Natural Heat Exchanger Engineering Technology (NHEET) Public Report

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Executive summary

Air delivery to deep underground mines in Canada often requires refrigeration and heating systems, which have significant capital and operational costs and produce large quantities of greenhouse gas emissions. Natural Heat Exchanger Engineering Technology (NHEET) is an engineered low-cost and green solution for conditioning mine ventilation air. NHEET uses fans to generate airflow through recycled waste rock to form a thermal energy storage system in which energy from the ambient air temperature cycles is stored in the rock mass. The system can provide steady-temperature air year-round, reducing overall refrigeration and heating requirements of mine ventilation. Moreover, peak refrigeration and heating demand during extreme weather events such as heat waves and cold spells are eliminated. NHEET is inspired by the Natural Heat Exchange Area (NHEA) at Creighton Mine that utilizes the remaining rock-filled pit from historical operations to condition its intake air. The NHEA operates under the same principle as NHEET, although, as an opportunistic system, it is oversized and inefficient.

Funded through the Natural Resources Canada Clean Growth Program and by industry sponsors, Mining Innovation, Rehabilitation, and Applied Research Corporation (MIRARCO) has led a research project aimed to assist in the integration of this technology in mines. As part of the research campaign, MIRARCO has constructed a lab-scale experimental apparatus and a prototype system, developed fundamental and high fidelity numerical models, and established an engineering methodology for constructing a NHEET system. The highlights from this work are:

- Drag coefficient, $\mathrm{C_D}$, and Nusselt number, Nu, are relevant non-dimensional groupings for pressure loss and heat transfer in packed beds. A literature review showed that numerous correlations have been proposed for various packed bed medias and operating conditions. However, particle-resolved Computational Fluid Dynamics (CFD)/Discrete Element Method (DEM) solutions for beds with uniform and poly-dispersed spherical and polyhedral particles (the later intended to be representative of waste rock) indicated that universal correlations exist provided that the correct dimensionless number definitions are used. (Cerantola and Lane, 2022)
- There are two fundamental properties impacting the thermal wave traversing through the waste rock: damping and phase shifting. As of the current state-of-the-art, the phase shifting operating condition creates too much pressure drop to be economically viable. Further operating improvements are realized when an ambient air bypass is introduced. For example, it is better if the system uses ambient air rather than colder air from the NHEET system outflow in the winter during the daytime. Venting the colder air under these conditions enables the heat storage to regenerate.
- The prototype constructed at Northern Center for Advanced Technology (NORCAT) was a proof-of-concept and demonstrated an engineering methodology for constructing a large-scale system. Numerical results for pressure loss, damping and phase shifting versus flow rate agreed well with experimental results, validating the methodology employed. (Cerantola et al., 2022)

- A critical design consideration for the NHEET system is the construction of the outlet. Flow converges and accelerates at the outlet, thereby resulting in significant local pressure loss. By making a void region at the outlet (e.g. using a perforated hollow structure such as the “birdcage” in the demonstrator) and using coarser material in the core, these losses can be significantly reduced, meaning less fan power is required to run the system. (Cerantola et al., 2022)
- Fine materials contribute significantly to the pressure drop and therefore the losses in the system by increasing the width of the distribution and reducing void fraction. They do not tend to contribute significantly to the mass fraction, which means removing them should not have a large impact on the amount of heat or coolth that can be stored in a unit volume. Removing them increases void fraction and reduces operating cost, at the expense of increased capital cost. Any material treatment to reduce resistance should be concentrated in regions of high flow velocity where the impact is maximized and neglected in all other areas.
- The NHEET system efficiency is highest when the amplitude of the ambient temperature cycle is large. The best conditions come from arid or very cold climates where ambient temperature damping by latent heat exchange through psychrometry is minimized.
- Simulations of a NHEET system using real weather data from January and July, 2022 in Sudbury, Ontario determined that it can heat or cool under extreme temperature conditions at very high COP. In the summer, the COP_R was 5.6. In the winter, the COP_HP was 12.4. By shaving extreme peak temperatures in summer and trough temperatures in winter, the NHEET system can also improve the COP of associated vapour-compression refrigeration equipment, on top of the aforementioned benefit.

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1. Introduction

As mines dig deeper to meet the growing demand for mineral extraction, there is an increasing necessity to reduce the environmental impact and associated costs of mining operations. 9% of Canada's energy consumption is used by the mining sector (Abdelaziz et al., 2011), and for underground mines, ventilation systems make up 40% of their usage (Natural Resources Canada, 2016). In areas with enough seasonal temperature fluctuations, the air needs to be sufficiently heated or cooled to maintain adequate working conditions. Thermal storage energy systems are sometimes employed to offset or eliminate the conditioning of intake air, but are not yet widely adapted.

One of such systems is the NHEA located at Vale's Creighton Mine in Sudbury, Ontario. The NHEA is a large broken rock mass formed from previous mining activities that coincidentally provides heating and cooling for the mine intake air. It acts like a large thermal capacitor, providing air at a relatively stable, average temperature year-round. While the NHEA significantly reduces the Creighton mine energy costs and greenhouse gas emissions, it has some limitations given that it is an opportunistic system.

There have been several studies attempting to model and improve the NHEA (e.g. Acuña et al. (2015); Amiri et al. (2018); Ghoreishi-Madiseh et al. (2017); Saeidi et al. (2017)), although few have focused on the technology in more general terms. With proper design guidelines established and assuming it is economically feasible to do so, other mines could adopt similar, engineered systems using readily available waste rock to likewise benefit from low-cost and green air cooling and heating. Widespread implementation has the potential to significantly reduce energy usage and carbon footprint in the mining industry. Such technology is hereafter referred to as NHEET.

The primary objectives of this work are to: establish correlations and general modelling techniques for NHEET that adequately describe all important phenomena (e.g. pressure loss, heat transfer) that are validated against experimental data; provide important insights into the best practices for designing such systems; consider the energy efficiency and economical benefits of adopting this technology for cooling at various scales compared to vapor compression refrigeration systems; and demonstrate the technology at a lab-scale and with a working prototype. To meet these objectives, a lab-scale apparatus and prototype were constructed and used to collect experimental data, and three numerical models were developed, a CFD/DEM model, a 1D packed bed model, and a porous media CFD model.

Some preliminary work was also completed to assess the constructability of a NHEET system by using hydraulic preconditioning of in-situ rock (Baidoo et al., 2022). A 3D model of a Discrete Fracture Network (DFN) was printed and tested on an anemometer test rig, and field testing of a hydraulic fracturing system in hard rock was completed. Early results indicated that the flow resistance through a DFN is so high that the scale of material required to be fractured is uneconomical.

2. Background and theory

2.1. Vale Creighton Mine - Natural Heat Exchange Area (NHEA)

Mining of the Creighton open pit commenced in 1901 under the Canadian Copper Company and later the International Nickel Company (INCO). Upon completion of the open pit in 1908, operations continued underground from the bottom of the pit downwards, although the open pit was viewed as an opportune location to dispose of waste rock.

As time progressed, mining moved further down the ore body and the infrastructure of the initial mining under the pit floor was abandoned. But in the 1950s, a senior ventilation engineer with INCO recognized that the body of broken rock and disposed waste material that had been produced could be utilized as a massive natural heat exchange medium to condition intake air. Subsequent efforts were made to draw airflow through the rock mass via box-holes and underlying slusher drifts into a collection manifold of airways to ventilate the mine, which resulted in the design of a ventilation system now referred to as the NHEA.

Today, the Natural Heat Exchange Area has been in operation for 50+ years, and this natural heat exchanger has allowed Vale Limited (formerly INCO to continue its underground operations at Creighton Mine to depths in excess of two and a half kilometers without the use of artificial refrigeration. The NHEA is estimated to deliver 18 megawatts of cooling capacity and 16 megawatts of heating capacity, and has provided cost savings in the tens of millions of dollars due to deferral of capital and operating costs of an artificial cooling system.

A 3D rendering of the NHEA is shown in Figure 2.1. The NHEA is on the order of one cubic kilometer in volume and reaches a depth of 450 m from surface. Its upper surface (olive coloured in the figure) is a depression that is close to the 800 Level (244 m) at its deepest point, and extends 900 m by 950 m across on either side (Natural Resources Canada, 2016). he former mine development openings that now make up the large scale air collection manifold are mauve coloured in the figure. All of Creighton's intake ventilation air (~800 m^3/s, 1,695,100 cfm) is drawn through the NHEA to this collection manifold by sub-surface fan installations. There are various control doors, which can be opened or closed to control flow through the system.

Production at Creighton Mine is projected to continue to a depth of three kilometers. Previous estimates have shown that the cooling capacity of the NHEA as it has been operated in the past will not be sufficient without an additional cooling source (Ramsden et al., 2014). Based on Vale's design reject temperature for working in heat, the current mine operation is already reaching its depth limit in the warmest months of the year underground, August to October (offset from the summer months because of a phase-shift imposed by the NHEA) (Acuña et al., 2015). This motivated efforts towards either improving the performance of the

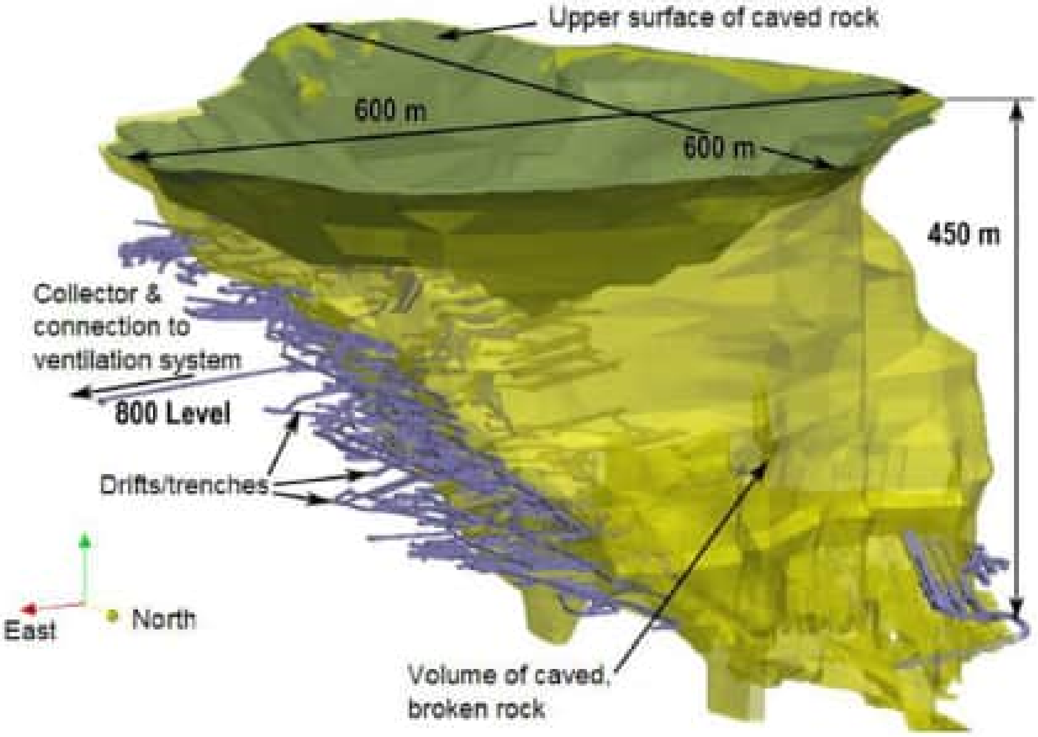

Figure 2.1: Three dimensional rendering of the NHEA and associated mine openings (Millar, 2015).

NHEA by assessing modifications to the system, its current operation, or replicating its benefits through a more engineered system. All of these efforts were aimed at avoiding the significant capital and operational costs of a refrigeration plant.

A 3D porous media CFD model of the NHEA was developed at MIRARCO prior to this project (Saeidi et al., 2017) and delivered to the Phase 4 Front-end Loading (FEL) 2 project team at Creighton Mine. The model was built with reference to the actual geometry of the NHEA and the size and location of the 96 control doors. The geometry was subdivided into different "blocks" and discretized with 1,831,416 tetrahedron mesh elements after mesh independence tests. Groups of control doors can be distinguished as the zones with higher mesh element density. The location and number of control doors for Blocks 3 and 4 are rough estimates from the old prints of the mine. Because of the uncertainties surrounding material properties in each block, the model needed to be calibrated against available measured data, and some assumptions were made. Transient simulations with actual ambient temperature conditions and door states were performed for a period of ten years. The model performed reasonably well in predicting actual temperatures at various doors. However, considering that there was no way to eliminate modelling uncertainties, there is little value in further developing this model.

In summary, Creighton's NHEA is an opportunistic system and it is too large to be economical to replicate. Moreover, the size and placement of the material was not engineered and it is difficult to model (Millar, 2015; Millar et al., 2014). To reiterate, there is a need for a detailed engineering design that provides a reliable guideline for professionals to implement and construct similar, efficient thermal storage systems in mines using broken rock as a storage media, and that is the purpose of the NHEET project.

2.2. Design consideration of experiments

The initial research proposal included four distinct geometries that were meant to mimic scenarios in which the resulting waste rock bodies from various mining activities formed a NHEET system (e.g. caved stope open to surface, backfilled underground stope, backfilled open pit). However, after performing an in-depth literature review and engineering and viability analyses, this experimental campaign was discarded in favour of one that would yield more general and thus more valuable insights and outcomes. Specifically, it was decided to focus the research on two well defined experiments.

The objective of the first experiment, referred to as the lab-scale experiment, was to provide a way to evaluate fundamental correlations for different materials under different flow conditions. To date, the focus of relevant literature was on uniform particle packed bed studies for a variety of media. For the purpose of developing a model to design and construct a NHEET system, expansion of the models to incorporate non-uniform particle size distributions was necessary. In particular, materials where the distribution spanned more than an order of magnitude have not been considered. Cerantola and Lane (2022) The primary function of the lab-scale experiment was to validate pressure drop and heat transfer correlations for lognormally-distributed particles, although a secondary function was to assess damping and phase-shifting in different media. The horizontal lab cylinder orientation was discarded early in the design phase to simplify loading and avoid the creation of a void at the top of the packed bed through which air could short circuit the bed. A well-instrumented vertical column with a bypass for finer control of low flow scenarios was designed instead.

A second experiment, referred to as the prototype or demonstrator, was constructed at the NORCAT Underground Center in a heap pile configuration. This configuration represented the lowest cost and simplest design that was fit-for-purpose among several that had been considered. The purpose of this experiment was to test and validate the prototype design, validate fill material pressure drop and heat transfer correlations and the overall 3D model, and assess the response to different air flow rates at scale, using real weather data. The tests were performed for a period of one year to capture the effects of changing weather conditions. During the design phase, it was determined that the majority of the pressure drop within the pile (and thus the majority of the energy required to pull or push air through it) was concentrated at the drawpoint in the core of the pile near the outlet pipe intake and within the pipe itself. This correlates to the fact that pressure drop in internal flows is a function of the square of velocity in a turbulent regime. To mitigate the high losses, a void was created in the center of the pile with a reinforced cage and screen; additionally, the cage was covered with coarse rock with a high void fraction to further reduce flow resistance.

2.3. Modelling workflow

Three types of numerical models were developed over the course of this project: a particle-resolved CFD/DEM model, a 1D packed bed model, and porous media CFD model. The flow chart in Figure 2.2 illustrates the purpose for these models and how they connect to the experiments (lab-scale and prototype).

Literature review showed correlations for pressure loss and heat transfer in packed beds corresponding to a variety of media and parameters, but none that would be adequate for unaltered waste rock due to its lognormal distribution and the irregular shape of its particles. The CFD/DEM model was used to develop these correlations (drag coefficient for pressure loss and Nusselt number for heat transfer) early on in the project, as published in Cerantola and Lane (2022). It is a state-of-the-art modelling method that resolves the interstitial flow between particles, but is limited to small-scale simulations and roughly a 1 order of magnitude particle size distribution range. The general correlations could be used in both other models to avoid the expensive computations involved with resolving interstitial flow.

The 1D model is the simplest model and the least computationally expensive. Thus, it is useful for rapid parameterization but is restricted to more fundamental studies. It was used to help design the lab-scale experimental apparatus. The lab-scale experimental results were then used to validate the correlations

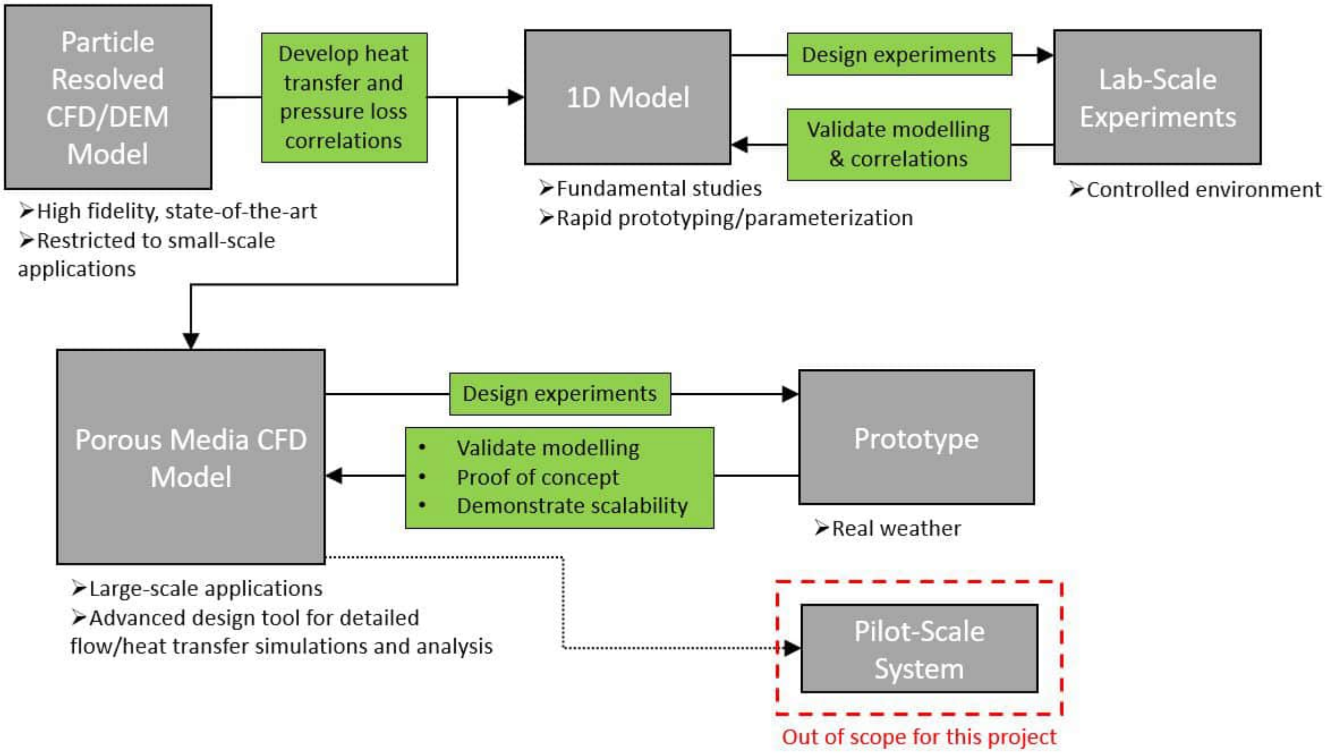

Figure 2.2: Project modelling work flow chart.

from the CFD/DEM study by using the 1D model.

The porous media CFD model is a 3D modelling tool that, despite not resolving the interstitial flow between particles, still provides reasonably accurate, simplified solutions for flow and heat transfer within the media. Moreover, it can be used at a much larger scale because it is less computationally expensive. The model was used to design the prototype. Model prediction capabilities were assessed against the experimental data of the prototype. It was intended that this model, paired with correlations for heat transfer and pressure loss developed from the CFD/DEM model, would be the most generally applicable modelling tool for NHEET design. Initial modelling work and validation against experimental data from the prototype was published in Cerantola et al. (2022).

3. Energy and economics

The objective of NHEET technology is to reduce the energy use and cost of air conditioning by leveraging storage of cyclic heat and coolth present in the environment. Both diurnal and annual temperature cycles are available for storage to eliminate or offset heating or refrigeration from other, less efficient sources.

3.1. NHEET as a component of an HVAC system

NHEET is fundamentally an energy storage technology. When the majority heat transfer mechanism is sensible, the average delivery temperature from a NHEET system will not deviate substantially from the average exterior air temperature over the trailing design cycle time (i.e. diurnal or annual). The heat and coolth delivered are stored rather than produced quantities and the output temperature is not controllable as with a vapour-compression refrigerator/heat pump. Therefore, the output of a NHEET system cannot consistently meet the specification for air conditioning on its own across variable environmental conditions.

Instead, it should be treated as a component of an HVAC system to reduce the capacity and energy consumption of a refrigerator/heat pump or other air conditioning system required to correct the output to meet the air conditioning target. For the purpose of the energy and cost analyses in this report, the NHEET system is coupled with a vapour-compression refrigerator/heat pump, compared to a refrigerator/heat pump alone.

3.1.1. Coefficient of Performance (COP)

The energy efficiency of air conditioning systems is defined as the amount of energy as heat or coolth delivered divided by the amount of energy required to deliver that heat or coolth. Because this value is always greater than unity for properly designed systems, this efficiency is called a COP.

$$\mathrm{COP} = \frac{\text{heat or coolth delivered}}{\text{energy consumed}} \tag{3.1}$$

For vapour-compression refrigerators, the numerator is the coolth extracted from the evaporator and the energy consumed is the electric, chemical, or mechanical energy (or work) required to operate the compressor to generate the coolth.

For vapour-compression heat pumps, the numerator is the heat extracted from the condenser and the energy consumed is the electric, chemical, or mechanical energy (or work) required to operate the compressor to generate the heat.

The difference between these measures is that the heat extracted from the condenser is greater than the coolth extracted from the evaporator by the mechanical work input into the compressor. All of the compressor work is rejected as heat into the refrigerant and shed via the condenser. That means that vapour-compression heat pumps have a $\mathrm{COP}_{\mathrm{HP}}$ higher than the $\mathrm{COP}_{\mathrm{R}}$ of a refrigerator with the same configuration by the conversion efficiency of the defined input energy type to mechanical work (η):

$$\begin{aligned}\mathrm{COP}_{\mathrm{HP}} &= \frac{\text{condenser heat}}{\text{energy consumed}} \\ &= \frac{\text{evaporator heat + mechanical work}}{\text{energy consumed}} \\ &= \frac{\text{evaporator heat}}{\text{energy consumed}} + \frac{\text{mechanical work}}{\text{energy consumed}} \\ &= \mathrm{COP}_{\mathrm{R}} + \eta \end{aligned} \tag{3.2}$$

In thermodynamics textbooks, η is typically reported as 1, because the analyses are based on mechanical (shaft) work rather than the type of energy that is paid for (e.g. electricity, diesel). For the purposes of this report, COP is taken to be the conversion efficiency of electrical to thermal energy.

3.1.2. Energy consumption

For a NHEET system, the energy consumption consists of the energy required to overcome its resistance to flow. The fan work or portion of the fan work required to operate the NHEET system is that required to take air from the atmosphere, pass it through the NHEET system, and return the pressure to atmospheric. The Steady Flow Energy Equation (SFEE) describes the scenario:

$$\frac{\left(u_1^2 - u_2^2\right)}{2} + g\left(z_1 - z_2\right) + w_{\text{fan}} = w_{\text{fan}} + \mathcal{F}_{12} = H_2 - H_1 - q_{12} \tag{3.3}$$

where u is velocity, g is the acceleration due to gravity, z is elevation, H is enthalpy, and q is heat transfer.

Considering only the first two expressions of the SFEE, some simplification is possible: (i) in atmosphere (state 1), the velocity is zero and (ii) surface installations of NHEET systems should not have significant differences in elevation between the intake and outlet[1]:

$$\frac{-u_2^2}{2} + w_{\text{fan}} = w_{\text{flow}} + \mathcal{F}_{12} \tag{3.4}$$

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[1] Where there is a significant elevation difference present, simply reinstate the elevation term into the equation. The SFEE is indicating a one-for-one equivalence of fan power with potential energy. Moving a kilogram of air down one meter or adding one meter of head with a turbomachine are equivalent operations in steady flow conditions. Remember that fans deliver head, not pressure.

If no net pressure has been added to the fluid, then the flow work is, according to both definitions, zero:

$$w_{\text{flow}} = \int_1^2 \nu dP = \frac{(P_2 - P_1)}{\rho} \qquad \text{(incompressible)} \qquad (3.5)$$

$$w_{\text{flow}} = \int_1^2 \nu dP = \left(\frac{\ln\left(P_2/P_1\right)}{\ln\left(T_2/T_1\right)}\right) \mathrm{R}_{\text{sp}} \left(T_2 - T_1\right) \qquad \text{(compressible)} \qquad (3.6)$$

where P is pressure, T is temperature, ρ is density, and R_{sp} is the specific gas constant.

What remains is that the fan work goes to overcoming friction (resistance) and increasing the velocity of the air, which is typically neglected in HVAC calculations:

$$w_{\text{fan}} = \mathcal{F}_{12} + \frac{u_2^2}{2} \qquad (3.7)$$

3.1.3. Fan heat

Using the second and third expressions of the SFEE and neglecting velocity change, it is demonstrable that the fan work is converted into heat in the process:

$$w_{\text{fan}} = H_2 - H_1 - q_{12} \qquad (3.8)$$

The portion of enthalpy change not accounted for by heat transfer is created by fan work. Fan work is converted to heat where the friction (resistance) occurs proportional to the amount of friction at that point. For ideal gases the following equation is used to calculate the temperature rise created by fan work:

$$H_2 - H_1 = c_{\text{p}} \left(T_2 - T_1\right) \qquad (3.9)$$

where c_{p} is the constant pressure specific heat capacity of the fluid. For non-ideal gases, numerical approximations, thermodynamic tables, or the equations of state can be used to perform this calculation.

In addition to the heat generated by friction, there is a point source of heat that is created at the fan that is the result of inefficiency of energy conversion from shaft power to fluid power. For a typical fan installation, expect 15-30% of the shaft power to be rejected as heat at this point. Under most operating conditions, the process of flow through a fan is considered to be adiabatic and all of the heat generated in this process can be added to the airflow.

The amount of fan heat generated in a complete ventilation circuit is equal to the total shaft power consumed by the fan. If the fan efficiency is known, this can be calculated using only process variables:

$$q_{\text{fan}} = \frac{P\dot{V}^3}{\eta_{\text{fan}}} \qquad (3.10)$$

where $\dot{V}$ is the volume flow rate and η_{fan} is the fan efficiency. Note that this relationship suggests an optimal operating efficiency of a NHEET system where the volume flow rate is low. Even when the NHEET system is intended to offer heating, this conversion is substantially less efficient than a heat pump would be to generate the same amount of heat.

For the purposes of conducting performance comparisons, the fan heat is prorated using only the portion of the fan work required to overcome the losses in the NHEET system and its associated ductwork.

3.1.4. NHEET system fan configuration

Waste heat rejected by the fan into the airflow increases the temperature of the air across the fan. Unlike a vapour-compression refrigerator, a NHEET system has only one place to reject heat and that is into the airflow that is being conditioned. If the air is being heated, the fan increases the total heat added. If the air is being cooled, the fan reduces the net coolth delivered. However, the fan position is somewhat flexible as a matter of system design. There are three NHEET system fan configurations to consider (Figure 3.1): (a) a forcing system where the fan is placed between the NHEET system and the air conditioned space, (b) an exhausting system where the fan is placed after the air conditioned space and (c) a forcing-exhausting system where fans are placed on both sides of the air conditioned space.

There is an additional constraint that emerges from the fan position: the pressure distribution within the system and particularly within the air conditioned space is limited by the fan position. In the forcing configuration, the pressure in the air conditioned space is always above ambient. In the exhausting configuration, the pressure in the air conditioned space is always below ambient; if the resistance of the NHEET system is high, the pressure can be much lower than ambient.

Buildings have strict limits on air pressure. If the pressure is too low, doors to the outside become too difficult to open. If the pressure is too high, doors to the outside can no longer be closed. In addition to introducing difficulty with opening and closing exterior doors, significant gauge pressures in a building or mine can cause ventilation short-circuiting, flow changes or reversals, or fluid hammer when doors or other exterior openings are opened or closed. Typically, a forcing-exhausting configuration is employed to maintain a neutral air pressure inside a building.

The relative fan work of the forcing and exhausting fans depends on the distribution of resistance to flow within the ventilation circuit. When the resistance is greater on the intake side of a building or mine opening, the forcing fan work will tend to increase. In the case of a building with a NHEET system, the NHEET component itself may represent the majority of the resistance through the intake air conditioner. In most cases, it should be expected that the fan required to overcome the NHEET system resistance will be in the forcing configuration.

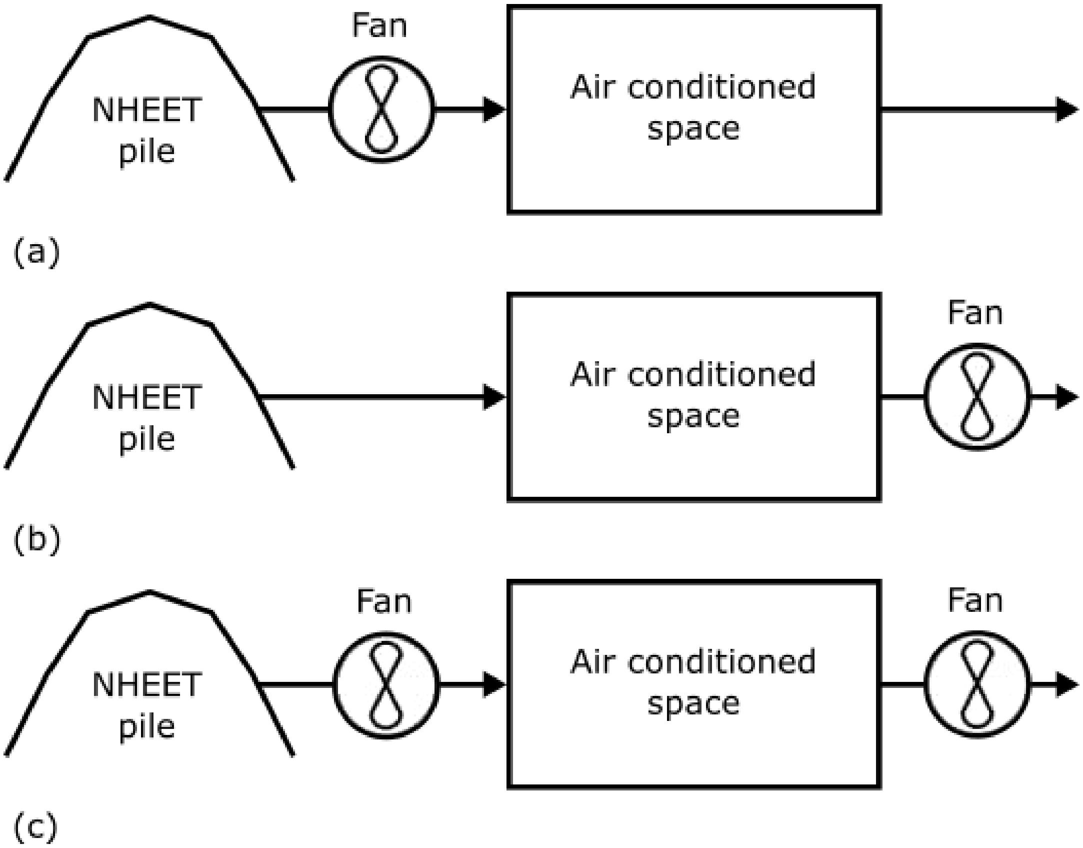

Figure 3.1: The three possible configurations of the NHEET system are (a) forcing, (b) exhausting, and (c) forcing-exhausting.

3.1.5. Combined performance evaluation

As an energy storage technology, the NHEET system does not generate heat or coolth. When only sensible heat transfer is considered, the average outlet temperature of a NHEET system converges on the average ambient temperature plus the temperature rise from fan heat. For an HVAC solution incorporating a NHEET, it does not make sense to characterize a COP for the NHEET component alone. Instead, the best approach is to quantify the over time cost reduction created by employing a NHEET system against the current state of the art. For cooling, the technology in use is vapour-compression air conditioning. For heating, it is natural gas forced air or vapour-compression air conditioning, depending on climate, local cost of natural gas and electricity, and regional established practice.

3.1.6. Ambient air bypass

In cases where the NHEET system is implemented to shave temperature peaks or troughs as a first stage air conditioner, an ambient flow bypass needs to be added to the system. This is applicable when the target air condition is not close to the average ambient air temperature. For example, in a winter heating scenario, the outflow from the NHEET system will tend to be colder than ambient air during the day. It is not useful to direct that flow of cold air into the next heating stage, so the solution is to create a bypass to vent the NHEET outflow to the atmosphere and introduce ambient air whenever the temperature of the NHEET outflow is below ambient. The fan must continue to operate during this time to regenerate the storage within the NHEET system. The same logic would apply for the summer cooling scenario except with the temperature logic reversed.

When the target temperature is between the ambient temperature cycle minimum and maximum temperatures, the control logic for the ambient air bypass becomes more complicated. It can no longer be based simply on temperature difference, because the $\mathrm{COP}_{\mathrm{HP}}$ and $\mathrm{COP}_{\mathrm{R}}$ are not the same for the same temperature difference. Instead, the optimal approach is to determine whether it is more efficient to condition ambient air or the air from the NHEET outflow to meet the target temperature. This more sophisticated control approach has not been implemented for the simulations presented in this chapter.

3.2. Scale-up simulation

The value delivered by thermal energy storage technology like NHEET is to deliver coolth when the temperature is high and heat when it is cold. NHEET cannot deliver thermal energy on demand, so it is best implemented to offset regular or predictable cycles. In the environment, the two cycles to target are the day-night (diurnal) and the winter-summer (annual) cycles.

The ideal scenario is where the target air temperature is close to the average ambient temperature, where a NHEET system can offset most of the refrigeration and heating costs. The economics of heating and cooling are different from one another, so scenarios that are predominantly or exclusively one-sided need to be treated separately. For these cases, it is optimal to introduce an atmospheric bypass control. For example, in a winter diurnal heating scenario, it is better to draw in ambient air for the half of the day when the NHEET system is colder than ambient.

The scale-up CFD simulation is based on the known effective geometry of the prototype experiment, for the purpose of evaluating the economic performance of the current NHEET system design. The target temperature of 18 ℃ is based on rule-of-thumb design criteria for building heating and air conditioning requirements (Environment and Climate Change Canada, 2011).

For the economic analysis, the CFD pressure drop result across the NHEET pile and temperature shift were preserved, but the pipe outlet arrangement was completely replaced with a larger diameter pipe (1.24 m diameter, up 50% from 0.83 m) with a total equivalent length of 100 m. This change was necessary to reduce the impact of the ductwork from approximately 30% down to 7% of the total system loss while preserving the positional flexibility afforded by the pipeline length. The fan efficiency was assumed to be 80% and the motor efficiency 95%. Refrigeration was assessed at a constant COP_R of 3 and heating at a constant COP_HP of 4. Fan heat was added to the temperature output from the NHEET pile[2].

For the purpose of delivering the maximum possible quantity of conditioned air through a fixed geometry, the original performance target was to set the flow rate through the NHEET system to achieve a 180° phase shift and mix with atmospheric air to create destructive interference and deliver air at near-constant temperature. Figure 3.2 illustrates the effect of phase shift and damping together. 180° phase shift occurs between 9.3 and 14.2 m^3/s. As the phase shift is increased, so too is the damping such that the amount of ambient air to be added to deliver near-constant temperature reduces with increasing phase shift.

The problem that emerges from the scale-up design evaluation is that the flow rate required to achieve the target 180° phase shift consumes so much flow work that the system performance is uneconomical. In addition, fan heat begins to be problematic at these high flow rates and is even apparent in the output curves in Figure 3.2. Table 3.1 shows why the system performance is so poor. In all cases, the air conditioner demand is reduced by the presence of the NHEET system, but the fan power radically increases due to the cubic scaling rule with respect to volume flow rate. The tabulated values represent the energy requirements with no ambient mixing. The low flow case isn't significantly improved with ambient mixing. The mid-flow case is improved with ambient mixing: it can do slightly better than breaking even with a 1:1 mixing ratio,

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[2] During this process, it was determined that the CFD model as it currently stands does not properly account for heat generation in the NHEET pile by friction. Because 93% of the friction losses through the NHEET circuit occur within the pile itself and the fan is 80% efficient, 74% of the fan shaft energy should be added as internal energy to the air in this part of the process. No detectable temperature rise was observed in the CFD results. Because of this, the economic analysis adds 100% of the fan shaft energy as heat on top of the CFD outlet prediction. This problem with the CFD formulation is immaterial to all other cases described in this report: the total temperature rise expected in the pile for the prototype experiment would not exceed 0.4 ℃ at maximum flow. This error is substantially smaller than that caused by psychrometry and is not material to the other results presented in this report. Typically, the same conditions that cause this source of error to be significant also cause the associated operating point to be uneconomical. This is not a high priority problem to be solved.

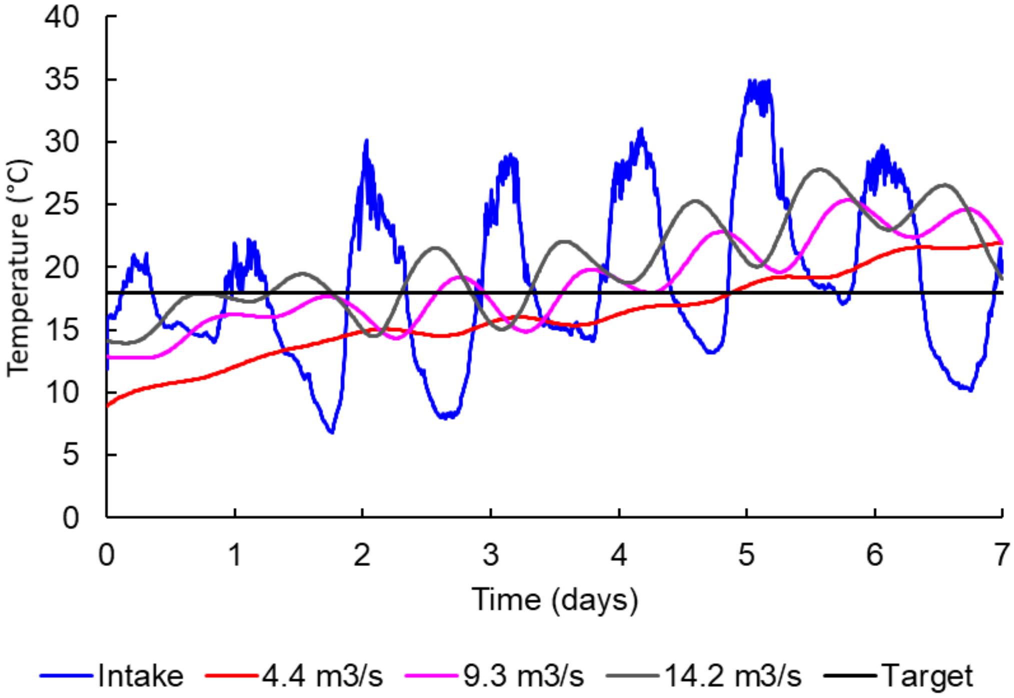

Figure 3.2: CFD output from the scale-up model at three different flow rates. The 4.4 m^3/s flow condition exhibits near-perfect damping.

but never by enough to pay back against even modest capital cost.

Table 3.1: Electricity use balance required to hit the target temperature of 18 °C for both the NHEET system + air conditioner (AC) and air conditioner only configurations at three simulated flow rates. All values represent no ambient mixing.

			Electrical Consumption			
Vol. flow rate (m^3/s)	**Fan temp. rise (K)**	**Scenario**	**Fan (kWh)**	**AC (kWh)**	**Total (kWh)**	**NHEET savings**
4.4	0.3	NHEET + AC	250	780	1030	25%
		AC only	0	1370	1370	
9.3	1.1	NHEET + AC	2080	1670	3750	-30%
		AC only	0	2880	2880	
14.2	2.4	NHEET + AC	7070	3090	10170	-131%
		AC only	0	4400	4400	

It may be possible to mitigate the pressure drop at higher flow rate. The resistance of the NHEET system would need to be reduced by at least a factor of 4 to make the 180° phase shift operating flow rate economical. To do so, an expansion of the void space at the core of the NHEET pile to increase the contact area between the void and the coarse rock layer by a factor of 4 may be sufficient.

All subsequent simulations presented in this section use an Excel model that approximates the behaviour of the scale-up CFD model (Figure 3.3) at 4.4 m^3/s for damping diurnal temperature cycles using a two-parameter fit: the Excel Solver tool was used to fit a phase shift in days and a damping ratio. It also applies some time averaging for noise filtering. For the 4.4 m^3/s case, the Solver tool didn't come to a good solution, so the function was manually fitted to the data with a phase shift of 1.50 days and a damping ratio of 100%. The Excel model was run against hourly weather data from Environment and Climate Change Canada (2023): summer data are from July 2022 and spring data are from April 2022. Missing data points are interpolated from surrounding data.

3.2.1. The scaling problem

The NHEA at Creighton Mine that inspired this project is a massive zone of broken rock that was created as a consequence of 50 years of mining activity. It is large enough to damp out the annual cycle temperature. However, it contains 49 000 000 m^3 of broken rock. Intentionally constructing such a large NHEET system would be impossibly expensive. What, then, is the minimum size to be effective for diurnal

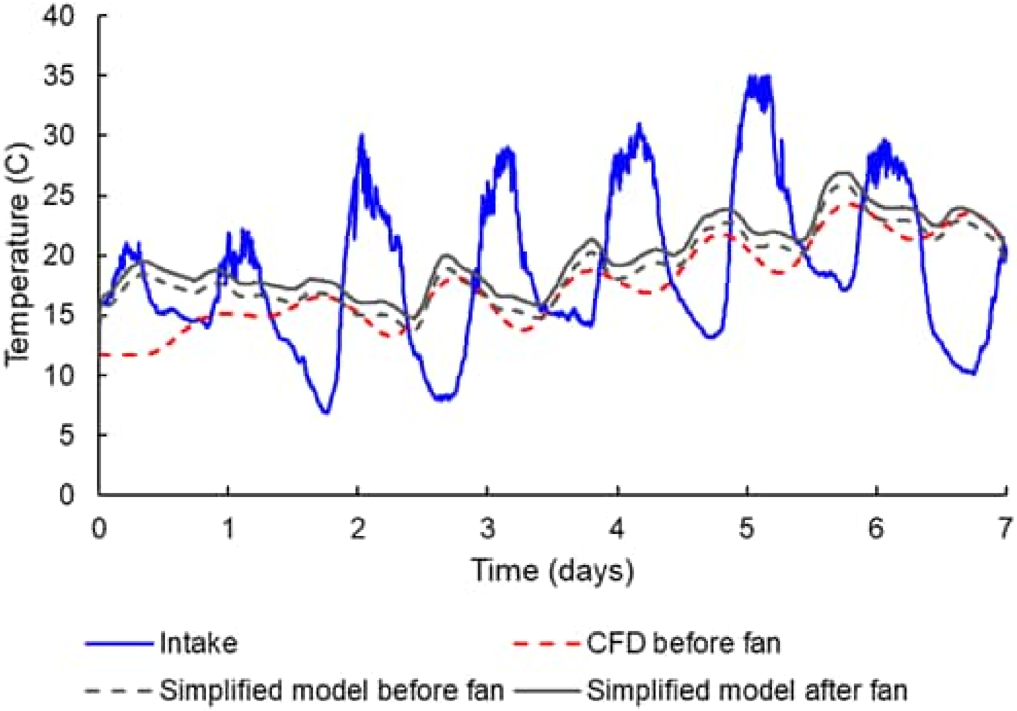

Figure 3.3: The simplified Excel model is fitted to the CFD simulation data at 9.3 m^3/s. The model faithfully, if roughly, captures the temperature cycle behaviour. The poor fit between the models at the beginning of the time series is due to the differing approach to initialization between the two models.

and annual scale NHEET systems?

Without capital engineering, it is not possible to be precise, but at least an approximate scale-up is possible. The analogue for how the capital cost should roughly scale is the total mass of rock required to build the system. Consider a mine that hoists 10 000 tonnes per day and requires 500 m^3/s of airflow.

The scale-up study has a volume of 623 m^3 and its only viable operating flow rate is 4.4 m^3/s. Assuming a bulk rock density of 1.5 tonnes/m^3, this translates to 935 tonnes. Therefore, at this scale, the NHEET system can condition 0.0047 $m^3/s{\cdot}$tonne. It is capable of fully damping the diurnal temperature cycle.

Scaling up to condition the full 500 m^3/s is linear, at worst, composed of several small parallel piles. The total mass required to build the NHEET system at this scale is 106 000 tonnes, or approximately 11 days of hoisting capacity. In terms of capital effort, this problem is tractable. At 114 times the flow rate of the scale-up model, the annual electricity consumption would be 1510 MWh if it runs year round with the same pressure drop. At $100/MWh, the annual operating cost would be $151 000.

Estimating the size of the annual scale NHEET system is more difficult due to a lack of simulation effort to date. Therefore, the capital estimation is not likely to be better than order-of-magnitude. Assuming the size must be of order 100 times larger than a diurnal scale NHEET system for the same flow rate, the mass required to condition 500 m^3/s would be 15 100 000 tonnes, or slightly more than 4 years of hoisting capacity. It is not an impossible mass, but accepting a higher operating cost or applying further design intervention to reduce scale would make this a more palatable option. It is more important to target a flow rate to achieve a 180° phase shift for an annual scale NHEET system than for a diurnal scale system because the temperature variability over a year is much greater than that over a day. If this can be achieved, the fraction of the total flow that needs to be conditioned is reduced and the required mass can be further reduced. The operating cost for an annual scale NHEET system should not be expected to increase over that of a diurnal scale system, because the draw points at the core will likely need to be larger or more numerous to apply more careful control of the internal velocity profile.

3.2.2. Winter heating

The standard technology used for winter heating in Canada is natural gas. It is the cheapest option by far in an environment of low fossil fuel prices and cold climate. In Ontario in 2023, natural gas costs $0.23/$m^3$ (Ontario Energy Board, 2023). When burned, it produces approximately 38 MJ/m^3 (NGV Global, 2023), which can be delivered as heat for a building at an efficiency of typically between 78-92% for a modern furnace (Manitoba Hydro, nd). Delivering 1 GJ of heat costs $6.3-8.0. This is the baseline against which all other heating methods must be compared.

The most efficient form of electric heating, barring geothermal, is a heat pump. In all cases, it has a higher efficiency than electric resistance heating. However, its $\mathrm{COP}_{\mathrm{HP}}$ drops significantly at low temperature.

Heat pumps capable of operating down to -30℃are available (British Columbia Hydro, 2022), but efficiency at these low temperatures is expected to be very low compared to typical nameplate values (Figure **??**). To be cost competitive with natural gas, the average $\mathrm{COP_{HP}}$ must remain above 3. For domestic and light commercial heat pumps rated for low temperature operation, a $\mathrm{COP_{HP}}$ of 3 corresponds to 0℃. At a $\mathrm{COP_{HP}}$ of 3, delivering 1 GJ with a heat pump costs $6.9-14.0, including the effect of current time-of-day pricing for electricity in Ontario (Hydro One, 2022). In addition to reduced efficiency, the capacity of a heat pump reduces proportionally to its $\mathrm{COP_{HP}}$.

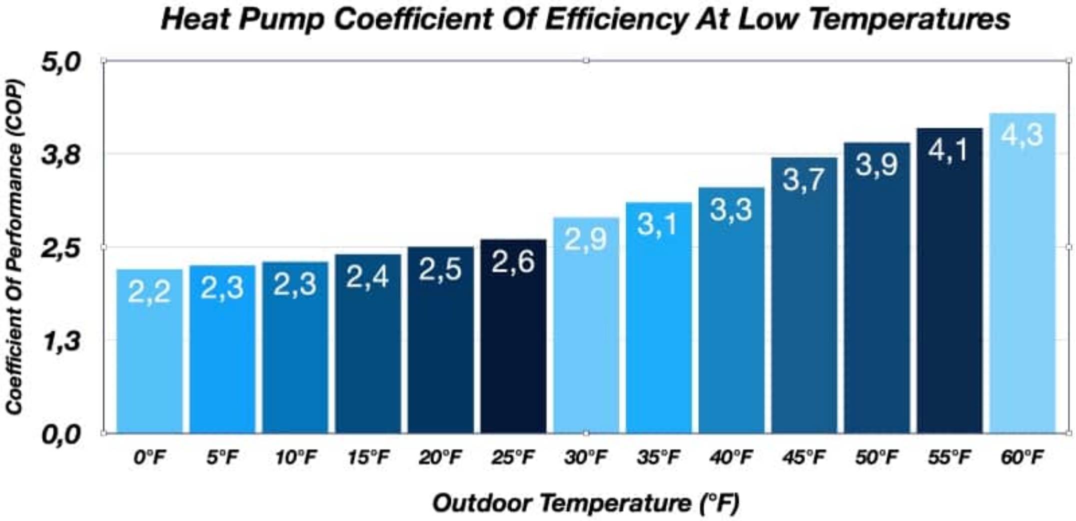

Figure 3.4: $\mathrm{COP_{HP}}$ reduces logarithmically with decreasing temperature (LearnMetrics, 2022).

Winter special case: trough shaving

If the purpose of the winter heating system is only to provide heat to ease minimum temperature troughs rather than achieve a set point for full temperature control, the economics change. Adding a NHEET system to a heat pump for cold weather heating makes sense only if an ambient air bypass is included in the design for regeneration. If this is not done, the NHEET system can only increase the cost of heat: from Figure 3.4, stepping a lower temperature up by some amount creates a small benefit to $\mathrm{COP_{HP}}$, but an equal step down from a higher temperature creates a larger deficit to $\mathrm{COP_{HP}}$, under all operating conditions.

In January, 2022 in Sudbury, Ontario, the minimum ambient temperature was -33℃ (Figure 3.5). With the simulated NHEET system operating unaided, the minimum temperature delivered would have been -22℃. Integrating the difference between the ambient temperature and the temperature delivered by the simulated NHEET system equipped with a bypass yields 15 365 kWh of heat created with 1244 kWh of electrical energy for an average $\mathrm{COP_{HP}}$ of 12.4. At this efficiency, it is well beyond what is attainable from a practical vapour-compression heat pump.

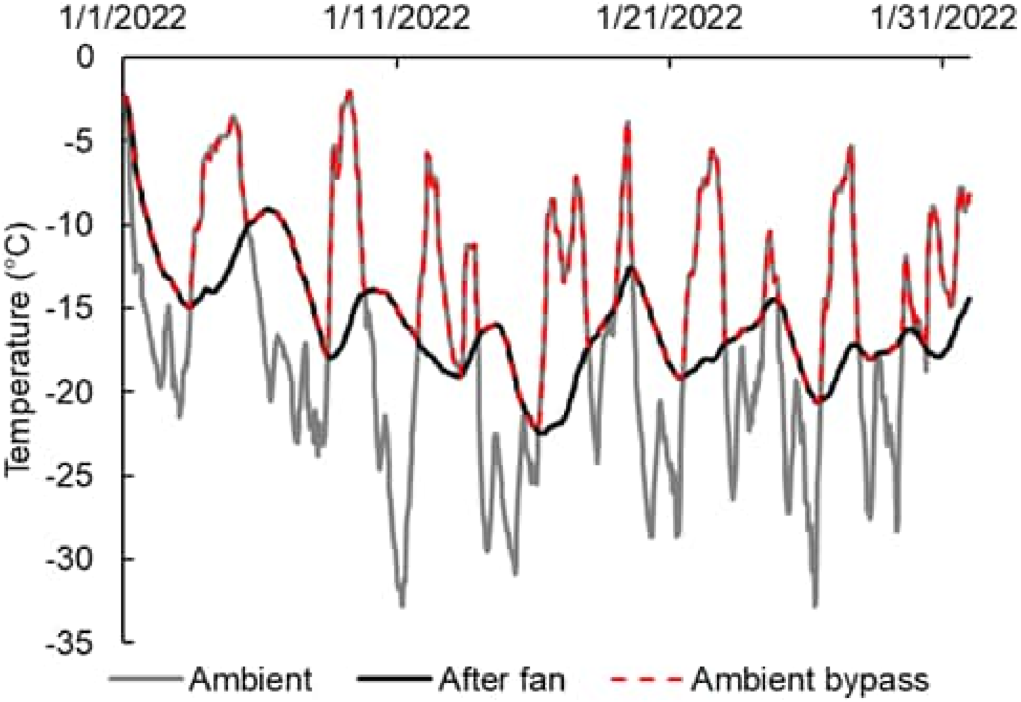

Figure 3.5: Simulated NHEET outlet temperature overlaying ambient temperature plot for the month of January, 2022 in Sudbury, Ontario. If an ambient air bypass is introduced, the air delivered by the system follows the dashed red line.

At low temperature, psychrometry is not a significant factor in damping temperature cycles in the environment or within the NHEET process. The superior performance of the NHEET system is aided by the large diurnal temperature cycle amplitude, which increases the integral of the trough temperature curve. In the winter heating case, the fan heat boosts the performance.

In regions where the temperature has routine excursions below the minimum operating temperature for a heat pump, a NHEET system can be used to increase the minimum temperature at which the heat pump evaporator needs to operate. By this process, heat pump use can be economically expanded into regions where the climate was previously too cold and the necessity of supplemental heat can be reduced.

3.2.3. Summer air conditioning

Summer air conditioning in Canada is typically only required during the daytime, with the possible exception of southern Ontario. The electrical energy use and cost of a simulated NHEET + air conditioner system was compared to an air conditioner only system required to meet a consistent target temperature of

18 ℃ against weather data from Sudbury, Ontario for the month of July in 2022 (Environment and Climate Change Canada, 2023). The air conditioner electric to thermal $\mathrm{COP}_{\mathrm{HP}}$ was fixed at 4.0 and its $\mathrm{COP}_{\mathrm{R}}$ was fixed at 3.0. Energy use is calculated based on a fixed volume flow rate of 4.4 m^3/s. Anticipating some effect from daytime peak shaving with respect to time-of-day electricity rates, electricity cost was calculated twice for each scenario using the Hydro One (2022) rate schedule and a fixed rate using the mid-peak rate.

Considering the combined refrigeration and fan energy use, the NHEET-enhanced and air conditioner only systems are virtually identical (Table 3.2). Almost all of the 28% energy reduction created by the NHEET system is the result of its reduced heating demand. The effect of introducing time-of-day electricity rates was approximately a 10% cost reduction for both simulated systems.

Table 3.2: Electricity consumption and cost for the month of July, 2022 in Sudbury, Ontario for the simulated NHEET-enhanced and air conditioner only systems.

	Electric energy (kWh)				**Electricity cost ($)**	
Scenario	**Fan**	**Heat pump**	**Refrigerator**	**Total**	**Fixed rate**	**Time-of-day**
NHEET + air conditioner	1090	320	1682	3092	315	286
Air conditioner only	0	1500	2804	4304	439	395

An additional effect of the NHEET-enhanced system is that its hourly power demand is much more stable than the air conditioner only system and the peak power demand on the air conditioner component is halved (Figure 3.6). In capital terms, this means the scale of the air conditioner plant can be half of what would normally be required to handle the conditions unaided.

Summer special case: peak shaving

If the purpose of the summer air conditioning system is only to provide refrigeration to ease maximum heat loads rather than achieve a set point for full temperature control, the economics change. Like the winter heating scenario, an ambient bypass should be introduced to eliminate the nighttime heating delivered by the NHEET system. Also like with the heat pump calculation for winter heating, the $\mathrm{COP}_{\mathrm{R}}$ would decrease as the condenser temperature increases in extreme heat conditions (Figure 3.4).

Considering the NHEET system operating unaided, the daily high temperature delivered by the NHEET system is reduced by an average of 5.3 ℃ (Figure 3.7). The maximum ambient temperature for the month was 31 ℃. The maximum temperature delivered by the simulated NHEET system would have been 24 ℃. Integrating the difference between the ambient temperature and the temperature delivered by the simulated

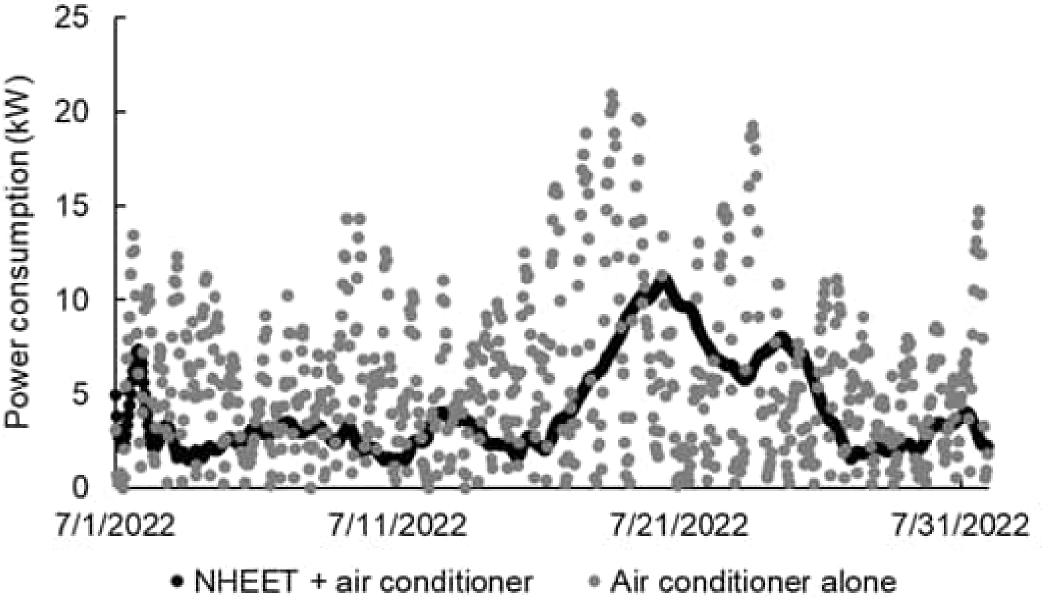

Figure 3.6: Total hourly power consumption for the month of July, 2022 in Sudbury, Ontario for the simulated NHEET-enhanced and air conditioner only systems.

NHEET system equipped with a bypass yields 6113 kWh of coolth created with 1090 kWh of electrical energy for an average $\mathrm{COP_R}$ of 5.6. At this efficiency, it is superior to what can be expected from practical vapour-compression refrigeration. The COP for summer cooling is substantially lower than for winter heating, because the temperature cycle amplitude is greater in the winter than in the summer. Latent heating and cooling due to psychrometry is largely responsible for this difference in sensible heat. Fan heat causes a small but not insignificant degradation of the performance.

Unlike a vapour-compression refrigerator, the $\mathrm{COP_R}$ of the NHEET system is not substantially affected by temperature. If further cooling is required, the new condenser temperature is lower, so the $\mathrm{COP_R}$ of the refrigerator would be improved. The NHEET system reduces the peak temperature by more in environments where the temperature swing in the diurnal cycle is greater, such as in arid climates. It is ideal for application as a first stage refrigerator, even if it cannot reduce the air temperature to the target cooling temperature.

3.2.4. Spring and fall defrost

In some applications, such as mines and greenhouses, the air must be conditioned to avoid freezing conditions. A NHEET system could be used to preheat air for a heat pump or natural gas burner to raise the temperature above freezing. The electrical energy use and cost of a simulated NHEET + heat pump system was compared to a heat pump only system required to meet a minimum target temperature of 3 ℃ against

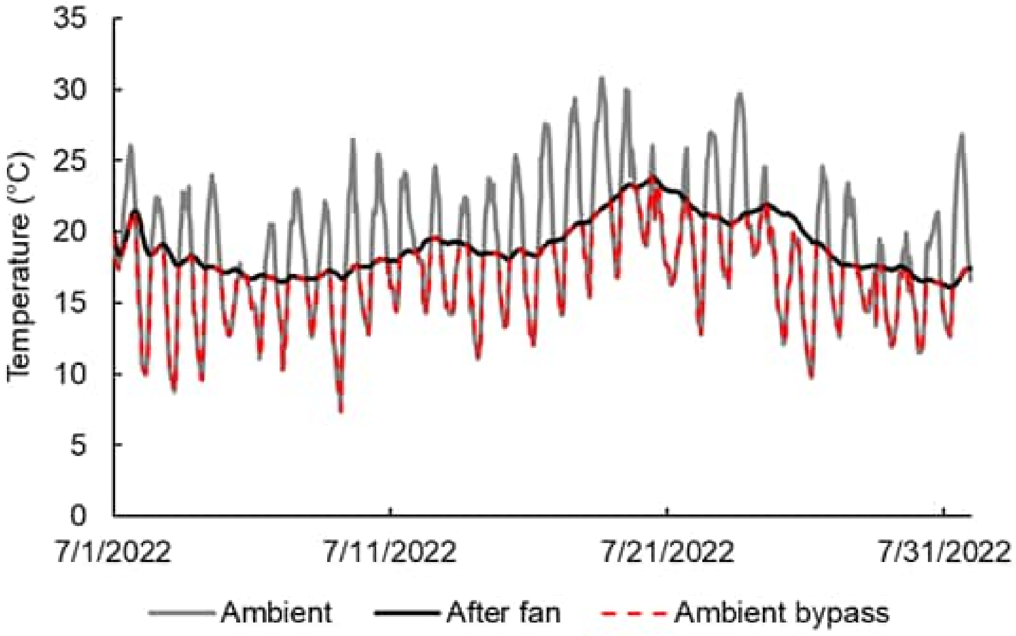

Figure 3.7: Simulated NHEET outlet temperature overlaying ambient temperature plot for the month of July, 2022 in Sudbury, Ontario. If an ambient air bypass is introduced, the air delivered by the system follows the dashed red line.

weather data from Sudbury, Ontario for the month of April in 2022 (Environment and Climate Change Canada, 2023). The heat pump electric to thermal $\mathrm{COP}_{\mathrm{HP}}$ was fixed at 4.0. Energy use is calculated based on a fixed volume flow rate of 4.4 m^3/s.

As expected, the heat pump load is reduced by the NHEET system (Table 3.3). However, the performance improvement is smaller than the energy consumed by the fan. Even if the fan energy were to be reduced to zero, the maximum reduction is about a quarter. The margin is too small to be a viable target for improvement with a NHEET system.

Table 3.3: Electricity consumption for the month of April, 2022 in Sudbury, Ontario for the simulated NHEET-enhanced and heat pump only systems.

	Electric energy (kWh)		
Scenario	**Fan**	**Heat pump**	**Total**
NHEET + heat pump	1118	1530	2648
Heat pump only	0	2057	2057

The system performs so poorly because it spends about half of its time idling to no benefit (Figure 3.8). The temperature profile is such that heating is only required for about half of the days in April. The NHEET system cannot be shut down between these demand periods, because it requires a few days of operation to develop the phase shifted and damped temperature profile that stores the heat. Additionally, the amplitude of the diurnal temperature cycle is smaller in April than it is in July, reducing the efficiency of the NHEET system relative to its summer performance.

3.3. Summary

Under the current design methodology, the primary method that a NHEET system economically delivers heat and coolth is by damping the environmental temperature cycles for which it is designed. At the current state of the research, the diurnal cycle NHEET system has excellent performance for both summer cooling and winter heating. At this time, the annual cycle NHEET system is out of reach, but there is potential for design improvements to the manifold pipe inlet arrangement to reduce the flow resistance enough to make it viable.

Simulated NHEET damping of the diurnal temperature cycles for weather data from January and July, 2022 in Sudbury, Ontario returned COPs of 12.4 and 5.6, respectively. These results are superior to what is viable for vapour-compression refrigeration under similar conditions. In both cases, an ambient air bypass control was necessary to allow the NHEET system to regenerate its storage. NHEET system performance was poor for avoiding freezing conditions in spring or fall due in part to the intermittent nature

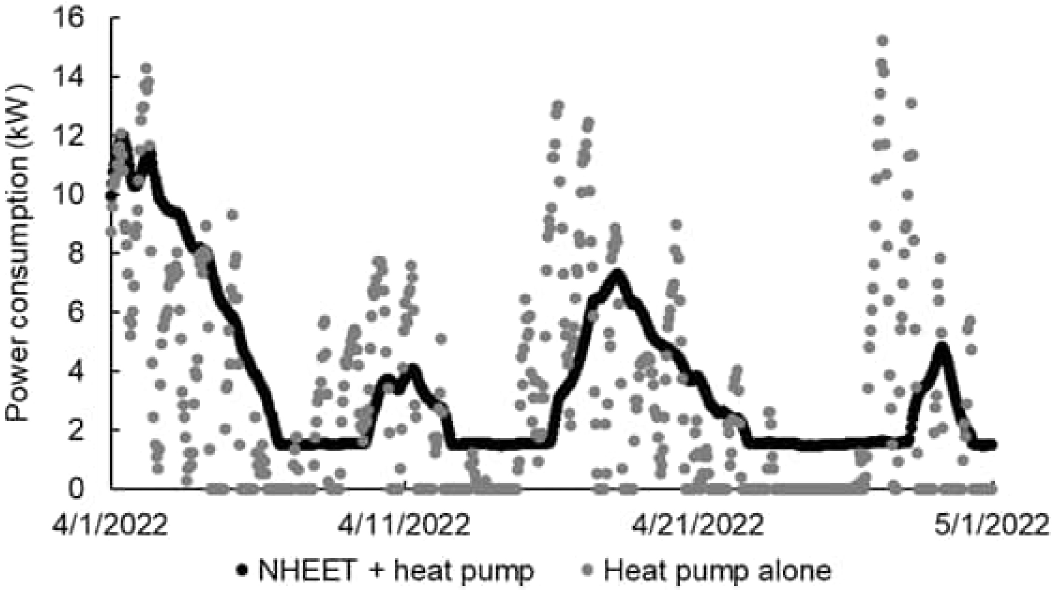

Figure 3.8: Total hourly power consumption for the month of April, 2022 in Sudbury, Ontario for the simulated NHEET-enhanced and heat pump only systems.

of the requirement for heating against the need for the fan to be powered at all times to maintain the thermal storage. Further improvement of the ambient air bypass control logic is necessary to optimize the performance of the NHEET system as designed. One of the design elements that limits the performance of the NHEA at Creighton mine is that its flow is always routed into the mine. According to Simon Nickson, a Vale project engineer who is familiar with the system, the hottest time of year underground is in October. As an opportunistic system, this limitation is not so much a design flaw as it is an unavoidable consequence of having the system outflow located underground, preventing rejection of waste heat away from the mine workings.

Climatic conditions where the amplitude of the temperature cycle is large, such as those common in summer and winter, create the best conditions for a NHEET system to reduce the energy cost of air conditioning. Arid climates are ideal for potential application. Wet climates where the local temperature cycles are already damped by the presence of a nearby body of water have lower potential for NHEET application. Furthermore, damping extreme temperature swings can improve the performance of refrigeration and heat pump systems. If the maximum temperature difference between the evaporator and condenser of a vapour-compression air conditioner is reduced, the COP is increased. Further work is required to quantify the magnitude of this effect.

4. Conclusions

4.1. Conclusions

Despite the multitude of correlations that exist in literature for packed beds implying that there are no universal correlations for drag coefficient and Nusselt number, the results of the CFD/DEM study suggest otherwise. Correlations were developed for drag coefficient (Eq. 4.1) and Nusselt number (Eq. 4.2) that fit the pressure loss and heat transfer results of the uniform and distributed spherical and polyhedral particles well.

$$\mathrm{C_D} = \frac{38.363}{\mathrm{Re}_{\mathrm{pore}}^{0.928}} + 0.291 \tag{4.1}$$

$$\mathrm{Nu} = 0.430\mathrm{Re}_{\mathrm{pore}}^{0.580}\mathrm{Pr}^{1/3} + 1.274 \tag{4.2}$$

Experimental results from literature further corroborate these correlations. The key finding is that derivations of the relevant non-dimensional groupings should use length scale $L^* = d_{32}\frac{\varepsilon}{1-\varepsilon}$ and velocity scale $u^* = U\tau/\varepsilon$ for correlations to be universal.

Using d_{32} = 8.0 mm for the waste rock and $d_{32} \approx d_{\mathrm{w}}$ = 10.8 mm for the uniform rock provided good agreement between the pressure losses measured in the lab apparatus and pressure losses obtained from the derived drag coefficient (Eq. 4.1). Because fines are unavoidable and yet can substantially impact the d_{32} derived from sieve data if included, it is important that future works establish guidelines for choosing a d_{min} that provides adequate values for d_{32}.

The heat transfer coefficient results obtained from numerical derivation of the experimental results from the lab apparatus and intended to further validate the Nusselt number correlation (Eq. 4.2) are ultimately inconclusive because of significant sources of experimental error, most notably heat transfer with surroundings and latent heat transfer. While the damping and phase shifting constants, $\mathcal{A}$ and $\mathcal{B}$, respectively, obtained from the sine tests encompass the same sources of errors in their derived values, they both still exhibit the expected trends of increasing with decreasing flow rate.

The prototype constructed at NORCAT effectively demonstrates damping and phase shifting of the ambient temperature signal at varying flow rates and provides confidence in the scalability of the technology. Neglecting latent heat, simplifying various geometries, applying adiabatic conditions to the ground and piping, taking d_{min} = 13.77 mm for the coarse rock and d_{min} = 4.76 mm for the waste rock, and otherwise using homogeneous properties for the waste and coarse rock piles were justified modelling assumptions in the context of the scale and purpose of the experiment and given the accuracy of the model predictions. Uncertainties surrounding the properties of the bed is likely the largest source of error in predicting pressure loss at lower flow rates, whereas for outlet pipe temperature, latent heat is suspected to be the major cause. This leaves opportunities for future model improvements.

Preliminary modelling of the prototype system led to the design with coarse rock and a cage at the pipe inlet to reduce pressure loss. Although significant losses were avoided, there was still an appreciable amount of pressure loss in the coarse rock and inlet portion of the pipe, as predicted by the CFD model. Pressure losses in each were of similar magnitude, roughly 3-4 times that of the losses in the waste rock, due to the higher local velocities present.

Significant system losses were avoided by designing the prototype system with coarser material in the core and a cage to create a void region around the pipe inlet. It is highly recommended to adopt a similar engineered design approach that targets regions with high flow velocities in future NHEET system builds because that will lead to vast improvements in efficiency. A larger pile aspect ratio and outlet duct are also suggested to reduce losses at a larger scale. Increasing the pile height does not have a significant impact on the pressure loss at a certain point, but will still increase overall damping and phase shifting.

Under the current design methodology, the optimal operating condition of a NHEET system is where the flow is low enough to create damping. Without further design effort to substantially reduce flow resistance, a system relying on phase shifting does not result in net energy improvements compared to vapour-compression air conditioning. Ideal conditions for maximizing the COP of a NHEET system come from environmental conditions where the amplitude of the temperature cycle is large, where the target air conditioning temperature is near the middle of the range of the temperature cycle, or both. Simulations of winter heating and summer cooling by the NHEET system produced significant efficiency improvements over vapour-compression air conditioning and would likely also serve to improve the efficiency of vapour-compression air conditioners paired with the NHEET system.

4.2. Future work

In future work, efforts should be made to better account for latent heat effects in the modelling of NHEET and NHEET-like systems, as they can have non-negligible effects on temperature. A balance in computational efforts and model efficacy must be considered.

Further experimental verification of the derived drag coefficient and Nusselt number correlations can provide more confidence in their applicability as universal CFD modelling inputs. In particular, more particle size distribution profiles of various widths and shapes should be tested. Guidelines for choosing a $d_{\min}$ that leads to a proper d_{32} need to be established. For verifying Nusselt number, isolating the experimental system from latent heat and external heat transfer is a priority.

Further engineering analysis can lead to a more effective NHEET system design. In particular, the outlet configuration of the system can be optimized to reduce losses, operating costs, and waste heat generation. In particular, the potential development of an annual scale NHEET system or one that employs phase shifting as a strategy will depend on this to reduce the total mass required to treat a given airflow. Consideration must be given to different construction methods and their associated risks and costs.

Capital engineering needs to be completed in order to complete the economic analysis to calculate net present value and return of investment before any commercial application is possible. Correct scaling rules need to be established for cost and performance.

Further development of the ambient air bypass control scheme and full annual simulation of the diurnal scale NHEET system needs to be completed to characterize the expected operational savings against current technology. Optimal operating and control rules should be established to minimize operating time when net losses can be expected.

5. Project metrics

5.1. Summary of benefits

The project advanced clean technology towards commercial readiness so that natural resource operations can better reduce their impacts on air, land and water while enhancing competitiveness and creating jobs. The technology could reduce the demand for harmful refrigerants and help reduce GHG emissions by reducing the use of natural gas for space heating if the technology was widely adopted across the 80 underground mines that operated in Canada in 2017. Additional key findings and deliverables are found in Table 5.1.

5.2. Project budget

Table 5.2: Summary of cash and in-kind contributions to project by partners.

Contibutor	Cash	In-kind	Total
NRCan – Clean Growth Program	1 717 006.31	-	1 717 006.31
STAC	-	462 600.00	462 600.00
Teck Resources Ltd.	150 000.00	75 000.00	225 000.00
Vale Canada Inc.	50 000.00	75 000.00	125 000.00
MIRARCO Mining Innovation	-	79 360.00	79 360.00
Laurentian University	-	159 240.00	159 240.00
Total	1 917 006.31	851 200.00	2 768 206.31

Table 5.1: Key milestones and deliverables at the end of the project.

Milestone/Deliverable	Description
Development of new correlations	New mathematical correlations for pressure drop and heat transfer of a rock particle distributions were developed and published as a result of a detailed parametric CFD/DEM study. These can be used to more accurately model the behavior of natural heat exchangers and other packed bed applications.
Lab-scale experiment	A lab-scale instrumented packed bed column apparatus was built and used to test the correlations found in the parametric study with three different media (uniform spheres, uniform rock, and waste rock) to demonstrate universal application.
Demonstrator experiment	A heap pile demonstrator experiment was built and tested over eight months at NORCAT Underground Center near Onaping. The gathered temperature data was used to further validate the correlations and inform a scaled up energy and economics study.
Publications	Two papers were published as a result of the works associated with the project, namely "The existence of universal pressure loss and heat transfer correlations for packed beds" by David Cerantola and Chris Lane, and "Performance assessment of a rock aggregate heat exchanger exposed to daily temperature variation" by David Cerantola et al.
Outreach and presentations	Various aspects of the project were communicated and presented to stakeholders and the public via conference presentations, exhibits, and webinars.
Seasonal peak shaving energy savings	A standard vapor compression plant combined with an engineered natural heat exchanger can achieve 25% energy savings throughout the year. This is accomplished by selectively diverting air through the exchanger in the summer and winter months where the respective positive and negative fluctuations of mean ambient temperature are damped.

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