JREE: Vol. 5, No. 4, (Fall 2018) 40-45

Journal of Renewable Energy and Environment

Journal Homepage: www.jree.ir

Research Article

Numerical Simulation of the Freezing Process in Geothermal Boreholes Using Solar Heat Injection

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P A P E R I N F O

Paper history:
Received 11 June 2019
Accepted in revised form 05 October 2019

Keywords:
Geothermal
Freezing
Solar Heat Injection
CFD Simulation

A B S T R A C T

Ground thermal energy as a clean and sustainable energy source has received significant attention lately. Several strategies and hybrid configurations have been proposed to harvest geothermal energy for air conditioning and industrial purposes. The possibility of moist soil freezing in the vicinity of borehole tubes is known to be the source of several benefits and difficulties. The high storage capacity during the freezing process and the structural damage are the major advantages and disadvantages of the thawing phenomenon, respectively. In the present study, the numerical simulation of the freezing process around the U-tube configuration of boreholes accompanied by the solar energy injection as the auxiliary heat source is investigated. Lower values of cold stream temperature result in the higher amount of recovered heat, while increasing the injected heat temperature intensifies the heat regaining. Moreover, the energy absorbed by the ice layer around the tube is directly related to the cold stream temperature.

1. INTRODUCTION

The utilization of the ground heat capacity as a possible sink/source for heat pumps has attracted much attention in recent years. Ground thermal energy is used by fluid passage through vertical tubes inside the ground called boreholes. For building heating purposes, the low-temperature working fluid recirculates through the ground to reheat; consequently, the ground temperature in the vicinity of the boreholes decreases. It is shown that the reduction of soil temperature near the boreholes results in lower coefficients of performance (COP) [1]. Therefore, several approaches are proposed to artificially inject thermal energy into the ground to recover its heating capacity. One of the most feasible and interesting methods is to use the solar energy systems with the common GCHP as hybrid systems [2].

However, considering the fact that the peak time of the solar system energy gain (near solar noon) does not coincide with the building power demand time (near midnight), some modifications to store the heat and postpone the required energy peak should be made. To do so, the saturated soil due to the high thermal capacity of water is proposed as a cheap, accessible and efficient heat source [3]. Another advantage of the saturated soil in comparison to the dry soil is related to tremendous heat of phase change during the freezing process [4]. In other words, when the heat demand of the boreholes is high, the water near the tubes freezes to provide the required energy during night, while the injected solar energy during day (with low energy demand of the Ground Coupled Heat Pump (GCHP)) causes the frozen water to melt and initiate the cycle.

However, the formation of ice region around the borehole tubes results in a significant reduction in heat removal from the working fluid, thus decreasing thermal efficiency [5,6]. Therefore, the characteristics of the freezing process and its impact on the overall system performance should be investigated comprehensively.

Recently, several numerical investigations have been performed related to the geothermal borehole freezing process. The conventional approach to the mentioned problem is done by 1D and 2D analytical or semi-analytical modeling. However, the 3D transient CFD simulation of the physical problem, especially ice formation pattern, is the major novelty of the present study. Moreover, the coupling between the solar injection and ice formation is another aspect of the present work, which should be investigated using CFD tool more thoroughly.

In the present study, the freezing process of boreholes and its influence on the overall system performance are numerically investigated. To do so, ice formation configuration and the system performance for various injected and evaporator temperatures are examined. The hot and cold U-tube streams, borehole, and the surrounding soil are modeled to determine the temperature distribution throughout the domain.

2. MATHEMATICAL MODELING

2.1. Governing equations

To simulate the flow field and freezing process, the finite volume approach is implemented. The governing equations including mass, momentum, and energy laws are solved numerically to determine the system behavior as a function of operating conditions [7,8].

The conservation of the mass equation is formulated as follows:

$$\frac{\partial}{\partial t}(\rho) + \nabla.(\rho\vec{v}) = 0 \quad (1)$$

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where ρ and $\vec{v}$ are the density and velocity vector, respectively.

The general form of the momentum conservation equation is:

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla.(\rho\vec{v}\vec{v}) = \nabla.[\mu(\nabla\vec{v} + \nabla\vec{v}^{T})] + \rho\bar{g} + \vec{F} - \nabla p \quad (2)$$

where p, μ, and $\vec{F}$ denote the pressure, viscosity, and body force, respectively.

The conservation of the energy equation has the following form:

$$\frac{\partial}{\partial t}(\rho) + \nabla.(\rho\vec{v}) = 0 \quad (3)$$

where k_{eff} is the effective conductivity, E is the energy, C_p is the specific heat, and S is the thermal heat source.

Several methods are currently available for liquid/solid phase change simulation. Among them, variable thermo-physical properties of an approach are known as a robust and effective approach. To implement the mentioned method, the thermo-physical properties of the simulated medium vary during the phase change. In other words, the enthalpy of phase change is utilized to introduce a significantly high specific heat, which is responsible for modeling heat absorption and/or release during the phase change process.

The effective value of the thermo-physical properties can be obtained based on the medium phase, which is related to the local temperature as follows:

Liquid phase	$T \geqslant T_{melt} + \Delta$	$k_{eff} = k_{ws}$	$(\rho c)_{eff} = \rho_s C_s (1-\phi) + \rho_w C_w \phi$	
Solid phase	$T \leqslant T_{melt} - \Delta$	$k_{eff} = k_{is}$	$(\rho c)_{eff} = \rho_s C_s (1-\phi) + \rho_w C_i \phi$	(4)
Transition phase	$T_{melt} - \Delta \leqslant T \quad T \geqslant T_{melt} + \Delta$	$k_{eff} = k_{is} + (k_{ws} - k_{is})/2\Delta * [T - (T_{melt} - \Delta)]$	$(\rho c)_{eff} = \rho_s C_s (1-\phi) + \rho_w [(C_w + C_i)/2 + H/(2\Delta)]\phi$	

where melting initiates at T_{melt} within a 2Δ temperature range, H is the latent heat per unit mass, and ϕ is the solid porosity.

Moreover, *w*, *I*, and *s* indexes represent water, ice, and soil media, respectively, and each combination of these symbols is utilized to signify the mixture state.

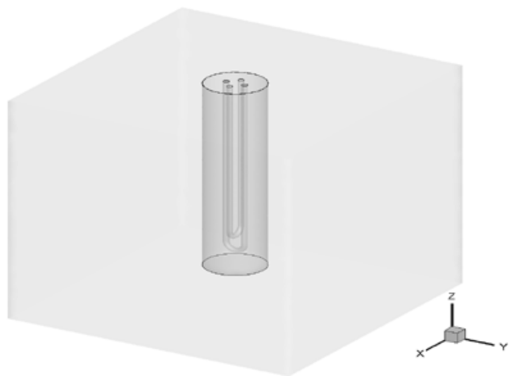
For the boundary conditions, both of the tubes' inlet ports are assumed to be characterized by mass flow rates. For the cold stream, the mass flow rate is assumed to be 0.44 kg/s, while, for the heat injection branch, the mass flow rate decreases to 25 % of cold stream (i.e., 0.11 kg/s) [5]. The flow boundary condition at the tubes' outlet is assumed as pressure outlet to the ambient. Since the domain is extended sufficiently around the borehole, the temperature boundary condition on the soil peripheral and in-depth surfaces is assumed as the adiabatic condition. Moreover, the temperature at the inlet of cold and hot streams is assumed to be 253 to 273 K, 278 to 318 K, respectively. Since the cold stream recirculates from the evaporator of a heat pump and the freezing process is required to occur, the conventional temperature range of -20 to 0 °C is selected for the cold stream. On the other hand, for the hot stream, the temperature range of 5 °C (shot-down solar collector) to 45 °C (full-load flat-plate collector) is selected based on the conventional operational condition of the flat-plate solar collector [5].

2.2. Simulation considerations

The governing equations were discretized and solved simultaneously by the finite volume method. The SIMPLE algorithm was utilized for the velocity-pressure coupling, and the convective and diffusive terms were discretized based on the second-order upwind and central schemes, respectively. The governing equations were solved numerically using the open-source code program of OpenFOAM. The numerical simulation was performed by means of a computer system with the following characteristics: Intel Core i7 CPU@2.8GHz, 16 GB of DDR4 RAM. Each simulation converged to the final results for about 16 h.

2.3. Geometry and mesh

The simulated geometry and the computational grids are shown in Fig. 1. The geometry is composed of two vertical U-tubes in a cylindrical borehole. Moreover, the ground around the borehole is also simulated to increase the accuracy of the numerical simulation.



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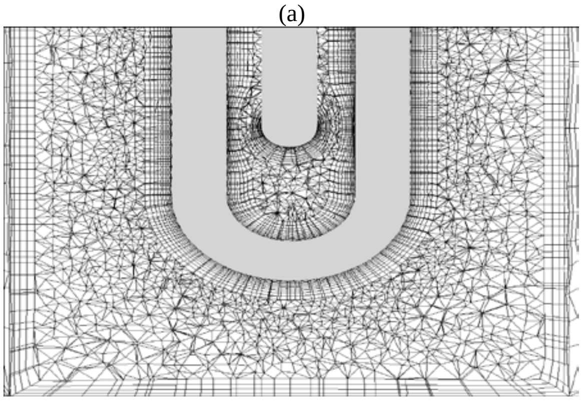

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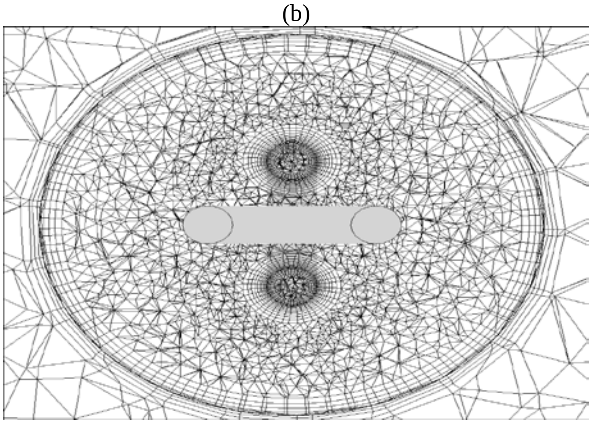

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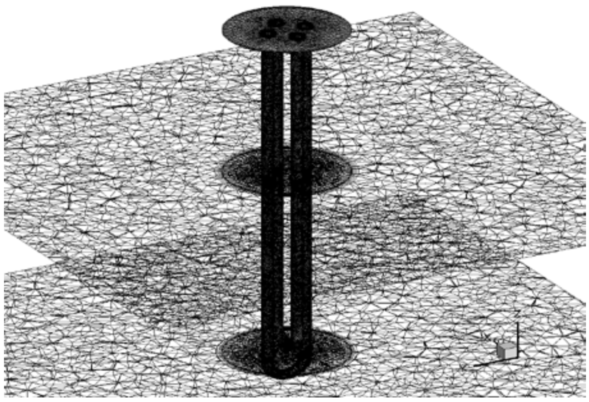

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Figure 1. Geometry and computational grid.

To capture sufficiently accurate results, the high resolution of the utilized computational grid should be employed. To do so, the cell's sizing near the U-tube and borehole walls should be reduced to adequately small values. Besides, the numerical solution and the obtained results should be independent of the mesh sizing and its number. Therefore, a grid independency test is performed with six different grids with the amount of 543, 246 to 2,578,874 computational cells.

Variations in the temperature along the curve passing through the center of hot tube in the case of hot and cold stream temperatures of 318 and 273 k, respectively, are calculated. The temperature profiles at the center of the U-tubes coincide approximately for the latter 4 cases. Therefore, given the enormous computational cost associated with solving the current problem, the computational grid with the number of 823,964 is selected for the numerical simulations.

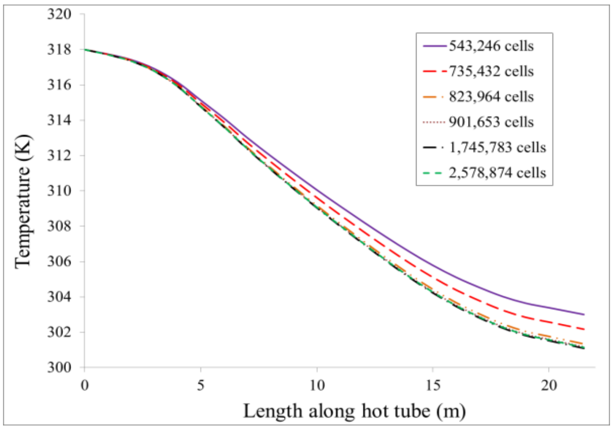


Figure 2. Grid study in the case of hot and cold stream tempertures of 318 and 273 k, respectively.

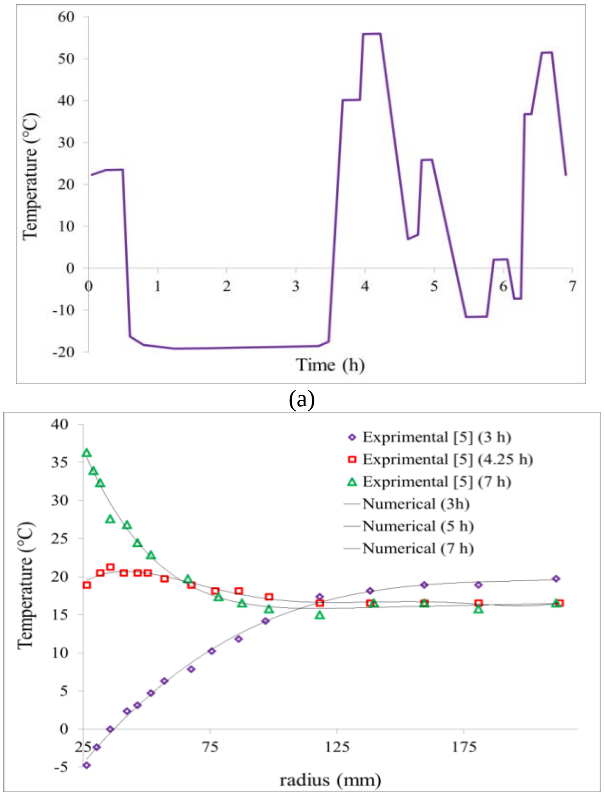
Table 1. Thermophysical properties.

	Grout	Ice	Water	Soil
k	1.3	2.22	0.6	3.5
ρ	1500	920	998	1500
C_p	850	2050	4200	850

3. RESULTS AND DISCUSSION

3.1. Validation

The numerical simulation of the present study is validated according to the experimental data of Eslami-Nejad and Bernier [5]. Of note, despite the fact that several researchers have focused on geothermal energy harvesting, the investigations regarding the freezing process of geothermal boreholes are very limited. The experimental setup [5] is similar to the hot-cold stream configuration of the present study. The borehole is filled with wetted sand (one can refer to [5] for the moisture percentage and other setup specifics). The cold stream at -20 °C is passing through the cold tube for the first 3.5 h; beyond that instance, the inlet temperature varies according to the profile illustrated in Fig. 3-a. The profile is selected to examine the capability of their 1D numerical modeling to estimate the temperature profile. The variations of temperature profile along circular cross-section radius are revealed in Fig. 3-b for both of the present numerical and experimental data. The temperature profiles of the current study are reported at the middle-height cross-section to be comparable to the 1D calculation of Eslami-Nejad and Bernier. According to the results, there is good agreement between the present 3D simulation and the experimental data.



(b)

Figure 3. a) Temperature variations at the inlet during freezing, b) temperature profile along radius in various instances.

The thermal performance of the geothermal boreholes for several cases is examined, and the results are discussed hereafter. The temperature of the recirculated heat pump evaporator through borehole is assumed to be between 253 and 273 K, while the solar injected heat source is supposed to heat the warm stream to 278-318 K. The fluid in both of hot and cold tubes is water, and the moist and dry soil are set for boreholes and surrounding regions. During the freezing process, the thermal properties of boreholes' materials are altered due to phase changes. The mentioned variations are associated with the amount of water fraction in the boreholes' soil (the moist content). In the present study, the moist content is set to 10 %, and the ratio of hot to cold water streams masses is assumed to be 10.

The contours of temperature at the vertical plate passing through the center of cold stream are illustrated in Fig. 4.

Since the variations of ground temperature in depth are considered, a nearly mild temperature increase is observed for all of the cases. The heat gain by the cold stream during its passage through U-tube is recognizable in each graph; however, the intensity of temperature increase is different in each examined condition.

At high levels of hot stream temperature (e.g., 308 and 318 K), the temperature gradient is more pronounced in the vicinity of the hot tube (at the bottom of the mentioned contours, where the hot tube passes through the selected vertical plane). In contrast, for lower values of hot stream inlet temperature, a more uniform temperature gradient is observable throughout the domain. In other words, an increase in the hot stream temperature intensifies the heat recovery of evaporator fluid by the conduction mechanism from hot to cold surfaces of U-tubes in the borehole, while, for lower temperature levels of hot stream, the heat transfer occurs mainly due to the conduction with the surrounding soil.

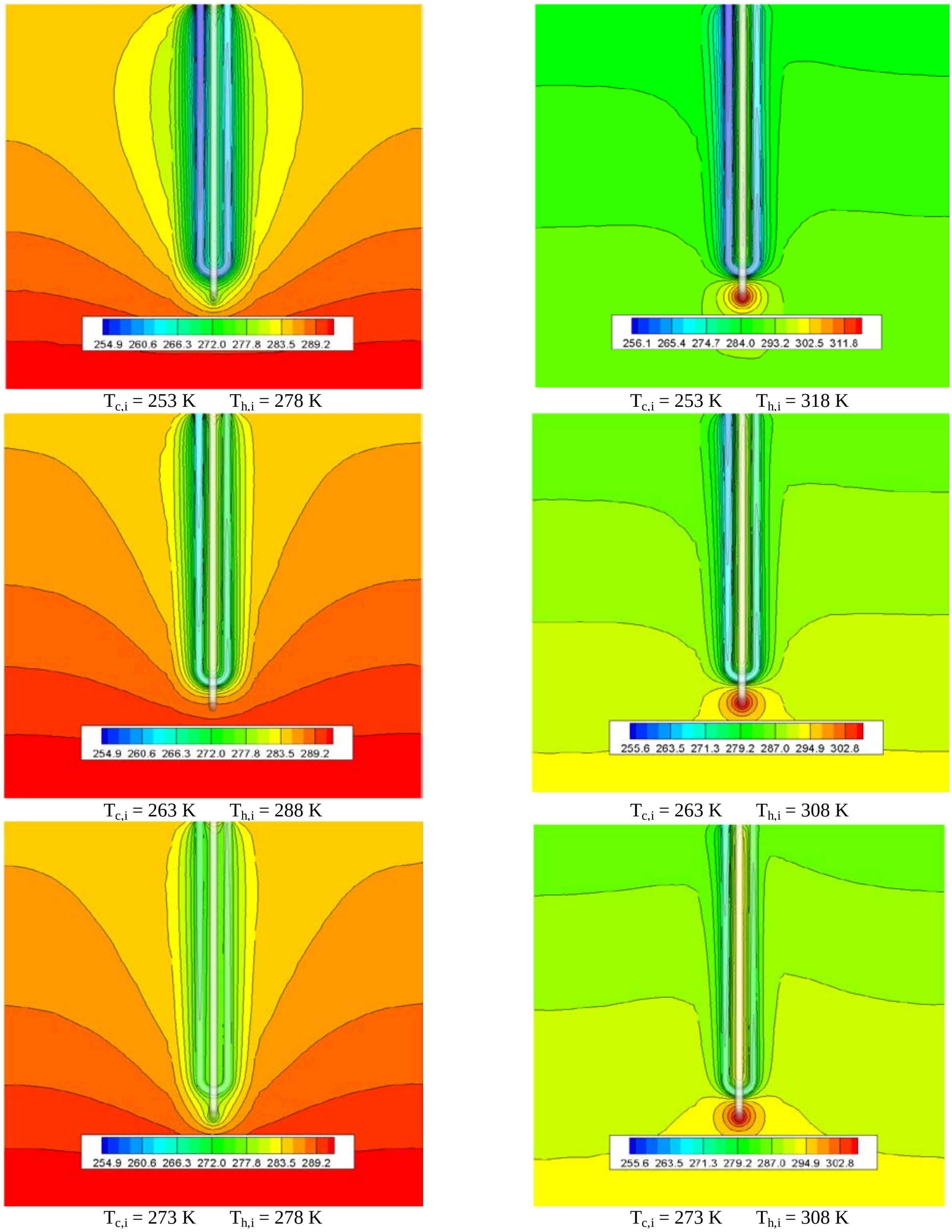


Figure 4. Temperature contours at the vertical midline plane for selected cases.

Ice formation configuration is depicted in Fig. 5. The freezing process, as it is expected, is only present for cases with inlet cold temperatures of 253 and 263 K. For the lowest temperature of solar stream (278 K), the highest amount of stream is created around the evaporator tube. Increasing the heat gain from the solar system (by rising the hot stream temperature from 278 to 318 K) reduces the freezing region. However, it should be noted that ice formation is not uniform around the evaporator tube. Thicker layers of ice are formed nearby the entrance of the cold tube, while its volume decreases passing through the pipe end. As a particular instance, in some cases with the high magnitude of injected heat, the ice is merely limited to the half-length of the U-tube.

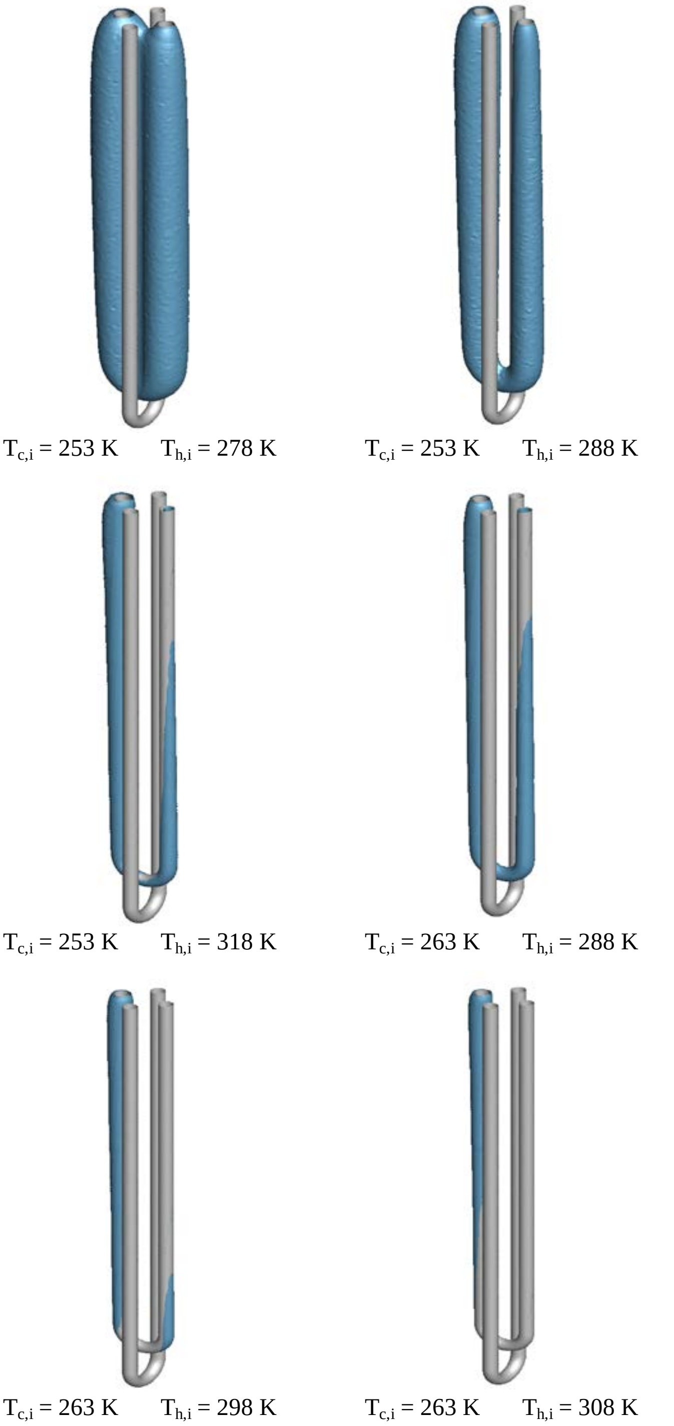


Figure 5. Ice formation pattern around the tubes for the selected cases.

A summary of the obtained results is depicted in Fig. 6. The recovered heat, which is the amount of energy transferred to the cold stream, inside the evaporator tube is shown in Fig. 6-a. The ultimate goal of a geothermal system is to exploit the high amount of stored heat energy inside the ground soil. Therefore, higher magnitudes of the recovered heat represent the better performance of the GCHP.

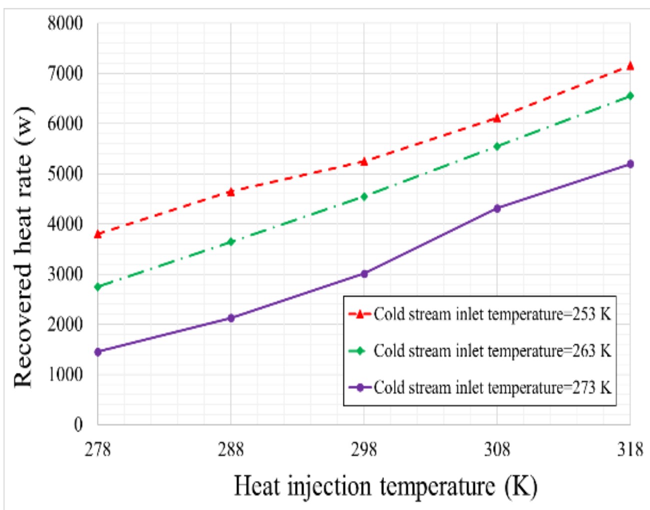
According to the results, lower values of cold stream temperature result in higher amount of recovered heat, while increasing the injected heat temperature intensifies the heat regaining. However, the effect of ice formation is clearly recognizable. The improvement of the amount of heat recovery slows down with a decrease in the evaporator temperature. In other words, the heat recovery is more pronounced in case of lower evaporator temperatures (in which the major ice portion is formed) in comparison to $T_{c,i}$=273 K, for which the freezing is not significant. Increasing the solar heat gain by preventing the freezing process reduces the mention difference.

Another important parameter that affects the GCHP performance is the rate of heat injection to the borehole. Based on the results (Fig. 6-b), the maximum added energy to the borehole belongs to the minimum evaporator temperature. The energy absorbed by the ice layer around the tube is directly related to the cold stream temperature. However, rising the solar stream temperature by increasing the temperature difference between the hot tube and the nearby moist soil increases the injected heat.

Considering the fact that the maximization of the heat recovery accompanied by the minimum injected heat from the auxiliary system provides an optimum system, the overall performance of the combined system is illustrated in Fig. 6-c. The ratio of recovered heat to injected heat rate is defined as a practical measure to identify the system characteristics.

In general, the utilization of the geothermal energy at lower evaporator temperatures (253 K) results in a higher recovered to injected heat rate ratio (with the exception of minimum utilized hot stream temperature, in which the highest evaporator temperature provides the best performance).

As the solar gained energy increases toward 318 K, the recovery to injection heat ratio reaches an asymptote value of 0.7.



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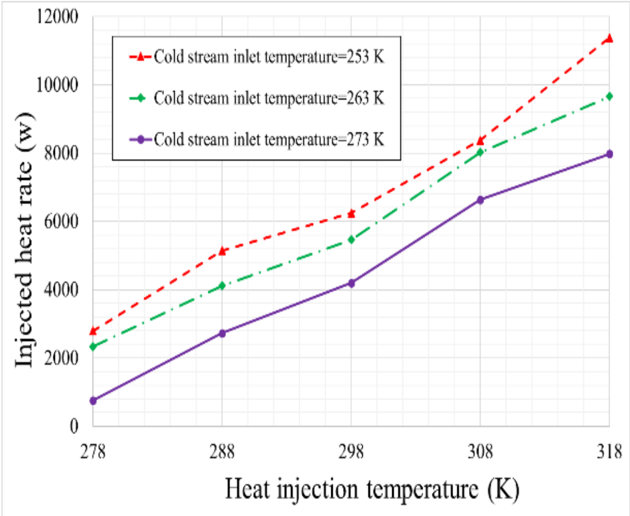

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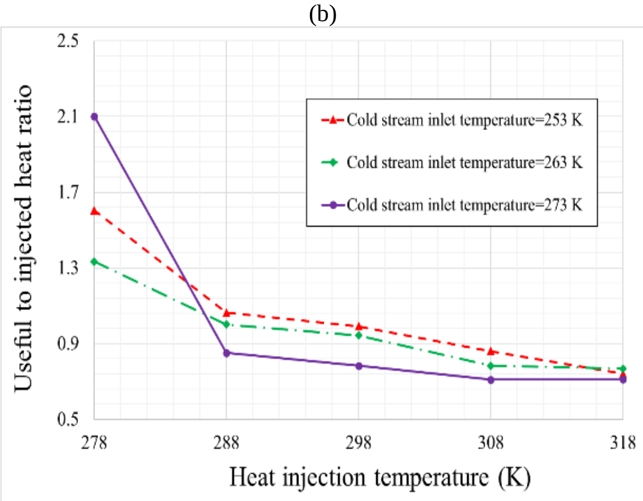

(c)

Figure 6. The geothermal system characteristics: a) heat recovery rate, b) heat injection rate, and c) useful to injected energy rate ratio.

4. CONCLUSIONS

The utilization of the ground heat capacity as a possible sink/source for heat pumps has been a hot topic in recent years. The freezing process of boreholes and its influence on the overall performance of the system were numerically investigated. To do so, ice formation configuration and the system performance for various injected and evaporator temperatures were examined. Based on the obtained results, the freezing process, as expected, was only present in cases with inlet cold temperatures of 253 and 263 K. At the lowest temperature of solar stream (278 K), the highest amount of ice was created around the evaporator tube. Thicker layers of ice were formed nearby the entrance of the cold tube, while its volume decreased while passing through the pipe end. Lower values of cold stream temperature resulted in higher amount of recovered heat, while increasing the injected heat temperature intensified the heat regaining. The maximum added energy to the borehole belonged to the minimum evaporator temperature. The energy absorbed by the ice layer around the tube is directly related to the cold stream temperature. As the solar gained energy increased toward 318 K, the recovery to injection heat ratio reached an asymptote value of 0.7.

5. ACKNOWLEDGEMENT

Authors would like to thank all Fasa University for supporting this research.

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