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Sensitivity analysis of fluid flow in a confined aquifer using numerical simulation

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ABSTRACT

Aquifers are underground porous domains containing groundwater. Confined aquifers are surrounded by the impermeable layers. They are saturated by pressurized water and are suitable for energy storage purposes. They have low thermal conductivity and large storage volume. In design of aquifer thermal energy storage (ATES) an applicable model is necessary to predict the aquifer behavior. In this research, by developing a three dimensional finite volume model via FLUENT software, the effects of operative parameters on pressure distribution are investigated. In the ATES, heat transfer is performed by both convection and conduction phenomena. The convective heat transfer in the ATES is occurred because of pressure gradient and hence, recognition of effects of operative parameters on pressure distribution is essential. These effective parameters are some geological parameters such as groundwater natural flow, porosity and permeability, injection and withdrawal rates from wells, number and arrangement (being linear, triangular or rectangular) of wells.

1. Introduction

Geothermal systems using heat stored in the underground have been used for cooling and heating of buildings in several countries such as the United States (Meyer and Todd. 1973; Molz et al. 1978; Papadopulos and Larson. 1978; Parr et al. 1983), European countries (Andersson. 2003; Sanner. 2003; Paksoy et al 2000; Preene and Powrie. 2009), and other countries (Umemiya and Satoh. 1990; Gao et al. 2009; Lee. 2008; Fan et al. 2007) since 1970s. Recently, thermal energy storage (TES) systems have become more popular in the world due to the problem caused by depletion of fossil fuels and increase of global warming (Rosen. 1999). There are two main TES systems: A closed system (e.g., borehole thermal energy storage: BTES), and an open system (e.g., aquifer thermal energy storage: ATES). Due to direct usage of groundwater with relatively high volumetric heat storage capacity, the ATES system has higher system performance than the BTES system and any other systems using low temperature geothermal heat. In the ATES system, the contamination and depletion of groundwater can be minimal, since the water circulated from underground to a heat exchanger is immediately re-injected though the injection well into the aquifer (Gao et al. 2009).

The numerical modeling is a powerful tool for flow simulation in porous media such as an aquifer (Shamsai and Vosoughifar. 2004). In the past years, several research works have been performed about the numerical flow simulation in the aquifers. They have also applied some numerical codes such as TRUST (Narasimhan. 1984), TRUMP (Narasimhan, 1973), PORFLOW (Runchal. 1984), UNSAT (Fayer and Jones. 1990), SUTRA (Souza. 1987), MODFLOW (Jobson and Harbaugh. 1999) to model the aquifer system. These codes are generally based on finite difference discretization.

Dong et al. (2012) used MODFLOW code to optimize the rate of pumped water in an aquifer. The weakness of application of this code in defining the geometry of the aquifer that is it has developed for porous media; on the other hand, considering facing the heterogeneous rocks through increasing the depth and crossing from the alluvium environment, the modelling has to consider its complexities. Krčmář and Sracek (2014) as well, used this code to model the underground water in a mine. Álvarez et al. (2015) modeled groundwater flow in an open pit located in limestones using the same code.

As it is obvious, most of the above mentioned studies have not performed a remarkable research about the parametric study on the pressure distribution inside the aquifer. In the present study a comprehensive investigation is performed on effective parameters that influence pressure distribution inside the aquifer would be used for thermal energy storage (TES) by numerical simulation. Also special consideration is given on the number and arrangement of injection/withdrawal wells.

2. Materials and methods
2.1. Governing equations

The system which is considered in this study comprise of a single phase water flow inside the saturated aquifer that confined by bedrock both above and below. In such a system the water flows only inside the aquifer.

Aquifer is a porous media that its porosity is equal to the volume of voids space to the total volume of the media and is expressed in terms of fraction or percent:

$$\emptyset = \frac{V_V}{V_O} \tag{1}$$

where $\emptyset$, V_V and V_0 are porosity, void and bulk volume of the aquifer, respectively. It is obvious that in saturated aquifers porosity is the ratio of water volume to the total volume. The porosity of the rocks varies from 0 to 45 %. For the TES, 20-30 % porosity is suitable (Tsang. 1980). By considering the porosity definition, the density of aquifer is defined as (Schaetzle. 1980):

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$$\rho = \rho_{Water}\emptyset + \rho_{Rock}(1-\emptyset) \quad (2)$$

Water flow depends on the pressure distribution and physical properties of porous media. In general, flow is proportional to pressure gradient, namely head gradient and area (Strack. 1989):

$$Q \propto A\frac{dh}{dL} \quad (3)$$

This flow equation is known as Darcy's law and its proportionality is called permeability or hydraulic conductivity and shown with K:

$$Q = -KA\frac{dh}{dL} \quad (4)$$

Another form of the Darcy's law is defined for the Darcy flux (or the Darcy velocity or specific velocity) which is the discharge rate per unit cross-sectional area. It is hard to define the velocity inside the aquifer because of the existence of pores with different cross sections. The velocity inside of the aquifer must be a rough average number as the cross section is ever not homogeneous at all. As a result, velocity is rarely used in geological evaluations. A velocity defined by dividing the flow rate (Q) by aquifer cross-sectional area (A) is known as the specific velocity, V_S (Strack. 1989):

$$\vec{V}_S = \frac{Q}{A} = -K\frac{dh}{dL} \quad (5)$$

Natural flow in an aquifer is subjected to the equations of flow. The natural flow in an aquifer can be stated as:

$$Q/_A = K\vec{\nabla}h \quad (6)$$

The groundwater flow has a 3D pattern. The specific velocity in a Cartesian system can be expressed as:

$$\vec{V}_{S,x} = -K_x\frac{\partial h}{\partial x} \quad (7)$$

$$\vec{V}_{S,y} = -K_y\frac{\partial h}{\partial y} \quad (8)$$

$$\vec{V}_{S,z} = -K_z\frac{\partial h}{\partial z} \quad (9)$$

In general, K_x, K_y and K_z are not the same. In such a case, the medium is called anisotropic. In this study, it is assumed that the aquifer is isotropic.

Generally, charge and discharge rates are performed as a constant value. Therefore, the flow is steady and the continuum equation in porous media satisfies the condition (Strack. 1989):

$$[\vec{\nabla}.(\rho\vec{V_S})]dV = S \quad (10)$$

where S is related to source term. In this study it is supposed that the porosity and density are constant, hence Eq.10 is converted to:

$$\vec{\nabla}.\vec{V_S} = \frac{S(x,y,z)}{\rho dV} \quad (11)$$

By considering the Darcy's equation, Eq.12 can be rewritten as follows:

$$\nabla^2 h = \frac{S(x,y,z)}{K\rho dV} \quad (12)$$

2.2. Numerical modeling

In this study, FLUENT® software which is a commercial finite volume program was used for simulating the ATES system. The meshed view of the considered domain has been shown in The Figure 1. In this meshing an unstructured 3D mesh with 259346 cells was constructed. The chosen element was Tet/Hybrid and the type was TGrid. For investigation of mesh size independency, so that the unique solution would be obtained, several mesh sizes were examined. Finally, the mesh sizes selected were 1m, 1m and 0.5m in x, y and z directions, respectively. The dependency of solution to the mesh sizes less that these values, was less than 1 percent.

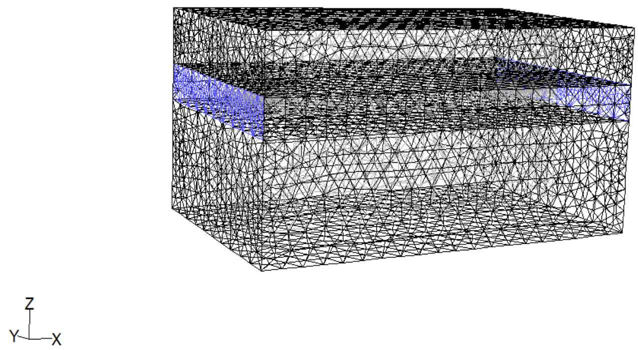

Fig. 1. Meshed view in the FLUENT.

2.2.1. Boundary conditions

According to the requirement, a value for flow rate of injection/withdrawal wells is considered. By considering groundwater velocity, a pressure gradient in the direction of x is added that obtained from the Darcy's equation as below:

$$\mathrm{H_{imp}} = \mathrm{V_{gw}}\frac{\mathrm{X_{Length}}}{\mathrm{K}} \quad (13)$$

The head in x=0 and $x = \mathrm{X_{Length}}$ were as follows:

$$\mathrm{h_{x=0}} = \mathrm{H_{imp}} \quad , \quad \mathrm{h_{x=X_{Length}}} = 0 \quad (14)$$

The initial head is equal to the model elevation. Boundary condition on the lateral and the lower and upper sides is no flow.

3. Results and discussion

The objective of this research is the investigation of different parameters on pressure distribution inside of the aquifer that will be used for the ATES. As mentioned above, in the ATES the water is withdrawn from one or more wells and after performing heat transfer is justified into the aquifer with the same rate through other well or wells. The physical properties of the aquifer and the specifications of the injection and withdraw wells are listed in Table 1. The length, width and height of the aquifer are 100m, 50m and 6m in x, y and z directions, respectively.

In the following discussions, although the pressure distribution is calculated in 3-dimension, because of symmetry of domain, the distribution is brought only in the xy plane and z=3m.

3.1. The effect of groundwater natural flow on the pressure distribution inside the aquifer

The pressure distribution inside the aquifer is shown in Fig.2 (a, b and c) when the natural flow is 30, 50 and 100 m/year, respectively. Since the natural flow is considered in x-direction, it is influenced by the pressure distribution in the boundaries and perpendicular faces on x-direction. By increasing the natural flow, the pressure in boundaries is increased. Consequently, the pressure distribution in whole of the aquifer is also increasing.

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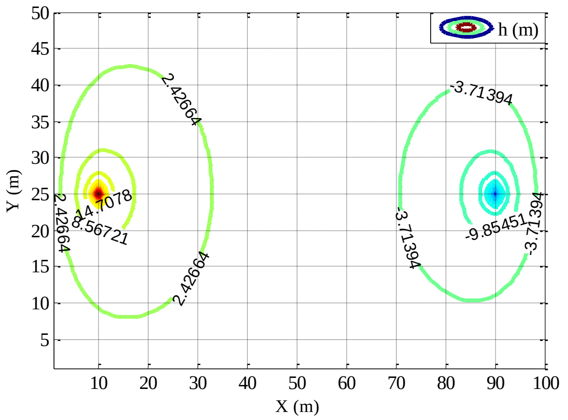
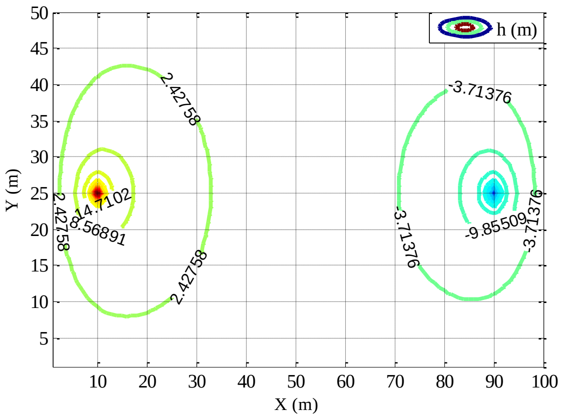
Table 1. Aquifer and well specifications in the base case.

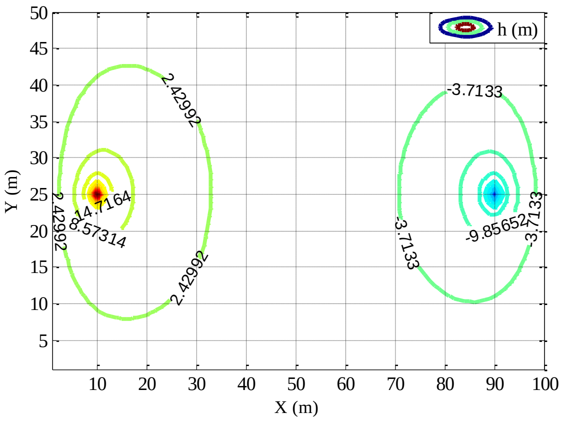
Property	Value
Permeability	$0.0017\ \times 10^{-3}\ \frac{m}{s}$
Porosity	0.4
Groundwater natural flow	$10\ \frac{m}{s}$
Water density	$1000\ \frac{kg}{m^3}$
Rock density	$1800\ \frac{Kg}{m^3}$
Injection/withdrawal rate	$740\ \frac{kg}{s}$
Number of injection/withdrawal well/wells	1
Dimension of injection pump	x = 10 m y = 25 m z = 3m
Dimension of withdrawal pump	x = 90 m y = 25 m z = 3m



a) Pressure distribution in xy plane and z=3m and k=0.0017 ، $\emptyset = 0.4$ ، $V_{GW} = 30\frac{m}{year}$ ، $Q = 0.74\ \frac{m^3}{s}$



b) Pressure distribution in xy plane and z=3m and k=0.0017 ، $\emptyset = 0.4$ ، $V_{GW} = 50\frac{m}{year}$ ، $Q = 0.74\ \frac{m^3}{s}$



c) Pressure distribution in xy plane and z=3m and k=0.0017 ، $\emptyset = 0.4$ ، $V_{GW} = 100\frac{m}{year}$ ، $Q = 0.74\ \frac{m^3}{s}$

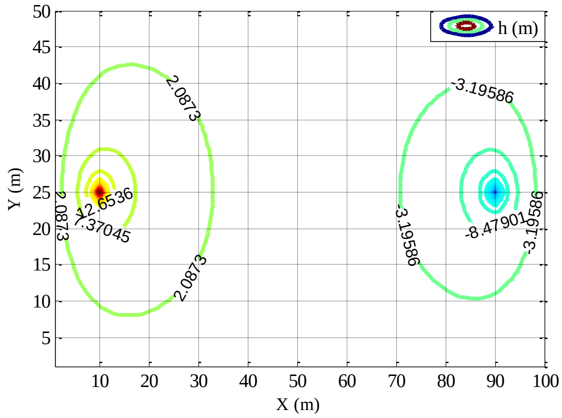
Fig. 2. Variation of pressure distribution with groundwater natural flow.

3.2. The effect of porosity on the pressure distribution inside the aquifer

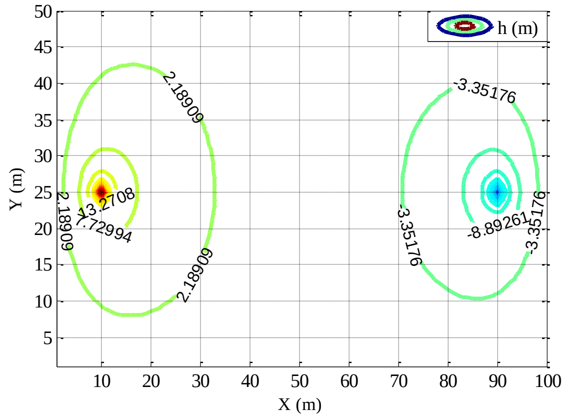
Fig.3 shows the pressure distribution inside the aquifer with respect to porosity variation. As it is seen, by decreasing the porosity, the pressure distribution decreases. This happens since the increment in porosity tends to decrease aquifer density as stated in Eq. 2 and then the pressure is increasing.

3.3. The effect of permeability on the pressure distribution inside the aquifer

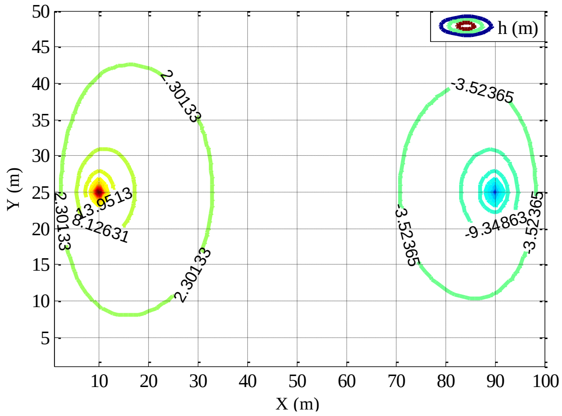
Hydraulic conductivity (permeability) is the ability of porous media for water transition. It should be noted that the hydraulic conductivity implies hydraulic resistance of the aquifer. Fig.4 (a, b and c) shows the variation of pressure distribution with respect to permeability. As permeability increases, the pressure distribution in whole of the aquifer is decreasing. It happens as suit of decrement of water penetration. This phenomenon is also justified mathematically by surveying Eq. 6, the pressure distribution varies with K inversely.



a) Pressure distribution in xy plane and z=3m and k=0.0017, $V_{GW} = 10 \frac{m}{year}$, $Q = 0.74 \frac{m^3}{s}$, $\emptyset = 0.1$

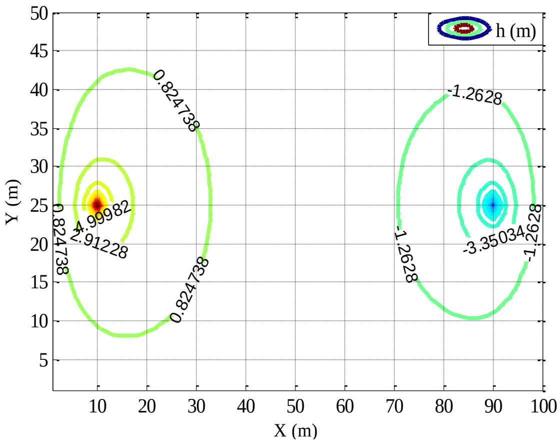


b) Pressure distribution in xy plane and z=3m and k=0.0017, $V_{GW} = 10 \frac{m}{year}$, $Q = 0.74 \frac{m^3}{s}$, $\emptyset = 0.2$

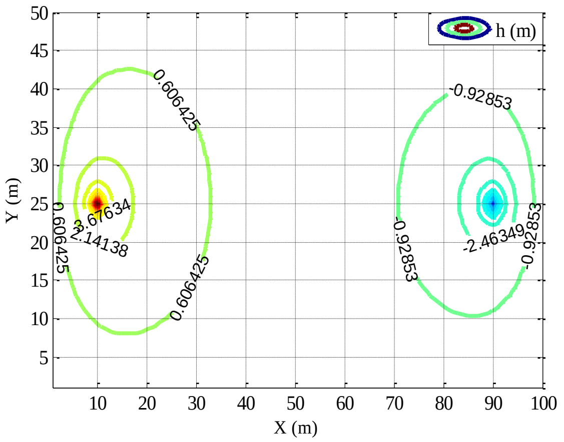


c) Pressure distribution in xy plane and z=3m and k=0.0017, $V_{GW} = 10 \frac{m}{year}$, $Q = 0.74 \frac{m^3}{s}$, $\emptyset = 0.3$

Fig. 3. Variation of pressure distribution with porosity.



a) Pressure distribution in xy plane and z=3m and $V_{GW} = 10 \frac{m}{year}$, $Q = 0.74 \frac{m^3}{s}$, $\emptyset = 0.1$, k=0.0051



b) Pressure distribution in xy plane and z=3m and $V_{GW} = 10 \frac{m}{year}$, $Q = 0.74 \frac{m^3}{s}$, $\emptyset = 0.1$, k=0.0068

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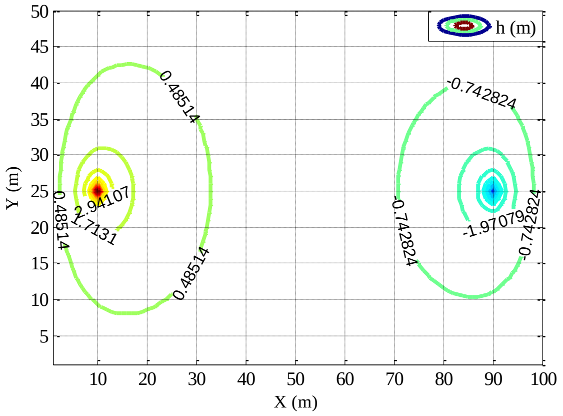
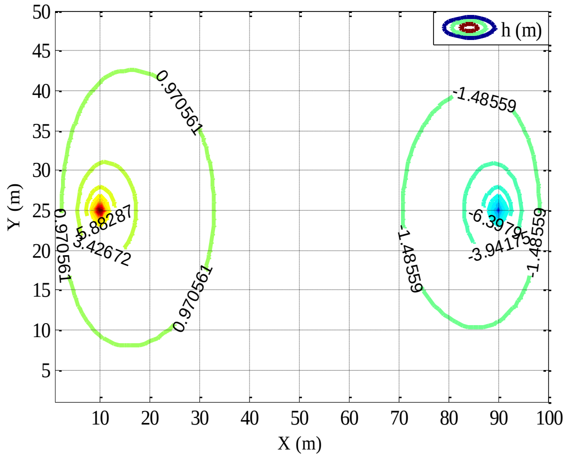


c) Pressure distribution in xy plane and z=3m and $V_{GW} = 10\,\frac{m}{year}$ ،$Q = 0.74\ \frac{m^3}{s}$،$\emptyset = 0.1$،k=0.0085

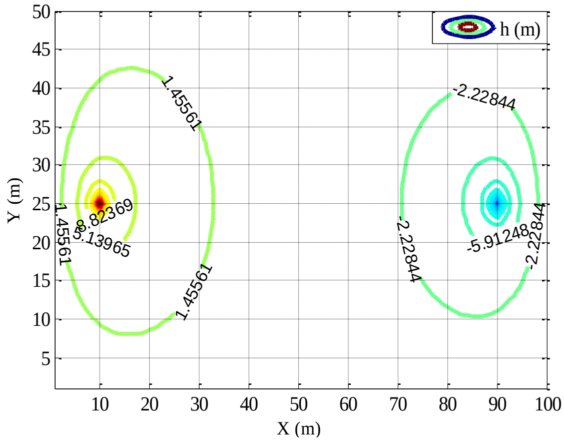
Fig. 4. Variation of pressure distribution with permeability.

3.4. The effect of injection/withdrawal rate on the pressure distribution inside the aquifer

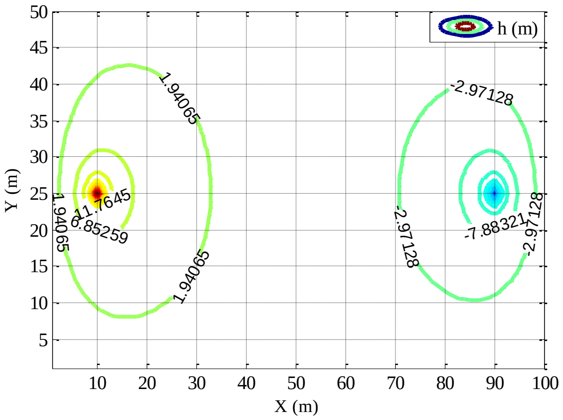
Fig. 5 (a, b and c) shows the effects of increment of injection/withdrawal rates on the pressure distribution. The injection/withdrawal rate is the source term in the pressure distribution equation. As shown in Eq.6, by increasing the flow rate, the pressure distribution is also increasing. When flow rate increases, the pressure in injection/withdrawal pump locations increases and then this effect is diffused all over the aquifer. It should be noted that in this research, the injection rate is the same as the withdrawal rate.



a) Pressure distribution in xy plane and z=3m and k=0.0017 ، $\emptyset = 0.4$ ،$V_{GW} = 10\,\frac{m}{year}$، $Q = 0.296\ \frac{m^3}{s}$



b) Pressure distribution in xy plane and z=3m and k=0.0017 ، $\emptyset = 0.4$ ،$V_{GW} = 10\,\frac{m}{year}$، $Q = 0.444\ \frac{m^3}{s}$



c) Pressure distribution in xy plane and z=3m and k=0.0017 ،$\emptyset = 0.4$ ،$V_{GW} = 10\,\frac{m}{year}$، $Q = 0.592\ \frac{m^3}{s}$

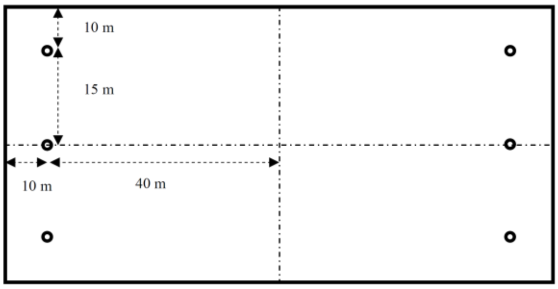
Fig. 5. Variation of pressure distribution with injection/withdrawal flow rate.

3.5. The effect of number and arrangement of wells on the pressure distribution inside the aquifer

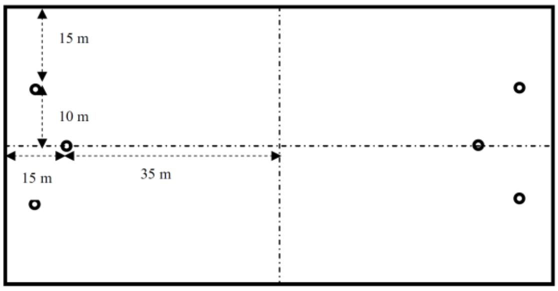
In the previous sections one injection/withdrawal well is used. The concession of this research in investigation of number and arrangement of wells (linear, triangular and rectangular) on the pressure distribution inside the aquifer is illustrated as follows:

3.5.1. Three wells array

Fig. 6 indicates the dimensions and arrangements of three wells for injection and three wells for withdrawal). The arrangements can be linear or triangular as shown in Figs. 6a and 6b, respectively.



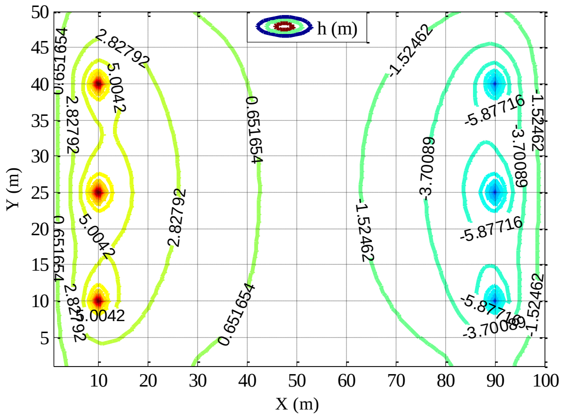
a) Linear arrangement



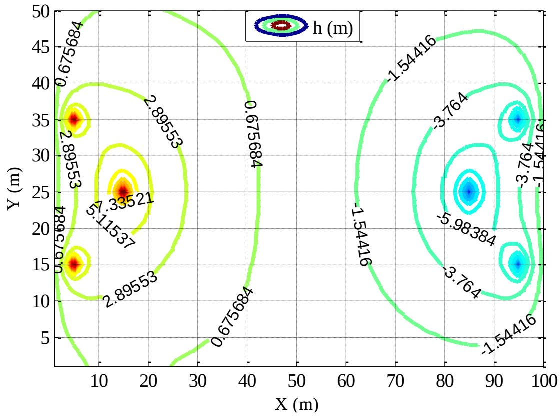
b) Triangular arrangement

Fig. 6. Three wells application

The pressure distribution in the aquifer is shown in Fig.7(a and b) in three wells application. As it is seen, the pressure value in triangular array is more than linear. It happens because triangular arrangement of pumps tends to increase the pressure distribution.



a) Pressure distribution in xy plane and z=3m and k=0.0017 ، $\emptyset = 0.4$ ، $V_{GW} = 10\,\frac{m}{year}$ ، $Q_{total} = 0.74\,\frac{m^3}{s}$ and linear arrangement



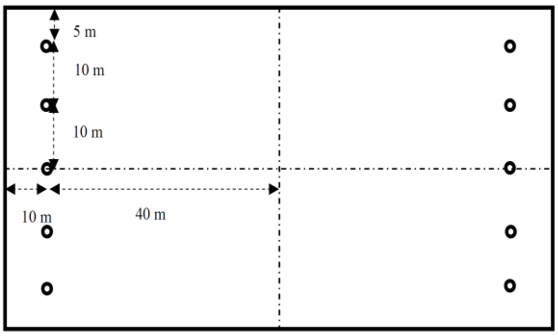
b) Pressure distribution in xy plane and z=3m and k=0.0017 ، $\emptyset = 0.4$ ، $V_{GW} = 10\,\frac{m}{year}$ ، $Q_{total} = 0.74\,\frac{m^3}{s}$ and triangular arrangement

Fig. 7. Pressure distribution in three wells application.

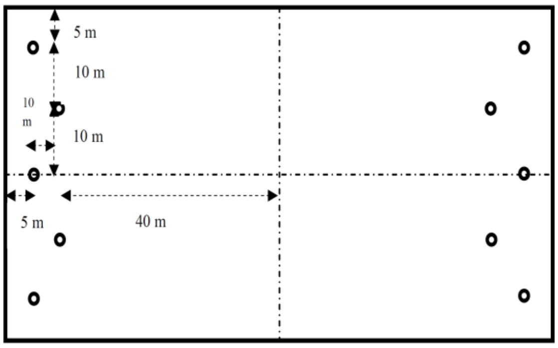
3.5.2. Five wells array

Fig.8 shows the arrangement of five wells application. In this case the array can be linear, triangular and rectangular as shown in Fig.

Fig.9 shows pressure distribution in five wells application. As it is seen, the pressure quantity in triangular arrangement is higher.



a) Linear arrangement



b) Triangular arrangement

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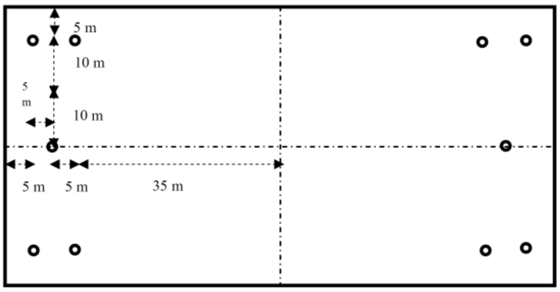
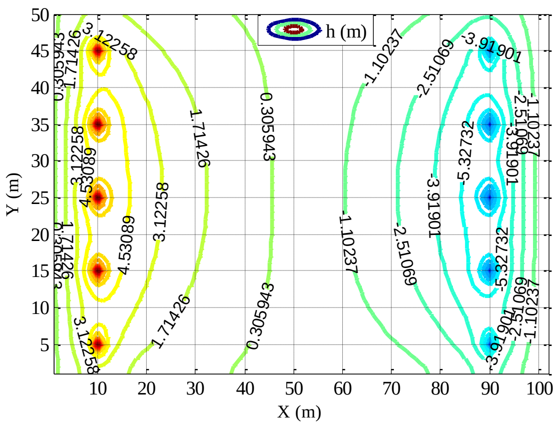
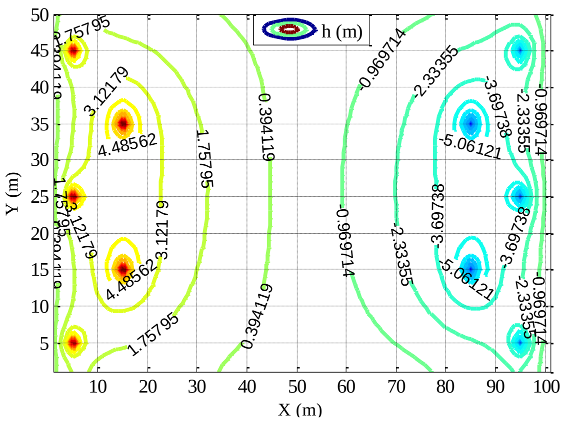


c) Rectangular arrangement

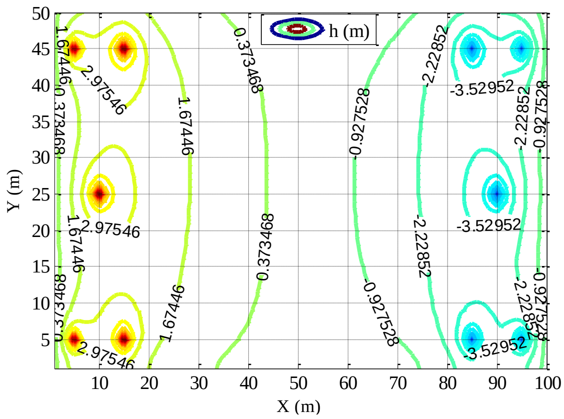
Fig. 8. Five wells application.



a) Pressure distribution in xy plane and z=3m and k=0.0017 ، $\emptyset = 0.4$ ،$V_{GW} = 10\frac{m}{year}$، $Q_{total} = 0.74\ \frac{m^3}{s}$ and linear arrangement



b) Pressure distribution in xy plane and z=3m and k=0.0017 ،$\emptyset = 0.4$ ،$V_{GW} = 10\frac{m}{year}$، $Q_{total} = 0.74\ \frac{m^3}{s}$ and triangular arrangement



b) Pressure distribution in xy plane and z=3m and k=0.0017 ،$\emptyset = 0.4$ ،$V_{GW} = 10\frac{m}{year}$، $Q_{total} = 0.74\ \frac{m^3}{s}$ and rectangular arrangement

Fig. 9. Pressure distribution in five wells application.

4. Conclusions

In this study sensitivity analysis of the fluid flow in an aquifer respect to some operational and physical parameters was carried out. The aquifer was employed for seasonal thermal energy storage. In the considered system, the flow is withdrawn and after heat transfer reinjected to aquifer through an injection well. The main conclusions of this research are as follows:

- By increasing the natural flow, the distribution in whole of the aquifer is increasing.
-Increment of the porosity tends to increase the aquifer pressure.
-The pressure distribution varies with permeability inversely.
-When the flow rate increases, the pressure increases all over the aquifer.
-The pressure distribution in triangular arrangement of wells is more than other arrangements.

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