

Heat Extraction from Shallow Ground using Closed Single-Phase Thermosyphons

by

Alireza Kazemi

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Artificial ground freezing could be costly. Except for drilling and installation costs, they may also include maintenance and electricity consumption. What if we can build a device that naturally works without a need of external energy? Closed thermosyphons filled with a working fluid (antifreeze) that has a proper thermal conductivity can be the solution. Whether there is a need for heat extraction for a greenhouse area or we intend to freeze the ground artificially, simple closed pipes installed under the ground can absorb heat from the ground (heat source) and dump it into the air (heat sink). A portion of the pipe is installed in the soil while the other one is in contact with the ambient air. The antifreeze's temperature would be a value between the soil's and the air's. Thus, the heat transfers from the high temperature zone, soil, to the low temperature zone, wellbore (conduction), it flows through the pipe by natural convection, travels through the pipe's casing (conduction) and finally into the air (convection). A set of geometric parameters (i.e., heated length, cooled length, inner diameter) of the pipe are subjects to study. Also, the impact of air temperature changes and soil properties are of interest. First, an analytical model is employed to model one single pipe. The next section entails a 2D model simulating multiple pipes. The results show that increasing the cooled length and the diameter makes the heat transfer rate high. It also causes the device to work in higher temperature differences between up and down inner walls of

the pipe. Depending on the depth should be involved in freezing, the length under the ground (heated length) is determined. A high heated length entails a high soil-water content that tends to freeze. Although higher heat content is extracted in this situation, the radial development of freezing would be smaller. With regard to the soil properties, the minimum temperature of the ground is obtained when the soil's conductivity is maximum, while its porosity, density and specific heat are minimum. The air temperature has the most significant impact on the performance. A low air temperature improves the performance in every aspect. However, it is worthwhile noting that a device in such situation works in high temperature differences and so the required changes in other parameters should be considered.

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Introduction

Passive single-phase thermosyphons for subgrade cooling are used for the storage of thermal energy and permafrost preservation in the North in the base of permafrost foundations of buildings and structures. Particularly, structures such as above-ground pipelines, communication and power transmission towers supported by piles do not shade ground from the warming effects of solar radiation and snow accumulation. In addition, often permafrost is affected by disturbances during construction activities [1, 2].

Single phase devices were intensively investigated in the 1970s [3, 4]. During the winter, heat from the soil or backfill ground surrounding the embedded portion of the thermosyphon is adsorbed by the pipe and warms the working fluid. Warm fluid has less density and rises up to the above-ground “radiator” section of the thermosyphon. The “radiator” portion of the pipe exposed to the cooler air releases the heat to the atmosphere. Series of performance tests conducted by Johnson demonstrated that the liquid convection system required as much as an 8.3°C temperature difference between the air and soil to overcome internal friction and start up [4]. Thermopiles can also reduce seasonal frost heave. Induced radial freezing decreases vertical moisture transfer and the formation of horizontal ice lenses. These may be applicable if the mean annual air temperature is less than -4°C [5].

Historically, single-phase liquid convection piles have been applied in construction practices in such regions as Alaska and Russia. Single phase systems used a liquid or air as heat transfer medium, and heat was carried from the soil to the atmosphere. Liquid convection pipes were installed and studied at the Irelyah Dam in Mirny, the Sokha Republic [6]. Liquid convention piles were used to refreeze deep talik in Mirny [7]. Load bearing thermosyphons have been applied to support a main school building in Nulato, Alaska and the post office building in Glennallen, Alaska [8].

Thermosyphons with heat exchangers are essential parts of a system that can store heat or cold in a medium. Furthermore, passive thermosyphons may be used for forming a shallow seasonal bulb of frozen soil to store cold temperatures during the closest summer [9]. A temperature difference between ground temperature and air temperature may be used for air-conditioning of buildings during hot summers. Cooling systems reduce HVAC operational costs and therefore capital costs [10].

The use of the ground as a medium for thermal energy storage is long established. A common use of Interseasonal Heat/Cold Transfer Systems (IHCTS) is to circulate an exchange medium such as water or antifreeze in summer to extract heat from buildings' hot environment and dump it to the ground and vice versa in winter [11].

IHCTS can provide sustainable temperature offset of the subsurface ground or medium that may improve soil properties (frozen ground) or can be applied to heating/cooling buildings and structures. In the case of cooling, the local ground temperature offset is produced as a result of heat dissipating from the ground to the atmosphere in winter, allowing cold storage in the ground [5, 10]. This process can be reversed in summer to cool down buildings. In this application, low temperatures can increase the resilience of buildings and foundations to heat waves, save

significant amount of energy, and decrease burning fossil fuels to produce heat and electricity. Seasonal heat removal integrated with a cold preservation system can also improve the efficiency and performance of ground source heat pumps [12, 13].

Application of IHCTS is one of the research efforts presently being carried out by the National Research Council of Canada (NRC). They have commenced testing a pilot IHCTS designed to research each element of the system. One of the essential elements of the system is a closed antifreeze filled thermosyphon that could act as a passive device with natural convection of coolant or an active device with forced circulation pump installed. Firstly, an analytical model of a passive or natural convection thermosyphon is discussed in the present study. Secondly, a 2D finite element model is employed to simulate multiple thermosyphons installed in a field.

The major objective of the project is to conduct a technical study of a single-phase thermosyphon system to examine the feasibility of heat extraction for a variety of applications. Such applications could include harvesting energy from shallow ground, and freezing underground to make it more stable for surface constructions (bridges, buildings, etc.).

The study will include analytical and numerical modelling with comprehensive parametrical studies under different thermal or geological conditions. Each specific set of local conditions (i.e., the temperature gradients, soil properties, etc.) requires a different system geometry and operational conditions. That being said, a parametric study should be conducted to show how one device can be optimized to obtain the maximum thermal benefit while we preserve the integrity of the ground in the long term. Investigating the impact of the atmospheric conditions is also a part of the study. The ambient temperature during the heating season does not stay steady and changes periodically. Different soil materials also have diverse thermal properties, and they affect the heat transfer process.

Single Pipe

2.1. Overview

Ranging from everyday applications such as electrical and electronic devices (e.g., ovens, thermostats, microchips, etc.) to industrial applications, such as nuclear reactors and turbine blades, closed thermosyphons are being used to cool down different device components to avoid overheating [14-16]. In shallow ground medium, however, closed thermosyphons are used in other applications, such as serving permafrost under building structures in cold regions [17] as well as estimating the temperature distribution in drilling operations in steam power fields [18, 19].

Unlike ground coupled heat pumps, in which the refrigerant reinjects in each cycle (and consumes energy) [20], a similar process naturally occurs inside a passive thermosyphon. A closed thermosyphon installed underground containing a fluid with a relatively high thermal conductivity can absorb heat from the ground. The most common fluid used in underground pipes is water; however, to avoid freezing pipes in cold regions, we may consider using different types of antifreeze [21]. The selected antifreeze not only should satisfy the thermal conditions of the cycle (i.e., transferring the required heat content) but also should have a relatively low melting point.

Japikse et al. proposed an experimental setup to visualize the fluid flow along with heat transfer measurements for a closed thermosyphon, working with a single-phase liquid [15]. The experimental setup was designed to show the nature of the fluid flow and the temperature distribution inside the thermosyphon. They also measured the corresponding heat transfer rates for both vertical and inclined apparatuses under distinct boundary conditions.

Fig. 2.1 shows a schematic illustration of an apparatus heating from the top and cooling from the bottom [22]. The heated and cooled lengths are equal. Streamlines form beside the heated wall moving upwards while they form beside the cooled wall moving downwards. The two path flows face together in the middle of the pipe where they can couple to each other in different ways.

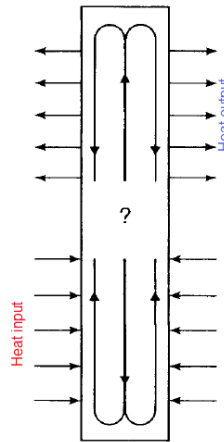


Fig. 2.1. Schematic of a closed vertical thermosyphon heated and cooled respectively from the bottom and top portions. Modified from [22].

Experiments conducted by Japikse et al. shows how a stable laminar flow behaves inside a closed thermosyphon [15]. **Fig. 2.2** shows an illustration of the steady laminar flow imposed by natural convective heat transfer upon heating and cooling respectively from bottom and top. As the bottom boundary heats the liquid, the boundary layer flow starts to rise. When the warm streams reach the mid-pipe, they face the cold streams moving downwards, and so they bend towards a horizontal

direction. Subsequently, at the centreline, the warm streams bend again and continue their axial direction upwards. For the cooled half of the pipe, when the fluid comes down beside the wall, it faces a dominant warm stream and returns to the top. Thus, the interaction between these two streams at the pipe mid-section causes forming a warm cluster of streams in the cold half and a cold cluster in the warm half. As shown in **Fig. 2.2**, the top half returning streams form a stable vortex. Although small rotational realignments are observed after several hours (without any significant mixing), the whole flow pattern would still be a stable laminar flow.

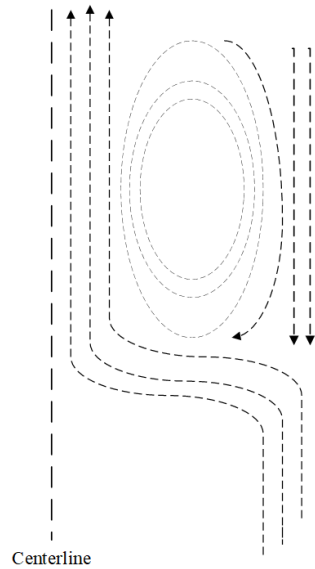


Fig. 2.2. Steady laminar flow induced by natural convection inside a closed pipe. Arrows and elliptic lines respectively indicate the flow streams and vortexes. Modified from [15].

Bayley and Lock proposed three possible flow pattern categories inside a closed thermosyphon [23]. As illustrated in **Fig. 2.3**, the bottom and top half streams can be coupled by (a) mixing, (b) convection, or (c) conduction. In the mixing mechanism, two streams are mixed at mid-pipe, meaning that the top and bottom temperatures will be the same at the mid-tube. In the convection mechanism, the boundary flow moves toward the core and continues its way toward the centerline. In the conduction mechanism, there would be two separate streams having heat transfer on the

core. None of the coupling mechanisms does not occur solely. In fact, a combination of them takes place. In terms of heat transfer capability, the convection mode has the highest rate, followed by the mixing mode, and lastly the conduction mode. Considering the mixing mode in calculations gives a closer estimation to the reality.

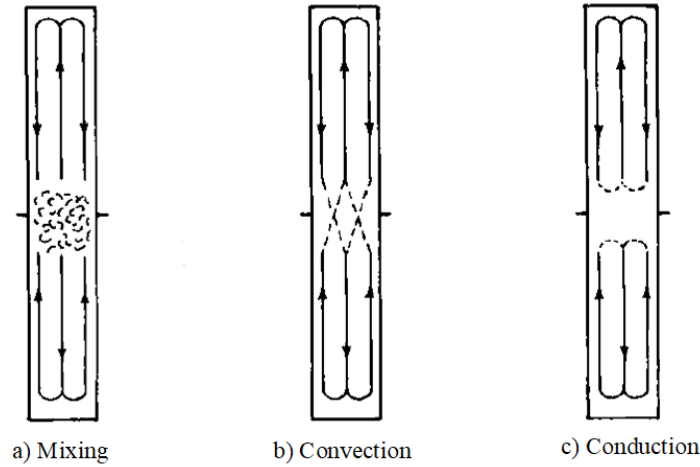


Fig. 2.3. Three ideal coupling mechanisms [23].

A closed pipe can be installed vertically inside the ground (a portion remains outside). In the winter, when ambient temperature is quite low while the ground is relatively warm because of the soil insulation nature, the installed pipe acts as a closed thermosyphon. The buried part of the pipe absorbs heat from its surroundings, causing the ground temperature to drop in the vicinity of the borehole, and a cold area develops radially around the apparatus over time. When the temperature in the ground drops below the water's melting point, the soil which is saturated with water starts to freeze. Considering the ground as a porous medium, the dominant phenomenon occurring in this point is conductive heat transfer in addition to phase change.

This study aims to explore the feasibility of using a closed passive thermosyphon for shallow ground (efficient operation that relies solely on natural convection with no pumping). The passive

thermosyphon uses a partially buried cylindrical pipe filled with antifreeze mixture. Initially, a half portion of the pipe is heated under the ground, and the other half is cooled in contact with the ambient air. Different length proportions are also subjects to study. In the bottom half of the pipe, the cold antifreeze absorbs heat from the warm surrounding surface and flows upward (natural convection). Similarly, the fluid flows downward in the top half. In other words, the dense fluid sinks, letting the lighter fluid rise. Of important factors to design a desirable heat extraction system are the net heat content needed from the ground and the mean temperature level inside the borehole [24]. Thus, a comprehensive parametric study will be conducted to investigate the feasibility of the system and to enhance the performance.

2.2. Modeling

The thermal modelling is divided into two parts:

- (a) Natural convection inside the pipe as a closed thermosyphon filled with a single-phase antifreeze, subjected to warm environment at the bottom and a cold environment at the top.
- (b) Conductive heat transfer for the soil (including the possibility of freezing), the surrounding backfill outside the borehole, and the pipe wall.

Fig. 2.4 shows a schematic of the proposed 2D-radial geometry of the wellbore and the surrounding soil and the associated heat transfer between them. Zone II is composed of unfrozen soil at temperature T_{inf} at infinity ($r \rightarrow \infty$). The temperature of this zone, $T_{II}(r,t)$, decreases to converge to the freezing temperature of water ($T_s(t) = 0^\circ\text{C}$) as it approaches the moving freezing-boundary ($r = S(t)$), denoted by the dashed circle (**Fig. 2.4 (a)**). Zone I represents the frozen region, which has temperature distribution, $T_I(r,t)$, decreasing from 0°C at the moving interface in the

direction towards the wellbore. The grey region in the middle of **Fig. 2.4(a)** shows the wellbore structure. A top view of the wellbore is shown in **Fig. 2.4(b)**. The wellbore considered in this study is a closed vertical pipe, in which antifreeze circulates by natural convection. Heat transfer from the soil occurs through the wellbore's structure. This structure is shown in **Fig. 2.4(c)**, revealing the cross section area of the wellbore wall in **Fig. 2.4(b)**. Wellbore's wall consists of casing and backfill with their associate radii shown in **Fig. 2.4(c)**.

The following steps represent the fundamentals of heat extraction from the shallow ground in this modeling using a single-phase closed thermosyphon: i) before the heat extraction process begins, water is in equilibrium temperature (T_{inf}); ii) at time $t = 0$, the heat extraction process begins, and soil temperature starts to drop upon heat transfer from the soil to antifreeze. Then, the antifreeze circulates inside the wellbore by natural convection and transfers this heat to the top of the wellbore and to the air. It should be noted that soil has a higher temperature than that of antifreeze. And iii) when the temperature at the external wall of the wellbore reaches the freezing point of water (0°C) and the latent heat of water is completely extracted, water freezing begins. A sharp moving boundary surface forms that shows the freezing rate and separates the frozen zone, Zone I, from the unfrozen zone, Zone II (**Fig. 2.4**).

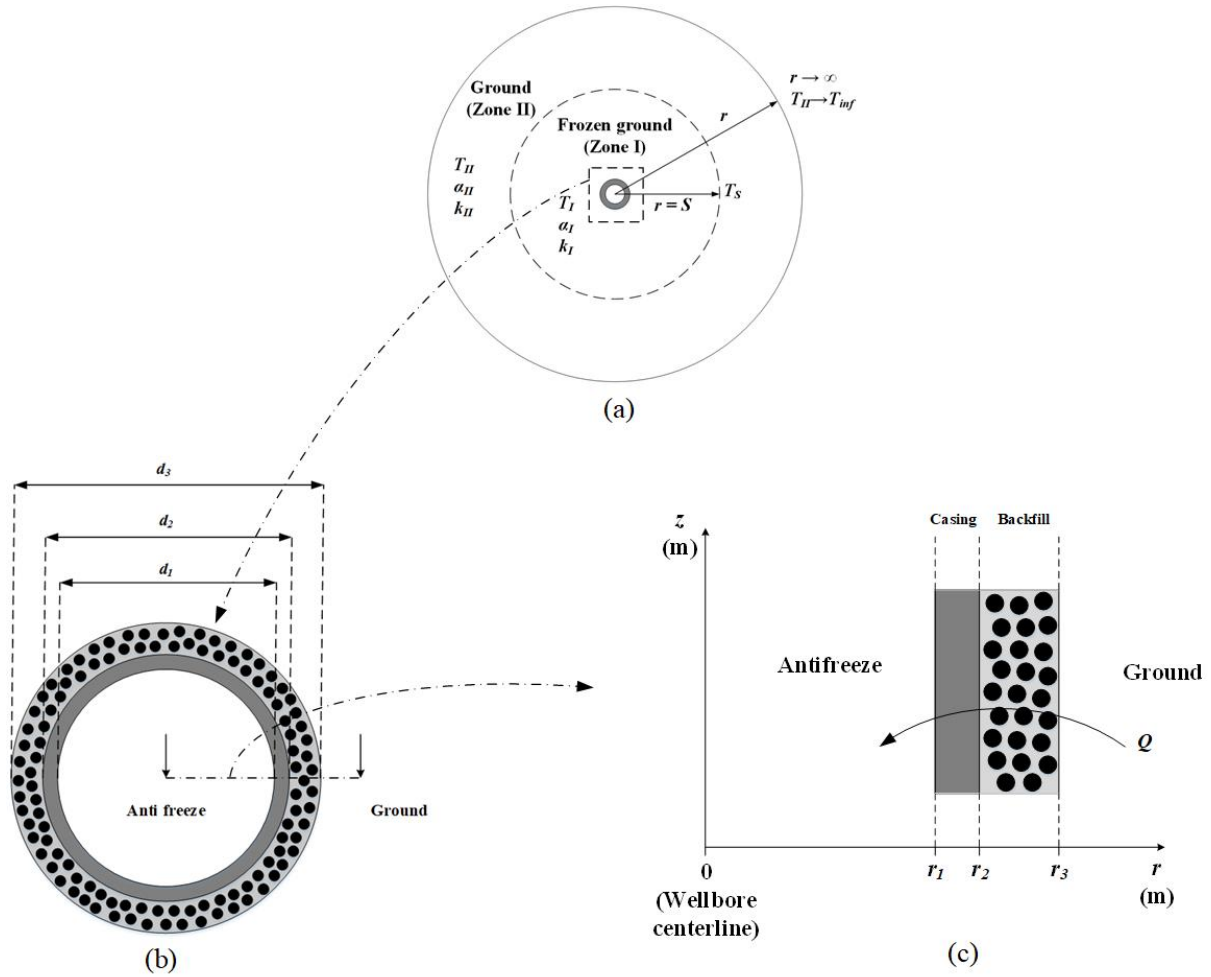


Fig. 2.4. The pipe configuration inside the ground: a) top view of the field, b) close-up view of the pipe and soundings, c) side view of the pipe and soundings.

During the heat transfer process, the temperature difference between Zone I and Zone II induces heat transfer from the Zone II to Zone I. Principally, heat transfer from soil to the wellbore causes:

- i) the temperature drop in the frozen soil in Zone I; and ii) water freezing and the temperature drop of the unfrozen soil in Zone I. Over time, Zone I becomes larger transferring lower amount of heat to the antifreeze due to its higher thermal resistance. This lower heat transfer reduces the freezing rate and the moving-interface speed.

With regard to the wellbore side, the antifreeze inside the closed pipe initially is in equilibrium temperature (T_{inf}). As soon as the operation starts, the soil temperature in the vicinity of the wellbore drops and the temperature difference created between the soil and antifreeze induces the heat transfer. The convection heat transfer occurs upwards through the antifreeze. The same amount of heat then transfers through the pipe's casing (conduction heat transfer) and dumps to the air (convection heat transfer).

Assumptions made in the models of the present work are in line with those of previous analytical works [25-29]. These assumptions are as follows:

- i) water completely fills the porous medium in the soil;
- ii) the water remains motionless in the porous medium over the whole period of study (no temperature gradient, no mass transfer);
- iii) the volume of water is negligible implying that the convection heat transfer by water is insignificant;
- iv) thermophysical properties of the phases in the ground remain constant over time;
- v) the produced ice instantaneously reaches thermal equilibrium with the local soil;
- vi) at the solid-liquid interface, the density difference between solid and liquid phases is neglected.

2.2.1. Heat transfer inside the wellbore

According to [23], a parametric comparison with an open thermosyphon helps to figure out how natural convection occurs in a closed one. The authors stated that for fluids with large Prandtl numbers, the Nusselt and Rayleigh numbers play the dominant role, while the Prandtl number has

a minor effect. Furthermore, Lighthill proposed a dimensionless parameter, t_d , for open thermosyphons to take into account the geometry effect [30]. This parameter is a combination of the diameter, heated length, and the Rayleigh number:

$$t_d = \frac{Ra_d d}{L_H} \quad (2.1)$$

where Ra_d is the Rayleigh number, d is the inner diameter of the pipe (m), and L_H is the heated length (m). In closed systems, which also contain a cooled length as well as a heated one, the geometry effect can be represented by a length ratio (i.e., L_H/L_C). The Rayleigh number (Ra) is a dimensionless value which is defined as the ratio of buoyancy and thermal diffusivity. This number is used to characterize the fluid flow regime (laminar/turbulent flow) in natural convection.

According to [30], each parameter's impact on heat transfer can be investigated by plotting the Nusselt number (Nu_d) versus t_d . An example of the mentioned plots for laminar flow regimes can be seen in **Fig. 2.5**. The convective heat transfer divided by the conductive heat transfer across a boundary is defined by the Nusselt number (Nu).

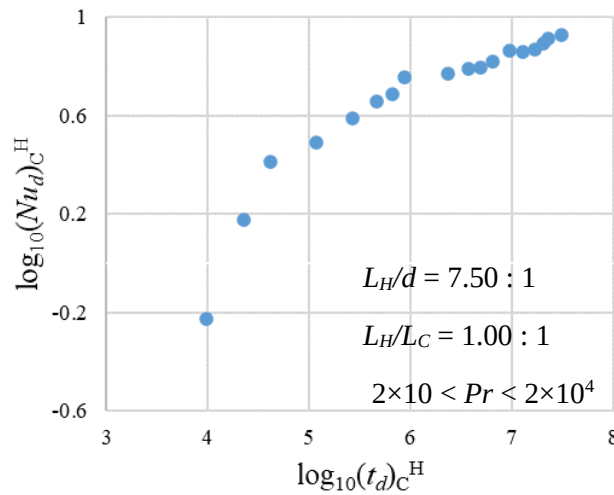


Fig. 2.5. Nusselt number versus t_d for a laminar flow regime L_H and L_C represent the heated and cooled lengths, respectively. Pr is the Prandtl number. The working fluid is glycerine [23].

Therefore, using those experimental plots, the Nusselt number for each flow pattern can be defined as a function of the Prandtl number, Rayleigh number, geometry dimensions, and the temperatures of the core and the walls for top and bottom. For a closed thermosyphon (heated from the bottom and cooled from the top), the dimensionless parameter, t_d , transforms to Eq. (2.2):

$$(t_d)_c^H = \frac{\beta g (T_H - T_C) d^4}{\nu \alpha L_H} \quad (2.2)$$

where $(t_d)_c^H$ is the dimensionless temperature difference for a closed thermosyphon. β is the thermal expansion coefficient (1/K) of the fluid inside and g denotes gravitational acceleration (m/s^2). ν and α are respectively the kinematic viscosity (m^2/s) and thermal diffusivity (m^2/s) of the fluid inside. d is the pipe inner diameter (m). T_H and T_C denote the temperatures ($^{\circ}\text{C}$) of the bottom wall and the top wall, respectively, and L_H is the heated length (m).

Among three types of coupling modes (**Fig. 2.3**), mixing is closer to what actually happens in reality. Using the calculated $(t_d)_c^H$, the Nusselt number for the closed thermosyphon in the mixing mode can be obtained as follows:

$$(\overline{Nu}_d)_c^H = \frac{0.677 \Psi_M^{0.25}}{\{1 + (L_H/L_C)^{0.75}\}} \left\{ 1 - \frac{1}{0.382 \Psi_M^{0.25} - 2} \right\}^{0.25} \quad (2.3)$$

where $(\overline{Nu}_d)_c^H$ is the mean Nusselt number for the whole cylindrical wall. L_H and L_C are the heated and cooled lengths (m), respectively, and Ψ_M is defined as:

$$\Psi_M = \frac{Pr \cdot (t_d)_c^H}{\left\{ Pr + \frac{20}{21} \right\} \{1 + (L_H/L_C)^{0.75}\}} \quad (2.4)$$

where Pr denotes the Prandtl Number, which is a dimensionless value estimating the ratio of momentum diffusivity (kinematic viscosity) to thermal diffusivity:

$$Pr = \frac{\nu}{\alpha} = \frac{C_p \mu}{k} \quad (2.5)$$

where C_p and μ are respectively the specific heat at constant pressure (J/(kg.K)) and dynamic viscosity (kg/(m.s)) of the fluid. k is the fluid's thermal conductivity (W/(m.K)).

After calculating the Nusselt number for the whole length of the wall, the total heat rate transferred through the wall is estimated by Eq. (2.6):

$$Q = \frac{p_d \cdot L_H \cdot (T_H - T_C) \cdot k \cdot (Nu_d)_c^H}{d} \quad (2.6)$$

where Q is the total heat rate transferred through the wall (W), and p_d is the pipe inner perimeter (m).

The same heat rate transfers from the ground through the casing and backfill to the antifreeze and also from the antifreeze through the casing into the air. For the bottom section, the thermal resistance of each section can be defined as:

$$R_{casing,bottom} = \frac{\ln(r_2/r_1)}{2\pi k_{casing} L_H} \quad (2.7)$$

$$R_{backfill} = \frac{\ln(r_3/r_2)}{2\pi k_{backfill} L_H} \quad (2.8)$$

where R is the thermal resistance (K/W), r shows the radial distance (m) from the pipe's centerline (refer to **Fig. 2.4(c)**), k_{casing} and $k_{backfill}$ are respectively the thermal conductivities (W/(m.K)) for the casing and backfill. Also, the thermal resistance for the casing on the top portion is calculated as follows:

$$R_{casing,top} = \frac{\ln(r_2/r_1)}{2\pi k_{casing} L_C} \quad (2.9)$$

The same amount of heat also transfers from the top side of the pipe into the air. To estimate the Nusselt number, the Prandtl number is calculated from Eq. (2.5). Moreover, the Grashof number, Gr , can be estimated as follows:

$$Gr = \frac{g\beta(T_{w,top} - T_{air})L_C^3}{\nu^2} \quad (2.10)$$

where g is the gravitational acceleration (m/s^2), β and ν are the thermal expansion coefficient ($1/K$), and the kinematic viscosity (m^2/s) of the air, respectively. $T_{w,top}$ is the temperature on the pipe's wall on the top portion ($^{\circ}C$), and T_{air} is the temperature of the air ($^{\circ}C$). d is the inner diameter of the pipe (m). The Grashof number (Gr) is a dimensionless value estimating the ratio between the buoyancy force to the restraining force (viscous force).

The Rayleigh number is the product of Prandtl and Grashof numbers:

$$Ra = Gr \times Pr \quad (2.11)$$

If the outer diameter (d_2) of the pipe is smaller than $\frac{35L_C}{Gr^{0.25}}$ then the mean Nusselt number for the top portion of the pipe is calculated as follows [31]:

$$\overline{Nu} = \frac{4}{3} \left[\frac{7Gr.Pr^2}{5(20+21Pr)} \right]^{\frac{1}{4}} + \frac{4(272+315Pr)L_C}{35(64+63Pr)d_2} \quad (2.12)$$

Otherwise, if d_2 is greater than or equal to the value $\frac{35L_C}{Gr^{0.25}}$ then the Nusselt number is calculated for a vertical wall [31]:

$$\overline{Nu} = \left\{ 0.825 + \frac{0.387Ra^{\frac{1}{6}}}{[1+(0.492/Pr)^{9/16}]^{8/27}} \right\}^2 \quad (2.13)$$

2.2.2. Heat transfer inside the ground

As the closed thermosyphon absorbs heat from its surroundings, the ground temperature starts to drop in the vicinity of the borehole. When the temperature is lower than the water freezing point (0°C), the soil which is saturated with water starts to freeze. Thus, a conductive heat transfer model should be employed, considering the phase change through the ground.

Fig. 2.6 shows the simplified temperature distribution in the soil after the water freezing begins. The temperature distribution in Zones I (T_I) and II (T_{II}) is respectively $T_{r_3} < T_I < T_S$ and $T_S < T_{II} < T_{inf}$ by assuming a constant pressure equal to the equilibrium pressure of water in Zone II. The temperature T_{r_3} , which is the wellbore's outer surface temperature, changes over time, but it is always higher than the temperature of the antifreeze inside the pipe.

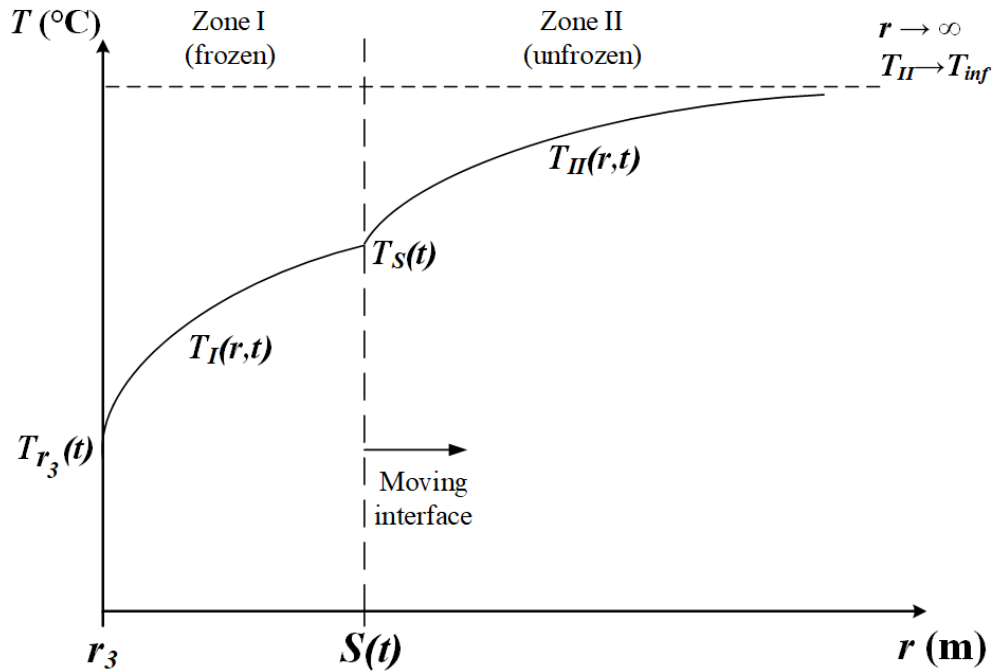


Fig. 2.6. Schematic of temperature distribution in the soil during the heat extraction process with water freezing.

The following equations are the fundamental formulas and the solution procedure used in the heat extraction modeling from soil. The modeling and solution approach employed in the present work are based on those of Roostaie and Leonenko's study on gas production from methane hydrate reservoirs using thermal stimulation method [25-27]. They developed 1D and 2D analytical models of phase transition as well as heat and mass transfer and fluid flow involved inside methane hydrate reservoirs and wellbore.

Eqs. (2.14) and (2.15) show the energy balance in Zones I and II, respectively:

$$\frac{\partial T_I}{\partial t} = \frac{\alpha_I}{r} \frac{\partial}{\partial r} r \frac{\partial T_I}{\partial r}, t > 0, \text{ in Zone I} \quad (2.14)$$

$$\frac{\partial T_{II}}{\partial t} = \frac{\alpha_{II}}{r} \frac{\partial}{\partial r} r \frac{\partial T_{II}}{\partial r}, t > 0, \text{ in Zone II} \quad (2.15)$$

where r is the radial location (m), α_I is the matrix thermal diffusivity (m^2/s) in Zone I, T_I is the soil temperature (K) in Zone I, α_{II} is the matrix thermal diffusivity (m^2/s) in Zone II, T_{II} is the soil temperature (K) in Zone II, and t is time (s).

As mentioned earlier in the modeling section, freezing does not start at time $t = 0$ if the soil temperature is above zero. Therefore, two models are built: i) one model with freezing; and ii) the other one without freezing. It should be noted that during the time frame that the freezing does not start, there is only the unfrozen zone (Zone II) in the soil. Eqs. (2.16) and (2.17) state the heat transfer from the reservoir to the wellbore's wall for the models respectively with and without freezing.

$$-k_I A_w \frac{\partial T_I}{\partial r} = \frac{2\pi L k_{well}}{\ln(r_3/r_1)} (T_H - T_I), r = r_3, t > 0 \quad (2.16)$$

$$-k_{II}A_w \frac{\partial T_{II}}{\partial r} = \frac{2\pi L k_{well}}{\ln(r_3/r_1)} (T_H - T_{II}), r = r_3, t > 0 \quad (2.17)$$

$$A_w = 2\pi r_3 L_H \quad (2.18)$$

$$k_{well} = \frac{k_{casing} \cdot k_{backfill} \cdot \ln\left(\frac{r_3}{r_1}\right)}{k_{backfill} \cdot \ln\left(\frac{r_2}{r_1}\right) + k_{casing} \cdot \ln\left(\frac{r_3}{r_2}\right)} \quad (2.19)$$

where A_w is the wellbore area (m^2) with its parameters shown in Eq. (2.18), k_I and k_{II} are the thermal conductivities ($W/(m.K)$) of respectively Zone I and Zone II, k_{well} is the wellbore thermal conductivity ($W/(m.K)$) consisted of backfill ($k_{backfill}$) and casing (k_{casing}) thermal conductivities ($W/(m.K)$) as shown in Eq. (2.19), L_H is the length of the wellbore inside the soil, T_H is the temperature ($^{\circ}C$) of the inner wall of the pipe (bottom section), and the subscripts 1 and 3 are schematically shown in **Fig. 2.4(c)**.

As mentioned previously, when the temperature of ground at the wellbore surface drops to $0^{\circ}C$ and the water latent heat is extracted completely, soil freezing begins by a freezing interface moving at specific speed in each time step with a constant temperature ($0^{\circ}C$). Eq. (2.20) shows the energy balance at this interface. The initial and boundary conditions in the models are: i) temperature at the inner surface of the wellbore (r_1) is known at each time step according to the calculations mentioned earlier for antifreeze's temperature inside the wellbore; ii) the temperature in the soil at the distance long enough from the wellbore is constant and equal to T_{inf} ; and iii) the temperature at the moving freezing interface is constant and equal to the freezing temperature of water ($0^{\circ}C$). These conditions are represented through Eqs. (2.20)-(2.24):

$$k_I \frac{\partial T_I}{\partial r} - k_{II} \frac{\partial T_{II}}{\partial r} = \phi \cdot \rho \cdot LH \frac{ds}{dt}, r = S, t > 0 \quad (2.20)$$

$$T_{r_1} = const., r = r_1, \text{ at each time step } (dt) \quad (2.21)$$

$$T_I = T_{II} = 0^\circ\text{C}, \quad r = S, t > 0 \quad (2.22)$$

$$T_{II} = T_{inf}, \quad r \rightarrow \infty, t > 0 \quad (2.23)$$

$$T_{II} = T_{inf}, \quad 0 < r < \infty, \quad t = 0 \quad (2.24)$$

Where T_{r_1} is the temperature (K) at inner surface of the wellbore, dt is the time step (s) in calculations, ϕ is the soil porosity, ρ is the water density (kg/m^3), LH is the latent heat of water (J/g), and S is the location (m) of the freezing interface.

As can be seen in **Fig. 2.6**, T_{r_3} connects the heat transfer of the wellbore and that of the ground. At each time step, T_{r_3} is applied to estimate the temperature inside the wellbore using Eqs. (2.7) and (2.8). Now that the temperatures inside the wellbore are determined from the top and bottom sections, the heat rate (Q) through the pipe can be calculated using Eq. (2.6). The same heat rate, Q , transfers from the ground side to the wellbore, so using Eqs. (S3) and (S4) in the Appendices section the temperature distribution on both frozen and unfrozen sides are linked to the wellbore inner temperature (T_H).

In the present work, a similarity solution is employed to transform, simplify, and solve the equations mentioned above. This solution approach, first introduced by Neumann [32, 33] meets the initial and boundary conditions and uses a dimensionless parameter represented in Eq. (2.25). This parameter relates the movement of the freezing interface to the square root of time ($t^{1/2}$).

$$\lambda = \frac{r}{\sqrt{4\alpha_i t}} \quad (2.25)$$

On the moving interface (S) and outer surface (r_3) of the wellbore, Eq. (2.25) respectively becomes Eqs. (2.26) and (2.27):

$$\lambda_S = \frac{S}{\sqrt{4\alpha_I t}}, \quad r = S, t > 0 \quad (2.26)$$

$$\lambda_{r_3} = \frac{r_3}{\sqrt{4\alpha_I t}}, \quad r = r_3, t > 0 \quad (2.27)$$

The previous equations in this subsection are simplified and transformed using the Eqs. (2.25)-(2.27) and are shown through the Eqs. S1-S15 in the Appendices, which also contains the solution procedure for the two time frames of before and after the freezing begins.

The following solutions are assumed for the temperature distribution (T_I and T_{II}) in soil for the two time frames. These solutions are based on the exponential integral (E_i) function, which has been recommended in previous works [25-27, 32, 33].

$$\text{Before the freezing begins: } T_{II}(\lambda) = T_{inf} - AE_i(-\lambda^2) \quad (2.28)$$

$$\text{After the freezing begins: } \begin{cases} T_I(\lambda) = A_1 - BE_i(-\lambda^2) \\ T_{II}(\lambda) = T_{inf} - CE_i\left(-\frac{\alpha_I}{\alpha_{II}}\lambda^2\right) \end{cases} \quad (2.29)$$

A , B , C , and A_I constants are defined in the Appendices.

2.2.3. Validation

A qualitative comparison to articles such as [34-37] shows that the ground temperature obeys the same trend while freezing. For instance, as per Fig. 4 in [36], the temperature of the ground shows three stages: (a) original cooling, which is a single-phase temperature drop of soil-water mixture; (b) steady freezing stage, in which the temperature remains constant at 0°C; and (c) rapid freezing with less latent heat stage in which the temperature of the soil-ice mixture starts to rapidly drop when it completely freezes. The same trend is observed in all the graphs of **Fig. 2.8** of the present work.

In addition, to quantitatively validate the results, a set of parameters used by Cai et al. were applied to the present model to investigate the temperature distribution of the ground [38]. In Cai et al.'s model, a single pipe with a diameter of 108 mm is buried under the ground with a constant wall temperature of -80°C . The phase change (water to ice) process occurs at -1°C , and the initial temperature of the soil is 20°C . The properties of the soil are obtained from Tables 1 and 2 of [38].

Fig. 2.7 shows the comparison between Cai et al.'s report and the results obtained with the present model. As per the figure, the average difference between two graphs is about 6.89%.

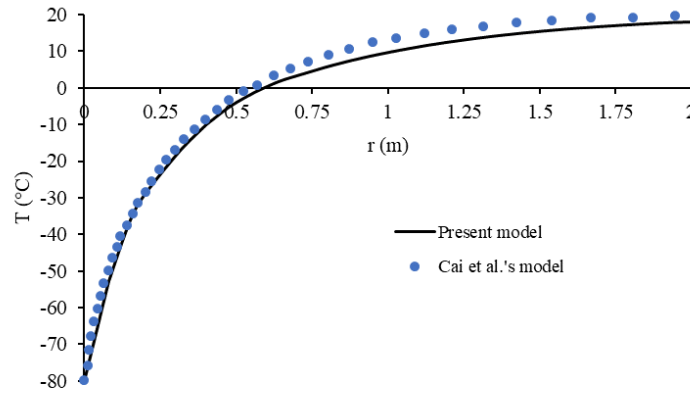


Fig. 2.7. Temperature distribution along with r-coordination after 10 days.

2.3. Results and discussion

2.3.1. Parameters

As shown in **Table 2.1**, different parametric scenarios are considered. The geometric parameters, including heated and cooled lengths (L_H , L_C), and the pipe's inner diameter (d) are subjects to study as well as the ambient temperature (T_{air}). These results are compared with those of a base model with specific parametric values, which are shown by bold numbers in **Table 2.1**. In the base model, the casing and backfill thicknesses are 0.3" and 0.25", respectively. When the inner diameter of

the pipe changes, the thicknesses also change with the same ratio so that they would have the same thermal resistance. The ambient air is considered dry, and its properties are obtained from [39] at the pressure of 1 atm (**Table 2.2**). The remaining air parameters (e.g., thermal diffusivity and the Prandtl number) can be calculated using the numbers from **Table 2.2**.

Table 2.1. Changing parameters of the wellbore and ambient air.

	Parameter	Value	Units
Wellbore	Cooled length (L_C)	1.5, 2, 2.5, 3, 3.5	m
	Heated length (L_H)	1.5, 2, 2.5, 3, 3.5	m
	Inner diameter (d)	3.9, 4.3, 4.7, 5.1, 5.5	inch
	Casing thickness	$(d_{in}/3.9") \times 0.3"$	inch
	Backfill thickness	$(d_{in}/3.9") \times 0.25"$	inch
Ambient air	Temperature	-10, -15, -20, -25	°C

Table 2.2. Dry air properties at different temperatures [39].

Temperature (°C)	Thermal conductivity (10^{-5} kW/m.K)	Kinematic viscosity (10^{-5} m ² /s)	Thermal expansion (1/K)	Density (kg/m ³)	Specific heat (J/kg.K)
-10	2.33	1.25	0.0038	1.34	
-15	2.29	1.20	0.0039	1.37	
-20	2.25	1.16	0.0040	1.40	1005.5
-25	2.21	1.12	0.0040	1.42	

To select the antifreeze inside the pipe, different solutions of ethylene glycol are considered (**Table 2.3**). A type of antifreeze must be selected in which the freezing temperature is below the coldest air temperature in the model (-25°C). From the most diluted antifreeze solution to the most concentrated one, the first solution that satisfy the required condition is 50%. More concentrated antifreeze solutions rise the costs. Furthermore, as shown in **Table 2.3**, higher percentage of ethylene glycol does not always have lower freezing point.

Table 2.3. Freezing points of different solutions of ethylene glycol [40].

Ethylene glycol solution (% by volume)	0	10	20	30	40	50	60	80	90	100
Freezing point ($^{\circ}\text{C}$)	0	-3.4	-7.9	-13.7	-23.5	-36.8	-52.8	-46	-30	-12.8

As the heat transfers through the pipe, the temperature of antifreeze is a value between that of the soil (in the vicinity of the pipe) and that of the outside air. The antifreeze's temperature decreases as the soil's temperature around the pipe drops. Therefore, the properties used for the antifreeze must be functions of its temperature. Bohne et al. proposed diagrams for estimating the thermal conductivity, dynamic viscosity, and density for different ethylene glycol solutions [41]. Then, the kinematic viscosity, thermal diffusivity and the Prandtl number can be estimated using the numbers from the diagrams (**Table 2.4**). The specific heat and thermal expansion are obtained from [40]. Using interpolation between the numbers from those resources, properties can be defined as equations. **Table 2.4** shows the properties of antifreeze as functions of temperature.

Table 2.4. Properties of ethylene glycol versus temperature.

Property	Expression	Units	Reference
Thermal conductivity	$-4.16 \times 10^{-6}T^2 + 0.001T + 0.41$	W/(m.K)	[41]
Dynamic viscosity	$2.37 \times 10^{-6}T^2 - 0.0002T + 0.007$	kg/(m.s)	[41]
Density	$-0.59T + 1068$	kg/m ³	[41]
Specific heat	$0.005T^2 + 1.8T + 3250$	J/(kg.K)	[40]
Thermal expansion	$4.62 \times 10^{-8}T^2 - 1.34 \times 10^{-5}T + 0.004$	1/K	[40]
Kinematic viscosity	$\nu = \frac{\mu}{\rho}$	m ² /s	-
Thermal diffusivity	$\alpha = \frac{k}{\rho C_p}$	m ² /s	-
Prandtl number	$Pr = \frac{\nu}{\alpha}$	-	-

The properties of the ground (frozen and unfrozen) and those of the wellbore structure (casing and backfill) are shown in **Table 2.5**. The pipe's casing and backfill are made of aluminum and quartz sand, respectively.

Table 2.5. The properties of the ground, and the wellbore.

	Property	Value	Units	References
General	Undisturbed temperature (T_{inf})	1	°C	-
	Porosity	28.4	%	[42]
	Density of water at 0°C	1000	kg/m ³	[43]
	Latent heat (water to ice)	334	kJ/kg	[44]
Unfrozen	Thermal conductivity	1.2	W/(m.K)	[42]
	Thermal diffusivity	4.1×10^{-7}	m ² /s	[42]
	Specific heat	1510	J/(kg.K)	[42]
	Density	1938	kg/m ³	[42]
Frozen	Thermal conductivity	1.7	W/(m.K)	[42]
	Thermal diffusivity	7.6×10^{-7}	m ² /s	[42]
	Specific heat	1142	J/(kg.K)	[42]
	Density	1958	kg/m ³	[42]
Wellbore	Thermal conductivity of the casing (Aluminum)	205	W/(m.K)	[45]
	Thermal conductivity of the backfill (quartz sand)	1.5	W/m.K	[46]

2.3.2. Results

Fig. 2.8 shows the temperature on the other surface of the wellbore, contacting with the ground (T_{r_3}). A glance at the graphs shows that all the lines follow the same trend. For all the cases, the initial temperature of the ground is equal to 1°C , from which the temperature immediately starts to decline. Having further extracted heat from the ground, the temperature then reaches 0°C where the water-soil mixture starts to freeze. At this point, the heat extracted is only used for phase change, and the temperature remains constant. Depending on the case contentions, such as pipe geometry and air temperature, the freezing time could be variable. The temperature then sees a sharp fall, followed by a steady decline.

In **Fig. 2.8(a)**, all the parameters are fixed (as stated in **Table 2.1**) except for L_C . As can be seen, shorter L_C 's lead to longer freezing times since the surface for heat dumping is smaller. Longer L_C 's result in lower temperatures during the whole period of study (e.g., after 60 days, for $L_C = 3.5$ m, $T \sim -8.5^\circ\text{C}$ while for $L_C = 1.5$ m, $T \sim -7.6^\circ\text{C}$). In **Fig. 2.8(b)**, L_H is variable while other parameters are constant. The longer the L_H is, the longer the freezing time will be (e.g., for $L_H = 3.5$ m, approximately 25 days are needed to freeze) because the amount of the water-soil mixture that should freeze is larger for longer L_H 's. During the whole period of study, shorter L_H 's lead to lower temperatures (e.g., for $L_H = 3.5$ m, $T \sim -6^\circ\text{C}$ while for $L_H = 1.5$ m, $T \sim -7.6^\circ\text{C}$). **Fig 2.8(c)** shows cases with different pipe's inner diameters. This parameter does not significantly affect temperature in different cases (i.e., maximum difference is about 0.4°C at the end of the time period). However, it is noteworthy that a larger diameter leads to a longer freezing time. As the diameter grows, the perimeter of the related cylinder and consequently the soil involved in freezing increases. Approximately until the first 8 days of operation, smaller diameters cause lower temperatures, and after that, longer diameters lead to lower temperatures. Therefore, to select the

proper diameter, it is necessary to determine the time period. In **Fig. 2.8(d)**, the ambient temperature is variable. The colder the air is the shorter it takes to freeze. Decreasing the air temperature from -10 to -15°C reduces the freezing time by half (from 5 to 2.5 days, respectively). For each air temperature, the temperature of the outer surface of the wellbore tends to reach a certain value (i.e., $T_{r_3} = 8, 12, 16, 21^\circ\text{C}$ for $T_{air} = -10, -15, -20, -25^\circ\text{C}$, respectively).

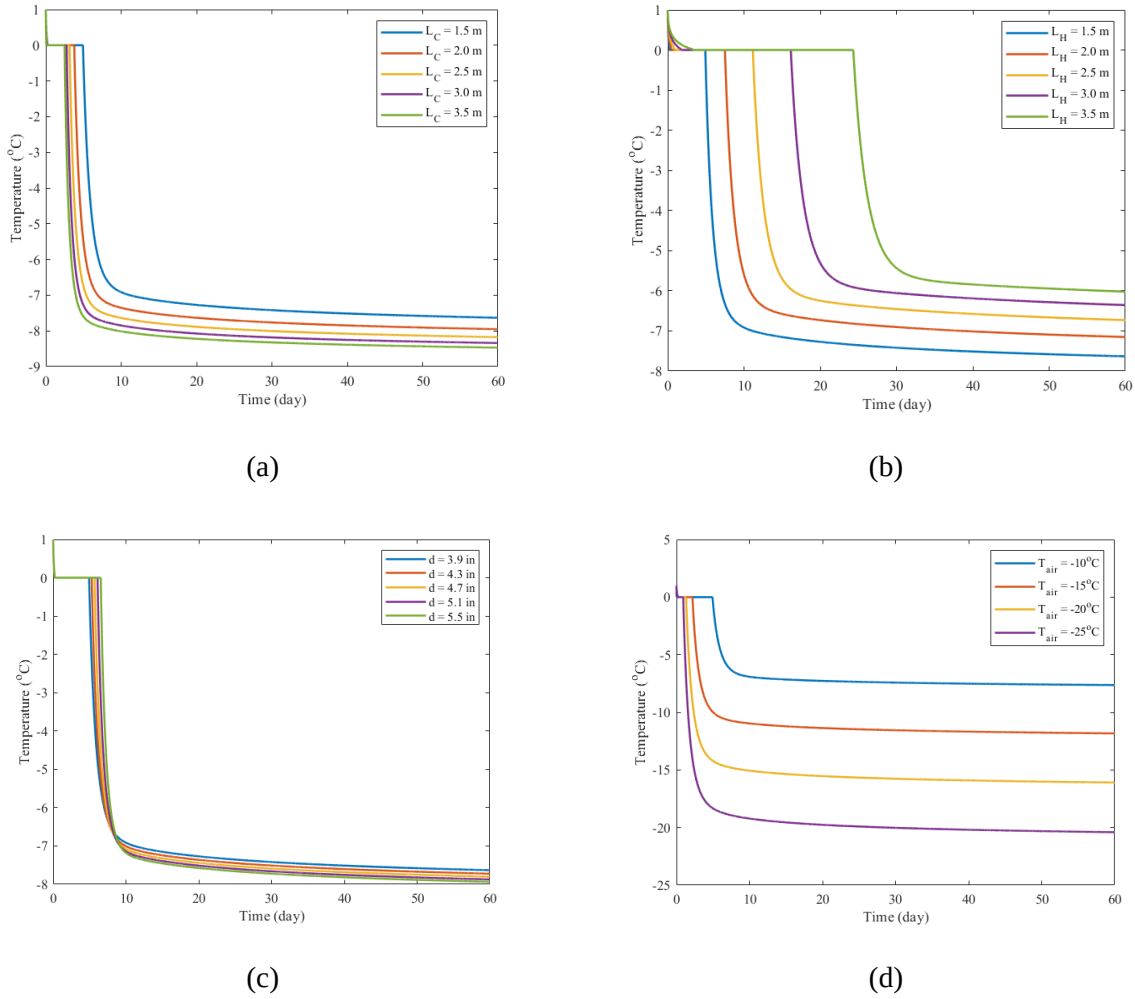


Fig. 2.8. Ground temperature on the outer surface of the wellbore over time for different cases: (a) variable cooled length, (b) variable heated length, (c) variable diameter, (d) variable air temperature.

Fig. 2.9 demonstrates the heat rate transferred through the pipe into the air for different scenarios. As per **Fig. 2.9(a)**, the longer L_C is, the higher the heat rate starts. Increasing the cooled length from 1.5 m to 3.5 m would increase the heat rate by 11 W (from 14 W to 25 W, respectively). After about 8 days, however, all the lines converge to a roughly same value, which is 2.5 W. For the cases with variable heated length (**Fig. 2.9(b)**), the heat rate lines start at the approximately same level, which is 14 W, and the freezing occurs at a value just above 12 W. As time elapses, all the lines tend to converge. Thus, at 60 days, the heat rate difference between the shortest and the longest heated lengths (i.e., $L_H = 1.5, 3.5$ m) is just about 2 W. However, the difference is quite high in the middle of the process. For instance, at 24 days, the heat rate for $L_H = 3.5$ m is about 12 W while the value is just above 2 W for $L_H = 1.5$ m. **Fig. 2.9(c)** shows the cases with different pipe diameters. A pipe with a larger diameter will transfer a higher amount of heat per unit of time. In overall, the heat rate difference is considerable at the beginning of the process, about 5.5 W between $L_H = 1.5$ m and $L_H = 3.5$ m. From the 8th day forward, the lines do not show a significant difference (below 1 W difference in the heat rate). **Fig. 2.9(d)** shows the highest difference in heat rate compared to other cases. The heat rate can increase by 10 W, only by lowering the air temperature by 5°C. For example, the heat rate is 30 W for $T_{air} = -20^\circ\text{C}$ at the beginning of the process, while it equals to 40 W for $T_{air} = -25^\circ\text{C}$ at the same time. After about 8 days, the lines tend to converge so at the end of the process (60 days), the heat rate does not exceed 5 W for the lowest air temperature (i.e., $T_{air} = -25^\circ\text{C}$).

As per **Fig. 2.9**, for achieving the highest heat rate, the longest L_C should be applied, maximizing the heat dumping surface. This case decreases the freezing time to the shortest time period. Although, the longest length of L_H causes the highest heat rate in general, selecting a too long L_H can significantly increase the time for freezing. Because for a longer L_H , there would be a larger

amount of water involved in freezing. Therefore, selecting a large L_H is not always beneficial. Larger pipe's diameter improves the heat transfer rate. However, a change in the pipe's diameter, in practical sizes (as used in the present study), does not show a significant impact on freezing time.

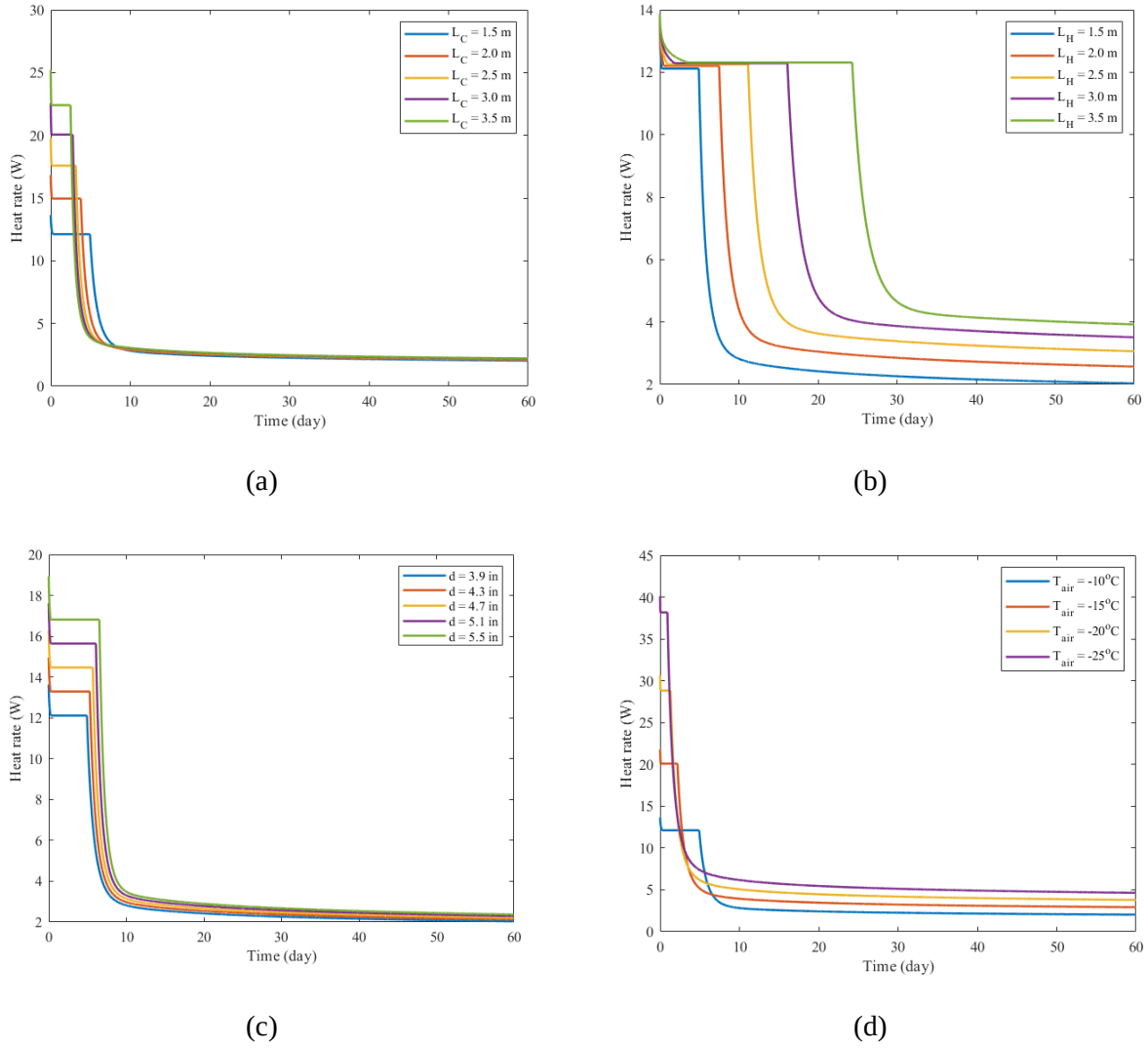


Fig. 2.9. Heat transfer rate through the pipe over time for different cases: (a) variable cooled length, (b) variable heated length, (c) variable diameter, (d) variable air temperature.

From Eq. (2) and Eq. (3), the Nusselt number could be illustrated versus the dimensionless temperature, i.e., $(t_d)_C^H$. As per Eq. (2), only temperatures (i.e., T_H and T_C) are changing for each

individual case. Thus, in **Fig. 2.10**, the horizontal axis (in the logarithmic scale) represents a multiple of the temperature difference between the cooled and the heated portions. The vertical axis (in the logarithmic scale) depicts the Nusselt number as a heat transfer factor through the pipe. The length of each line in **Fig. 2.10** shows the operation limits for each case. As per **Fig. 2.10(a)**, by increasing the cooled length (L_C), the lines get expanded from both sides, meaning that the apparatus can work in a wider range of temperature difference, and as a result, higher Nusselt numbers can be reached. Moreover, by increasing the L_C , the lines get higher y-intercepts. Thus, with the same value of temperature difference, $(t_d)_C^H$, an apparatus with a longer L_C works with a higher Nusselt number. As the cooled length increases, the lines become closer to each other. Therefore, by increasing the L_C , the sensitivity of the Nusselt number to L_C changes tends to minimum. According to **Fig. 2.10(b)**, expanding the pipe length below the ground not only causes the apparatus to work in lower temperature differences but also makes the operation range quite smaller, resulting in lower Nusselt numbers. Considering the base model as the reference ($L_C = 1.5$, $L_H = 1.5$, blue line in **Fig. 2.10(a) & (b)**), all the lines with an L_H greater than 1.5 m are placed below the reference while the lines with an L_C greater than 1.5 m are placed above it. Therefore, the heat transfer through the pipe would be maximum provided that the L_H and L_C would be minimum and maximum, respectively. As the L_H increases, the sensitivity of the Nusselt number to the L_H changes tends to get smaller. Thus, based on the application, for these geometrical parameters, it is only practical to change them in a certain range. In **Fig. 2.10(c)**, all the lines with different diameters have the same slope and the only difference is the range of temperature difference. The greater the diameter is, the higher the temperature difference is, and consequently the greater the Nusselt number will be. Similar to **Fig. 2.10(c)**, in **Fig. 2.10(d)**, the lower air

temperatures lead to higher temperature differences, $(t_d)_C^H$. Thus, as seen in **Fig. 2.9**, with a greater wellbore diameter and lower air temperature, the heat will transfer with a higher rate.

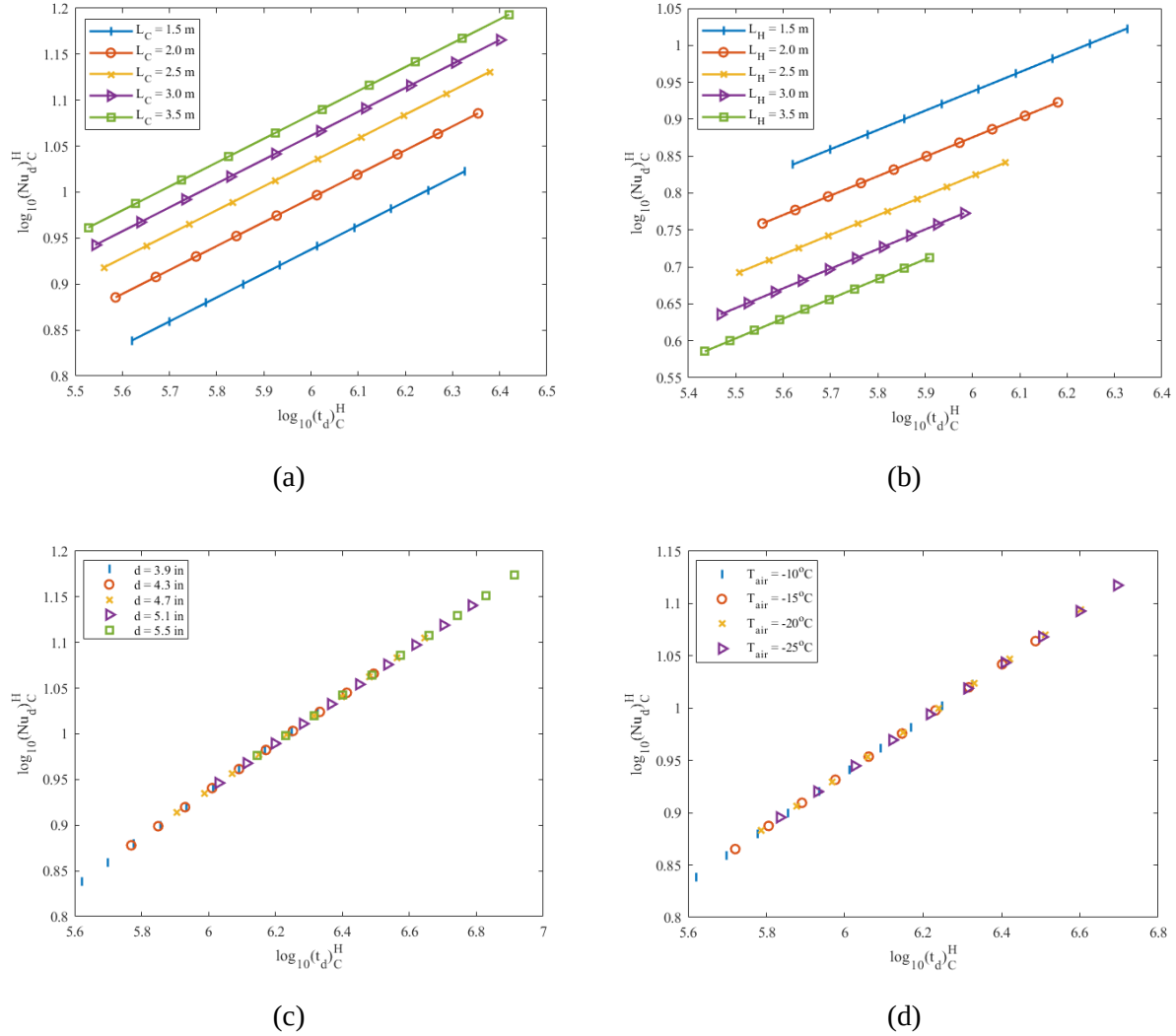
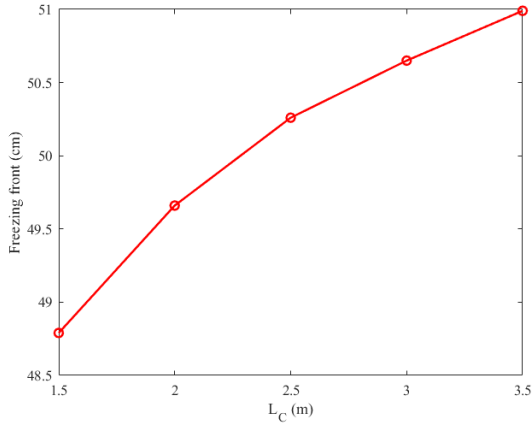


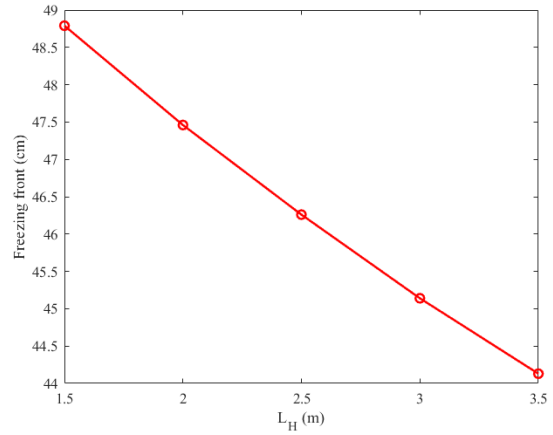
Fig. 2.10. The mean Nusselt number inside the pipe versus the dimensionless temperature difference. Both axes are in logarithmic scales: (a) variable cooled length, (b) variable heated length, (c) variable diameter, (d) variable air temperature.

Fig. 2.11 shows how far the freezing area has developed at the end of the time period (i.e., 60 days). From **Fig. 2.10(a)**, it is revealed that a longer L_C helps the heat to transfer faster. Thus, as can be seen in **Fig. 2.11(a)**, the longer the L_C is, the further the freezing front moves. As the

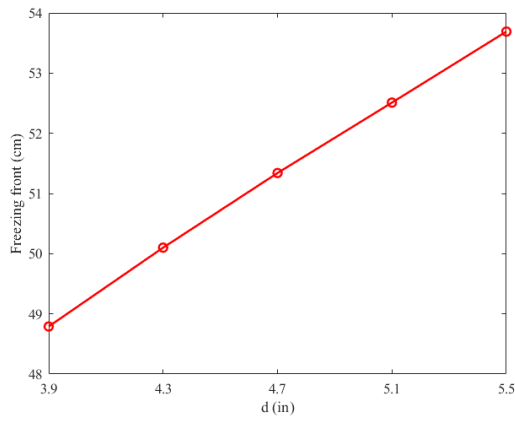
freezing develops, the heat transfer rate reduces due to the lower temperature difference between up and down (refer to **Fig. 2.9**). On the other hand, as the area that involves in freezing expands, the apparatus will try to freeze a greater area with a lower heat extraction force. Therefore, the differences between L_C cases are quite small (just above 2 cm between $L_C = 1.5$ m and $L_C = 3.5$ m). As a result, the pace of the freezing development decreases over time. As per **Fig. 2.11(b)**, the freezing front difference is higher among L_H cases (about 5 cm between $L_H = 1.5$ m and $L_H = 3.5$ m). The reason for this phenomenon is that the L_H 's length directly involves in the area that should freeze. The longer the L_H is, the greater volume of soil involves in freezing, and consequently the slower the freezing will be. In addition, according to **Fig. 2.10(b)**, a longer L_H entails a lower Nusselt number and heat transfer rate. According to **Fig. 2.11(c)**, the freezing front has an approximately linear relationship with the pipe's diameter. Although the volume involved in freezing increases by expanding the diameter, as per **Fig. 2.10**, since the Nusselt number also increases in this case, a larger diameter leads to a more developed freezing front (e.g., just below 49 cm for $d = 3.9$ ", and just below 54 cm for $d = 5.5$ "). The most effective factor in freezing development is the temperature of air (**Fig. 2.11(d)**), since it directly affects the temperature difference and consequently the Nusselt number. Reducing the air temperature just by 5°C can make the freezing develop further by 10 cm (e.g., $T_{air} = -10^\circ\text{C}$ to $T_{air} = -15^\circ\text{C}$).



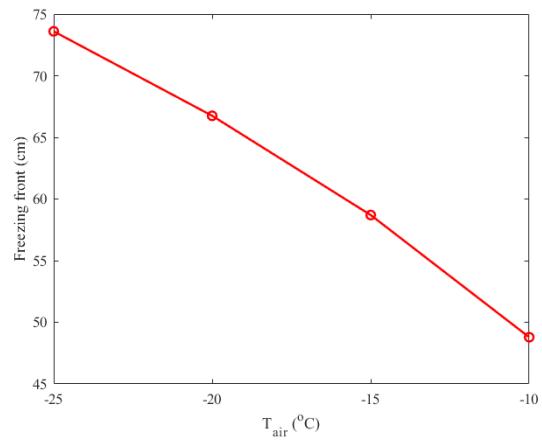
(a)



(b)



(c)

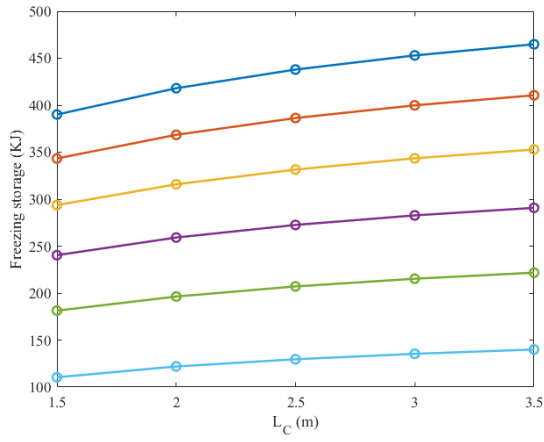


(d)

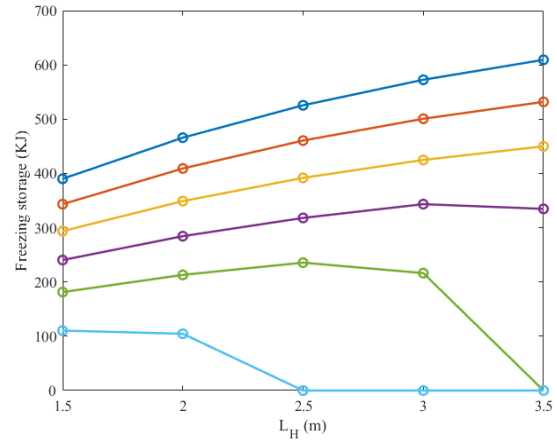
Fig. 2.11. The freezing front after 60 days versus different parametric scenarios: (a) variable cooled length, (b) variable heated length, (c) variable diameter, (d) variable air temperature.

After a soil-water content freezes completely, its temperature starts to decrease below 0°C . The amount of heat extracted from this point is applied to lower the temperature of the frozen content. Thus, the soil remains frozen, and the freezing area expands. Therefore, it can be evaluated that how much energy is extracted from underground only for the use of freezing storage (**Fig. 2.12**). From **Fig. 2.12(a)**, as time elapses, the lines become closer, indicating that heat extraction gets slower gradually. Increasing the L_C improves the freezing storage, and it becomes more

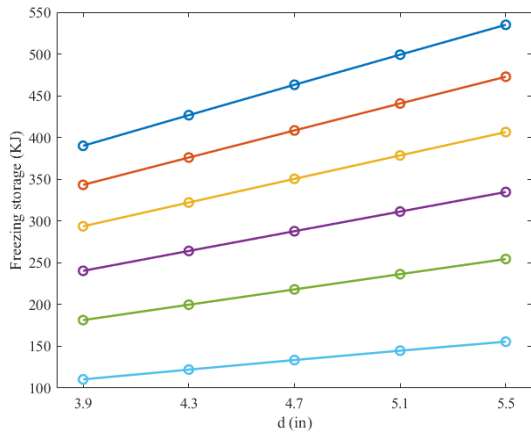
considerable over time (slope of Day = 60 is higher than that of Day = 10). At the end of the time period, the freezing storage difference between $L_C = 1.5$ m and $L_C = 3.5$ m is slightly above 50 kJ. For L_H cases (**Fig. 2.12(b)**), the difference is quite higher. At the end of the 60th day, $L_H = 3.5$ m stores 200 kJ more than that stored in the case with $L_H = 1.5$ m. According to **Fig. 2.9** and **Fig. 2.10**, a longer L_H leads to a lower heat transfer rate, and as per **Fig. 2.11**, it reduces the freezing front. Therefore, a higher freezing storage for higher L_H 's compared to other cases means that the heat extracted is used for temperature reduction of the frozen content. In other words, if a highly cooled frozen area is desirable close to the pipe, a high L_H is an option. For $L_H = 2.5, 3.0$, and 3.5 m at day = 10 full freezing did not occur. The same result is for $L_H = 3.5$ and day = 20. Thus, for a long heated-length, it might take longer time to freeze. Thus, in the short term, long L_H 's may not be desirable, but they provide more accumulative energy in the long term. **Fig. 2.12(c)** reveals that the pipe's diameter has a significant impact on freezing storage. As a comparison, the freezing storage difference between $d = 3.9$ " and $d = 5.5$ " at the end of the time period (60 days) is 150 kJ, while this difference between the $L_C = 1.5$ m and $L_C = 3.5$ m is 50 kJ. Thus, instead of increasing the cooled length by 2 meters, expanding the diameter by 1.6 inches increases the freezing storage by 3 times. **Fig. 2.12(d)** shows that by decreasing the ambient temperature, the lines tend to diverge. Thus, in colder temperatures, the range of energy changes is wider over time.



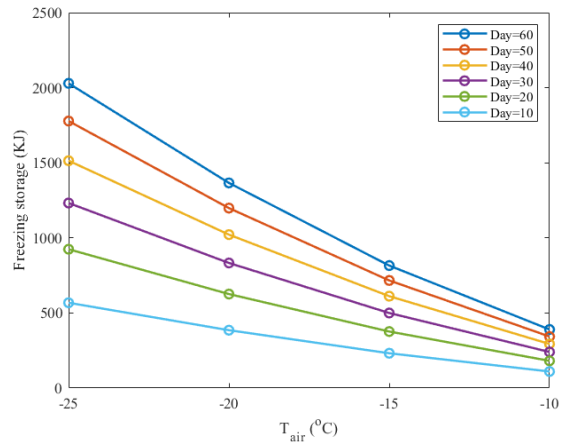
(a)



(b)



(c)



(d)

Fig. 2.12. The content of energy extracted from the ground after freezing point (freezing storage) versus different parametric scenarios: (a) variable cooled length, (b) variable heated length, (c) variable diameter, (d) variable air temperature.

Multiple Pipes

3.1. Overview

Natural convection transfers much less amount of heat than the amount forced convection does. Therefore, using single phase thermosyphons for artificial ground freezing or heat extraction from shallow ground is practical only if they are used in multiple. Unlike the single pipe scenario in which the thermosyphon is able to absorb heat from an infinite surrounding, multiple pipes are restricted by each other and have to compete for heat absorption. Thus, the factor that is much expected to affect multiple-pipe system functionality is the spacing between the pipes.

In terms of installation, pipes could be planted in different configurations. Unsymmetric configurations will not be the subject of this study and only equal spacing between the pipes on the field is taken into account. To avoid complexity, this study aims to find a method to only simulate one pipe out of many. Thus, the performance of one pipe on the field can be estimated quickly without dealing with the whole area.

In order to simulate multiple pipes (for a comparison reason), a 2-dimensional space is needed. A 2D model gives a complete understanding of the performance of the field while not making the

computational load unnecessarily high (e.g., 3D model). Thus, by using COMSOL Multiphysics® as the simulation platform, a 2D model is employed for the study.

3.2. Modeling methodology

3.2.1. Model assumptions

- (a) Since the initial temperature of the ground is considered close to the freezing point, water transforms to ice quickly and the water flow can be ignored.
- (b) Subsequently, the frozen area is immobile, and the ice movement is zero.
- (c) The soil is fully saturated, and the total porosity remains constant during the time.
- (d) The freezing point depression is negligible.

3.2.2. Model description

In the present study, first the freezing time is calculated, after which the ground temperature is zero or below zero. This time is calculated based on the initial conditions of air (temperature), ground (temperature and properties), antifreeze (temperature and properties), and wellbore geometry. Then, the program starts the heat transfer/extraction process and provides heat fluxes and temperature distributions from time zero until the ground temperature (right at the outer surface of the wellbore) reaches zero. If the time of the process (the time from zero second until now) is above the freezing time calculated previously, freezing starts, and the temperature distribution inside ground is estimated, which should be below zero. On the other hand, if the time of process in this step is below the freezing time calculated previously, it means that the freezing does not start now, and the ground's temperature still remains at zero, and the process continues without freezing until the time goes beyond the freezing time, then the freezing starts. It should be

noted that in this period, during which the ground temperature is kept at zero, the heat flux is constant as all the temperatures (ground, antifreeze, and air) are constant.

When a number of freezing pipes are installed in the vicinity of each other, they compete with each other to absorb energy. Assuming to have equal spacing between the pipes, each pipe gets equal amount of energy to its neighbors'. For a sole pipe this would be equivalent to a situation that the pipe is restricted by the no heat flux boundaries at the middle of the two pipes' distance (**Fig. 3.1**). It is worthwhile noting that the pipes far from the field's center are exemptions since they are closer to the undisturbed area.

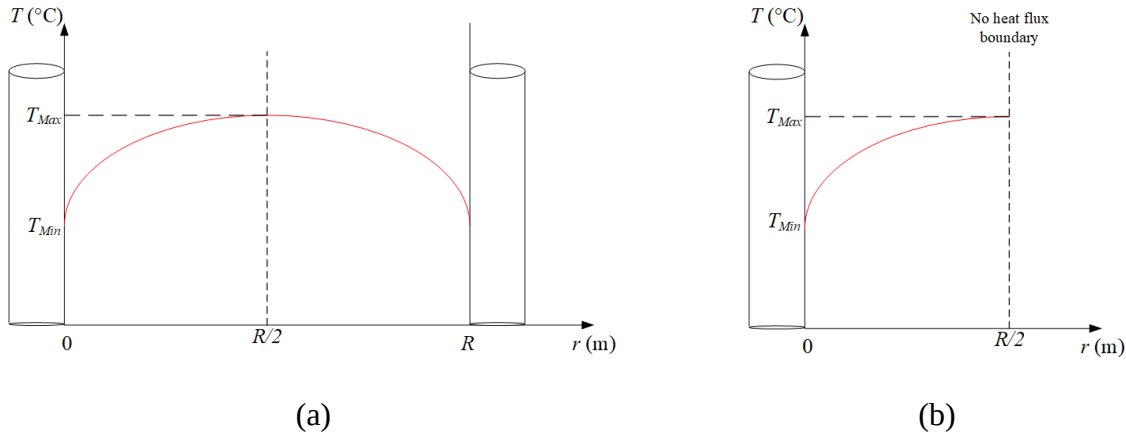


Fig. 3.1. Temperature distribution between (a) two wellbores, and (b) one wellbore restricted by a no heat flux boundary.

As shown in **Fig. 3.1(a)**, when two same wellbores compete to absorb heat, they receive the same amount of energy. Thus, the temperature distribution is symmetric on the two sides of the centerline between them. The maximum temperature occurs at the centerline. If the second wellbore is removed and a no heat flux boundary is replaced the centerline, then the exact same temperature distribution will happen for the first wellbore (**Fig. 3.1(b)**). Therefore, if the geometry

is symmetric, to reduce the computational load, it is possible to simulate one wellbore and gain the results for more.

Inside a field that the pipes are installed symmetrically, the no heat flux boundary could be considered in a number of ways:

- (i) Four pipes on the corners of a square
- (ii) One pipe on the center of a circle
- (iii) One pipe on the center of a square

3.2.2.1. Four pipes on the corners of a square

(a) Methodology and description

In this scenario, the no heat flux boundaries connect four neighbor pipes' centers so that one quarter of each pipe remains on the corners of a square (**Fig. 3.2**).

Fig. 3.2(a) illustrates a field containing 36 pipes. No heat transfers through the four linear boundaries. The field's dimensions ($25\text{ m} \times 25\text{ m}$) are selected in a way that the distance between the furthest pipes at the corners and the boundaries could be considered infinite (for certain amount of operation time). The distance between the pipes is 1 m in both x and y directions. A square portion containing four pipes at the center of the domain are segmented and shown in **Fig. 3.2(b)**. Each corner contains one quarter of a pipe, and the boundaries transfer no heat flux.

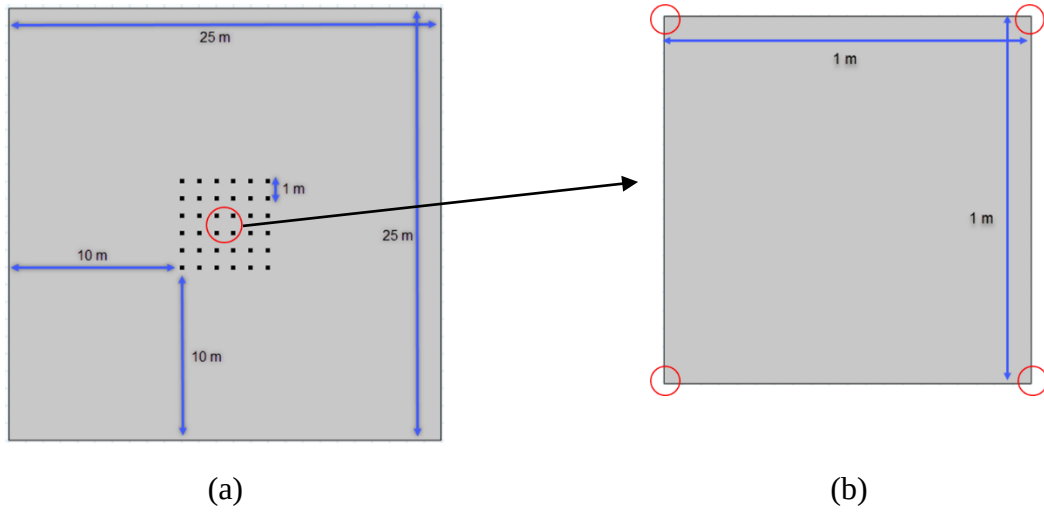


Fig. 3.2. Selection a segment containing four pipes from the field.

(b) Comparison with the unsegmented model

The whole domain is considered porous media with a porosity of 30%. It is assumed that the whole pore spaces are initially filled with water which completely transforms to ice after freezing is done. The ground temperature is uniform and initially 1°C. The outside air is considered dry and at -25°C during the study time period. The ground soil, water and ice properties are shown in **Table 3.1**.

Table 3.1. Properties used in the comparison model.

	Property	Value	Units	References
Initial Conditions	Initial temperature of the ground	1	°C	-
	Air temperature	-25	°C	-
Dry Soil (Sandy Clay)	Thermal conductivity	1.00 (0.15-1.8)	W/m.K	[47]
	Specific heat	1381	J/kg.K	[48]
	Density	1600	kg/m ³	[49]
	Porosity	0.3	-	[50]
Water*	Thermal conductivity	0.56	W/m.K	[51]
	Specific heat	4220	J/kg.K	[52]
	Density	1000	kg/m ³	[43]
	Ratio of specific heats (γ)	1	-	[52]
Ice**	Thermal conductivity	2.22	W/m.K	[53]
	Specific heat	2050	J/kg.K	[53]
	Density	916	kg/m ³	[53]
	Ratio of specific heats (γ)	1	-	[53]

* Water properties are taken at 0°C.

** Ice properties are taken at 0°C.

Fig. 3.3 shows a 2D view of temperature distribution for the whole field of pipes (**Fig. 3.3(a)**) and for the four pipes segmentation (**Fig. 3.3(b)**) after 60 days of time period. As can be seen, the lowest temperature in both illustrations is roughly equal (~ -14 to -14.5°C). The temperature distribution between the two wellbores at the domain center is also the same and for both illustrations, it changes from around -14°C at the wellbore area to around -13°C at the centerline between two wellbores.

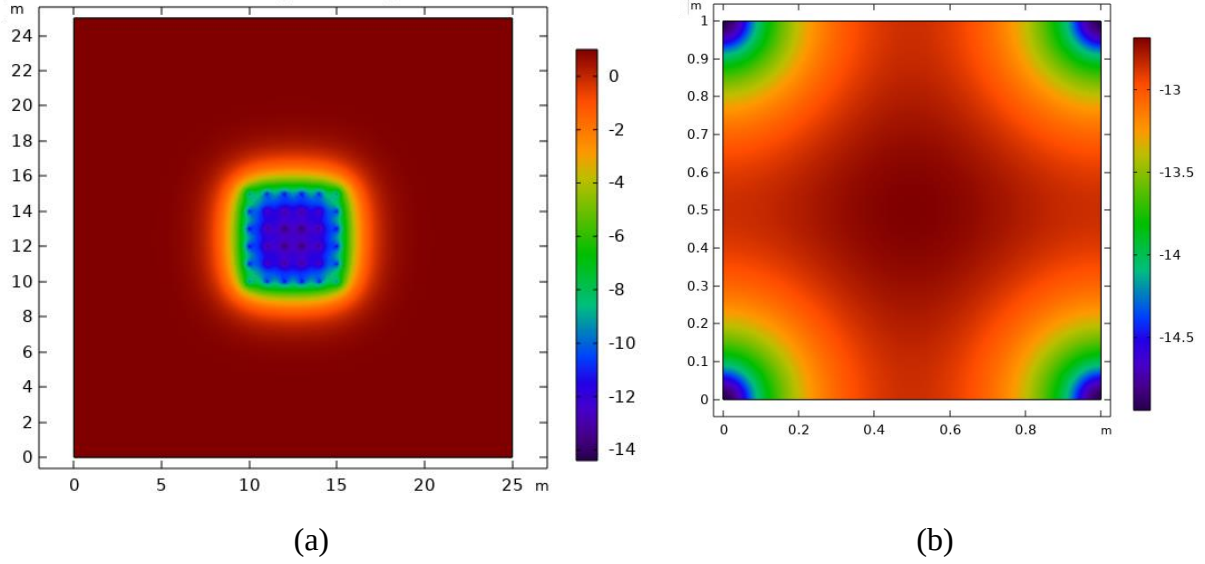


Fig. 3.3. Temperature distribution for (a) the whole field, and (b) four-pipe segmented models, after 60 days. Temperatures are in Celsius.

To better understand how similar the two model could be, the temperature profile between two wellbores is illustrated for both in three different operation times (**Fig. 3.4**). As can be seen in **Fig. 3.4(a)** and **(b)**, the two lines are mostly match except for the wellbore areas where they have a minor difference (around 0.3°C for 20 days and 0.35°C for 40 days). As shown in **Fig. 3.4(c)**, the two lines also have difference within their distance, but still the maximum different does not exceed 0.5°C .

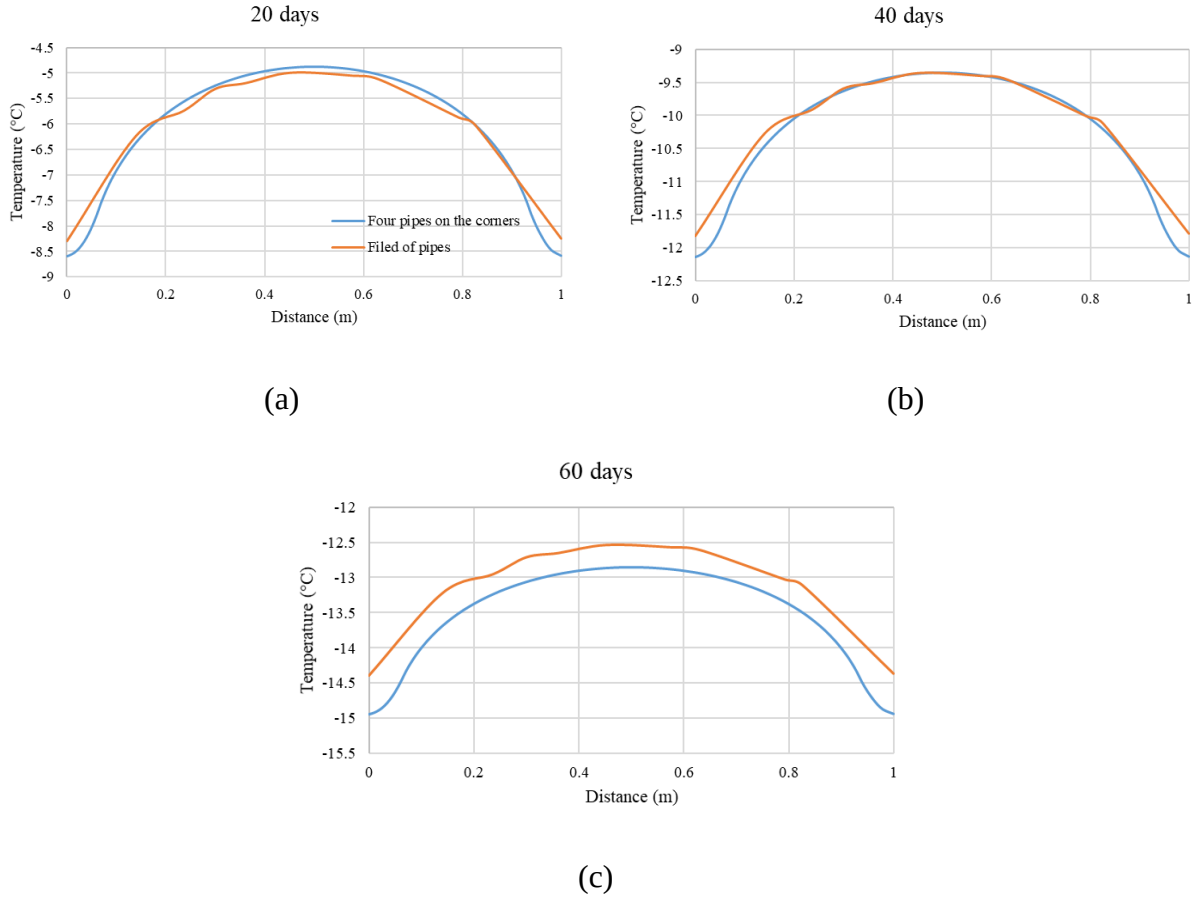


Fig. 3.4. Temperature profile between two wellbores at the center of the domain for the four-pipe segmented and whole field models: (a) after 20 days, (b) after 40 days, (c) after 60 days.

3.2.2.2. One pipe on the center of a circle

(a) Methodology and description

The no heat flux boundary could be considered a circle around the pipe as the center. Thus, this scenario could be equivalent to a situation in which there are pipes around the circle's center with a same distance of the circle's diameter. As shown in **Fig. 3.5**, a circular area is segmented from one of the pipes at the center of the domain in which the pipe is the circle's center.

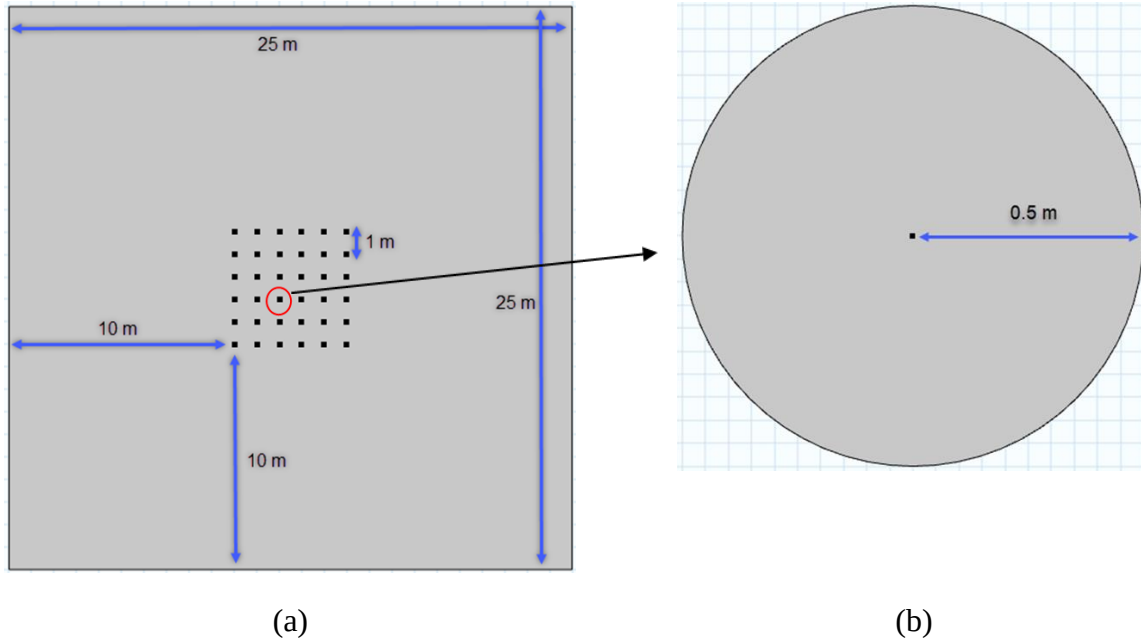


Fig. 3.5. Selection of a segment containing a circular domain with a pipe at the center.

(b) Comparison with the unsegmented model

The parameters used are obtained from **Table 3.1**. As shown in **Fig. 3.6**, the temperature distribution between the segmented and unsegmented models are similar, but the difference is quite high compared to that of the four-pipe segmented model. The minimum temperature is around -14°C in the unsegmented model while it is about -16.6°C in segmented one.

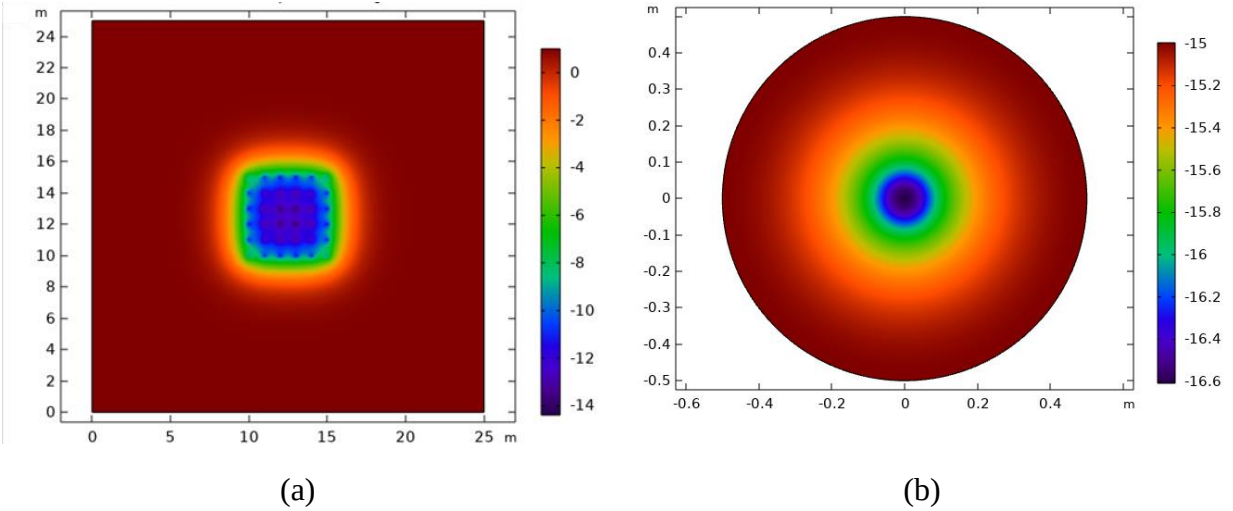


Fig. 3.6. Temperature distribution for (a) the whole field, and (b) circle segmented models, after 60 days. Temperatures are in Celsius.

Fig. 3.7 depicts the temperature profile for both models at three operation times (20, 40, 60 days). Since segmented model only includes a half of the distance, its temperature profile also shows half of the space between two wellbores. The difference between segmented and unsegmented models are noticeable even at 20 days ($\sim 1.2^{\circ}\text{C}$ maximum), it increases by time. Thus, the maximum difference is 1.7°C and 2.2°C for 40 and 60 days, respectively. Therefore, it seems that circle segmented model does not reveal quite accurate results compared to those of four-pipe segmented model.

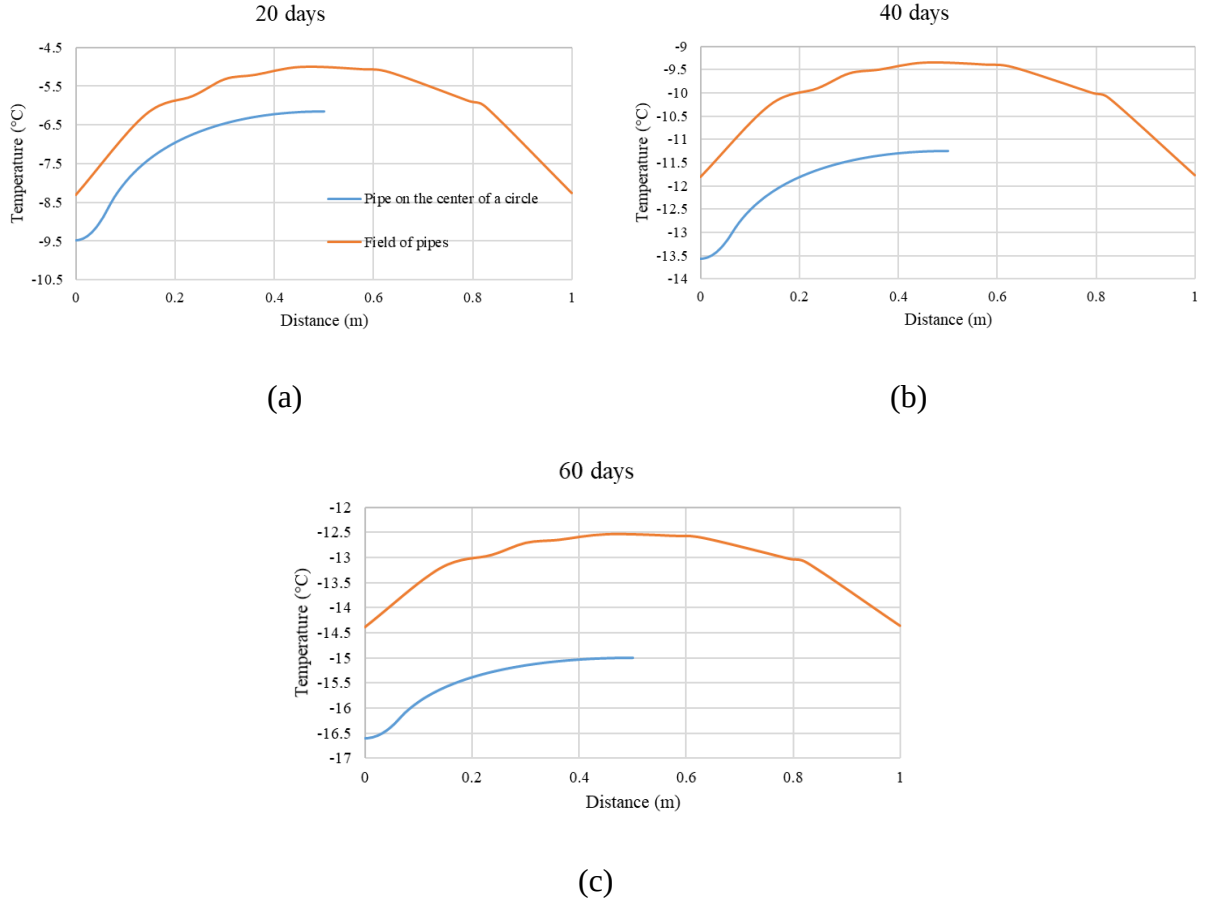


Fig. 3.7. Temperature profile between two wellbores at the center of the domain for the circle segmented and whole field models: (a) after 20 days, (b) after 40 days, (c) after 60 days.

3.2.2.3. One pipe on the corner of a square

(a) Methodology and description

Fig. 3.8 shows a square segmented from the field with a pipe at its center. Like the previous models, the pipe is selected from the one of the four pipes at the center of the field (**Fig. 3.8(a)**). The four sides of the segmented square are no heat flux boundaries.

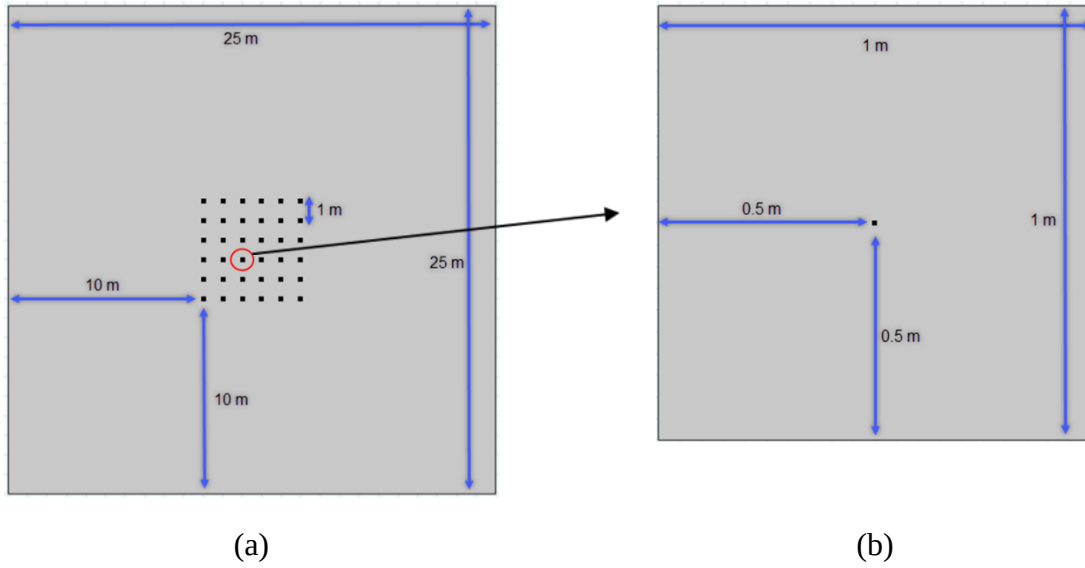


Fig. 3.8. Selection of a square segment with a pipe at the center.

(b) Comparison with the unsegmented model

The parameters used are obtained from **Table 3.1**. As shown in **Fig. 3.9**, the current model shows more accurate results compared to those of the circular segmented model. The lowest temperatures for both illustrations are close, around -14°C and -14.5°C for unsegmented and segmented models, respectively.

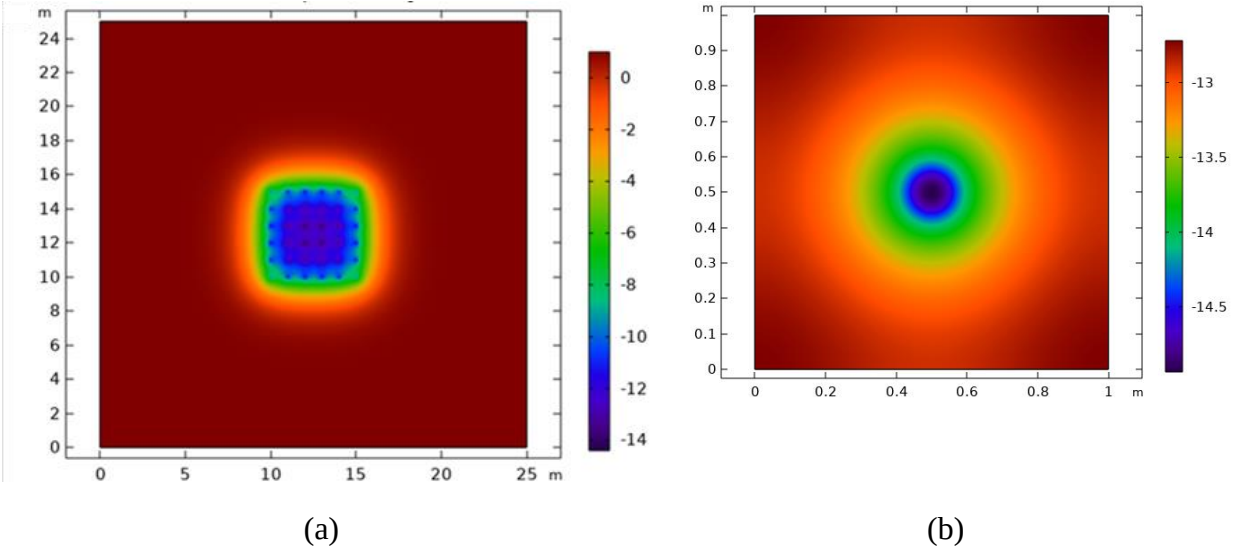


Fig. 3.9. Temperature distribution for (a) the whole field, and (b) square segmented models, after 60 days. Temperatures are in Celsius.

The temperature profile towards the distance between the wellbores gives a better understanding of how close the two models' results are. As can be seen in **Fig. 3.10**, the lines closely match together. The maximum differences are 0.3, 0.35, 0.5°C for 20, 40 and 60 days, respectively. Again, the difference values grow by time, but for a 60-day time period, a maximum difference of 3.5% is acceptable.

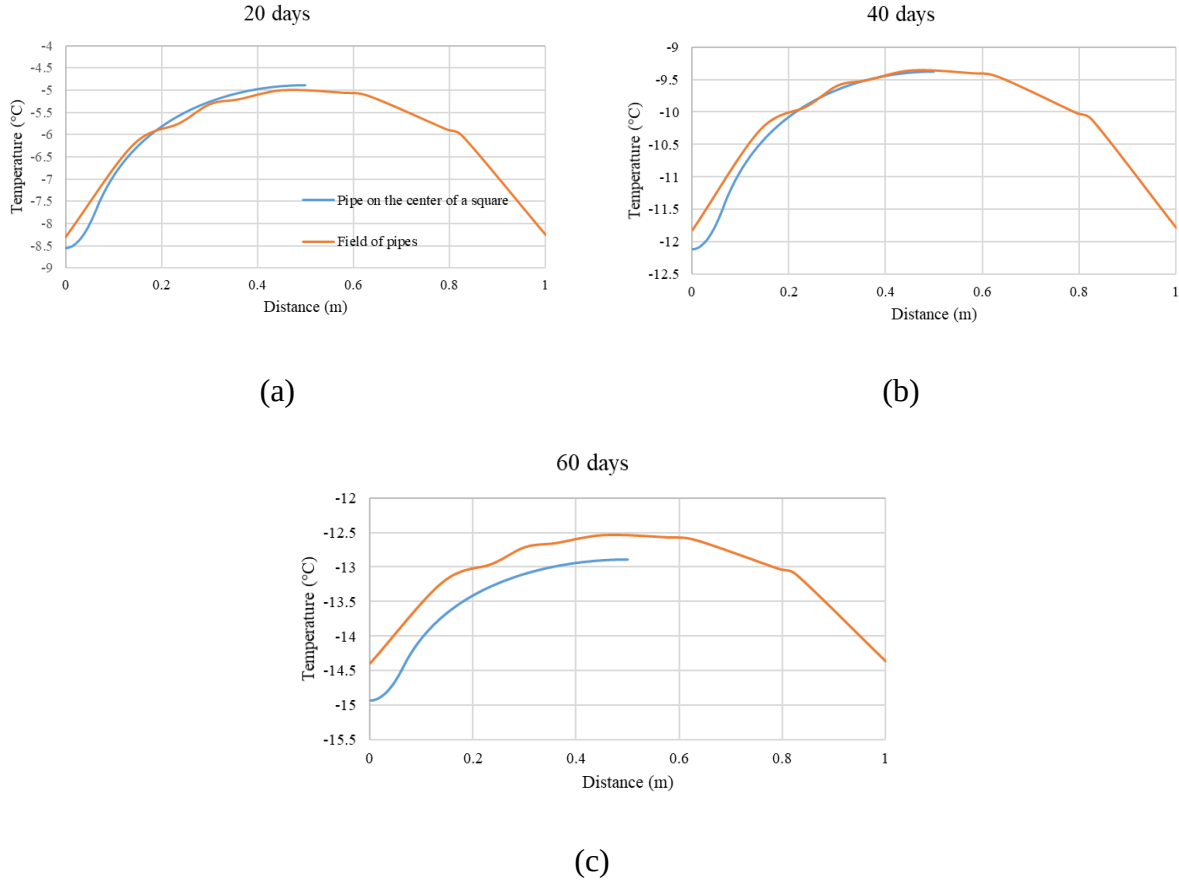


Fig. 3.10. Temperature profile between two wellbores at the center of the domain for the square segmented and whole field models: (a) after 20 days, (b) after 40 days, (c) after 60 days.

3.2.3. Mesh independency and validation

In this project, a set of different geometric configurations and parameters are subjects to study. Thus, grid system should be selected so that the mesh size has the minimum effect on simulation results. To find the acceptable mesh fineness, several mesh sizes were examined so that the results were stabilized, and the error was minimum. **Fig. 3.11** shows the temperature distribution after 60 days along with the half distance between two wellbores for 1-meter-distance case conducted by different number of domain elements (mesh sizes). According to **Fig. 3.11**, as the number of elements increases, the lines become closer and the difference tends to minimum. The maximum

difference between 24914-element and 6282-element cases is about 0.04%, therefore, the 24914-element system is selected.

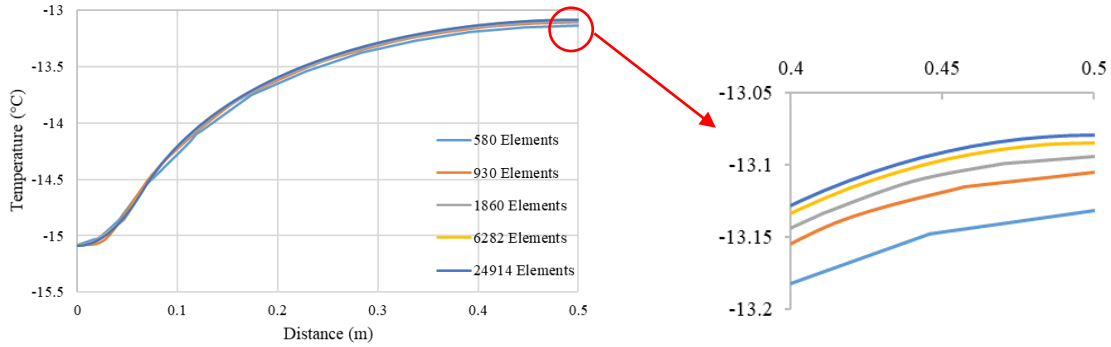


Fig. 3.11. Temperature along with half of the distance between two wellbores after 60 days, performed for different element numbers.

To quantitatively validate the results of this study, a set of parameters used by Cai et al. [38] are applied to the present model to measure the freezing front development versus time. In Cai et al.'s model, a single pipe with 108 mm diameter and a constant temperature of -80°C is buried into the soil. The water freezing occurs at -1°C and the initial temperature of the soil is 20°C . The properties of the soil can be obtained from Tables 1 and 2 from [38]. **Fig. 3.12** shows the freezing front development during 10 days of study period. Comparing the results obtained from the presented model and Cai et al.'s shows a maximum difference of about 9.57%.

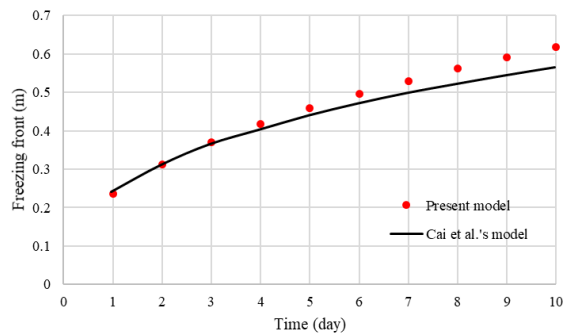


Fig. 3.12. Freezing front versus time.

3.3. Results and discussion

3.3.1. Soil properties

Of important factors influencing the performance are soil properties. In this section, different properties of the soil, thermal conductivity, specific heat, density and porosity, will be studied to investigate their impact on the temperature profile between two wellbores at the center of the domain. **Table 3.2** shows a set of different scenarios in which a specific property changes while others are constant. Bold numbers belong to the base model.

Table 3.2. Soil properties for different modeling scenarios.

Scenario#	Property	Value*	Unit
1	Thermal conductivity	1.0 , 1.2, 1.4, 1.6	W/m.K
2	Specific heat	1081, 1181, 1281, 1381	J/kg.K
3	Density	1400, 1500, 1600 , 1700	kg/m ³
4	Porosity	0.3 , 0.4, 0.5, 0.6	-

* The value ranges belong to sandy clay. Bold numbers belong to the base model (**Table 3.1**).

Fig. 3.13 depicts the temperature profile between two wellbores at the center of the domain after 60 days of time period. All the properties are obtained from **Table 3.1** and are fixed, except for the soil thermal conductivity which changes according to **Table 3.2**. A glance at the figure reveals that all the lines have the same temperature in the vicinity of the wellbores (i.e., just below -15°C). From around 7 cm away from the wellbores, the lines diverge so they make different maximum values. This maximum values are -13, -13.3, -13.5, -13.6 for the conductivities 1.0, 1.2, 1.4, 1.6 W/m.k, respectively. Thus, higher conductivities lead to lower temperatures between two wellbores and so higher amount of freezing storage. However, as the conductivity increases the sensitivity of the temperature to the conductivity changes decreases.

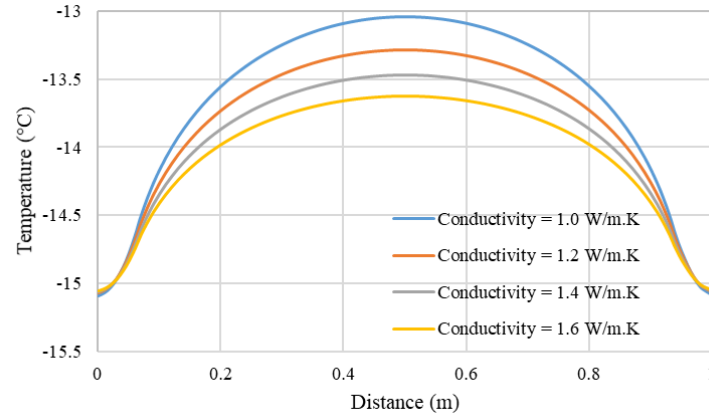


Fig. 3.13. Temperature profile between two wellbores towards x direction for different thermal conductivities after 60 days.

In **Fig. 3.14**, the impact of soil specific heat is the subject of study. Unlike **Fig. 3.13**, lines do not have the same value at the wellbore area ($T = -16.2^{\circ}\text{C}$ and -15.1°C for the lowest and the highest specific heats, respectively). In general, the lower specific heat is, the lower the temperature will be. For every 1000 J/kg.K increase in the specific heat, the temperature increases by 0.5°C towards the whole distance.

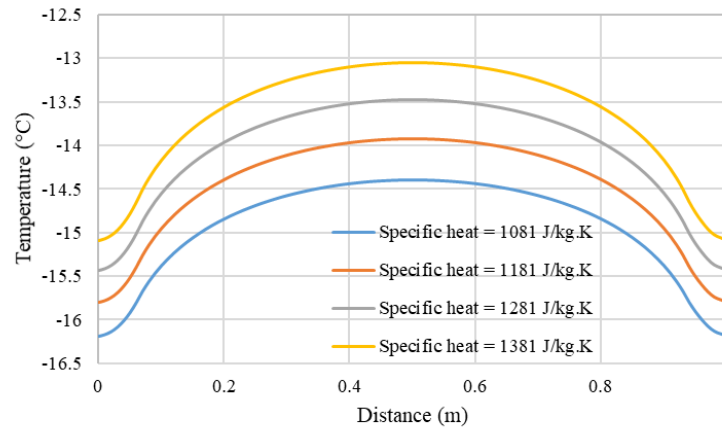


Fig. 3.14. Temperature profile between two wellbores towards x direction for different specific heats after 60 days.

According to **Fig. 3.15**, a soil type with a lower density leads to a lower temperature towards the whole distance between two wellbores. Thus, for the lowest density (i.e., 1400 kg/m^3), the temperature of the wellbore wall and the maximum temperature are -15.7°C and -13.8°C , respectively, while the same temperatures for the highest density (i.e., 1700 kg/m^3) are -14.8°C and -12.7°C . Consequently, a less dense type of soil is capable of store more amount of cold content.

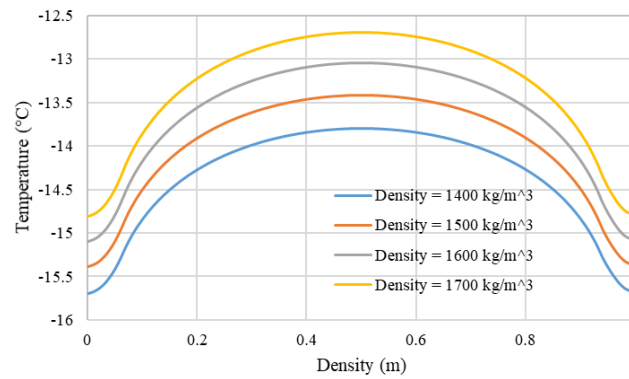


Fig. 3.15. Temperature profile between two wellbores towards x direction for different densities after 60 days.

According to **Fig. 3.16**, a 10-percent change in the soil porosity can change the temperature by more than 1°C . The reason is that a high-porosity soil contains more content of ice that has a higher value of specific heat.

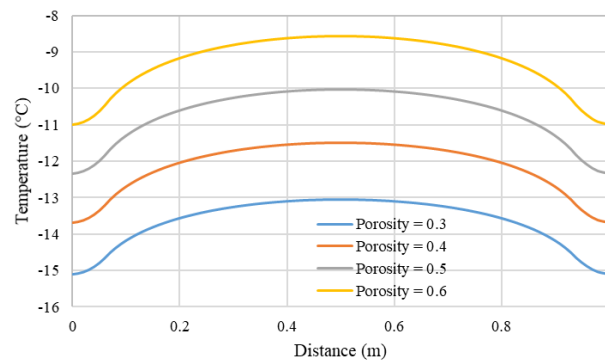


Fig. 3.16. Temperature profile between two wellbores towards x direction for different porosities after 60 days.

3.3.2. Pipe geometry

In this section, changes are applied in three main geometric parameters of the pipe, cooled length (L_C), heated length (L_H) and the inner diameter (d), to investigate the system's performance in each scenario. **Table 3.3** shows a set of different values for each parameter.

Table 3.3. Geometry parametric study.

Scenario#	Parameter	Values	Unit
1	Cooled length (L_C)	1.5, 3.0, 4.5	m
2	Heated length (L_H)	1.5, 3.0, 4.5	m
3	Inner diameter (d)	3.9, 6.4, 8.9	in

Each of the aforementioned scenarios will be investigated for four distance values between the wellbores: 0.25, 0.5, 1.0, 2.0 m. Considering a single wellbore in the field, the pipe has the maximum possible heat absorption, since there are no other pipes as competitors. Considering the single pipe as the reference, a performance coefficient can be defined as the heat transfer through a pipe in a field of pipes divided by the heat transfer through a single pipe ($\frac{Q_{one\ pipe}}{Q_{single\ pipe}}$). Therefore, it can be revealed that how the performance of one pipe in a field is similar to a single pipe or in other words ideal heat absorption.

A glance at **Fig 3.17** reveals that as the distances between the wellbores (spacing) grows the Q -ratio increases, which means the pipes perform more similarly to the single pipe (i.e., at 60 days, for $L_C = 4.5$ m, if distance = 1 m, Q -ratio = 0.3, and if distance = 2 m, Q -ratio = 0.8). The shorter the spacing is, the sooner the Q -ratio reaches zero (refer to distance = 0.25 m), which means that no heat flow transfers through that pipe (temperature gradient between up and down reaches zero).

At one specific value of spacing, the lower cooled length has the higher Q -ratio (e.g., at spacing = 1 m and $t = 60$ days, for $L_C = 1.5$ m, Q -ratio = 0.47 while for $L_C = 4.5$ m, Q -ratio = 0.29).

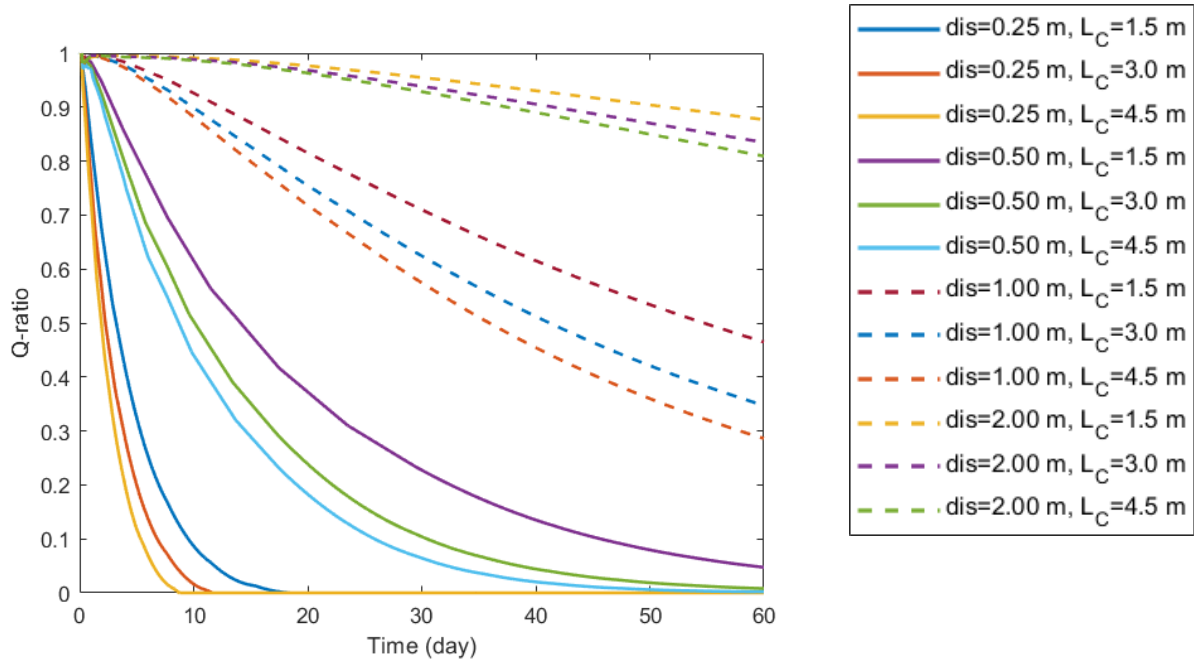


Fig. 3.17. Q -ratio vs time for different cooled lengths and spacings.

Fig. 3.18 shows the Q -ratio during 60 days for different set of heated lengths at different spacings. By increasing the spacing from 0.25 to 2 m, the sensitivity of the Q -ratio to the heated length decrease. For instance, the Q -ratio difference between $L_H = 1.5$ m and 4.5 m for the 0.5 m spacing is 0.2 while the value for the 2 m spacing is about 0.06. The longer the L_H is, the higher the Q -ratio will be. Therefore, a pipe with a longer heated length works more similarly to its single counterpart. The low spacing cases (0.25 m) reach the low Q -ratios very soon which means that although they absorb heat far less than a single pipe, since there are more pipes in a unit of ground area, the freezing and subsequently temperature equilibrium between up and down occur very soon.

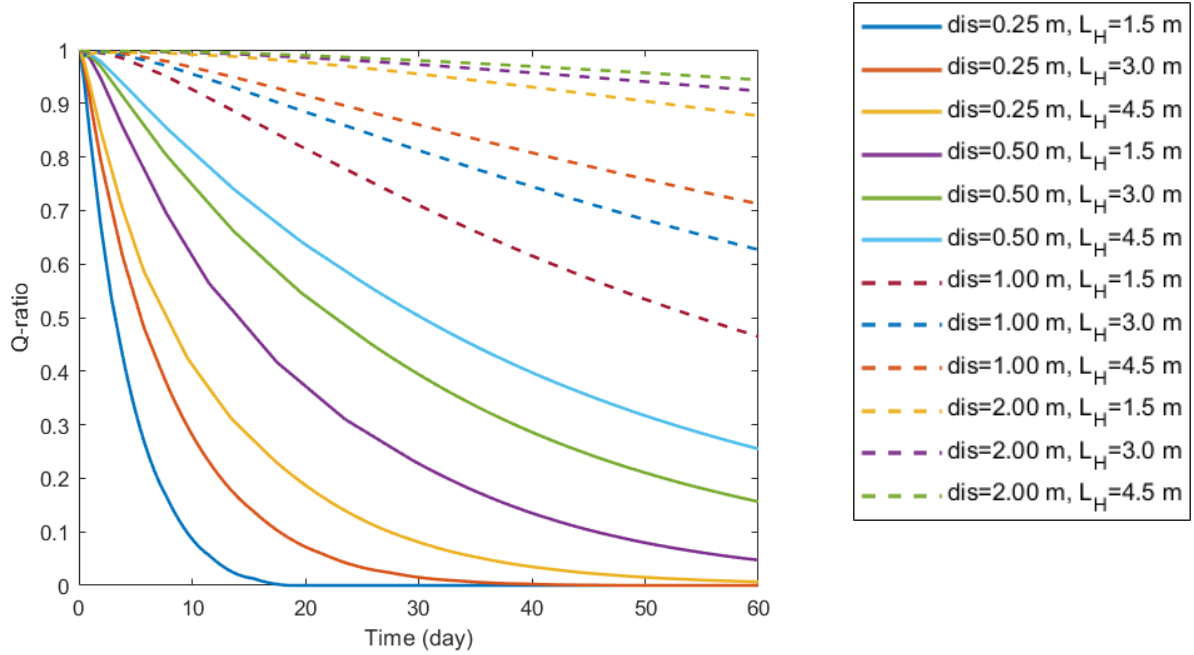


Fig. 3.18. Q-ratio vs time for different heated lengths and spacings.

Fig. 3.19 shows the Q-ratio graph for different inner diameter values. It is worthwhile noting that the outer diameter of the wellbore is calculated according to **Table 2.1**. As shown in **Fig. 3.19**, the lower the diameter is, the higher the Q-ratio will be. According to the figure, five cases reach zero Q-ratio (thermal equilibrium) before 40 days, three lines from 0.25 m spacing and two lines from 0.5 m. Consequently, an increase as small as 2.5 inches in diameter can make the Q-ratio decrease significantly.

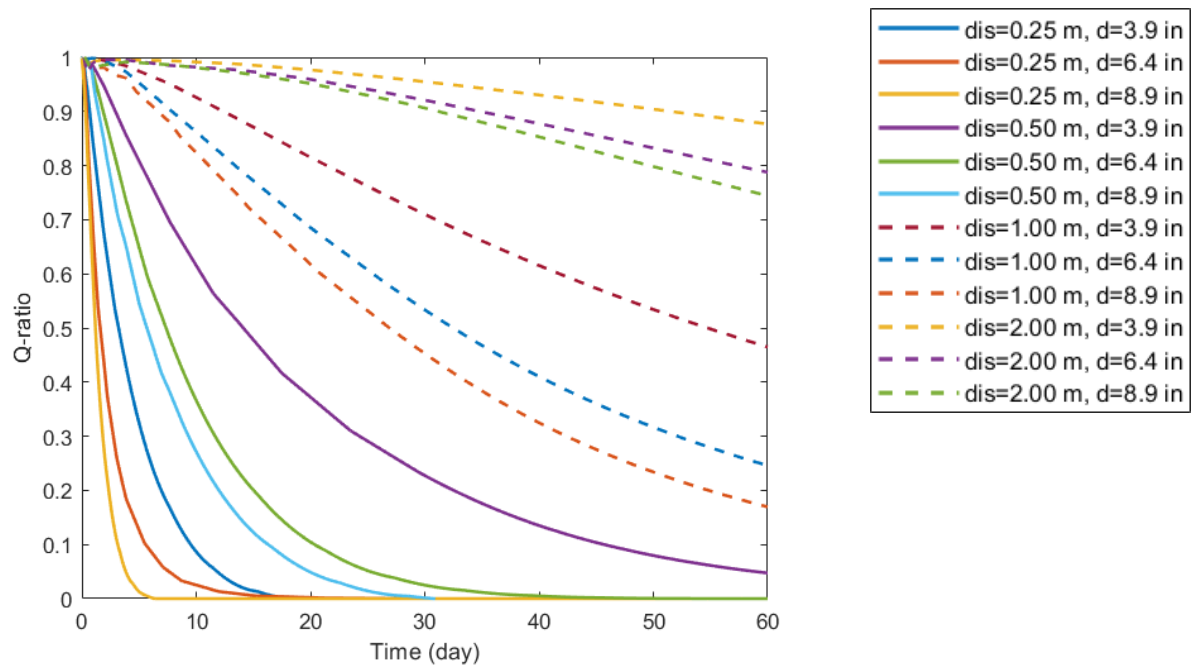


Fig. 3.19. Q-ratio vs time for different diameters and spacings.

Conclusions

In the first section of this study, an analytical approach was presented to model a closed pipe coupled with the ground and outside air. A single-phase antifreeze is considered inside the pipe for the heat transfer purposes. Heat transfers inside the ground towards the wellbore (conduction), and then travels through the pipe (convection), and lastly dumps into the air (convection). Although the results show that the heat transfer rate is not quite high compared to that of the forced convection, this type of devices does not impose any costs while running (e.g., no electricity consumption). Therefore, they can be used in multiple (e.g., a farm of installed pipes) for the artificial freezing purposes. The first section focuses on how to improve the performance of one pipe using parametric studies.

Depending on the application, the desirable device can be different. The results show that if a high heat transfer rate is of interest, the cooled length must be expanded. A longer L_C also gives a wider range of temperature difference ($(t_d)_C^H$) for the device to run. Thus, if seasonal temperature changes are expected, a long cooled length would be desirable.

If we intend to freeze to a high depth, a long heated length should be selected. Although the heat rate is smaller and the pipe works in a smaller temperature difference range in this scenario, a

higher freezing storage would be obtained. The freezing develops quite slower, but more soil volume is involved in freezing in this situation. Therefore, the heat extracted is mostly used to decrease the freezing zone's temperature.

Inner diameter of the pipe has a significant impact on the performance. Increasing the diameter by a few centimeters causes the freezing to develop further compared to that caused by a large increase in cooled length. Although increasing the diameter makes the device operate in higher temperature differences ($((t_d)c^H)$) that can be nonpractical for some applications.

The impact of outside temperature is higher than geometric parameters; however, considering both in accordance with each other can lead to select the proper combination in each scenario. For a device working in cold air, the temperature difference between up and down is already high. Thus, having a pipe with a large diameter and long cooled length is an appropriate option in this case.

The second section entails a 2D finite element model simulating multiple installed pipes. An approach was presented to simulate one pipe instead of many to achieve the same results. Considering a pipe operating at the center of the field, it is equivalent to a situation in which the pipe is surrounded by the no heat flux boundaries located at the middle of the distance between two wellbores. The results show that the temperature profile between two wellbores can reach lower temperature values provided that the soil's material entails higher thermal conductivity, and lower porosity, density and specific heat. One single pipe has the maximum heat absorption since it has no competitor. Defining a performance factor, the heat rate of a pipe on the field divided by that of a single pipe, we can determine how close a pipe's performance is to the maximum. The results show that in a multiple pipe situation, pipes with shorter cooled length, longer heated length and smaller diameter have more similar performance to their single counterparts.

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Appendices

The transformation of the fundamental equations in terms of λ is provided in the following:

$$\frac{d^2 T_I}{d\lambda^2} + \left(\frac{2\lambda^2 + 1}{\lambda} \right) \frac{dT_I}{d\lambda} = 0, \quad \lambda_{r_3} \leq \lambda < \lambda_S \quad (\text{S1})$$

$$\frac{d^2 T_{II}}{d\lambda^2} + \left(\frac{2\lambda^2 + 1}{\lambda} \right) \frac{dT_{II}}{d\lambda} = 0, \quad \lambda_S < \lambda < \infty \quad (\text{S2})$$

$$\frac{-k_I A_w}{\sqrt{4\alpha_I t}} \frac{dT_I}{d\lambda} = \frac{2\pi L k_{well}}{\ln(r_3/r_1)} (T_H - T_I) = Q, \quad \lambda = \lambda_{r_3} \quad (\text{S3})$$

$$\frac{-k_{II} A_w}{\sqrt{4\alpha_{II} t}} \frac{dT_{II}}{d\lambda} = \frac{2\pi L k_{well}}{\ln(r_3/r_1)} (T_H - T_{II}) = Q, \quad \lambda = \lambda_{r_3} \quad (\text{S4})$$

$$k_I \frac{dT_I}{d\lambda} - k_{II} \frac{dT_{II}}{d\lambda} = 2\phi \cdot \rho \cdot \alpha_I \cdot LH \cdot \lambda_S, \quad \lambda = \lambda_S \quad (\text{S5})$$

For the model without freezing, Eq. (2.28) in terms of λ becomes:

$$\frac{dT_{II}}{d\lambda} = \frac{\exp(-\lambda^2)}{\lambda} (-2A) \quad (\text{S6})$$

S6 at $r = r_3$ is:

$$\frac{dT_{II}}{d\lambda} = \frac{\exp(-\lambda_{r_3}^2)}{\lambda_{r_3}} (-2A) \quad (\text{S7})$$

Now, by substituting S7 into S4, A is obtained as follows:

$$A = \frac{-Q\lambda_{r_3}\sqrt{4\alpha_I t}}{2k_{II}A_w \exp(-\lambda_{r_3}^2)} \quad (\text{S8})$$

For the model with freezing, Eq. (2.29) in terms of λ becomes:

$$\frac{dT_I}{d\lambda} = \frac{\exp(-\lambda^2)}{\lambda}(-2B) \quad (\text{S9})$$

S9 at $r = r_3$ is:

$$\frac{dT_I}{d\lambda} = \frac{\exp(-\lambda_{r_3}^2)}{\lambda_{r_3}}(-2B) \quad (\text{S10})$$

Now, by substituting S10 into S3, B is obtained as follows:

$$B = \frac{-Q\lambda_{r_3}\sqrt{4\alpha_I t}}{2k_I A_w \exp(-\lambda_{r_3}^2)} \quad (\text{S11})$$

By substituting S10 into Eq. (2.29), and considering the fact that $T_I = 0$ at the moving interface ($r = S$), A_1 is obtained as follows:

$$A_1 = BE_i(-\lambda_s^2) \quad (\text{S12})$$

By considering the fact that in Eq. (2.29), $T_{II} = 0$ at the moving interface ($r = S$), C is obtained as follows:

$$C = \frac{T_{inf}}{E_i\left(-\frac{\alpha_I}{\alpha_{II}}\lambda_s^2\right)} \quad (\text{S13})$$

Now, Eq. S5 by inserting Eq. (2.29), T_I and T_{II} , becomes:

$$\frac{k_I(-B)}{k_{II}T_{inf}} \underbrace{\left(\frac{\exp(-\lambda_s^2)}{\lambda_s}\right)}_{G(\beta)} + \underbrace{\left(\frac{\exp\left(-\frac{\alpha_I}{\alpha_{II}}\lambda_s^2\right)}{\lambda_s E_i\left(-\frac{\alpha_I}{\alpha_{II}}\lambda_s^2\right)}\right)}_{H(\beta)} = \underbrace{\phi\rho\alpha_I L_H \lambda_s}_{I(\beta)} \frac{1}{k_{II}T_{inf}} \quad (\text{S14})$$

Rearranging the equation S14 gives:

$$k_{II}T_{\text{inf}}H(\lambda_s) - k_I BG(\lambda_s) - I(\lambda_s) = k_{II}H(\lambda_s) \quad (\text{S15})$$

The solution of the above equation returns λ_s (λ at $r = S$), which is the dimensionless freezing rate and location of the moving interface (the definition for beta). All the calculations are performed in MATLAB programming software.