Structural optimization of underground pipe network for geothermal heat extraction

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ABSTRACT

Geothermal resources can be classified into shallow and hydrothermal geothermal resources according to the formation temperatures of reservoirs. Hydrothermal geothermal resources can be explored for space heating and power generation, which have been attracted more researching attentions than the shallow geothermal due to their higher coefficient of performance and stability. The traditional ways of heat extraction from hydrothermal geothermal reservoirs include briefly: drilling production and injection wells in a confined aquifer or an artificial fractured reservoir in hot dry rocks. In recent years, there exists a few researches on heat extraction using a closed pipe loop without pumping geofluids out of surface, such as the U-shaped deep borehole heat exchanger. However, that whether the route design of pipe underground is optimal remains to be answered. This paper proposes an underground pipe network optimal method to improve the heat extraction efficiency through increasing the heat transfer between the circulating working fluid in the loop and reservoir. To this end, a structural topology optimization issue associated with the heat transfer in porous media has to be taken into account. A simplified flow and heat transfer model is adopted to transform the three-dimensional wellbore into one-dimensional pipeline, which can reduce the computational cost. Then, the ground structure method is used to optimize the underground pipe network with multi objectives of minimizing the flow resistance and maximizing the heat transfer efficiency under the constraint of total pipe volume. Adjoint method and method of moving asymptotes are used to solve this topology optimization problem. Influences of different parameters, such as total pipe volume, flow velocity and temperature, on the optimal structure are analyzed to provide reference for the design of underground pipe network. The obtained results are helpful in finding a new method for geothermal exploration and improving the heat extraction efficiency.

1. INTRODUCTION

In order to solve the increasingly prominent environmental issues caused by the overutilization of fossil energy, most countries have announced relevant energy policies to reduce the carbon emissions. The development of clean and sustainable energy sources such as solar energy, wind energy and geothermal energy to replace the conventional fossil fuels is an attractive way to achieve the carbon neutral. Geothermal energy has large development potential in the fields of heating, cooling and power generation as one of the most widespread renewable energies. Its superiority compared with solar and wind energies is not affected by climate, which could supply stable energy.

Geothermal energy can be divided into shallow geothermal resources, hydrothermal geothermal resources and hot dry rock geothermal resources. China ranks first in the world in geothermal utilization, and shallow geothermal energy is still the mainstay of geothermal heating and cooling in China at present. Although shallow geothermal energy has matured technology and wide applicability, it has a large footprint and suffers from the problem of unbalanced cooling and heating loads, which limits its application in urban areas with high building density and cold areas with low shallow ground temperature. Compared with shallow geothermal heat, hydrothermal geothermal heat has advantages of higher temperature and energy density, good stability and less impact on the environment. There is great potential for development and utilization of hydrothermal geothermal heat.

Traditional heat extraction methods for hydrothermal geothermal resources include single well pumping and re-injection, U-shaped wells and multi-branch wells, double wells or multiple wells pumping and re-injection. double wells or multiple wells pumping and re-injection model, geothermal water in the heat reservoir is drawn from production wells, and then injected into the injection wells after passing the user side. Although this method could maximize the extraction of geothermal energy, it may lead to the loss and pollution of geothermal water. The continuous change in formation temperature and flow path blockage would result in physical and chemical reactions. The scale generated could lead to the increase of injection pressure and the reduction of fluid flow efficiency.

In view of the shortcomings of the traditional heat extraction methods for hydrothermal geothermal resource, it is necessary to develop new efficient way to explore the geothermal energy. With the continuous development of drilling technology and drilling robots, complex well structure gradually becomes possible. Therefore, this paper proposes an underground pipe network structure for the exploitation of hydrothermal geothermal resource. It could avoid the reinjection problem of heat extraction method of production and injection, and increase the heat exchange area compared with the single well heat extraction method. However, the pipe arrangements and pipe diameter distribution have significant effects on the feasibility, economy and heat extraction efficiency of this system. How to reasonable arrange the pipe network structure is extremely important. In this paper, we use the topology optimization method to optimize the underground pipe network structure. The optimization objective is to maximize the outlet temperature and minimize the pressure drop of the system, taking the total volume of the underground pipe network as the constraint. So as to obtain the best pipe diameter distribution and improve the heat extraction efficiency of the system.

2. METHODOLOGY

2.1 System of underground pipe network

The system of underground pipe network shown in Figure 1, is proposed to extract geothermal energy from the heat reservoir. The system is composed of two wellbores (injection well and production well) and the pipe network between them.

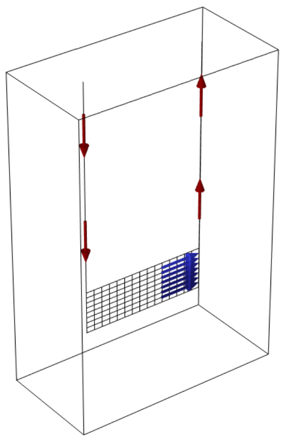


Figure 1: Schematic diagram of system of underground pipe network

To extract geothermal energy, the cold water as working fluid continuously flows into the injection well, then flows through the pipe network to extract heat from the surrounding rock, and finally the hot working fluid flows out from the production well. The heat transfer between working fluid surrounding reservoir is also occurred in injection and production wells.

In actual engineering, insulation segments were provided on the outer wall of the wellbore. In the system of underground pipe network, the insulating segment were modeled with 1600 m in depth, we assume that there is very little heat dissipation of wellbore. Besides, considering computation cost and grid quantity, our pipe network at the depth of 1620 m is used in the model, as shown in Figure 2. Specific parameters of reservoir and sizes are show in Table 1.

Table 1 computational domain parameters of system of underground pipe network

Parameter	value
Pipe network depth, m	1620
Reservoir depth, m	1800
Range of reservoir, m	1600-1800
Total Length of horizontal pipe, m	400
Length of each horizontal pipe, m	40
Length of each vertical section, m	20
Total Length of vertical pipe, m	80
Permeability, cm^2	10^{-7}
Porosity	0.3

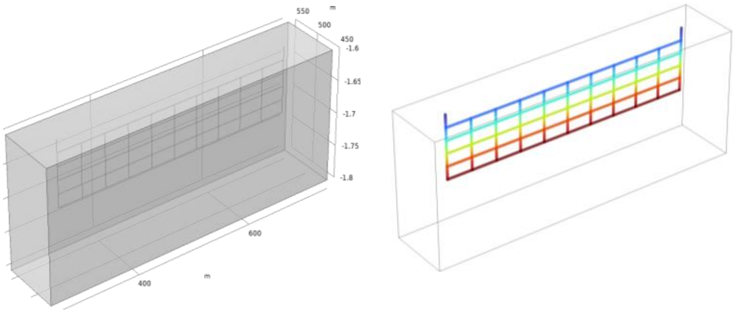


Figure 2: Simplified structure of system of underground pipe network.

2.2 Modeling methods

2.2.1 Modeling assumption

A 3D model considering the complex convection process in the hydrothermal reservoir is established. In addition, the convective heat transfer in wellbores and pipe network is simplified to one dimension with a non-isothermal pipe flow model. In order to facilitate the solution, the following assumptions need to be made for the heat exchange process:

(1) There is no phase transition for liquid water, and its thermos-physical parameters change with temperature.

(2) The local thermal equilibrium is adopted to describe the heat transfer behaviors in the heat reservoir, which means that there is no temperature difference between the rock and geothermal fluid.

(3) The thermos-physical parameters of hydrothermal reservoir are constant. Reservoir temperature only changes with formation depth

2.2.2 Governing equations

The system of underground pipe network includes two parts: the flow and heat transfer of working fluid in pipeline and the flow and heat transfer of geothermal water in hydrothermal reservoir. Governing equations for the working fluid in pipeline are as follows:

The mass conservation and momentum equations can be given by:

$$\frac{\partial\left(A_{\mathrm{c}}\rho_{\mathrm{f}}\right)}{\partial t}+\nabla\cdot\left(A_{\mathrm{c}}\rho_{\mathrm{f}}u_{\mathrm{f}}\right)=0 \tag{1}$$

$$\rho_{\mathrm{f}}\frac{\partial\left(u_{\mathrm{f}}\right)}{\partial t}=-\nabla p_{\mathrm{w}}-\frac{1}{2}f_{\mathrm{D}}\frac{\rho_{\mathrm{f}}}{d_{\mathrm{p}}}\left|u_{\mathrm{f}}\right|u_{\mathrm{f}}+F \tag{2}$$

where ρ_{f} is the density of the working fluid. A_{c} is the cross-section area of wellbore or pipe. u_{f} is the cross-section average velocity. p_{w} is the fluid pressure of the cross-section of the wellbore. d_{p} is the mean hydraulic diameter of the wellbore or pipe. The section and third terms on the right-hand side in Eq. (2) are the pressure drop due to the viscous shear and the fluid gravity, respectively. f_{D} is the Darcy friction factor, which is determined by the Churchill model. The heat transfer equation is written as:

$$\rho_{\mathrm{f}}A_{\mathrm{c}}C_{\mathrm{f}}\frac{\partial T}{\partial t}+\rho_{\mathrm{f}}A_{\mathrm{c}}C_{\mathrm{f}}u_{\mathrm{f}}\cdot\nabla T=\nabla\cdot\left(A_{\mathrm{c}}k\nabla T\right)+\frac{1}{2}f_{\mathrm{D}}\frac{\rho_{\mathrm{f}}A_{\mathrm{c}}}{d_{\mathrm{p}}}\left|u_{\mathrm{f}}\right|u_{\mathrm{f}}^{2}+Q_{\mathrm{wall}} \tag{3}$$

where T is the working fluid temperature. C_{f} is the fluid thermal capacity. Q_{wall} denotes heat transfer rate through the per-unit length of the pipe wall. k is the thermal conductivity of working fluid.

$$Q_{\mathrm{wall}}=\left(hZ\right)_{\mathrm{eff}}\cdot\left(T_{2}-T\right) \tag{4}$$

$$\left(hZ\right)_{\mathrm{eff}}=\frac{2\pi}{\dfrac{1}{r_{0}h_{\mathrm{int}}}+\dfrac{1}{r_{\mathrm{N}}h_{\mathrm{ext}}}+\Sigma\dfrac{\ln\dfrac{r_{\mathrm{n}}}{r_{\mathrm{n}}-1}}{k_{\mathrm{n}}}} \tag{5}$$

where $(hz)_{\mathrm{eff}}$ is an effective value of the heat transfer coefficient times the wellbores perimeter Z (m). T_2 is reservoir temperature. r_0 is the inner radius of the pipe. r_{n} is the outer radius of the nth wall. h_{int} and h_{ext} are the film heat transfer coefficients on the inside and outside of the wellbore, respectively. And k_{n} is the thermal conductivity of the nth wall.

Hydrothermal reservoir can be considered as a uniform porous media area with isotropic porosity and permeability. The natural convection of aquifer is simultaneously considered in 3D model.

The mass conservation and momentum equations in the reservoir can be described as below:

$$\frac{\partial \varepsilon_{\mathrm{p}} \rho}{\partial t}+\nabla \cdot(\rho u)=Q_{\mathrm{m}} \tag{6}$$

$$\frac{1}{\varepsilon_{\mathrm{p}}} \rho \frac{\partial u}{\partial t}=\nabla \cdot[pI+K]-\left(\mu K^{-1}+\beta p|u|+\frac{Q_{\mathrm{m}}}{\varepsilon_{\mathrm{p}}{}^{2}}\right) u+F \tag{7}$$

$$K=\mu \frac{1}{\varepsilon_{\mathrm{p}}} \nabla\left(\nabla u+(\nabla u)^{\mathrm{T}}\right)-\frac{2}{3} \mu \frac{1}{\varepsilon_{\mathrm{p}}}(\nabla \cdot u) I \tag{8}$$

where ρ is the density of the porous medium. u is the Darcy velocity field, which is related to seepage velocity in the hydrothermal reservoir. p is the fluid pore pressure. ε_{p} is porosity. K is the stress tensor. F is the volume force.

The energy equation is written as:

$$\left(\rho C_{\mathrm{p}}\right)_{\mathrm{eff}} \frac{\partial T_{2}}{\partial t}+\rho_{\mathrm{cf}} C_{\mathrm{cf}} u \cdot \nabla T_{2}+\nabla \cdot q=Q_{\mathrm{vd}} \tag{9}$$

where C_{cf} is the fluid heat capacity at constant pressure. ρ_{cf} is the fluid density. Q_{vd} represents a heat source (or sink). q is the conductive heat flux. $(\rho C_{\mathrm{p}})_{\mathrm{eff}}$ is an effective volumetric heat capacity at constant pressure.

$$q=-k_{\mathrm{eff}} \nabla T_{2} \tag{10}$$

$$\left(\rho C_{\mathrm{p}}\right)_{\mathrm{eff}}=\varepsilon_{\mathrm{p}} \rho_{\mathrm{cf}} C_{\mathrm{cf}}+\theta_{\mathrm{s}} \rho_{\mathrm{cs}} C_{\mathrm{cs}} \tag{11}$$

$$k_{\mathrm{eff}}=\varepsilon_{\mathrm{p}} k_{\mathrm{f}}+\theta_{\mathrm{s}} k_{\mathrm{s}} \tag{12}$$

where k_{eff} is the effective thermal conductivity. k_{f} and k_{s} are the thermal conductivity of fluid and solid in porous medium, respectively. ρ_{cs} is the solid matrix density. C_{cs} is the solid matrix heat capacity at constant pressure, Θ_{s} is the solid matrix volume fraction.

2.2.3 Boundary conditions

Table 2 Initial and boundary conditions of the system of the underground pipe network

Parameter	value
Injection rate (inlet), kg/s	10.0
Injection temperature (inlet), K	293.15
Outlet pressure, Pa	101325
Initial temperature of reservoir, K	0.03[K/m]·depth+293.15
Initial temperature of the working fluid, K	0.03[K/m]·depth+293.15
Temperatures of left and right boundaries, K	0.03[K/m]·depth+293.15
Top and the bottom of the reservoir	Adiabatic boundary

In this study, the initial conditions of the pipe network refer to the initial temperature of working fluid and reservoir. The boundary conditions include inlet and outlet conditions of the working fluid in pipe flow model. Moreover, the boundary conditions include boundary conditions of reservoir. All the initial and boundary conditions are summarized in Table 2. The initial temperature of the working fluid in wellbore and pipe network are set equal to that of reservoir.

2.3 Optimization problem formulation

In this study, the pipe network diameter is considered as a design variable to maximize the heat transfer efficiency and minimize drop pressure under the constraint of total pipe volume. The mathematical description of optimization problem is given by:

$$\begin{aligned} &\min \quad -a\frac{\Delta T}{\Delta T_0}+(1\text{-}a)\frac{\Delta p}{\Delta p_0} \\ &s.t. \quad \begin{array}{l} 0.01\text{m}<r<0.05\text{m} \\ V=\text{contant} \end{array} \end{aligned} \tag{13}$$

where a is the weight coefficient between 0 and 1. $\triangle T$ is temperature difference between inlet and outlet. $\triangle T_0$ (K) is initial temperature difference between inlet and outlet. $\triangle p$ is pressure difference between inlet and outlet. $\triangle p_0$ is initial pressure difference between inlet and outlet. r is underground pipe network radius. V is total volume of underground pipe network.

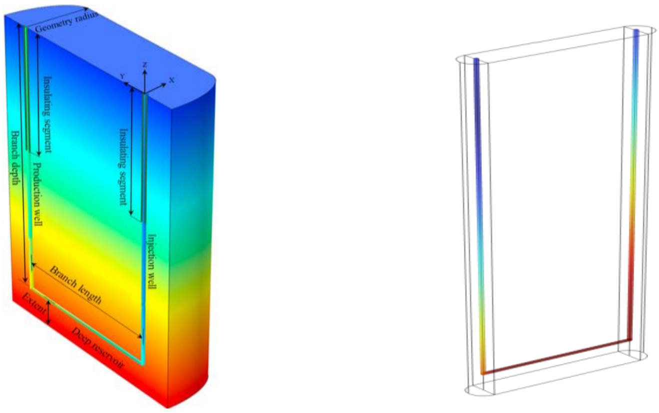
2.4 Numerical procedures

The geometric model in this study is meshed using the COMSOL Multiphysics numerical simulation software. By employing a combination of a three-dimensional network and a one-dimensional line element network, the calculation time can be significantly reduced.

The optimization problems are solved using the Method of Moving Asymptotes (MMA), which is more suitable to deal with topological optimization problems with complex objective functions. Only the differentiation of the constraint function can be obtained analytically or numerically, and the MMA method has better suitability for complex topology optimization problems.

2.5 Model Verification

In our model, the convective heat transfer is simplified to one dimension using a non-isothermal pipe flow model in the wellbore and pipe network. There is a lack of field data for system of underground pipe network to conduct an actual validation of our model. Therefore, a U-shaped well structure is used to verify the simplified model by comparing with a conjugate heat transfer model. The conjugate heat transfer model in 3D is employed to verify the simplified one-dimensional (1D) convective heat transfer model (Figiure.3). The simplified model is considered reliable since the deviation of the production temperature between the two models is less than 1.0 ℃. The computational domain parameter of the model is from Ref. [1].



(a) (b)

Figure 3: Schematic diagram of verification. (a): A conjugate heat transfer. (b): Convective heat transfer in this study

3. DISCUSSION OF RESULTS

3.1 Analysis of optimization result

This study takes the temperature difference and pressure drop between inlet and outlet as the optimization objective, and different weight coefficients are applied to investigate the influence of optimization objective. This section discusses the temperature, velocity and pipe diameter distribution of the pipe network, taking the working condition at weight coefficient of 0.5 as the example. The variation of temperature and fluid velocity of underground pipe network fluid and reservoir are important indexes to evaluate the performance of geothermal system in a steady state.

3.1.1 Temperature and fluid velocity of underground pipe network

The fluid temperature of underground pipe network is shown in Figure 4. Outlet temperature of production well is about 307.77 K after optimization, which increases about 1 K compared with the results at initial steady-state. The optimized structure has little effect on improve the outlet temperature. However, the optimized pipe diameter distribution has great effect on reducing the pressure drop. The reduction of pressure drop is up to 65% compared with that without optimization. It means that consuming less pump power could obtain the same amount of geothermal energy when using the optimized pipe network. Flow velocity of working fluid in the underground pipe network is presented in Figure 5, showing symmetrical distribution. The velocity of working fluid in the middle vertical section is about 0 m/s, which implies that the intermediate pipe segment can be removed from the pipe network in the later result processing to reduce the investment in actual geothermal engineering.

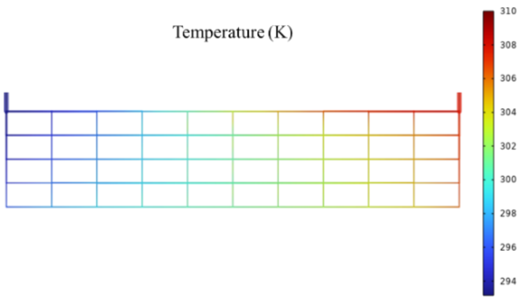


Figure 4: Temperature of underground pipe network.

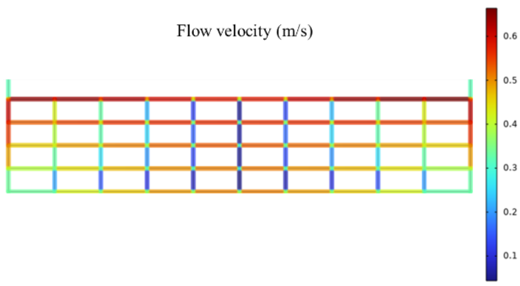


Figure 5: Flow velocity of underground pipe network.

The optimized diameter distribution of underground pipe network is shown as Figure 7. Initial pipe diameter is 0.07 m in this system. The upper limit value of pipe diameter is 0.2 m and the lower limit value is 0.001 m. In addition, the production and injection wells remain the same diameter and are not optimized. It can be seen from Figure 7 that the minimum pipe diameter is about 0.04 m, which does not exceed the setting value. The closer the two wells the larger the diameter of the pipe section. Horizontal pipe diameter decreases with reservoir depth. The diameter of the horizontal pipe section decreases from the middle to both sides. Vertical pipe diameter increases from the middle to both sides. The diameter distribution pipe network is similar to a semicircle shape.

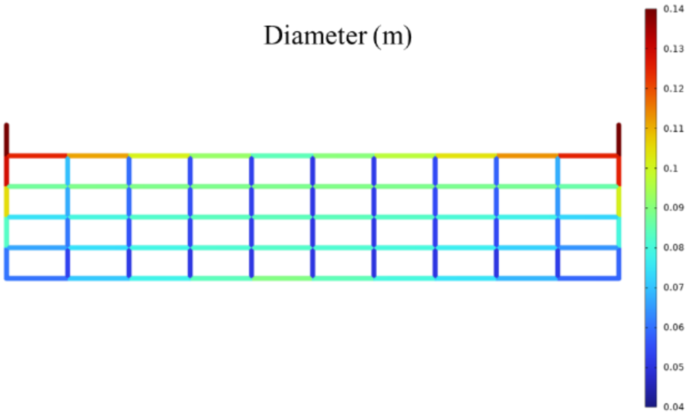
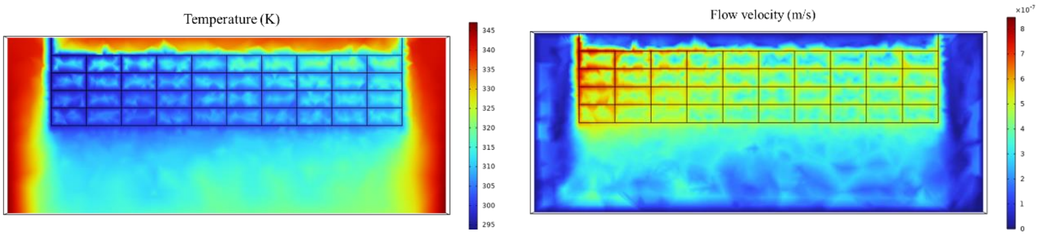


Figure 7: Diameter distribution of underground pipe network

3.1.2 Temperature and fluid velocity of reservoir

The temperature and velocity fileds are shown in Figure 6. The temperature and velocity variations near the injection well is more intensive. Therefore, the natural convection is stronger at the left side. The radius of influence is about 100 m. It has affected the lower boundary at the steady-state.



(a) (b)

Figure 6: Temperature and velocity distributions of reservoir. (a): Temperature filed. (b): Velocity filed.

3.2 Influence of weight coefficient

The optimization results at different weight coefficients are shown in Figure 8 to investigate the effect of weight coefficient on the performance of underground pipe network. It is obviously that weight coefficient has a great influence on the variation of pressure drop. The pressure drop gradually decreases with the increase of weight, and the largest reduction is about 67%. However, there is little effect of weight coefficient on outlet temperature.

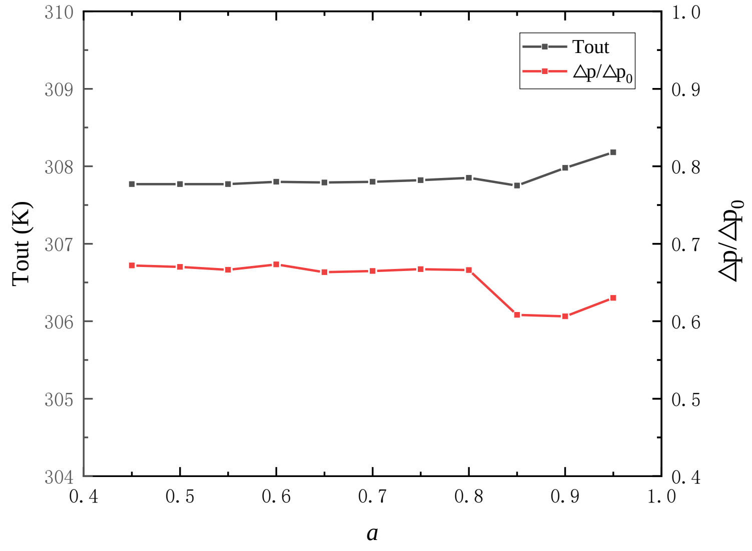


Figure 8: Influence of weight coefficient on the optimization results.

The optimized underground pipe network diameter distribution under weight coefficient of 0.6 and 0.9 are shown in Figure 9. The minimum diameter of pipe network diameter after optimization is more closer to the set value when the weight coefficient is larger.

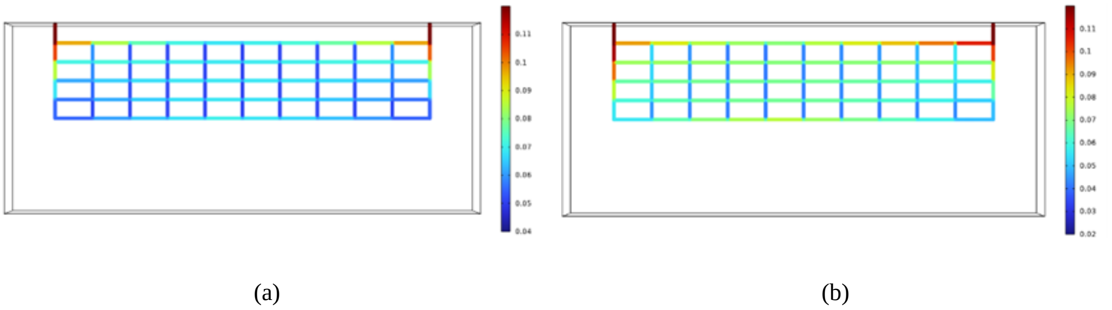
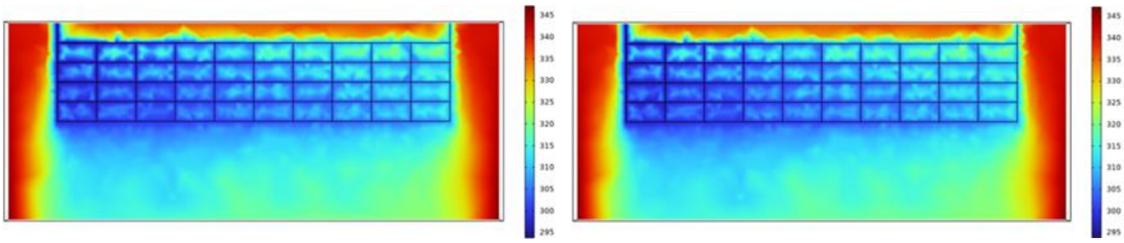


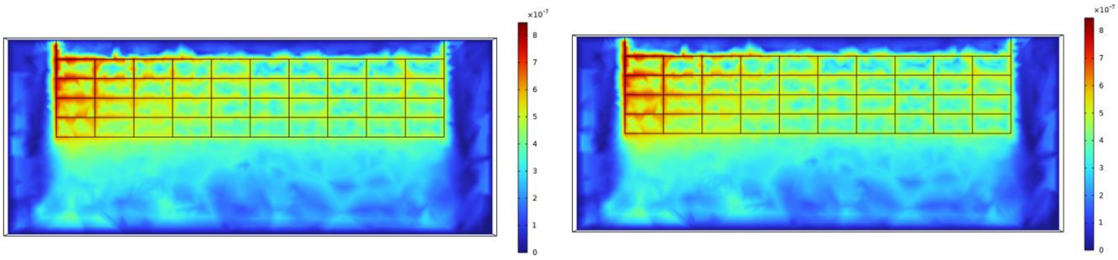
Figure 9: Diameter distributions of underground pipe network at different weight coefficients. (a): a=0.6. (b): a=0.9.

The temperature and velocity distributions of heat reservoir at the *x-z* interface are shown in Figure 10 and 11, respectively. After optimization, the distribution of reservoir temperature and flow velocity is basically consistent at different weight coefficients.



(a) (b)

Figure 10: Temperature distributions of heat reservoir at different weight coefficients. (a): a=0.6. (b): a=0.9.



(a) (b)

Figure 11: Velocity distributions of heat reservoir at different weight coefficients. (a): a=0.6. (b): a=0.9.

4. CONCLUSIONS

Based on the development of drilling technology and the current heat extraction method of geothermal energy, a new heat extraction way using underground pipe network is proposed as an exploration. The underground pipe network is optimized through topology optimization method to achieve best performance in heat extraction and reducing flow resistance. The temperature and pressure drop are optimized as a multi-objective function. The conclusions can be drawn as follows:

The optimized temperature increases by about 1 K and the pressure drop decreases by about 67% when the weight coefficient is 0.5, proving that the optimized system can significantly reduce the pumping power consumption. Besides, from the optimized flow rate distribution and pipe diameter distribution of the pipe network, the working fluid velocity of vertical pipe section is close to 0 m/s. The pipe diameter is small in these pipe section and there is almost no convection heat transfer with the heat reservoir.

The influence of weight coefficients on the pressure drop is significantly greater than that on the temperature. The pressure drop decreases with the increase of the weight coefficient. From the variations of temperature and pressure drop with the weight coefficient, there is an optimal weight coefficient to maximize the outlet temperature and minimize the pressure drop.

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