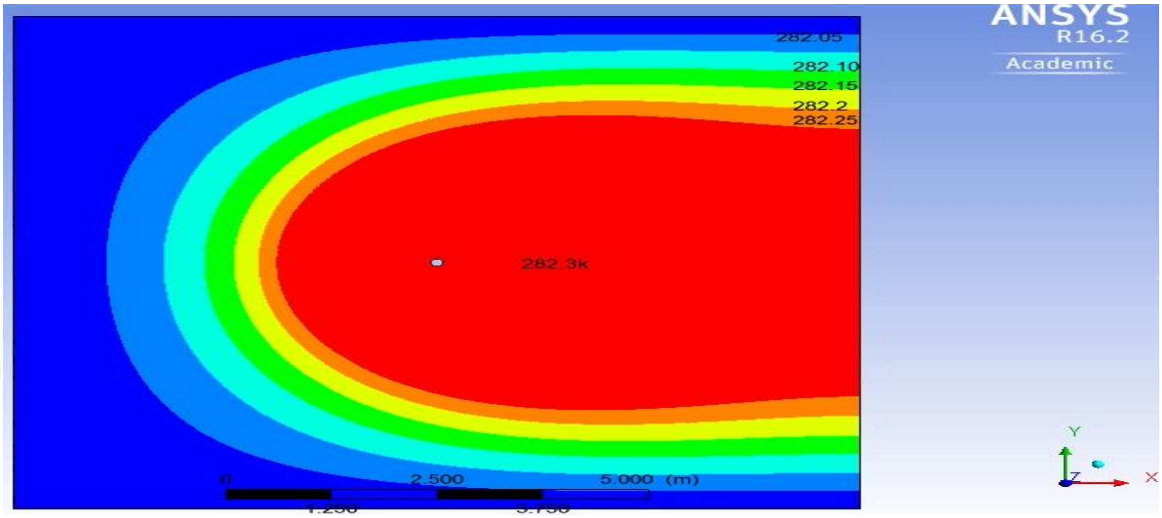


Fig.4.14 Temperature contours after 200 days with GW velocity 10m/year

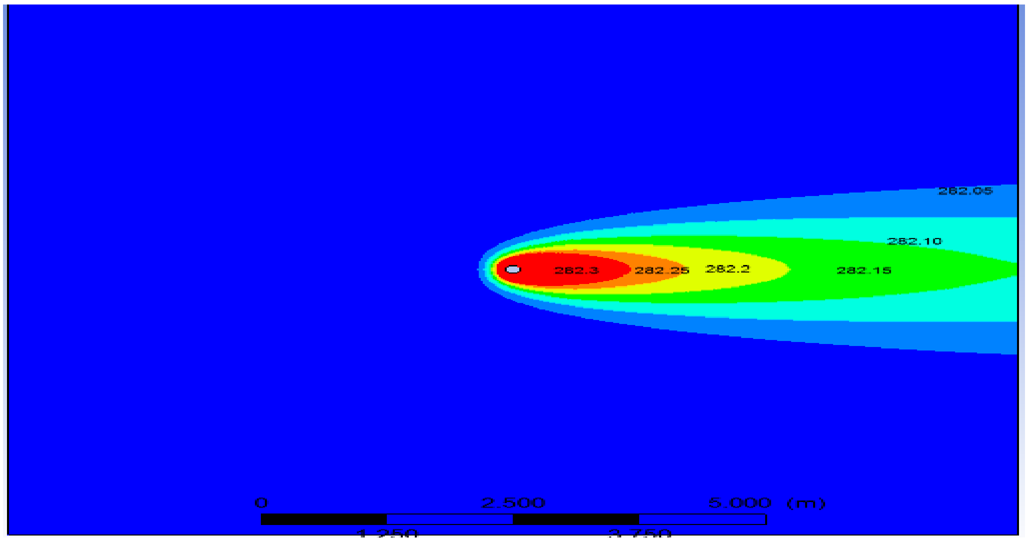


Fig.4.15 Temperature contours after 200days with 0.5*10^{-5}m/s

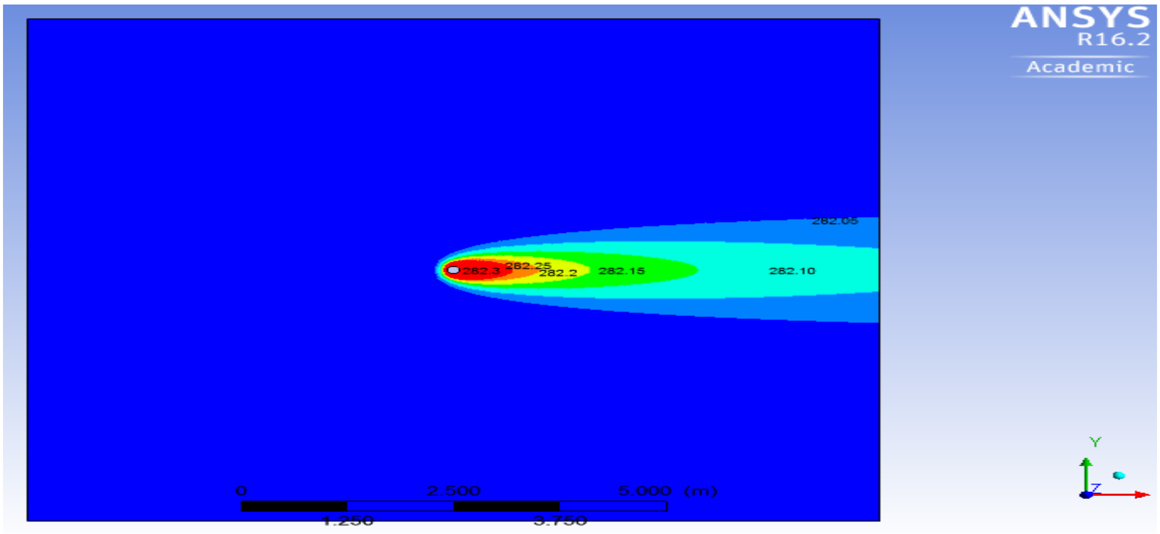


Fig.4.16 Temperature contours after 200 days with 1*$^{10-5}$ groundwater velocity

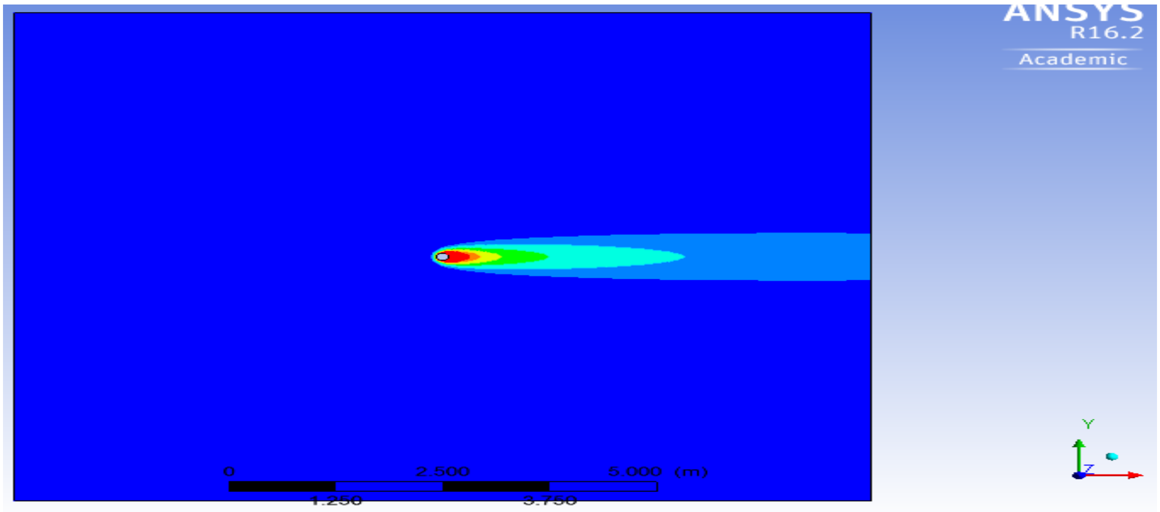


Fig.4.17 Temperature contours after 200 days with 2*$^{10-5}$ groundwater velocity

The meant fluid temperature at outlet was calculated by thermal resistance with equivalent diameter pipe model. Then the percentage change in mean fluid temperature is calculated by-

$$\%\Delta T = \frac{T_{CONDUCTIION} - T_{CONVECTION}}{T_{CONDUCTION}} \times 100$$

Table.4. Drop in mean fluid temperature with GW velocity

Groundwater velocity(m/s)	Mean fluid temperature at outlet					
	After 50 days		After 100 days		After 200 days	
	℃	% drop	℃	% drop	℃	% drop
0	12.79	-	12.95	-	13.02	-
$1.58*10^{-8}$	12.77	0.1	12.92	0.18	12.98	0.25
$3.17*10^{-8}$	12.70	0.63	12.86	0 .66	12.92	0.71
$3.17*10^{-7}$	12.59	1.5	12.70	1.8	12.66	2.7
$0.5*10^{-5}$	12.15	5	12.04	7	11.97	8
$1*10^{-5}$	11.51	10	11.15	14	10.93	16
$2*10^{-5}$	10.48	18	10.23	21	10.03	23

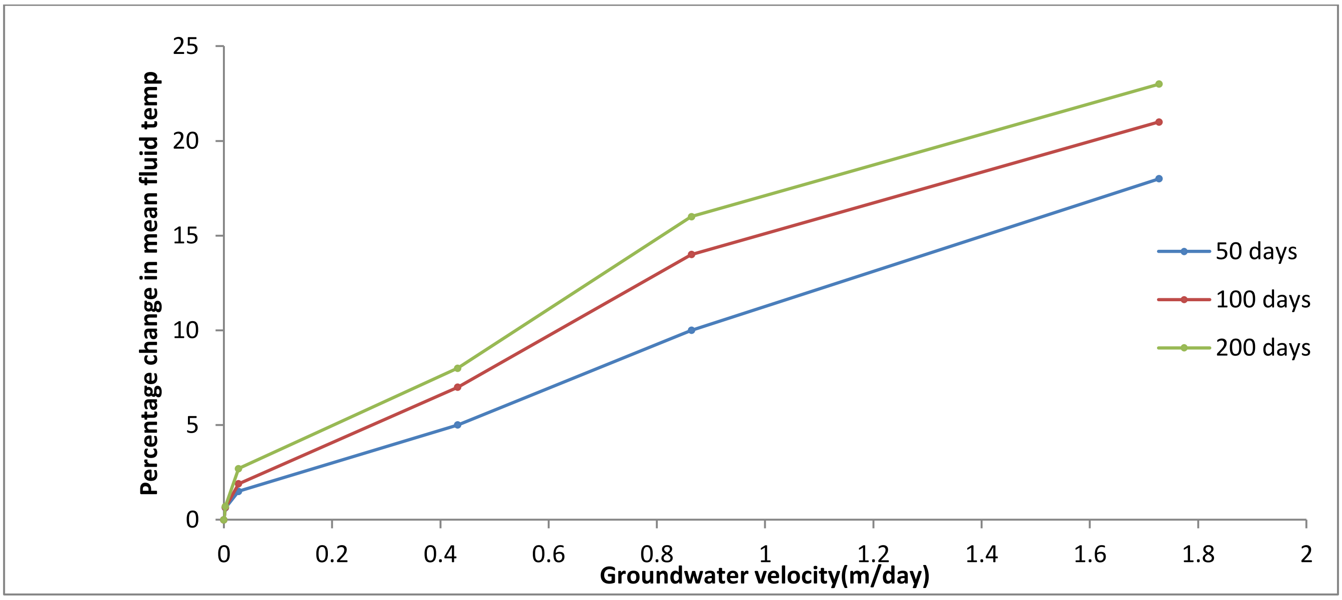


Fig.4.18 Percentage drop in mean fluid temperature at outlet with groundwater flow

The results shows that for short period of working to have sufficient drop in mean fluid temperature the groundwater velocity should be very high. At moderate groundwater flow, for longer period of working of GSHE only a little drop in mean fluid temperature can be obtained. A groundwater velocity of magnitude 1-10m/year or the Peclet number (0.044-0.44) can yield a 0.63-1.5% drop in mean fluid temperature for 50 days working, while 0.71-2.7% drop for 200 days of working.

Chapter 5: Summary and Conclusion

The conclusion of the above work is that presence of groundwater will enhance heat transfer form borehole via advection when it has movement. However the advection phenomenon dominates if the groundwater velocity exceeds certain value. In absence of groundwater, as the working period of borehole heat exchanger increases it starts accumulating heat flux around it. This accumulation of heat around the borehole retards the further heat transfer. When a sufficient amount of groundwater is available advection phenomenon dominates and less heat is accumulated around the borehole which increase the heat transfer mechanism between borehole and subsurface. Also the properties involved in advection and diffusion in subsurface are varied and their impact is seen on the heat transfer mechanism in form of movement of the isothermal contour and change in mean fluid temperature. From the isothermal contour plots we can conclude that thermal conductivity of the groundwater does not influence the advection-diffusion heat transfer mechanism significantly and therefore impact of variation in thermal conductivity of fluid is negligible on thermal affected zone. Therefore while calculating the Peclet number we can neglect the thermal conductivity of fluid. While porosity and thermal conductivity of soil has a little influence on the duo-mechanism but in comparison of other factors that is very small. Now the three properties which have considerable effect on the advection-diffusion phenomenon are heat capacity of the soil, groundwater velocity and heat capacity of the groundwater and later two have comparatively large impact on the advection-diffusion heat transfer mechanism and both contributes in positive direction of heat transfer mechanism enhancing the efficiency of the GSHP. Both the properties are associated to the presence of the subsurface water movement and hence estimation of groundwater is very important while designing the ground source heat exchanger. All of the above parameters are involved while we calculate the Peclet number except heat capacity of soil that results shows has a significant impact on TAZ and also on mean fluid temperature at outlet. Therefore while calculating a Peclet number for any geological site apart from groundwater heat capacity we should also consider soil heat capacity. Base on the results we tried to define the range of minimum groundwater velocity in terms of minimum percentage drop at outlet temperature we can have at certain duration of time. So that while designing the GSHE we can reduce setup cost by proper estimating effect of GW flow on performance of heat exchanger.

Initially when flow was not significant enough there was not sufficient change in mean fluid temperature but the results show a groundwater velocity of magnitude 1-10m/year can yield a 0.63-1.5% drop in mean fluid temperature for 50 days working, while 0.71-2.7% drop for 200 days of working. Means for the same range of the Peclet number we get two ranges of percentage drops in mean fluid temperature, therefore the Peclet number should be defined with respect to time period. On further increase in groundwater velocity higher percentage drop in mean fluid temperature can be achieved for the same period of time. Also initially the drop of mean fluid temperature was more in starting phase of working of exchanger. With increase of time rate of drop of temperature reduces. Presence of pumping well can also affect the heat transfer mechanism as subsurface water movement is affected by it.

Future Recommendations

There are still no criteria of minimum GW velocity which enhance the heat transfer mechanism around borehole but we can minimize the range of groundwater velocity for percentage drop in mean fluid temperature we can get. The simulation for variation in mean fluid temperature for different heat capacity and conductivity of soil have to be performed for a longer duration and so that the effect of heat capacity of soil can be considered while defining the range of the Peclet number for a certain percentage drop in mean fluid temperature at outlet .

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