Thermal Design of Small Modular Reactors in Northern Regions

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Abstract. Small Modular Reactors (SMRs) are increasingly recognized as safer and more flexible alternatives to conventional nuclear power plants in today's industry. Their safety and flexibility, coupled with their lower time and capital investment requirements, make SMRs an ideal choice for clean energy in Canada's remote communities. These communities are currently heavily dependent on fossil fuels, and transitioning to clean energy sources like SMRs will be essential for Canada to achieve its net-zero emissions target by 2050. However, the application of SMR technology in permafrost regions affected by climate change raises concerns. Permafrost degradation can cause serious deformations and settlements, which can result in elevated maintenance costs and reduced durability of SMR infrastructure. With a warming climate, the traditional civil engineering approach of assuming climate stationarity is unreliable for ensuring safe and durable infrastructure. Therefore, a non-stationary climatic approach must be considered. This article presents a heat transfer model for permafrost foundations and investigates the combined effects of heat loss via SMRs and global warming on permafrost degradation. By examining the interaction between SMRs and permafrost degradation, the article sheds light on the potential risks and challenges associated with the use of SMRs in permafrost regions.

Keywords: Small Modular Reactor (SMR) · Permafrost · Heat Transfer

1 Introduction

Nuclear power, as a clean energy source, plays a crucial role in the economic development of the northern regions. Other sources of clean energy such as solar, wind, and geothermal provide intermittent and/or partial electricity and are not generally practical for long-term solutions in islanded, micro-grid communities, and resource projects. Further, the geopolitical importance of Canada's Arctic necessitates a viable and continuous source of energy in such remote areas. Compared to conventional nuclear power plants (NPP), SMRs are considered to be safer, more cost-effective, and more flexible, requiring smaller capital input with shorter construction periods [2]. Such features make SMRs an ideal energy source in remote communities that are heavily dependent on diesel and other

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fossil fuels. For instance, almost all of Nunavut's electricity is generated currently from diesel fuel imported during the summer and then stored for year-round use [1]. SMRs, which would replace fossil fuels for heat and power generation to homes and heavy industries, will assist Canada in meeting its commitment to achieving net zero emissions by 2050. This would additionally improve the quality of life for people living in remote communities by improving air quality and reducing reliance on fuel imports.

While SMRs are faster to construct and easier to implement compared to NPPs, many concerns still need to be addressed especially in vulnerable (sub)arctic regions that are adversely affected by climate change and associated permafrost degradation. In terms of design, a substantial part of the reactor unit itself can be partially or fully embedded in the ground. The interaction between the reactor unit and surrounding soil/rock, especially with accelerating climate change in northern regions, can raise issues for the structural integrity of SMRs. For example, the ground's strength and stiffness may be significantly reduced due to thermal disturbance of the permafrost, resulting in structural settlement and stability problems. The ensuing damage will potentially shorten the lifespan of the infrastructure and increase maintenance costs, leading to significant operational and financial risks. It may also cause adverse environmental impacts and safety concerns from the public. Therefore, local permafrost conditions must be assessed and adequately protected around the structural foundations of the SMR facility when constructing an SMR on/or in permafrost soils or bedrock. For instance, the reactor core in SEALER developed by LeadCold operates between 390 °C and 432 °C [10], which would significantly affect the depth of active layer if not properly sealed.

Globally, there are currently over 50 prototypes of SMRs with varying modularity and scalability, all competing for widespread adoption. In Canada, there have been several proposals to utilize SMRs for power generation in different regions of the country. Notable among these proposals are the Stable Salt Reactor - Wasteburner (SSR-W) developed by Moltex Energy and the SEALER developed by LeadCold [3]. The Government of New Brunswick, Canada has selected Moltex and the SSR-W design for power production in the province, and stakeholders in the arctic regions of Canada have expressed their interest in investing in the SEALER reactor as a new means of power generation in those areas [10]. In the SSR-W technology, molten salt tanks would operate at temperatures around 550 °C to store thermal energy when the reactor's working capacity is not required. Although this technology has proven to be cost-effective and the concept has been studied for a long time, it would not be beneficial to install such facilities in permafrost-bearing regions like Nunavut. Studies suggest that heat loss via the bottom of the molten salt tanks is considerable, even if multiple layers of thermal insulation are involved [8, 11]. Since storing the produced energy is an important factor in the economic feasibility of SMR projects, this problem needs to be investigated in permafrost regions. It is worth mentioning that there is a lack of data in the literature on actual heat generated by the reactor core buried in the ground [9], and the thermal boundary conditions for these facilities lack precision.

Moreover, changing climatic conditions may degrade the physical and mechanical properties of the permafrost soils over and above the changes caused by the thermomechanical interaction between the SMR and surrounding soils. As our climate changes (non-stationarity), the demands or loads arising from weather conditions change over time. Because of these changing climatic patterns, erratic changes in ambient and ground temperature may occur resulting in detrimental transformations in the permafrost properties both spatially and temporally. Changing loads (demands) and capacities because of climate change and permafrost degradation create additional challenges in the structural design of SMRs. The lack of appropriate provisions for the incorporation of future weather and climate information into the design, operation and management of infrastructure remains a significant barrier to systematically improving the climate resilience and structural integrity of civil infrastructure, particularly SMRs.

Considering the above issues, in this paper, we simulate the thermal interaction between a SEALER reactor and permafrost foundations by considering AI-powered ground surface temperature predictions, which account for climate thermal non-stationarity, until 2050.

2 Numerical Modelling

The model presented in this paper consists of an axisymmetric cross-section of a SEALER reactor developed by LeadCold, which is planned to be used in Nunavut, Canada. The model is developed with COMSOL Multiphysics software, and it consists of ground and concrete elements. The soil domain extends at a depth of 24 m below the SMR's foundation and reaches to an elevation of −30 m. The axisymmetric condition has been assigned to the left boundary of the soil domain. The total radius of the model spreads for 15 m which is eleven times the radius of the SMR structure. The thickness of the concrete below-grade envelope is assumed 1 m. In Fig. 1(a), a general view of the geometry of the 2-D model has been shown. The mesh of the model was constructed using the physic-controlled sequence type, with a fine mesh refinement applied in the vicinity of the basement structure. The design of the reactor can be seen in Fig. 1(b).

2.1 Governing Equations

Frozen soil is a three-phase porous medium, which is composed of solid grains, water, and ice. The governing equations for transient heat conduction in freezing soils, which take into account the latent heat released during the phase change of pore water, can be defined as follows [7]:

$$\left(\rho C_p - L_f \rho_i \frac{\partial \theta_i}{\partial T}\right)\frac{\partial T}{\partial t} + \nabla.\mathbf{q} = Q \tag{1}$$

in which $(\rho C_p - L_f \rho_i \frac{\partial \theta_i}{\partial T})$ is the apparent volumetric heat capacity, L_f is the latent heat of fusion per unit mass of water (approximately 3.33×10^5 J/kg), ρ_i is the density of ice and $\theta_i = n - \theta_w$ is the volumetric fraction of pore ice by knowing that n is the porosity of the soil and θ_w is the unfrozen water content, ρC_p is the volumetric heat capacity of the soil which can be estimated by the sum of the volumetric heat capacity of each constituent of a saturated freezing soil (solid skeleton, water, and ice) multiplied by its volumetric fraction as described below:

$$\left(\rho C_p\right) = \rho_w C_w \theta_w + \rho_i C_i \theta_i + \rho_s C_s \theta_s \tag{2}$$

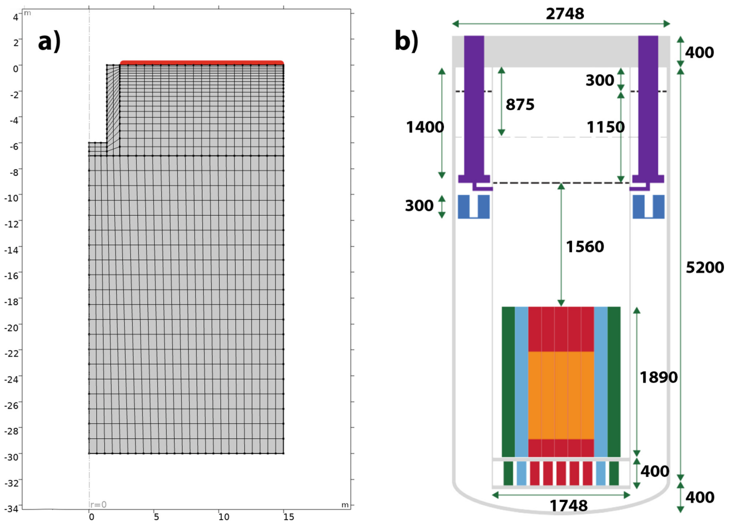

Fig. 1. a) The model is axisymmetric along r = 0 m (dashed line). The dimentions are in meters. b) Design and dimensions of the SEALER core reactor developed by LeadCold [5]. The dimentions are in milimeters.

Fourier's law is used to describe the heat flux, **q**, in Eq. 1:

$$\mathbf{q} = k\nabla T \tag{3}$$

The effective thermal conductivity and effective heat capacity terms are calculated as follows:

$$k = k_w\theta_w + k_i\theta_i + k_s\theta_s \tag{4}$$

In order to determine the unfrozen water content of the soil in the model, the following equation is used [4]:

$$\theta_w = \theta_{wr} + (\theta_{w0} - \theta_{wr})e^{(a(T-T_0))} \tag{5}$$

where θ_{wr} is the residual unfrozen water content which is assumed to be 0.05 in this study [7] and a[1/°C] is a parameter that controls the curvature, taken here 0.16 [7].

To consider climate non-stationarity in the analysis, an AI-powered ground surface temperature projection until 2050 is considered. The bottom boundary of the model is set to replicate the geothermal gradient effect, which is q = 0.032 W/m^2 [6]. The boundary conditions at the interface between the SMR reactor (underground wall and floor slab) and the soil are based on the thermal characteristics of the SEALER [5]; the environment around the reactor is considered as an infinite heat sink and the temperature of the concrete pit is set to a constant value of 90 °C. An adiabatic condition was assigned to the left and right boundaries of the model where no heat flow was assumed. In addition, the initial temperature of the soil domain is assumed to be equal to −4.8 °C. The physical properties of the soil's components and concrete used in the simulation can be found in Table 1. Concrete properties are adopted from [9].

Table 1. Physical properties of model components

Components	Density (kg/m^3)	Heat Capacity (J/kg.K)	Thermal Conductivity (W/m.K)
Solid grains	2600	795	2.62
Water	1000	4192.2	0.6
Ice	917	2090	2.2
Concrete	1920	840	1.4

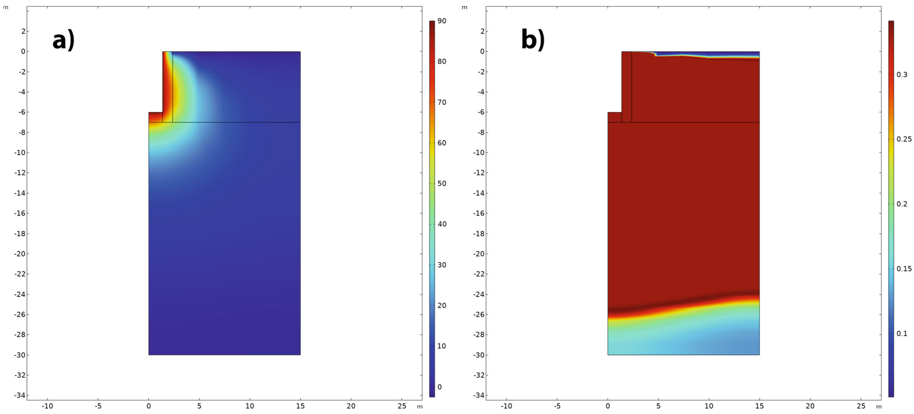

Fig. 2. Model results after a duration of 25 years, from 01 Jan 2025 to 01 Jan 2050. a) Temperature profile on 01 Jan 2050 b) Water content data on 01 Jan 2050.

3 Results and Discussion

The temperature profile of the ground at the end of the running duration (25 years) is shown in Fig. 2(a). The effect of heat loss via the reactor is best understood when comparing the temperature profiles in 2D graphs. In Fig. 3, the blue line represents the temperature profile at the centerline below the reactor, and the orange line is the temperature profile on the right side of the model domain (15 m away from the center of the reactor core). The lines are from the last time step, which is on 01 Jan 2050. It is observed that directly under the reactor core, the depth of the active layer goes as deep as 27 m, while this depth is around 24 m at 15 m from the centerline. This shows that after 25 years, large areas under the reactor facility could be affected by heat loss via the SMR structure.

After five years, in the month of January, the water content profile of the domain is shown in Fig. 2(b). As expected, the effect of heat loss through the reactor is more severe directly below and around the structure. Although the temperature variations at the ground surface have caused some irregular freezing away from the reactor, the regions close to the facility seem to contain the maximum unfrozen water content in the model, even in the coldest time of the year.

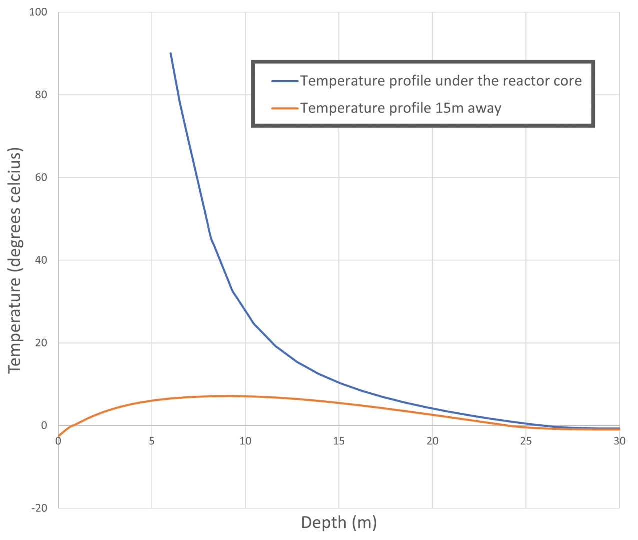

Fig. 3. Temperature profile directly under the reactor core (blue line) and 15 m away from the reactor core (orange line).

4 Conclusion

The thermal effects of an SMR reactor installed on a permafrost foundation in Nunavut were investigated for a duration of 25 years. If the concrete pit is kept at a temperature of 90 °C, the depth of the active layer could become as deep as 27 m, and the thermal stability of the region is severely affected. This thermal destabilization of the ground could lead to irregular settlement of the SMR site. A possible solution to this problem could be the installation of refrigeration facilities to keep the temperature around the reactor from rising, and the standard temperature could be determined according to the optimal value determined by the ongoing research. The use of more advanced insulation material around the reactor can also contribute to preventing heat from adversly affecting frozen soil layers. More investigation is needed in this area regarding the effect of coupled heat and mass transfer and different thermal mitigation techniques for the SMR reactor.

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