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Development Model and Analysis of Single Well Circulating Shallow Geothermal Energy Based on Mathematical Modeling

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Abstract. Shallow geothermal energy has been used as an important energy because of its wide distribution, large reserves, rapid regeneration and high utilization value. As a new exploitation method of shallow geothermal energy, single well circulation has been widely concerned. In this paper, the mathematical model of single well circulation mining mode is analyzed from the point of view of mathematical modeling, and the practical problems encountered in the process of single well circulation mining are considered by using concepts of conceptual model, mathematical equation and numerical calculation method, and hydrogeology and hydrodynamic process are considered by assigning specific constants and variables. The influence of heat and mass transfer on geothermal energy exploitation. Based on the above model, the problems encountered in shallow geothermal exploitation are analyzed and discussed in depth, and the corresponding conclusions are drawn. To solve the current problems encountered in shallow geothermal energy exploitation, and provide a theoretical basis for the future development and utilization of new energy.

1. Introduction

Shallow geothermal energy is a new type of renewable energy sourced from the heat and solar radiation inside the Earth. Shallow geothermal energy is widely found in many media such as rocks, soils, and water sources, and is located in a constant temperature zone within 200m of the surface. Its mining is an energy and environmental protection technology that has gradually developed with the global energy crisis and environmental problems. Its research is particularly important for China, which relies heavily on the rapid development of petrochemical energy economy.

Many scholars and organizations at home and abroad have made unremitting efforts in the research of shallow geothermal energy and achieved fruitful results [1-3]. At present, the main utilization methods of shallow geothermal energy are water source heat pump with surface water source as heat source and soil source heat pump with surface rock and soil medium as heat source. The research object of this paper is the single well circulation heat transfer ground energy collection well [4], which is an original new shallow geothermal energy development technology suitable for various geological conditions. This single well circulation shallow geothermal energy development method combines the advantages of the above two traditional geothermal energy collection methods, and realizes the complete recharge of circulating water in the same aquifer, thereby successfully realizing the single geothermal circulation shallow geothermal energy. The equipment has low production cost, no water pollution, convenient maintenance, and is easy to promote in areas with shallow groundwater, realizing real green energy utilization. Because China's shallow geothermal energy is widely distributed and rich in resources, it is of great significance to carry out this research and vigorously develop this single well circulation shallow geothermal energy to ensure energy security and reduce environmental pollution. In this paper, the complete conceptual model and mathematical model of the single well circulation heat transfer energy collection well are established, which is of great significance for the in-depth understanding of its mathematical principles, hydrogeology and physical processes, and the efficient development and utilization of this single well circulation shallow geothermal energy.

2. Physical Concept Model and Porous Media Characteristics of Collection Wells in Single Well Circulating Heat Exchange Wells

2.1. Physical Concept Model

The single well circulation heat transfer energy collection well uses circulating water as a medium to collect thermal energy with a subsurface temperature lower than 25 °C to achieve complete recharge of the same layer of groundwater. This type of well does not consume or contaminate groundwater and is therefore safe for groundwater quality.

This type of ground energy collection well is divided into two types: energy storage particle type and non-storage particle type.

The physical process of collecting wells using single well circulation heat transfer and energy storage particles is that the circulating water is pumped out through the submersible pump in the pumping area of the insulated well wall and sent to the heat pump unit after the heat release. Or endothermic. Return to the ground to collect the inside of the pressurized backwater area above the well. Water flows in the annular space between the insulating wall and the separator, with energy storage particles, most of which enter the lower pumping zone, and a small portion of the wall of the through hole is separated from the pressurized return water zone by the permeate flow. Enter the soil medium. Finally, return from the pump area. All backwaters from the surface collection well is pumped from the heat pump to the heat pump unit via a submersible pump.

Single well cyclic heat transfer without energy storage particles can collect the space between the adiabatic well wall and the isolation membrane in the well, without energy storage particles, filled with medium water, the rest of the structure and mass transfer heat transfer physical process and energy storage particle single well cycle The heat exchanger can collect the same well as shown in Figure 1.

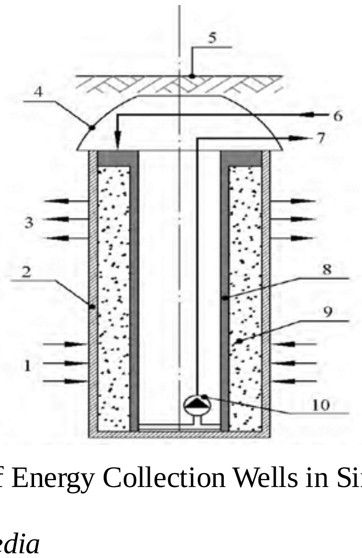

Figure 1. Chematic Diagram of Energy Collection Wells in Single Well Circulation Heat Transfer

2.2. Characteristics of Porous Media

There are two types of porous media that can collect wells in a single well cycle heat exchange. One is to fill the heat storage particles between the insulating wall and the partition, which is characterized by good heat storage properties. The heat storage coefficient of the heat storage particles is large, that is, the ratio of the amplitude of the heat flow fluctuation to the temperature amplitude is large. The other is a saturated soil porous medium outside the separator for exchanging heat and water, ie heat and mass transfer, between the water and the energy storage particles. It can be seen that the single well circulating heat transfer energy collecting well is a hydrothermal coupling body containing convective heat transfer and mass transfer of two porous media, wherein water plays the most important role.

3. Mathematical Model of the Collection Well Of Single Well Circulation Heat Transfer

The mathematical model of the energy storage particle collection well in the single well circulation collection well has only one calculation area of porous medium, and the non-storage particle collection well includes two calculation areas of porous medium and water filling. The selection of the mathematical model is more complicated. The former can be considered by considering the hydrodynamic model of the solid skeleton. In addition, the latter needs to increase the turbulence model to calculate the calculation area only filled with water. When the filled water is laminar. The turbulence model degenerates into a laminar flow model calculation. It can be seen that a typical single well cyclic heat transfer can collect three flow regimes in the well, namely turbulent flow and laminar flow in the aqueous medium and laminar flow in the soil (energy storage particles), see table 1.

Table 1. Two Kinds of Single Well Circulation Heat Transfer Ground Energy Collection Well Mathematical Model List

<table>
<tr><td>Kind
Index</td><td>Single-cycle heat exchange with energy storage particles</td><td colspan="2">Single well circulation heat transfer energy collection well without energy storage particles</td></tr>
<tr><td>Full media type</td><td>Soil (porous medium)
Energy storage particles (porous media)</td><td colspan="2">Soil (porous medium)
water</td></tr>
<tr><td rowspan="2">Computational domain flow</td><td>Laminar flow in soil</td><td rowspan="2">Turbulence when the Re number is greater than the critical value</td><td rowspan="2">Laminar flow when the Re number of water is less than the critical value</td></tr>
<tr><td>Energy storage particles are laminar</td></tr>
<tr><td>Mathematical model governing equation</td><td>Laminar flow equations for soil and energy storage particles (three equations of mass, momentum, and energy conservation)</td><td colspan="2">1. Laminar flow equations for soil (three conservation equations of mass, momentum, and energy)
2. The turbulent flow model k-s equation for water (water degenerates into a laminar flow equation for water at low Re numbers, where there is no soil solid skeleton)</td></tr>
<tr><td>Determining conditions for mathematical models</td><td>Initial condition (no turbulent flow energy)
Boundary conditions (no turbulent flow energy)</td><td colspan="2">Initial conditions (with turbulent flow energy)
Boundary conditions (full flow energy)</td></tr>
</table>

3.1. Mathematical Model of Collecting Wells with Energy Storage Particles

3.1.1. Control Equation

Because of the single-well circulation of the energy storage particles, all parts of the collection well are porous media, and the filled fluid is water. The flow rate of water in the porous medium is very slow and is calculated by the laminar flow of the viscous incompressible layer. The flow of water in a porous medium takes into account the solid skeleton, following the mass conservation equation, the momentum conservation equation, and the energy conservation equation [5].

(1) Mass conservation equation

$$\frac{\partial(\gamma\rho)}{\partial t} + \nabla\cdot(\gamma\rho V_i) = 0 \tag{1}$$

Where γ is the porosity of the porous medium, ρ is the fluid density, t is the time variable, and V_i is the velocity tensor of the fluid, i = 1, 2, 3.

(2) Momentum conservation equation

$$\frac{\partial(\gamma\rho V_i)}{\partial t}+\nabla\cdot(\gamma\rho V_i V_i)=-\gamma\nabla\mathrm{p}+\nabla\cdot(\gamma J_k)+\gamma\rho g+S_m \tag{2}$$

Where p is hydrostatic pressure, $J_k$is the stress tensor, j, k = 1, 2, 3, g is the gravitational acceleration, S_m is the momentum source term of the porous medium, γ, ρ, t, V_i have the same meaning as (1).

(3) Energy conservation equation

$$\frac{\partial(\gamma\rho_f E_f+(1-\gamma)\rho_s E_s)}{\partial t}+\nabla\cdot\left(V_i\left(\rho_f E_f+p\right)\right)=\nabla\cdot\left(k_e\nabla T-\left(\sum_l h_i J_i\right)+\left(J_k V_i\right)+S_f^h\right. \tag{3}$$

Where E_f is the total energy of the fluid in the porous medium, E_s is the total energy of the solid skeleton in the porous medium, h_i is the baking of the fluid and various solid skeletons in the porous medium, and J_i is the fluid and various solid skeleton components in the porous medium. i is the mass flow rate per unit area relative to the mass average velocity, i = 1, 2, ..., S_f^h is the source term of the fluid, p γ, ρ, t, V_i, $J_k$have the same meaning as (1) , k_e is porous The effective thermal conductivity of the medium is weighted according to the thermal conductivity of the fluid in the calculation zone and the thermal conductivity of the solid framework. It is apparent that the above equation degenerates into a laminar flow control equation for an incompressible fluid when the porosity is 100%.

3.1.2. Determining Conditions

There are many types of settlement conditions, which can be listed according to the specific conditions in the actual project. The common settlement conditions are as follows.

(1) Initial conditions

Calculate the flow field in a static state, that is, the initial time velocity V(0) is zero, the initial time pressure P(0) is the external atmospheric pressure P0, and the initial time temperature T(0) is a constant T0, the expression is as follows

$$V\ (0)\ =0 \tag{4}$$

$$P\ (0)\ =P_0 \tag{5}$$

$$T\ (0)\ =T_0 \tag{6}$$

(2) Boundary conditions

1. Calculate the import boundary of the domain

Import flow Qin is the constant Q1, i.e.

$$Q_{in}\ =Q_1 \tag{7}$$

Inlet temperature Tin is constant T1, which is

$$T_{in}\ =\ T1 \tag{8}$$

Import pressure Pin is a constant P1, i.e.

$$P_{in}\ =P_1 \tag{9}$$

2 Calculate the exit boundary of the domain

The outlet flow rate Qout is constant Q2, i.e.

$$Q_{out}\ =Q_2 \tag{10}$$

The outlet temperature Pout is unknown, is not set, and is calculated from known conditions.

The outlet pressure P. Is a constant P, i.e.

$$P_{out}\ =P_2 \tag{11}$$

3.1.3. Calculate Other Boundaries of the Domain

The soil isothermal boundary Γ_1 and the adiabatic outer boundary Γ_2 are expressed as follows.

$$T|_{\Gamma 1}=t_0 \tag{12}$$

$$q|_{\Gamma 2} = 0 \tag{13}$$

The fixed heat flux boundary conditions are as follows

$$q|_{\Gamma 2} = c \tag{14}$$

The flow velocity V on the boundary is zero, ie.

$$\vec{V}\big|_{\Gamma 1 \cup \Gamma 2} = 0 \tag{15}$$

In the formulas (12) to (15), T represents the temperature of the boundary Γ_1, and q represents the heat flux density of the boundaryΓ_2.

3.2. Mathematical Model of Collecting Wells without Energy Storage Particles

3.2.1. Control Equation

The calculation area of the non-storage particle single well circulation energy collection well is divided into two parts: a porous medium calculation area and a non-porous medium calculation area. The two parts use different control equations.

(1) There is a porous medium calculation area.

The flow of porous soil in a single well with no energy storage particles can be laminar. The governing equation is exactly the same as the governing equations (1) to (4) for collecting wells with energy storage particles in a single well.

(2) No porous medium calculation area.

The non-storage granules can collect the inlet water pressurization pipe and the pumping return pipe part of the well without porous media, all filled with water, and adopt the standard K-ε model country of viscous incompressible turbulence.

The general form of the K-ε differential equation is as follows

$$\frac{\partial}{\partial \mathrm{t}}(\rho\varphi) + div(\rho V_i \varphi) = div(\Gamma_\varphi \mathrm{grad}\varphi) + S_\varphi \tag{16}$$

Where t is a time variable, ρ is the fluid density, φ is any dependent variable studied, V_i is the fluid velocity tensor, i=1, 2, 3, Γ_φ is the diffusion coefficient, S_φ Is the source item. The four items in equation (16) are the unsteady term, the convection term, the diffusion term and the source term, respectively. For details, please refer to the relevant literature.

3.2.2. Determining Conditions

The conditions of the enthalpy flow energy k and the enthalpy flow energy dissipation rate ε are added to the initial conditions and the inlets and boundaries, and the other contents are the same as in 3.1.2.

4. Calculation Model and Parameter Setting of the Collection Well of Single Well Circulation Heat Exchange

4.1. The Calculation Conditions of the Calculation Model

The single well cycle energy collection well simulation calculation needs to make the following reasonable assumptions:

(1) The heat transfer process is instantaneously completed between the solid skeleton of the soil and the fluid:

(2) The solid skeleton and fluid of the soil are homogeneous, isotropic or anisotropic continuous media:

(3) The filled fluid medium is an incompressible water body, and the water is set according to turbulent conditions. When the Reynolds number of water reaches laminar flow conditions, the flow pattern degenerates into laminar flow:

(4) The water is laminar at the interface where the unconsumed particle calculation area intersects with the animal energy particle calculation area:

(5) The inertial force is only the downward gravitational acceleration;

(6) In the momentum equation, the porous medium is calculated as a source term of the computational domain to simplify the programming calculation of fluid and heat transfer:

(7) The apparent velocity of the fluid is used in the simulation calculation, not the actual velocity of the fluid in the solid skeleton tunnel, which is convenient for calculation:

(8) In the simulation calculation, the thermal process such as the upper bound solar radiation in the calculation domain and the heat exchange with the atmosphere can be easily calculated which is more conducive to reflecting the physical nature of the problem.

The assumptions of the calculation model need to be adjusted in combination with the specific situation in the actual project, and can be determined after repeated argumentation by scientific assumptions.

4.2. Numerical Calculation Method

The research methods of shallow geothermal energy utilization mainly include field test methods, heat storage estimation methods, analytical methods, numerical simulation methods, and combinations of the above methods. The numerical simulation methods include the finite element method, the finite volume method, the boundary element method, the mixed element method, etc., and the related content can be referred to related materials, and will not be described herein.

In the field of computational fluid dynamics, the finite volume method is widely used, which divides the calculation area into many control volumes, and then integrates the partial differential equations into each control volume to obtain discrete equations. The key problem of the finite volume method is discrete. The process is assumed by the distribution of the function and its derivatives. The coefficients of the obtained discrete equations are clear and conservative. The method is computationally efficient due to the small amount of computation.

In recent years, with the rapid development of numerical heat transfer and computational fluid dynamics, many related professional software have been developed and applied, and CFX, FLUEVT, STAR2CD, and ANSYS software can be used. When the interior of the calculation area is homogeneous and homogenous, the MATLAB software can also be used to solve the above partial differential equations, and the graph corresponding to the calculation result can be drawn.

4.3. Physical Model

The generalized physical model is illustrated by taking a single well circulation heat transfer energy collection well with energy storage particles as an example. A three-dimensional cylindrical radial symmetric region with a diameter of 100m and a depth of 50m is set up. The single well circulation energy collection well is located at the upper part of the geometric center with a depth of 20m, as shown in Figure 2.

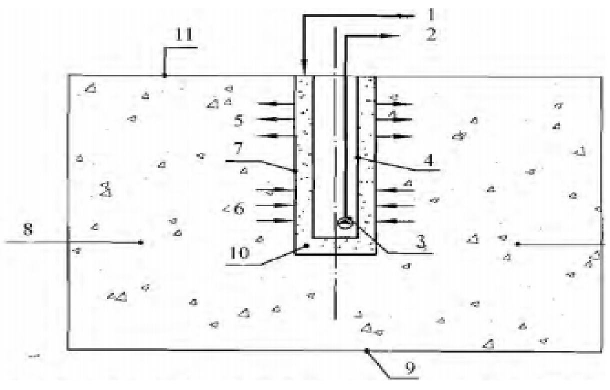

Figure 2. Schematic Diagram of the Energy Collection Well and Study Area of Single Well Circulation Heat Exchange

The inlet flow rate of the ground energy collection well is 50L/s and 80L/s, respectively, and the inlet water temperature is 30K and 290K respectively. The soil temperature and the outer boundary of the soil are calculated according to the constant temperature. The annular cavity between the separator and the insulated inner wall is filled with heat storage particles and water; the outside of the separator is the soil medium, and the water inlet and the submersible pump suction nozzle. The ground can collect the inner wall of the well as an adiabatic boundary condition.

4.4. Geometry Model

Taking the area of Figure 2 as an example to illustrate the establishment of the geometric model, this example uses the appropriate software to establish the space model of the study area, and then uses the meshing software to generate a certain number of rectangular cell grids for each area of the outer boundary. For a face, each intersection is a node of the unit. The area where the well can be collected near the ground is densely divided to meet the accuracy requirements of the calculation results. See Figure 3 and Figure 4 for details. When the calculation area is three-dimensional, its geometric model is usually divided into three-dimensional grids.

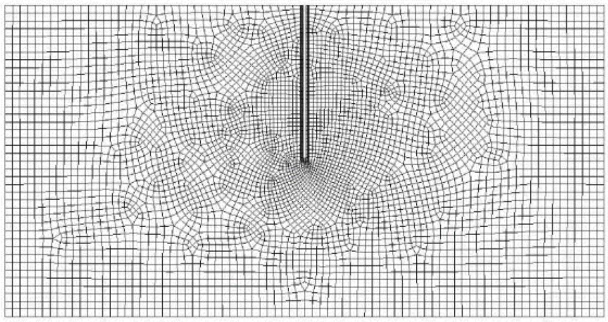

Figure 3. Mesh Section of the Study Area of Single Well Circulation Heat Transfer Ground Energy Collection Well

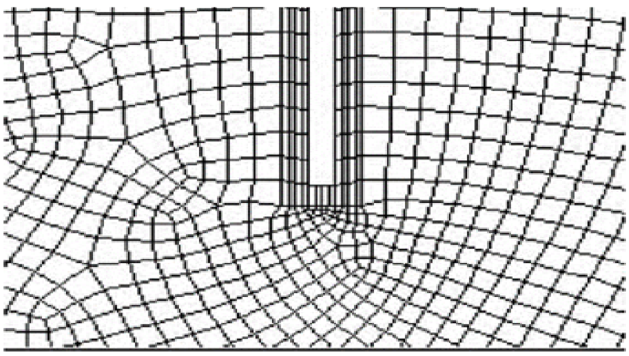

Figure 4. A Schematic Diagram of Local Grid Encryption near the Well Pumping Well

4.5. Parameter Settings

The type of calculation model is mainly including flow state (laminar flow or turbulent flow), whether it is a steady flow, the magnitude and direction of gravity acceleration, and whether temperature is considered.

The medium in the calculation area that needs to set parameters includes water, soil, and energy storage particles.

(1) Water

It is necessary to set the temperature, density, specific heat capacity, viscosity coefficient, standard state enthalpy, and standard state entropy.

(2) Energy storage particles

Need to set density, specific heat capacity, heat transfer coefficient, porosity, viscous drag coefficient, inertial drag coefficient.

(3) Soil

Need to set density, specific heat capacity, heat transfer coefficient, porosity, viscous drag coefficient, inertial drag coefficient.

The setting conditions of the solution include: initial time velocity, initial time pressure, initial soil temperature, inlet water flow, outlet pressure, soil boundary temperature, adiabatic boundary heat flux density, flow field velocity on the boundary, and rough constant of the soil outer boundary.

Since the flow rate of water in the porous medium is very slow, it belongs to the laminar flow state, and the viscous drag coefficient of the energy storage particles and the soil solid skeleton is 1/a.

$$1/a = \rho g/(K\mu) \tag{17}$$

Where 1/a is the viscous drag coefficient; g is the gravitational acceleration; K is the permeability coefficient, and μ is the kinematic viscosity coefficient of water.

The calculation of the inertia drag coefficient C2 can be borrowed from the Eugen formula commonly used in the chemical industry. It is simplified to the following formula only after considering the laminar flow term:

$$C_2 = \frac{3.5}{D_p} \cdot \frac{1-\varepsilon}{\varepsilon^3} \tag{18}$$

Where C_2 is the inertia drag coefficient; D_p is the equivalent diameter of the particles; ε is the porosity of the porous medium. Since the inertial drag coefficient of the laminar flow regime in the porous medium is small, mainly because the viscous drag coefficient acts, a smaller value or a straight zero can be taken. After the above steps are completed, a simulation calculation is performed to obtain a desired series of results.

5. Conclusions and Recommendations

In this paper, the physical and hydrogeological models and mathematical models of single well circulation heat transfer energy collection wells with energy storage particles and non-storage energy particles are given, which provides a theoretical basis for quantitative calculation.

Due to the complexity of the heat and mass transfer process of a single well cyclic heat transfer, the numerical simulation method is needed for temperature calculation. Accurately simulating and predicting the temperature values of soil and effluent medium has important guiding significance and reference value for theoretical research and production practice of shallow geothermal energy development. Compared with model test and field test, it can save a lot of money and short construction period.

In this paper, the complete process of mathematical equations, numerical calculation methods, computational models, geometric models, and various parameter assignment methods including constants and variables for the ideal single well circulation heat transfer energy collection well is given, and the hydrogeological process, the hydrodynamic process, heat and mass transfer process are unified in a mathematical model to facilitate research. In the actual research and production process, combined with the observation data and the inversion of the differential equation parameters, the mathematical model of the actual situation of the reaction is obtained through model identification. According to the above method, the simulation calculation and solution can be used for production research.

By assigning different values to the parameters in the numerical model to obtain different results, the influence of different hydrogeological parameters, thermodynamic parameters and hydrodynamic parameters on the collection well of single well circulation heat transfer can be analyzed. The choice of parameters in the design provides the main basis.

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Through the numerical simulation and analysis based on the development of shallow geothermal energy in single well circulation, it is beneficial to deepen its scientific understanding.

The scientific implementation of numerical simulation of shallow geothermal energy development in single well circulation also depends on the further development of forced convection, natural convection, heat conduction and heat dispersion theory in the flow and heat transfer process. The development of various turbulence modes in fluid mechanics and heat transfer promotes the development of the thermal energy discipline is a powerful proof.

The technology of collecting wells in single well circulation heat transfer has been applied in many important projects at home and abroad including China National Grand Theater, and has obtained good economic and social benefits. Through numerical simulation analysis, this kind of green energy can be used more effectively to benefit human society and provide strong support for the sustainable use and development of population-resource-environment.

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