Renewable energy-based artificial ground freezing as an adaptation solution for sustainability of permafrost in post-climate change conditions

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Abstract. Climate change is expected to impose higher ground temperatures, seriously challenging the sustainability of permafrost regions by thawing irreversibly, compromising ground stability and causing high seepage flows. Mining operations are particularly vulnerable to permafrost removal, and in extreme cases may face catastrophic consequences in their waste management systems, such as tailings dams. So far, artificial ground freezing has been promoted as a reliable and technologically possible solution to maintain permafrost against raises in ground temperature. However, considerable amounts of electric power are required which can be challenging especially in remote areas. A solution can be sought by taking advantage of cold winter temperatures to provide artificial ground freezing. In this renewable energy-based technique, thermosyphons use subfreezing winter temperatures to create enough freezing in the permafrost layer which can last during the summer as well. The present paper underlines the importance of developing the proposed technology and evaluates its techno-economic feasibility through numerical and experimental studies. It offers a numerical model for a renewable energy-based artificial ground freezing system and validates its results against laboratory experiments. The results suggest that the utilization of thermosyphon along with cold-energy storage increases and maintains the thickness of the permafrost, especially during the summer season.

Keywords: Artificial ground freezing; thermosyphon; permafrost; climate change; adaptation; sustainability

1. Introduction
Permafrost, which is permanently frozen ground, is an essential parameter to be considered in the development and management of mining operations in Northern Canada. It supports mines’ infrastructure foundation, such as roads and airports, and improves the drilling process [1, 2]. However due to its vulnerability to rising global temperatures – notably in high latitudes [3]– in a changing climate, permafrost has been thawing over the last 50 years [4-8]. Some studies suggest this situation tends to intensify in the next decades [9, 10], which represents a serious challenge for mining operations. It also has implications for mine closure, since the foundations of some waste management systems relied on permafrost stability during construction; changes may therefore lead to catastrophic dam failures if not adequately managed [11]. Although this phenomenon sounds unavoidable, mining specialists provide several support approaches to overcome this problem. Among other geotechnical support methods, artificial ground freezing (AGF) is the most favorable method for long-term
environmental projects. The AGF method is commonly employed to compensate the melted permafrost spots [12, 13]. The associated AGF system, however, has to operate continuously to maintain a sufficient thickness of the frozen body. This operation mode requires intensive energy input, which leads to immense operational and maintenance costs – not to mention a large carbon footprint! These expenses could put great pressure on the available resources and arouse cost-effective concerns regarding the AGF systems, especially in the case of long-term implementation. Therefore, a reliable, cost-effective AGF operational technique is critical to sustaining the permafrost, which, in turn, support the plans for sustainable mineral extraction and environmental protection. The effect of thermosyphon on the thickness of the permafrost have been evaluated by several studies [14-18]. Wei et al. [15] studied the importance of a passive cooling system to maintain the thickness of the permafrost. The results of their studies suggest that under the current global warming situations, a sustainable approach must be implemented ice-rich, warm areas.

This study aims to investigate the impact of a novel concept of a sustainable AGF system on the sustainability of permafrost. The proposed system comprises of a thermosyphon and a phase-change material (PCM) that serves as "cold" energy storage. The fundamental notion behind this idea is to freeze the PCM in winter to store the coolth energy and utilize it in summer when the ambient temperature rise beyond certain limits. The main objective of this study is to evaluate, by means of a mathematical model, the growth of permafrost in the last ten years utilizing the proposed method.

| Nomenclature          | Equation                        |
|-----------------------|---------------------------------|
| \( c_m \) mushy constant | \( k \) thermal conductivity    |
| \( g \) Gravitational acceleration | \( K \) permeability            |
| \( h \) enthalpy       | \( p \) pressure                |
| \( h \) heat transfer coefficient | \( t \) time                    |
| \( \Delta H \) latent heat | \( T \) temperature             |
| \( \rho \) density      |                                 |

2. Model Development

In this study, a two-dimensional axisymmetric computational domain consists of a vertical thermosyphon and porous ground matrix, as depicted in figure 1. The local thermal equilibrium (LTE) approach is considered within the ground strata [19]. The LTE hypothesis is implemented when the local temperature difference between the pore-ice, pore-water, and soil particles is insignificant, as compared with the global temperature difference. The ambient temperature is considered based on the daily averaged temperature readings of the city of Yellowknife NWT, Canada [20].

![Figure 1](image-url)

Figure 1. Schematic diagram of the computational domain that includes a thermosyphon and the surrounding ground.

2.1. Governing Equations

A 2D mathematical model describing the conservation equations of mass, momentum, and energy is derived considering the local volume-averaged formulations and the LTE assumption:
- Conservation of mass:
\[
\frac{\partial}{\partial t}(\rho) + \nabla \cdot (\rho \mathbf{u}) = 0
\]

- Conservation of momentum:
\[
\frac{1}{\varepsilon} \frac{\partial}{\partial t}(\rho \mathbf{u}) + \frac{1}{\varepsilon^2} \left[ \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) \right] = -\nabla p + \frac{1}{\varepsilon} \nabla \cdot (\mu_{\ell}(\nabla \mathbf{u} + \nabla \mathbf{u}^T)) + \rho_{\ell} g = \left[ \frac{\mu_{\ell}}{k} \mathbf{u} + u_{cm} \frac{(1 - \gamma)^2}{\gamma^3} \right]
\]
The last two terms are Darcy and the mushy source terms, respectively. The former represents the bulk resistance to the flow, while the latter characterizes the phase-change process in the porous medium. The mushy source term takes a value of zero in the liquid zone. The conservation equation of momentum is then approximated by Darcy law. Within the freezing zone, the source term starts to increase from zero into a large value. As the local liquid fraction, \( \gamma \), reaches a value near zero, the modified Darcy source term (mushy source term) becomes the most dominant source terms which, in turn, mitigate the velocity, \( \mathbf{u} \).

- Conservation of energy:
\[
\frac{\partial}{\partial t} (\rho h) + \nabla \cdot (\rho \mathbf{u} h) = \nabla \cdot (k_e \nabla T) - \Delta H \left( \frac{\partial}{\partial t} (\gamma \rho_{\ell}) + \nabla \cdot (\gamma \rho_{\ell} \mathbf{u}) \right)
\]
where,
\[
(\rho h)_e = \varepsilon [\gamma \rho_{\ell} h_{\ell} + (1 - \gamma) \rho_s h_s] + (1 - \varepsilon) \rho_p h_p
\]
The effective thermal conductivity, \( k_e \), is formulated using the parallel arrangement approach as:
\[
k_e = \varepsilon [\gamma k_{\ell} + (1 - \gamma) k_s] + (1 - \varepsilon) k_p
\]
During the freezing process and within the mushy-zone the value of the local liquid fraction, \( \gamma \), decreases from its liquid value of 1 to 0, which, in turn, induce the contribution of the latent heat, \( \Delta H \), to the conservation equation of energy.

2.2. Initial and Boundary Conditions
The initial and boundary conditions are specified as below:
- Initial Condition: \( T = T_i ; \quad \mathbf{u} = \mathbf{u}_i \)
- Ground Surface: Convective boundary condition \( q = h(T - T_{amb}) \)
- Thermosyphon wall: \( T = T_w \)
- Ground Bottom: \( q = q_{geo} \)

3. Numerical Methodology
A two-dimensional axisymmetric domain was developed and meshed using ANSYS software package 16.1 and was labeled with proper boundary conditions. Different mesh sizes were implemented and analyzed to ensure a mesh-independent solution. A fine mesh with 320,800 cells provided a practical balance between simulation time and results accuracy.

The governing equations were solve using a finite-volume solver (ANSYS Fluent 16.1). The solidification/melting approach was activated to simulate the freezing in the porous ground structure; the mushy constant was calibrated at \( 5 \times 10^6 \). A user-defined functions (UDFs) code was implemented in the simulation to specify the ambient temperature, the sand properties, and the temperature-dependent properties of the groundwater. The concept of a simple thermosyphon without energy-storage was implemented automatically by changing the boundary condition of the freeze pipe's wall from constant wall temperature (in winter) to a zero-heat-flux (in summer) using a logical algorithm in a scheme-language command and journal scripting. The transient time step was set to ensure sufficient convergence criteria (predetermined at \( 5 \times 10^{-5} \)). The equations were solved with a second-order upwind discretization and by implementing the Semi-Implicit Pressure-Linked Equation (SIMPLE) algorithm.

4. Results and Discussion
In this study, the influence of the thermosyphon with and without coolth energy storage on the sustainability of the permafrost was evaluated. The results of this study aim to quantify the growth of permafrost over a period of time for alternative scenarios, i.e. with and without the implementation of thermosyphons. The results are monitored over ten years taking into consideration the alternating seasons. Accordingly, a sinusoidal function is considered in this study to model the ambient temperature of the four seasons. The temperature is oscillating, roughly, between 20 (summers) and -25 °C (winters).

Figure 2. The readings of the ambient temperature and ground temperatures at one-meter depth and one meter away from the thermosyphon at different scenarios in the course of (a) ten years and (b) one year.

Figure 2 quantifies the impact of using a thermosyphon on the temperature of the ground for ten years. The ambient temperature is based on the actual daily average temperature readings at Yellowknife, Canada between the period of 2009 and 2017. The ground temperature was measured at a depth of one meter and a distance of one meter from the thermosyphon. The measurements are recorded for three different scenarios: (i) the absence of thermosyphon; i.e., the natural effect of the seasonal temperature variation on the permafrost, (ii) the implementation of a basic thermosyphon. In this case, the thermosyphon is designed to operate only when the ambient temperature is below -5 °C, and (iii) the implementation of a thermosyphon with cold-energy storage. In this scenario, the PCM stores the cold energy in winter and utilize it in summer when the ambient temperature exceeds certain limits that prevent the thermosyphon to operate properly. This concept allows the thermosyphon to provide a steady cold temperature. The ground temperature is highly affected by the variation of the ambient temperature in all cases. The utilization of the thermosyphon, however, helps in reducing the ground temperature in summers, as depicted in figure 2-a.

On the other hand, figure 2-b shows that at certain points the ground temperature without implementing a thermosyphon is colder than the other two scenarios. This is due to the fact that in this study, the thermosyphon was designed to provide a -5 °C. In cold winters, the ambient temperature could reach -25 °C (such as winter 2013; after 1460 days), which will make thermosyphon acts as a heater. Therefore, it is crucial to determine the design parameters of the thermosyphon carefully.

Figure 3 illustrates the liquid-fraction contours of three different scenarios. Figure 3 (a) and (d) represent the natural growth of the permafrost whereas figure 3 (b) and (e) mirror the permafrost formation with the presence of a basic thermosyphon, and figure 3 (c) and (f) shows the growth of the permafrost with the support of a thermosyphon and cold-energy storage. It is important to highlight here that these contours are for the permafrost formation after ten years. Therefore, the contribution of the previous winters to the frozen ground formation is clear; the previous summers were not warm enough to thaw the whole permafrost, as suggested by figure 3 (a), (b), and (c). Furthermore, the contribution of the thermosyphon to the growth of the permafrost is demonstrated by the thickness of the frozen body. Figure 3 (b) shows the contribution of the basic thermosyphon to the formation of the frozen ground in winter. On the other hand, the thermosyphon does not operate in summer, which allows the ambient temperature to thaw the upper part of the frozen body. However, a comparison between figure 3 (e) and (d) will show the contribution of the thermosyphon to increase the thickness of the frozen body.
Moreover, the cold-energy storage improves the role of the thermosyphon by increasing the thickness of the frozen body in winter and maintaining a certain thickness of the permafrost in summer. – it is important to highlight here that figure 3 (f) pictures the shape of the permafrost on the warmest day of summer 2017, where averaged ambient temperature was around 20 °C.

Figure 3. The formation of the permafrost at different scenarios after ten years: (a) and (d) winter and summer of 2017 without thermosyphon, (b) and (e) winter and summer of 2017 with a basic thermosyphon, and (c) and (f) winter and summer 2017 with a thermosyphon and a cold-energy storage.

5. Conclusions
A two-dimensional mathematical model based on the conservation mass, momentum, and energy was derived and analyzed to quantify the impact of the seasonal temperature variation on permafrost formation. The study discussed the impact of utilizing a novel concept of thermosyphon and a cold-energy storage system on the sustainability of the permafrost. The study compared the temperature of the ground and the thickness of the frozen body under several scenarios. The results displayed an increase in the thickness of the permafrost when the thermosyphon is utilized. Moreover, the cold-energy storage improved the performance of the thermosyphon by maintaining, to an extent, the thickness of the permafrost. The contribution of the cold-energy storage is clear during the summer season; it reduces the ground temperature around 4 °C, as compared to the traditional thermosyphon.

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7. References
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