DIESEL EXHAUST HEAT RECOVERY: A STUDY ON COMBINED HEAT AND POWER GENERATION STRATEGY FOR ENERGY-EFFICIENT REMOTE MINING IN CANADA

by

Durjoy Baidya

B. Sc. Engg., Chittagong University of Engineering and Technology, 2015

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

(Mining Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

April 2019

The following individuals certify that they have read, and recommend to the Faculty of Graduate and Postdoctoral Studies for acceptance, a thesis/dissertation entitled:

Diesel Exhaust Heat Recovery: Development of A Combined Heat and Power Generation Strategy for Energy-Efficient Remote Mining in Canada

submitted by Durjoy Baidya in partial fulfillment of the requirements for

the degree of Master of Applied Science

in Mining Engineering

Examining Committee:

Dr. Seyed Ali Ghoreishi-Madiseh
Supervisor

Dr. Scott Dunbar
Supervisory Committee Member

Dr. Nadja Kunz
Supervisory Committee Member

Additional Examiner

Additional Supervisory Committee Members:

Supervisory Committee Member

Supervisory Committee Member

Abstract

Remote, off-grid mining operations in cold climate regions, like northern Canada, exclusively depend on diesel generators for power generation. Even with the best available technology, a typical diesel generator converts only one-third of its diesel fuel thermal capacity into electricity. The rest of this valuable heat is commonly discarded as waste heat. This research exhibits that the amount of energy discarded as heat through the exhaust of a diesel generator is almost the same as the amount of electrical energy generated by the generator. All the while, remote mines in cold regions, like those of Canada's North, have a high demand for heating throughout most of the year which is generally met by burning fossil fuels. Aiming to provide this necessary heating in a greener way, the quantity and the quality of the thermal energy discarded from different types and sizes of generators have been analyzed thoroughly in the present thesis. A shell and tube heat exchanger-based heat recovery system for the exhaust of a small-scale diesel generator has been designed numerically with ANSYS Fluent and validated with appropriate experimental results. Various parametric studies have been conducted to evaluate the benefits of deploying the proposed system in both underground (pre-heating the mine intake air) and surface (space and process heating) applications. The results project significant savings for all evaluated remote locations and suggest that considerable reductions of carbon footprint can be achieved by using the proposed system. The equivalent carbon emission assessments show that employment of the proposed combined heat and power generation system can help remote mining operations with transitioning towards less carbon intensity.

Lay Summary

Reliance on diesel for both power and heat is an inevitable part of remote mining operations. The present work evluates the techno-ecnonomic feasiblity of combined heat and power technology to develop a greener solution by recovering waste heat from the exhaust of a diesel generator with a simple, off-the-shelf heat exchanger technology. Necessary parametric studies are conducted to justify the applicability of the proposed combined heat and power generation system in remote mining. Achievable reductions in the consumption of fossil fuels needed to preheat the mine intake air or to provide space heating have been evaluated for different off-grid mine site locations. The potential carbon tax savings have been found to be sizeable for an energy-intensive industry like mining.

Preface

This research was supported generously by GOE2, an initiative to spark innovation in mineral resource extraction. The entire study was conducted under the supervision of Dr. Ali Madiseh, Assistant Professor, Norman B. Keevil Institute of Mining Engineering at The University of British Columbia. The author was responsible for all the background studies and data collection for the research. The numerical model and related studies were developed in collaboration with Mr. Marco Antonio Rodrigues de Brito. The experimental setup of the study was built with effortless support from Mr. Aaron Hope, Millwright, Norman B. Keevil Institute of Mining Engineering at The University of British Columbia.

The results of this research work have been published in the following journal papers:

- **Baidya, D.**, de Brito, M.A.R., Sasmito, A.P., Scoble, M., Ghoreishi-Madiseh, S.A., 2019. Recovering waste heat from diesel generator exhaust; an opportunity for combined heat and power generation in remote Canadian mines. J. Clean. Prod. 225, 785–805. https://doi.org/10.1016/J.JCLEPRO.2019.03.340
- Ghoreishi-Madiseh, S., Fahrettin Kuyuk, A., Rodrigues de Brito, M., **Baidya, D.**, Torabigoodarzi, Z., Safari, A., (2019). Application of Borehole Thermal Energy Storage in Waste Heat Recovery from Diesel Generators in Remote Cold Climate Locations. Energies, 12(4), 656. https://doi.org/10.3390/en12040656
- Ghoreishi-Madiseh, S. A., Safari, A., Amiri, L., **Baidya, D.**, de Brito, M. A. R., & Kuyuk, A. F. (2019). Investigation of viability of seasonal waste heat storage in rock piles for

remote communities in cold climates. Energy Procedia, 159, 66–71. https://doi.org/10.1016/j.egypro.2018.12.019

Also, the findings of this research have been accepted in the following conference:

- Rodrigues de Brito, M. A., **Baidya, D.**, Ghoreishi-Madiseh, S. A. “Investigation of the techno-economic feasibility of recovering waste heat of diesel generator exhaust for heating”, 17th North American Mine Ventilation Symposium (Montréal, QC, Canada, from April 28 to May 1, 2019).

Table of Contents

List of Tables

List of Figures

List of Symbols

Symbol	**Description**
C	Heat capacity rate (W/°C)
c_p	Isobaric specific heat (J/kg.°C)
T	Temperature (°C)
t	Time (s)
W	Work
ε	Effectiveness
m	Mass flow rate (kg/s)
ρ	Density
ΔT	Temperature difference (°C)
ΔP	Pressure drop (Pa)
$\dot{Q}$	Heat transfer rate (W)
$\dot{V}$	Volumetric flow rate (m^3/s)

List of Abbreviations

Abbreviation	Description
BC	British Columbia
CAPEX	Capital expenditure
CUA	Cost per unit thermal size (C$.K/W)
DEHR	Diesel exhaust heat recovery
EC	Yearly electricity cost (C$)
EHR	Exhaust heat recovery
ekW	Electrical kilowatts
Exh	Exhaust
FC	Fuel cost (C$/L)
Gen-sets	Diesel generator sets
HDD	Heating degree days (°C.days)
HEx	Heat exchanger
IC	Internal combustion
LCA	Life cycle assessment
LHV	Low heating value (GJ/kg)
LMTD	Log mean temperature difference
MF	Manufacturing cost of heat exchangers (C$)
MWe	Electric output in megawatt
NWT	Northwest Territories

OPEX	Operational expenditure
ORC	Organic Rankine Cycle
PBP	Payback period
QC	Quebec
RC	Rankine cycle
RPM	Revolutions per minute
STES	Seasonal thermal energy storage
TEG	Thermoelectric generator

Glossary

Subscripts	**Description**
a	Actual
air	Air
amb	Ambient
c	Hot fluid
d	Cold fluid
f	Demand
h	Fuel
man	Manufacturing
max	Maximum
min	Minimum
o	Overall
op	operation
s	Saved
set	Set-point

Acknowledgments

I would like to express my sincere gratitude to Dr. Seyed Ali Ghoreishi-Madiseh, my supervisor for his gracious mentoring throughout this journey as a research student. I would also like to thank Dr. Agus Pulung Sasmito, Assistant Professor, Department of Mining Engineering, McGill University for recommending me to Dr. Madiseh while I was looking for a supervisor to enter in a research program. Special acknowledgement is owed to Dr. Peter Bradshaw, a long-term supporter of minerals and mining research at The University of British Columbia.

My sincere gratitude to Dr. Malcolm Scoble, Professor, NBK Institute of Mining Engineering, The University of British Columbia, for his enormous support and guidance. Special acknowledgment to Mr. Aaron Hope, Millwright, NBK Institute of Mining Engineering, The University of British Columbia. Without his effortless support, developing the experimental setup will be more difficult.

Special thanks owed to Mr. Marco Antonio Rodrigues de Brito who is also an equivalent collaborator of this research, for being an ideal friend and colleague throughout this wonderful journey.

Heartiest thanks owed to GOE2, an initiative to spark innovation in mineral resource extraction whose generous contributions and support made this work possible.

Dedication

I want to dedicate this thesis to Jagat Jyoti Das, the first civilian freedom fighter who sacrificed his life only at the age of 21 in the liberation war of my beloved homeland, Bangladesh.

Chapter 1: Introduction

1.1 Background

The present work aims at studying a waste heat recovery system for the exhaust of the diesel generators in remote mining operations in Canada. Capturing the waste heat from the exhaust and determining the potential of using it as a greener source to serve the extreme heating demand of mines in the cold climate regions of Canada are the primary focuses of this study.

Several factors including the expansion of the global economy, population growth, preferences of the consumers along with all the developing environmental policies are influencing the thriving demand of metals and other minerals [1]. For instance, the worldwide production of copper and aluminum should have a 5-18% cumulative yearly increment to serve the growing demand for renewable energy or technology-oriented industries [2].

In the same way, insufficient production of various metals, such as lithium, nickel will hinder the rapidly expanding industry of electric vehicles [3]. To convene this flourishing demand, the quest for newer mineral deposits in conditions beyond norm has become an inevitable reality. Powering up an entire mining operation in such condition has always been a prime concern. Isolation from the national power grid or natural gas pipelines (in the case of North America) define those conditions as remote [4]. Currently and, in most cases powering up mines in those remote conditions, is being done by the deployment of several diesel generators.

Canada, being a global leader in mining, is facing this identical reality. Currently, there are 32 remote mines (including proposed and operating) with a total power demand of 658 MWe which ranges from and 4 MWe ~ 125 MWe [5]. These mining operations in remote location solely or mostly depend on diesel generators, called diesel gen-sets which are usually assisted by a few backup units are known as diesel gen-sets [6]. This dependence of these remote mining operations on the diesel generators is expensive in terms of both logistics and economics and results in significant surcharge on the price of fuel (in some locations two or three folds) [7], [8]. This is due to the inefficient energy conversion of the diesel generator which even with the best technology can convert around 33% of the energy content of the consumed diesel into electricity [9]. This means a typical diesel generator, deployed in a remote mining operation discards 2 out of 3 barrels of consumed diesel as heat. Depending on the price of the delivered fossil fuel at the location of the remote mine, a typical mine with a power demand of 10 MWe discards thermal energy equivalent of 3.5 to 7 million CAD per year.

Figure 1-1 Diavik diamond mine (a remote mine located in NWT, Canada) [10]

Due to being located near the arctic pole, mines in northern Canada are required to work under extreme climatic conditions. During the winter, the ambient temperature can go below -40°C. Preheating the subfreezing intake air above +1 °C (generally to 4~7 °C) becomes a must to prohibit frost formation in underground workings and equipment [11]. This intake air is either heated directly by using fossil fuel (diesel/propane) burners or indirectly by using a heat exchanger where the heat is supplied by burning fossil fuels. The annual cost for preheating the mine intake air can reach up to \$2,000 m^3/s [12]. In some extreme cold locations where the temperature reaches around -40 °C, the heating cost can be the same as the cost of generating airflow [11].

Furthermore, mining operations in cold climate conditions have a significant demand of space heating in communal areas like campsites, truck shops, warehouse, office complexes, processing and other essential facilities that are not domestic (or sanitary) areas where hot water is used [13]. This heating demand is usually supplied by a boiler which is also usually diesel fueled in remote mines. The high energy intensity and stability of the diesel and long-term storage options make burning diesel the most cost-effective solution for remote mines where in some cases proper road access is available only for a few weeks in a year [14].

While diesel gen-sets discards a significant amount of heat through exhaust and other streams, remote mines in Canada spend millions of dollars' worth of fossil fuels (diesel or propane) to preheat the mine intake or to provide space heating [15]. Recovering only 30%~40% of the discarded heat through the exhaust, which is feasible via current practiced technology, will lead to saving millions of dollars. This high-grade heat from the exhaust can primarily be used in preheating the subfreezing intake air in underground mining operations and replacing the conventional fossil fuel supported burners to provide space heating in both underground and surface operations. It also holds the certain potential to supply the necessary heating to endothermic mineral processes (batch or continuous) by taking the place of conventional fossil-based heating sources.

Mining operations all over the world, especially in Canada are trying to cut down carbon emissions due to various environmental regulations and financial constraints. Mining companies have always been facing economic challenges due to the constant fluctuation of fossil fuels prices, and thus directly affecting the operating costs. This has caused the mining companies look for ways to reduce fossil fuel consumption to avoid overwhelming the operating costs of mines. Moreover, the increasing carbon tax is obligating this energy-sensitive industry to collect carbon credits and avoid associated taxes. Considering these contexts capturing this waste heat from the exhaust of the diesel generators and replacing the fossil fuel dependent thermal energy sources holds the potential to be a practical step towards ultra-energy-efficient remote mining.

1.2 Thesis Objective

This study attempts to project a comprehensive understanding of the feasibility of a combined heat and power generation application for the diesel generators dependent remote mines, located in the cold climate regions of Canada. The primary objective of this research was to study the concept of recovering waste heat from the exhaust of diesel generators found operating in remote mining operations and accessing its applicability to reduce fossil fuel dependence in the case of preheating the mine intake air and providing space heating. The following intermediate objectives were structured to reach the primary objective:

- Conduct a detailed literature review on recovering waste heat from the exhaust of the diesel generators or engines
- Present a comprehensive overview of waste heat recovery or unconventional heating projects in Canadian mining operations
- Waste heat capture; study of heat capture from the exhaust of a diesel generator employing a selected heat exchanger
- Transportation of waste heat; study of heat, mass and momentum transfer phenomena inside the heat exchanger
- Heat transfer analysis between the exhaust from the diesel generator with the heat capturing fluid (water) in the heat exchanger
- Development and analysis of a numerical model of a diesel exhaust heat recovery unit
- Building an experimental test setup as a prototype model to validate the results from the numerical study and present the proof of concept at a small scale
- Evaluation of potential saving in terms of fossil fuel, carbon and associated environmental tax

1.3 Thesis Structure

This thesis is comprised of six chapters.

Chapter 1 establishes the background motivation and sets the primary and other key objectives of this research.

Chapter 2 provides a detailed literature review. It begins with the working principles of diesel generators and previous general studies on the waste heat discarded through different streams.

Basic working principles and previous studies for both direct (through various heat exchangers) and indirect (through organic rankine cycle, thermoelectric generators) methods of waste heat recovery from diesel exhaust have been discussed. This section ends with a highlight on the previous waste heat recovery strategies developed in mining operations within Canada.

Chapter 3 presents a detailed energy analysis of diesel generators of various sizes and types along with the performance variation at different load factors. It also describes the details of the development of the numerical model and the experimental prototype which is built to validate the numerical study. This includes the details of all the equipment used for the test setup, method for monitoring and data collection.

Chapter 4 presents the results from both the numerical study and the experimental set-up as well as validation of the numerical model. It also contains an optimization for an industrial scale recovery system. This is followed up by necessary parametric studies to evaluate the potential savings in terms of fossil fuels and the carbon tax.

Chapter 5 contains the key findings of the research and based on those, recommends the future work in this field.

Chapter 2: Literature Review

This chapter presents a holistic overview of the available literature related to the study. This starts with a description of the diesel generator and associated energy loss as waste heat through different streams. The follow-up section describes various waste heat recovery applications (both direct and indirect) in a summarized format. As the study focuses on direct heat recovery options, the literature review focuses primarily on those types.

Moreover, it should be mentioned that there were hardly any scholarly articles found that focused on the exhaust heat recovery system for the mining operations. Finally, a section is added discussing the various waste heat recovery projects proposed and implemented in the different mining operations in Canada.

The number of scholarly articles is one of the tools that present the development rate in any particular sector [16]. Based on that, a search in the Engineering Compendex database with the keywords of ‘Diesel generator,’ ‘Diesel engine’ and ‘Exhaust heat recovery’ shows up 438 peer-reviewed articles on 03 February 2019. Though the first article found on this field is from 1922, the field started expanding in numbers in the last decade. However, there were no studies found that particularly focused on the mining industry. This certainly demonstrates the necessity of the present study. Figure 2-1 shows the result of the search.

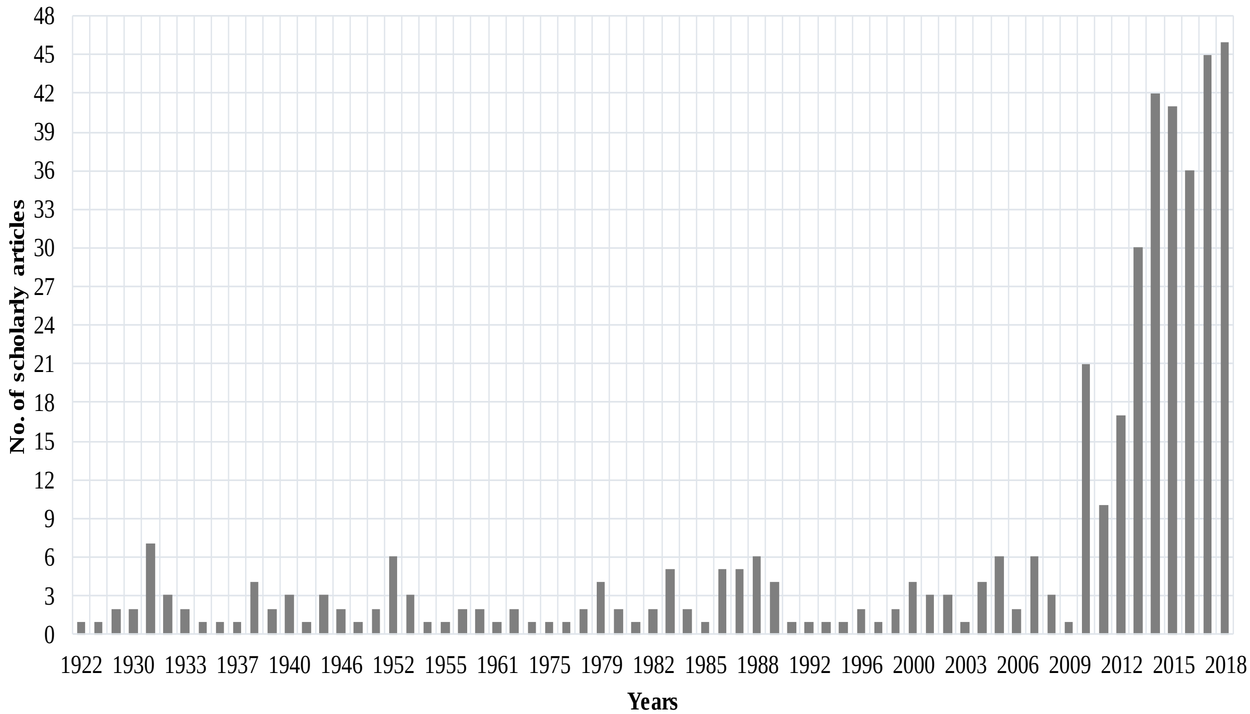


Figure 2-1 Number of scholarly articles over the time on diesel exhaust heat recovery system (search terms: 'Diesel generator,' 'Diesel engine' and 'Exhaust heat recovery')

2.1 Waste Heat from Diesel Generators

A diesel generator is primarily a combination of an Internal Combustion (IC) engine (diesel) and an electric generator along with various ancillary instruments. i.e. sound attenuation, canopy, control systems, circuit breakers and so on. A diesel generator converts mechanical energy into electricity and during this process, even with the employment of the best technology available ensures the conversion of only 33% of the energy stored in the fuel into electricity [9]. This means that for every 3 barrels of diesel as input in a diesel generator, only 1 barrel is converted into electricity. The remaining 2 barrels are discarded as heat. This waste heat is mostly discharged via the following mechanisms; aftercooler, water-jacket, oil cooler, radiation to the atmosphere and exhaust stream.

A study by Cummins Power Generation, a corporation that designs, manufactures, and distributes engines; filtration, and power generation products, shows that 65% of the overall diesel energy input is lost as heat during the combustion stage. This energy loss occurs due to the incomplete combustion of the fuel in the engine.

A similar study was conducted on the diesel gen-sets of rural villages in Alaska which included Ambler, Chevak, Noorvik and Scammon Bay and a rough estimate of the fuel energy distribution was made. According to the study, 30% of energy input is discarded through the exhaust to get 38% electrical output. The estimation of that study is shown in Figure 2-2.

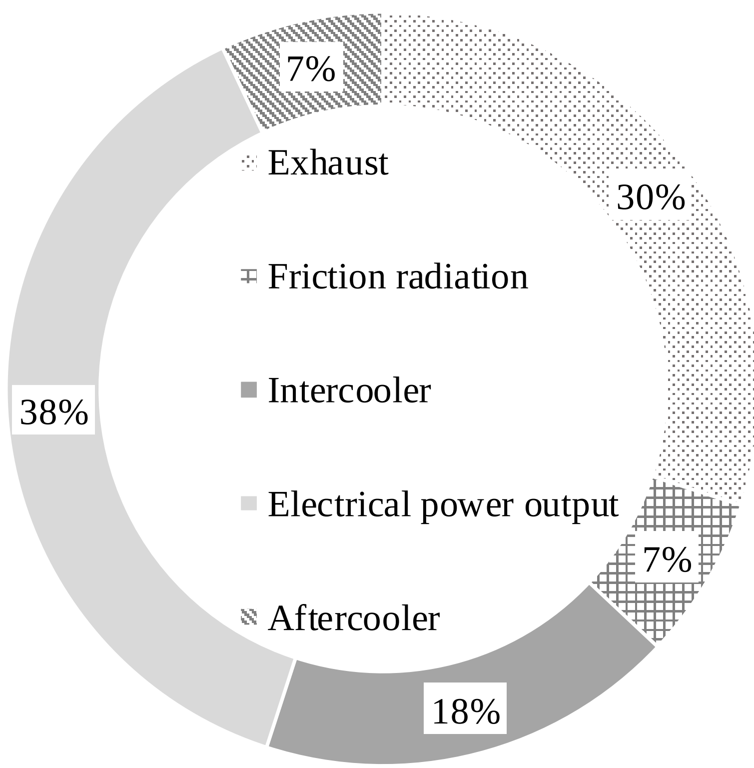


Figure 2-2 Energy distribution of a diesel generator [17]

There are more studies available presenting the general energy analysis of a diesel generator. However, no studies were found that covered the various sizes and types of generators' and provide their respective energy analysis at various load factors.

2.2 Heat Exchanger Based Exhaust Heat Recovery System

As this study aims at providing a sustainable heating solution for the remote, off-grid mines in the cold regions of Canada, the literature review focused on the studies which presented energy recovery from the exhaust of the diesel generators as heat. However, to justify the target of the study and also to provide a foundation for future extension of the current work significant works on diesel exhaust heat recovery for power generation purpose were reviewed.

2.2.1 Basic Heat Exchanger Principles

Heat exchangers, through a separating wall, allow the heat transfer between two fluids with different temperatures while keeping them separated from getting mixed. The rate of heat transfer through a series. An *overall heat transfer coefficient,* U_o is the parameter on which the performance of the heat transfer depends. Two methods can be applied in the selection of the heat exchanger: *log mean temperature difference (LMTD)* method and *effectiveness-NTU* method [18].

LMTD is applicable when the inlet and outlet temperatures of the hot and cold sides of a heat exchanger are known. Based on that, the following basic equations can lead to the design of the heat exchanger [19].

$$\dot{Q} = U_O AF(LMTD) \tag{2.2.1-1}$$

where,

$\dot{Q}$ = Heat transfer rate

U_o = Overall heat transfer coefficient

A = Heat transfer area

$$\text{LMTD} = \frac{\Delta T_h - \Delta T_c}{\ln(\Delta T_h / \Delta T_c)} \tag{2.2.1-2}$$

F= Correction factor; this is dependent on the geometry of the heat exchanger [18]

When the inlet and outlet temperatures of the hot and cold sides of a heat exchanger are unknown, the heat exchanger size can be measured by using the NTU-Effectiveness method. The actual rate of heat transferred ($\dot{Q}_a$) can be calculated by the following equation:

$$\dot{Q}_a = C_h\left(T_{h,in} - T_{h,out}\right) = C_c\left(T_{c,out} - T_{c,in}\right) \tag{2.2.1-3}$$

where C is given by

$$C = \dot{m}c_p \tag{2.2.1-4}$$

For each of the hot and cold fluids. Thus, the effectiveness of the HEx can be found by the following relation

$$\varepsilon = \dot{Q}_a / \dot{Q}_{max} \tag{2.2.1-5}$$

where the maximum rate of heat transfer can be calculated by

$$\dot{Q}_{max} = C_{min} \times \Delta T_{max} = C_{min}\left(T_{h,out} - T_{c,in}\right) \tag{2.2.1-6}$$

The waste heat from the diesel generator (discussed in 2.1) is generally discarded into the environment disregarding its energy and economic potential that can be reutilized in diverse functional purposes [20]. For every energy-intensive industry like mining, recovering even a small portion of this waste heat can bring economic and environmental savings. Assessing the scenario, recovering waste heat from the exhaust of the diesel generator has been a subject of interest for a long time. The potential for using the recovered waste heat from the fossil fuel-based electricity generators, motors and compressors was advocated decades ago [21]. To recover the thermal energy from the exhaust of the electricity generators, the availability of the gas-to-gas heat recovery technologies were evaluated [22]. In a discussion on different types of heat exchangers available for the waste heat recovery purpose, the flue-gas heat recovery was prioritized [23].

For the scope of the study heat pipes and shell and tube-based diesel exhaust heat recovery system were given priority.

2.2.2 Heat Pipes Based DEHR System

Due to the flexibility in being adapted in a system and effective thermal control, heat pipes are have always been considered a promising option in waste heat recovery from various sources [24]. It was recommended to use gas-to-gas heat exchangers while dealing with high-temperature gases and heat pipes were commended more advantageous in terms of recovering heat from polluted and corrosive fluids like exhaust. This study [25] further suggested putting emphasis on selecting suitable materials for the heat exchanger to handle the corrosion problems . Several studies were found available recommending the combination of energy storage with simplified heat recovery units [26]. A heat pipe-based heat exchanger was designed to recover the waste heat from the laboratories and hospitals where the air was needed to be changed almost 40 times per hour [27].

To provide heating to the passengers of a diesel operated bus in cold winters, a heat pipe based heat exchanger was designed that recovered heat from the automotive exhaust gas of the bus [28]. An existing open heat pipe (small diameter tube bundle) method implemented to recover heat from the exhaust of a diesel engine showed stable performance with the extreme variation in the conditions of the exhaust [29]. Deployment of split heat pipe heat exchanger solved the corrosion issues in a diesel exhaust heat recovery system attached in a fishing boat [30].

However, there are several limitations (e.g., boiling limit, capillary limit, capillary limit, sonic limit and viscous limit) that set the boundary of the operation of the heat pipes [31]. They also underperform while working against gravity [32]. In case of working with a temperature higher than (200 °C), special heat pipe fluid is required [33] All these together restrict the application flexibility in terms working fluid and scale of the heat recovery system [34]–[36].

2.2.3 Shell and Tube Based DEHR System

Shell and tube heat exchangers are the uncomplicated kinds of heat exchangers that have been being used in the process industry for a long time [37]. These heat exchangers are considered to be the most versatile heat exchangers for medium- to high-heat duties due to the following reasons [38]:

- They can deal with a high vacuum to ultra-high operating pressure for fluid. Usually, for the shell side, the pressure is limited to 30 MPa and for the tube side it can go up to 140 MPa.
- It can withstand high-temperature range (-250 °C ~ 800 °C [39]) which is only restricted by the materials selected.
- Shell and tube heat exchanger has a lower cost per unit of heat transfer surface area than a gasketed plate exchanger.

- In terms of dealing with corrosive fluid shell and tube heat exchangers are exclusive sustainable options.
- Shell and tube heat exchangers have a lower possibility of fluid flow leakage comparing gasketed heat exchangers.
- If the heat transfer unit demands absolutely no fluid contamination (e.g., diesel exhaust heat recovery system) shell and tube heat exchangers are the best suitable option.
- Shell and tube heat exchangers offer great flexibility on the selection of the materials of the heat exchangers while compact heat exchangers need to use metal or ceramic specifically.

Design flexibility, operational adaptability in case of heavy fouling, corrosion and erosion have made the shell and tube heat exchanger the most popular choice in the industry [38]. Several studies are available demonstrating the use of shell and tube heat exchanger in the diesel exhaust heat recovery system.

A shell and finned tube-based diesel exhaust heat recovery system employed in Alaska on average captured 66% of the waste heat from the exhaust of a 125-ekW diesel generator at different load factors. The amount of soot accumulated in the tube was 97.5% less than the theoretical estimation [17]. By using a counter-flow, shell and dimple-tube heat exchanger, 10% of the maximum engine brake power equivalent heat was captured from the exhaust of the diesel engine while it was running at 1500 rpm and the Reynolds number of the flow in the tube was 8,875 [40]. An experimental result showed 60~70% effectiveness (i.e., the ration of the total heat recovered to the total possible heat transfer) for most of the load factors of a diesel engine by using finned-tube heat exchanger-based exhaust heat recovery system [41]. An optimized design for a finned shell and tube heat exchanger successfully reached 76% effectiveness in the proposed diesel exhaust heat recovery system [42]. Use of a parallel flow shell and tube heat exchanger confirmed at least 50% of energy recovery in a DEHR system [43].

In case of using a shell and tube-based DEHR system, a fluidized bed filter improved the heat recovery from the exhaust gas and prevented fouling effect [44]. Adding thermal energy storage to shell and finned tube-based DEHR system gave the option to store 10~15% of the fuel energy [20]. It is crucial to optimize the most functional shell and tube heat exchanger for DEHR system. It was found that an unoptimized parallel flow shell and tube gave effectiveness of 52% where an optimized one increased it to 74% [45].

Few other types of heat exchangers-based (e.g., finned tube, cross flow and so on) diesel exhaust heat recovery systems were found in the literature search. However, as applications of these heat exchanger were found mostly case specific and was decided not to describe further in this study.

2.3 Power Generation Purpose

Converting waste heat from different sources into electricity has always been a subject of interest in different regions of the world that are challenged by the energy crisis [46], [47]. Studies found advocating the idea of converting the waste heat from diesel generator exhaust into electricity by the thermoelectric generator (TEG) and Organic Rankine Cycle (ORC).

Waste heat from the exhaust of a diesel engine could be applicable a source of electric power or an alternative to the alternator of the diesel-operated vehicles [48]. When a heavy-duty diesel engine was attached to a highly efficient turbocharger, mechanical turbo-compounding proved to be a more dependable option than turbo-compounding [49]. A rectangular heat exchanger assisted with 18 thermoelectric generators proved more functional in terms of geometric design while recovering waste heat from the IC engine. A finite difference method guided model was developed that integrated finned heat exchanger with a thermoelectric device to recover heat from the diesel exhaust [50]. In terms of coupling heat exchanger and thermoelectric generator together, heat pipe was recommended due to its flexibility in design and ability to reduce the thermal resistance and pressure losses in the system [51].

However, comparing with the direct heat recovery technologies, there are still economic and technological constrictions present which are restricting to offer a merchantable solution to harvest electricity from the exhaust of the diesel generator [52].

The energy crisis in the 1970s made the application of Rankine Cycle popular for exhaust heat recovery due to its lower emission of greenhouse gas and toxic per kW power produced overall [53]–[55]. According to a study [56] that reviewed an RC-EHR application, in 1981 it was claimed to reduce fuel consumption by 10~15% through the implementation of RC-EHR on diesel engine [57]. Later, the possibility of recovering 50% of the available energy from exhaust gas for utilization by the deployment of an RC-EHR was validated [58], [59]. Meanwhile, using an organic fluid in the RC system caught significant attraction. Use of modern refrigerants as working fluid showed the possibility to improve 10% fuel economy of the IC engine via waste heat recovery by cycle expander [60]. Coupling between various types of heat exchangers and ORC was also compared based on vital engine parameters like BSFC, fuel conversion efficiency, volumetric efficiency and so on [61]. The selection of the working fluid and the systematic geometrical design of the system were proved to be the most challenging part in designing ORC-EHR system for DEHR [56].

However, like the thermoelectric generators, conversion of waste heat from the exhaust of a diesel generator into electricity via ORC is also subject to substantial energy losses. This makes the payback period such system higher than any direct heating system [62]. As direct heating system has less energy loss (the only loss is in transporting the energy) associated, it would be more logically and financially viable to reuse the high-grade heat available in the exhaust of the diesel generator to meet the heating demand, especially when there is a huge amount heating needed in remote mining operations.

The entire findings can be summarized in the following diagram

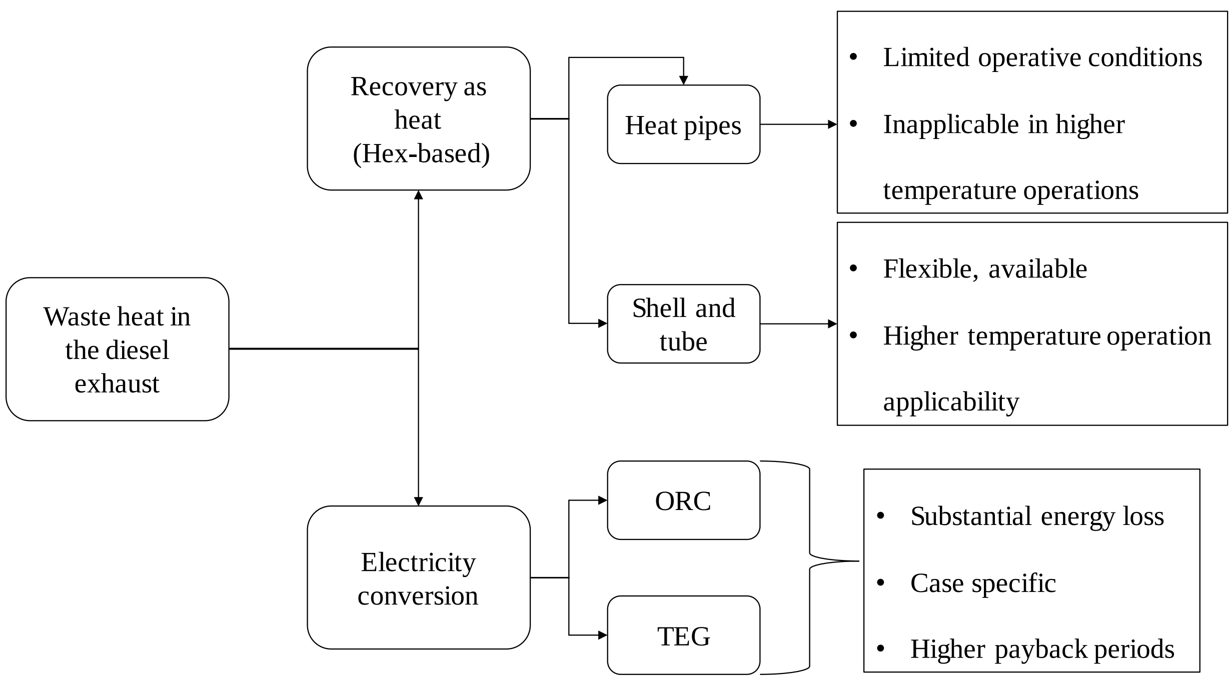


Figure 2-3 Literature review

2.4 Waste Heat Recovery Strategies in Canadian Mining

Recovering waste heat from various sources and further utilization of the recovered heat have been considered a sustainable strategy toward energy management in mining operations in Canadian mines. The earliest publication found regarding waste heat recovery in mining dates back to 1973 [63] and advocated for energy conservation through the reutilization of the waste heat from various sources like electric motors, fossil fuel based power generation units and compressors [21]. Later 1979, an energy audit in Sudbury operations pointed to significant potential savings in energy associated cost through waste heat recovery from compressors and mine air and other management initiatives [64]. Since then several waste heat recovery initiatives and studies have been undertaken in mining operations in Canada.

Several studies have been found investigating the potential of abandoned mines as a source of waste heat. Jessop et al. showed estimated recovery of about 4,000,000 m^3 of water with a temperature of 18°C on the surface from an abandoned, flooded coal mine in Nova Scotia could be a potential source of clean energy [65]. Raymond et al. scoped the feasibility of providing heat to the industrial buildings by recovering heat from the water of the flooded mines [66].

Feasibility studies are available evaluating the potential of preheating the mine intake air with the recovered heat from the exhaust of the mine itself. On this regard, heat exchangers with glycol or water as working were proposed for Potash mines in Saskatchewan. However, due to the corrosiveness of the potash dust, the design was considered unsuccessful [67]. Articles found proposing heat pipes between mine inlet and exhaust shafts to preheat the mine intake air with heat from the exhaust of the mine [68]. As the use of heat pipe has a limitation over the distance between the inlet and exhaust, the proposal could not offer enough flexibility. The first successful mine exhaust heat recovery system was tube and fin heat exchanger-based system that used to save annual 1.5 MW of total power in Creighton mine (Sudbury Ontario). However, failure to maintain the proper operating condition caused the shutdown of the system [69]. The Stratchona mine located in Ontario had MEHR system that was recovering maximum power of 8 MW and the coils of the system had to be replaced after eight winters due to lack of coating. This coating problem was taken into concern in designing a MEHR system in Kiena mine (Dubuisson, Quebec) which was basically a closed-loop glycol circuit delivering heat from return air to the fresh intake air [70]. A glycol-air closed loop heat exchanger with a 3.8 years payback period was proposed in a feasibility study and later implemented for the Williams mine [71].

Several initiatives have been taken to recover heat from the mine water and air compressor for heating the intake air. In Macassa mine, located in Kirklan, Ontario, two glycol loops were developed; one to transfer heat from the cooling system of the compressors to a portion of mine water and the second one to transfer the heat from the mine water to the intake air [70].

Mines located in the off-grid locations of Northern Canada (e.g., Diavik[72], Ekati [73], Gahcho Kue [74], etc.) depend on diesel generators for their power generation. Finding out the potential of the waste heat of these generators (mentioned in section 2.1), these mines have initiated projects to recover heat from various streams of the diesel generators. All these initiatives have significantly reduced the fuel consumption of these mines and also brought out associated savings from the transportation and the storage of fossil fuels [63].

All these projects justify the need for waste heat recovery project in mining operations located in the cold climate regions of Canada. It also evaluates any potential heat source mandatory considering the economic and environmental values.

2.5 Summary

The general energy analysis of the diesel generator provided a rough estimation of the amount of energy lost as heat in the exhaust. At the same time, it also showed the necessity of the detailed, in-depth analysis regarding this (discussed in 3.1). The comparative analysis regarding different methods of recovering the exhaust heat made the research outline more specific. The overview of the significant heat recovery projects in mining in Canada showed the necessity of the present study.

Chapter 3: Methodology and Description of the Proposed DEHR System

In 2.1, several studies showing the general analysis of a diesel generator or an engine were pointed. However, for the sake of this research, it was crucial to analyze the energy analysis of diesel generators of different types and sizes. Performance of a typical generator at different load factors was also necessary to review. To get a holistic view, several vendors were contacted by the author and technical datasheets of generators of wide ranges were gathered. As the research scopes in the remote mining operations in the cold climate regions of Canada, the emphasis was put on the conventional generator those are used in such application. Keeping that in focus, generators with prime and continuous ratings were selected. To make the evaluation easily understandable, all the calculations for different generators and generators at different load factors were broken down to unitary analysis and presented in detail in section 3.1.

A heat recovery system was proposed to recover the waste heat from the exhaust of the diesel generators in mines and reuse it for multiple purposes. This system comprising of three simultaneously working heat exchanger units:

- Exhaust heat recovery unit to recover waste heat from the exhaust of the diesel generator
- Intake air heating unit that will transfer the recovered heat from the exhaust to the mine intake air through the appropriate working fluid
- Hydronic heating and domestic heating system that will transfer the recovered heat from the exhaust to provide necessary heating to campsites

The target is to recover the heat from the exhaust of the diesel generator through an exhaust heat recovery unit and transfer it to the intake air heating unit and the hydronic heating and domestic hot water system on demand basis. For the present work, the focus was only on the exhaust heat recovery unit. However, there is another study on the intake air heating system at NBK Institute of Mining Engineering, The University of British Columbia, where the author is equivalently involved. The hydronic heating and domestic hot water system are already established and commercially available units which kept them out of the research scope. Figure 3-1 shows a schematic of the entire system.

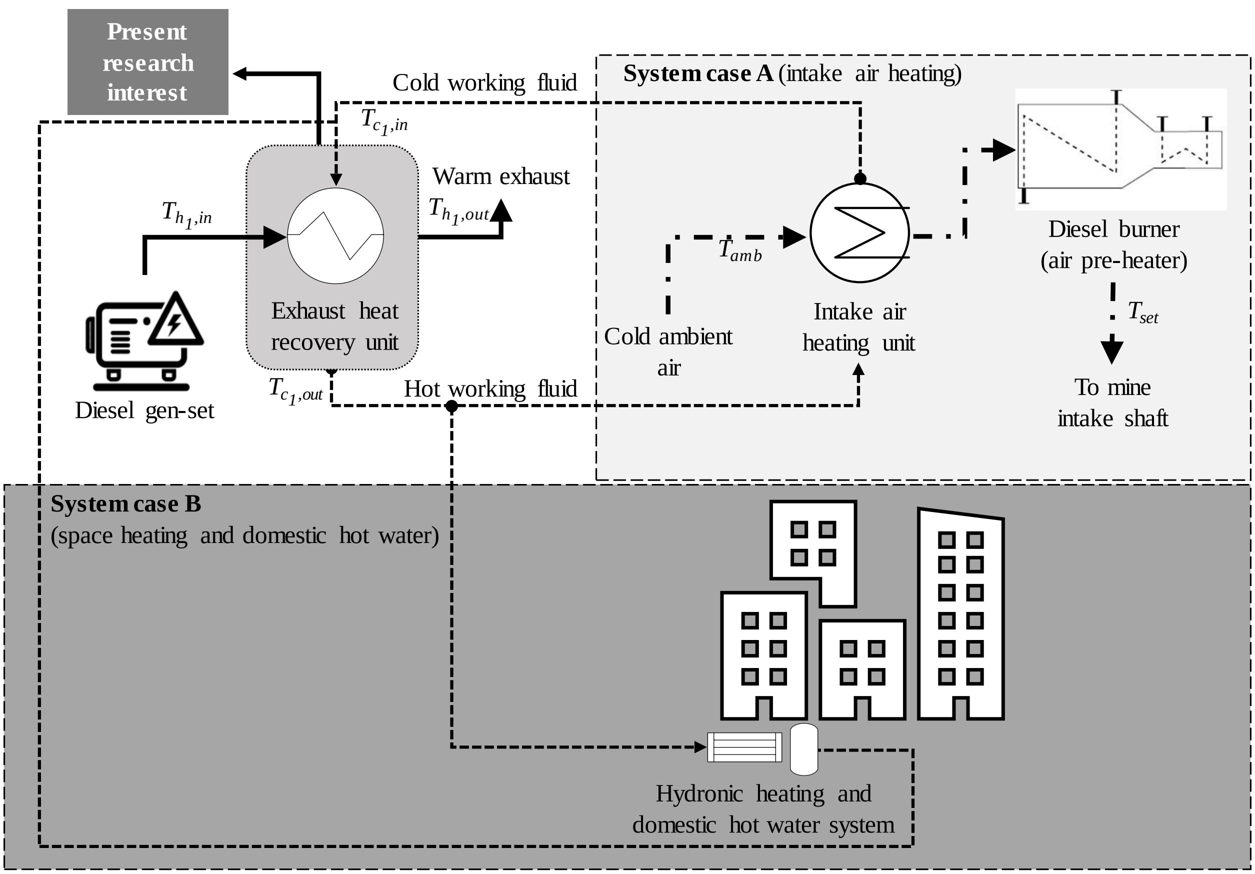


Figure 3-1 Proposed heat recovery system for heating mine intake air (Case A) and/or space heating and domestic hot water system for campsites (Case B)

Based on the comparative analysis presented in the literature review of this study and availability in the market [37], a single pass shell and tube heat exchanger was proposed and selected for the exhaust heat recovery system. In this system, the exhaust manifold will be directly connected to the heat exchanger inlet. There the heat will be transferred to the preferable working fluid which will later carry out the heat to the end-user system. As this system was being proposed to operate in the remote, off-grid mines in the cold climate of Canada where the temperature goes below -40° C, the working fluid should have anti-freezing properties. An ethylene-glycol mixture was well recommended while operating the system in remote, cold climate locations.

There are two major applications evaluated for the recovered heat from the exhaust. Case A was especially for the underground mines where the recovered heat would be used to preheat the mine intake air. Case B was for both surface and underground mining, where this recovered exhaust heat could provide necessary heating to the campsites and other facilities.

To prove the concept, an exhaust heat recovery system was developed to recover the heat from the exhaust of a 5 ekW diesel generator both numerically and experimentally. A heat exchanger (which was not optimized for the diesel generator) was bought for this application from the marketplace. It was a single pass shell and tube heat exchanger that was used as the recovery unit and a portable load bank of 10 kW was used to control the load factors of the generator to validate the numerical model with experimental results. The details of the experimental setup are available in section 3.2. Later, the heat exchanger was modeled numerically by using CFD software ANSYS Fluent to achieve reasonable agreements with the experimental results and conduct further study. The details of developing the numerical model are available in section 3.3.

3.1 Detailed Energy Analysis of Diesel Generator

Depending on the type of applications, the diesel generators can be classified into three separate power ratings: standby, prime and continuous. Standby generators can be used as backup units when there is no need for a continuous supply of electricity and commonly seen in the areas which are connected to the grid but subject to load shedding for a limited time. These generators cannot work as a standalone source of power for a long time. Both prime and continuous rated generators can be deployed in off-grid locations to get an uninterrupted power supply for a long time. However, generators with prime rating can be operated at variable loads for a higher number of hours in every year with a few restrictions on the running time at maximum load factor. Generally, the allowable maximum load factor for prime generators is around 70%. On the other hand, continuous generators can supply electricity at 100% load factor for a large number of hours in a year [75].

Both prime and continuous generators are employed in remote, off-grid mining and have been considered in this study. After discussing with the vendors that supply generator in the mining industry, 15 different generators in the range of 364 ekW to 3100 ekW power generation capacity were selected to study. The study had two approaches. The first one was to identify the amount of waste heat from the diesel generators in total and through exhaust particularly along with the diesel consumption while the generators were running at their 100% load factor (Figure 3-2). The second approach was to evaluate the amount of diesel required by these generators at their 100% load factor to generate 1 kW of electricity along with the total amount of waste heat discarded, mainly through exhaust (Figure 3-3). For the analysis, the diesel was converted to its heating value which was the average of the lower and the higher heating value of the ultra-low sulfur diesel fuel.

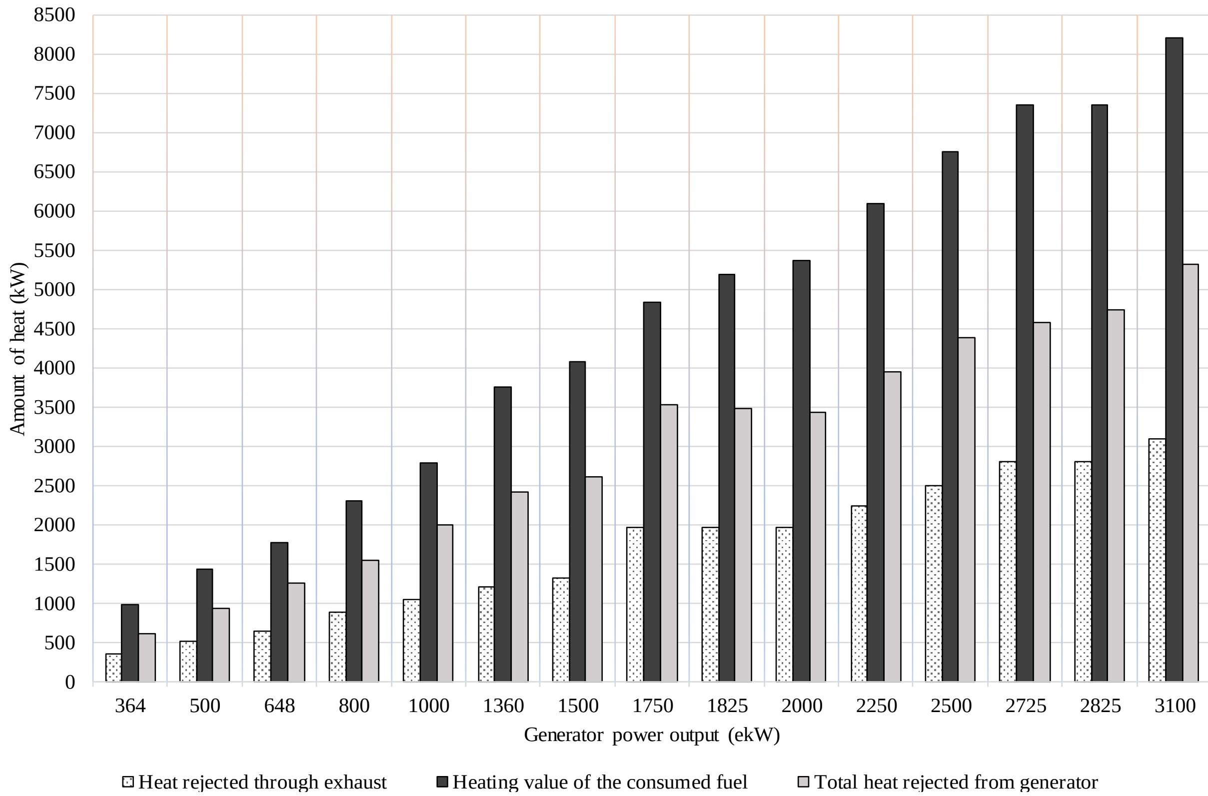


Figure 3-2 Waste heat analysis on diesel generator of several distinct power outputs (364 ekW ~ 3100 ekW)

Three significant conclusions were drawn from Figure 3-2 Figure 3-3:

- For all the generators with different capacities of power generation, the highest amount of the heat was being rejected through the exhaust. It was ranging between 50~60% of the total waste heat from the diesel generator.
- No matter what the size of the generator was, the exhaust was containing 31~41% of the heating value of the consumed fuel.
- The generators had to consume 2.5~3.0 kW (heating value) worth of diesel fuel in order to generate 1 kW of electricity. During this process, a total amount of 1.7~ 2.0 kW of waste heat was being rejected in total and in particular, through exhaust the discarded heat was almost 1kW.

In a line, disregarding the size or type of the generator, at 100% load factor, the discarded heat through the exhaust of all the diesel generator is almost equivalent to their power outputs.

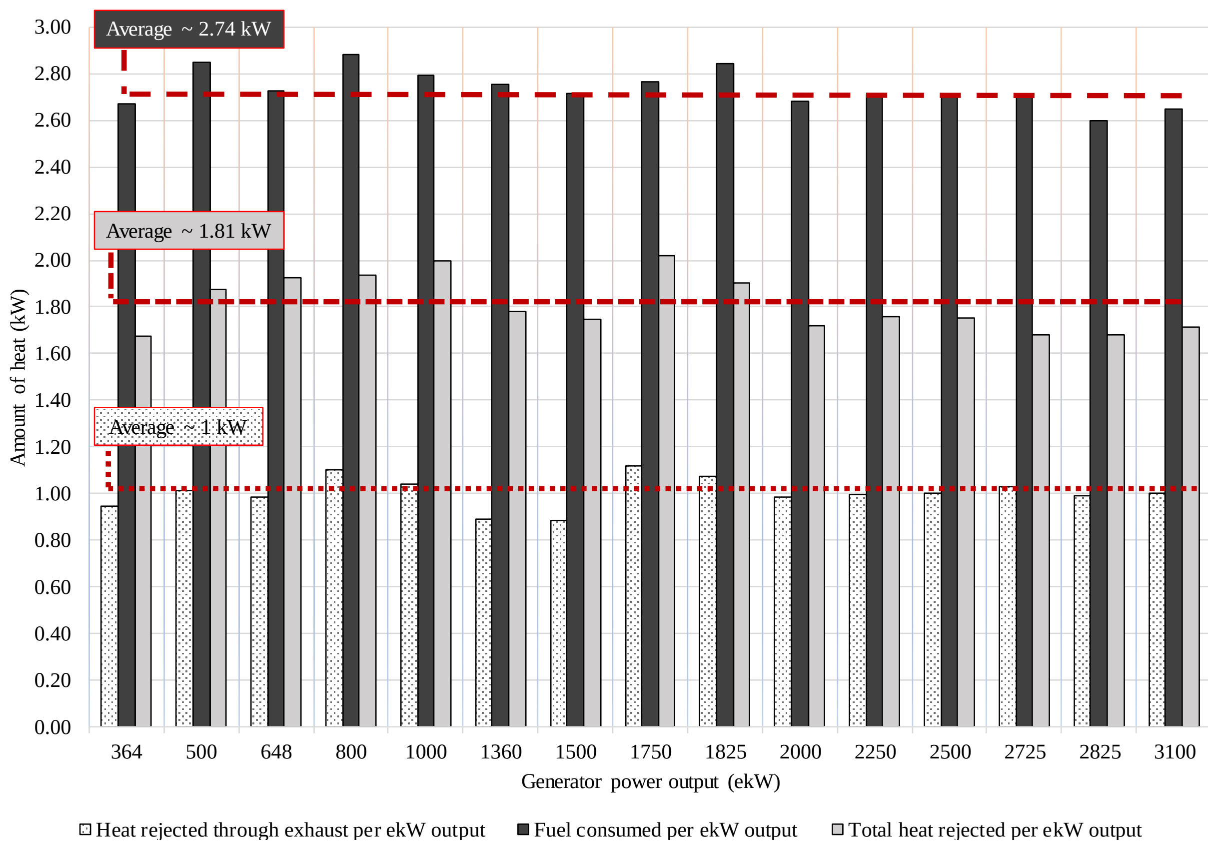


Figure 3-3 Waste heat analysis on diesel generator of several distinct power outputs (364 ekW ~ 3100 ekW) per kW electricity generation

The next step was to identify the amount of waste heat from a diesel generator in total and through exhaust particularly along with the diesel consumption while the same generator was running at various load factors (10~100%) (Figure 3-4). As the previous analysis, the second approach was to evaluate the amount of diesel required by a generator at various load factors (10~100%) to generate 1 kW of electricity along with the total amount of waste heat discarded, mainly through the exhaust. After proper correspondence with the vendors, a 1750 ekW generator was chosen for this analysis (Figure 3-5).

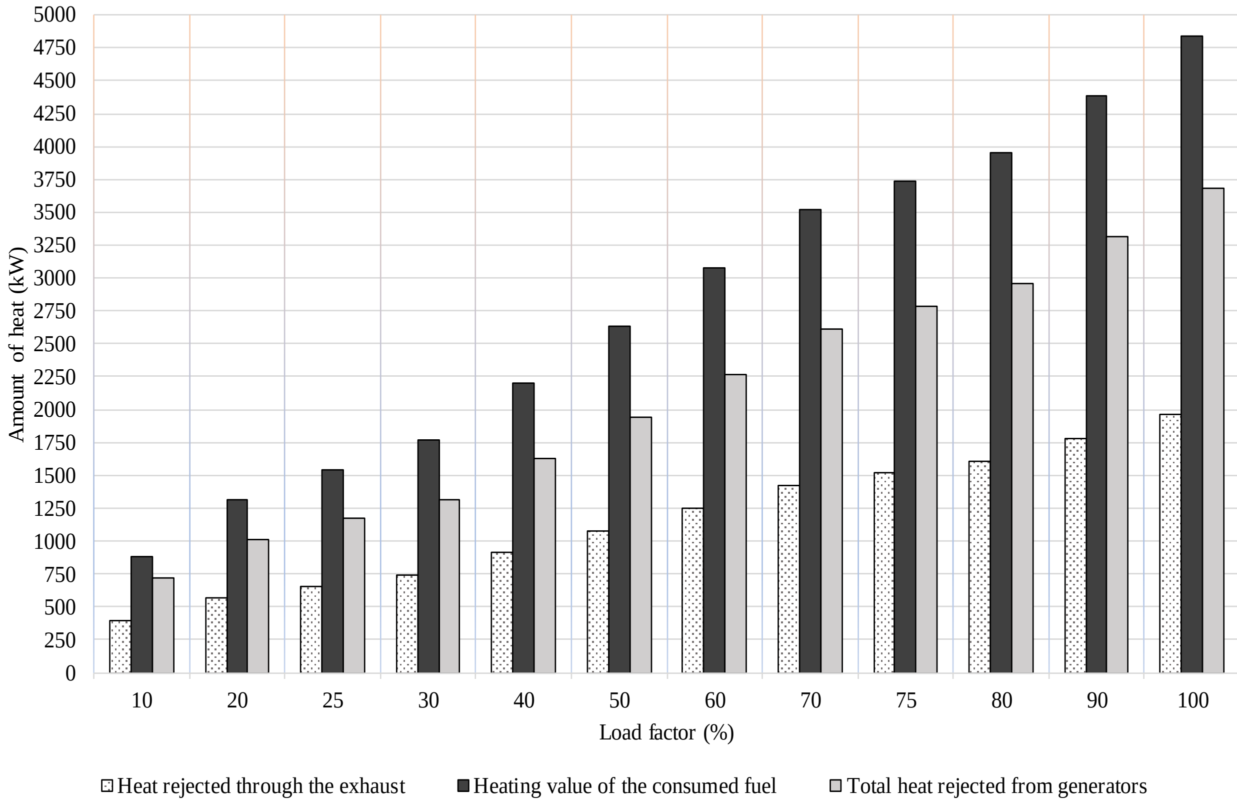


Figure 3-4 Waste heat analysis on a 1750 ekW diesel generator at various load factors

The following conclusions were depicted in the analysis:

- At almost all the load factors, the amount of rejected heat through the exhaust ranged between 53~56% which supported the previous findings. The exception to this was found at lower load factors which are below the normal operating conditions of a diesel generator for continuous operation.
- Through the exhaust, between 39% to 47% of the energy obtained from the fuel was discarded from the generator operating at different load factors. The percentage of this exhaust heat had a decrease with increasing load but stayed in the range of previous

findings. However, this discrepancy can be justified by referring to the fact that previous data was collected at 100% load factor.

- The generators had to consume 2.6~5.2 kW (heating value) worth of diesel fuel in order to generate 1 kW of electricity. During this process, a total amount of 1.4 kW (on average) of waste heat was being rejected in total and particularly, through exhaust the discarded heat was almost 1.4 kW.
- The analysis also showed a rapid fluctuation at 10% load factor due to the above normal operating condition.

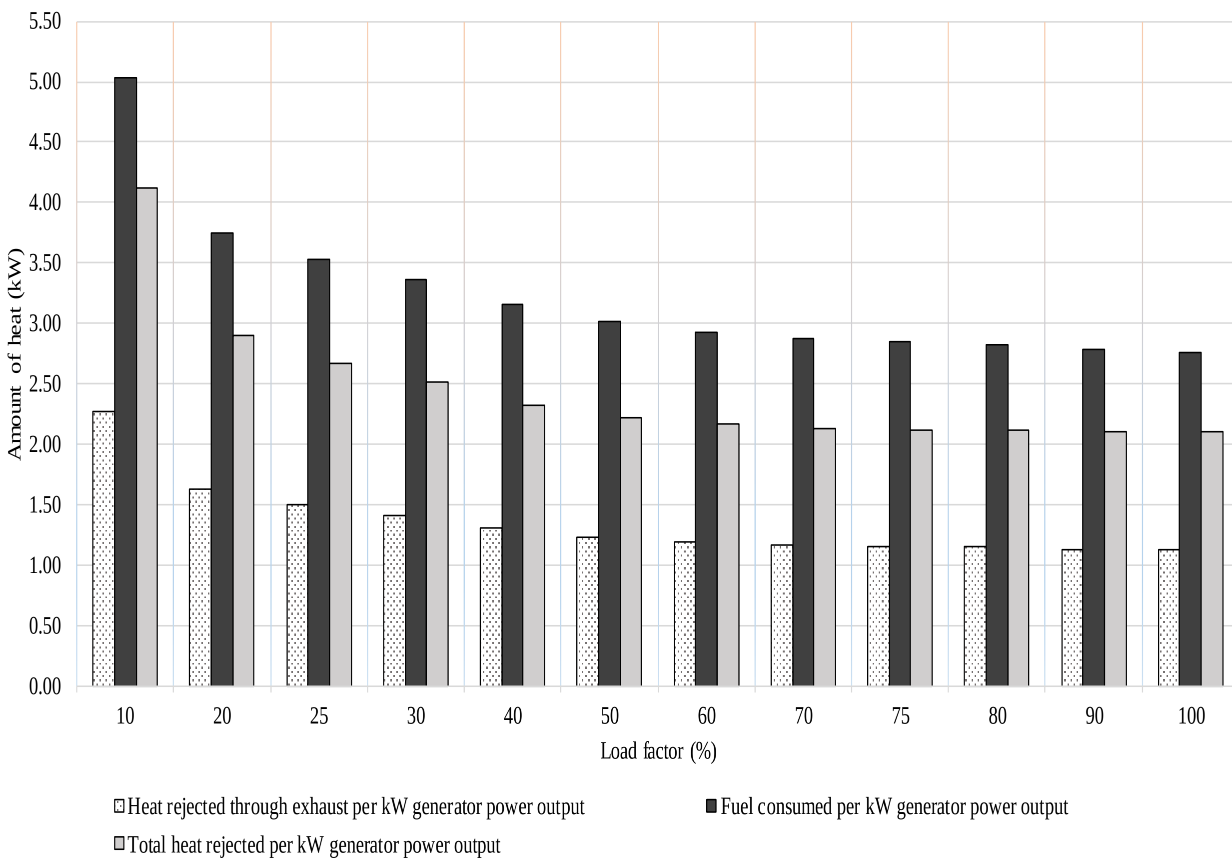


Figure 3-5 Waste heat analysis on a 1750 ekW diesel generator at various load factors per kW electricity generation

In a line, under regular operating point, at almost all the load factors, the discarded heat through the exhaust is almost equivalent to its power outputs.

Based on these analyses, it was proved that the exhaust of the diesel generators holds the potentiality to be a source of green heat in remote mines, operating in cold climatic conditions of Canada. Recovering a considerable amount of heat could contribute effectively in reducing the operating costs of the mine and the carbon footprint.

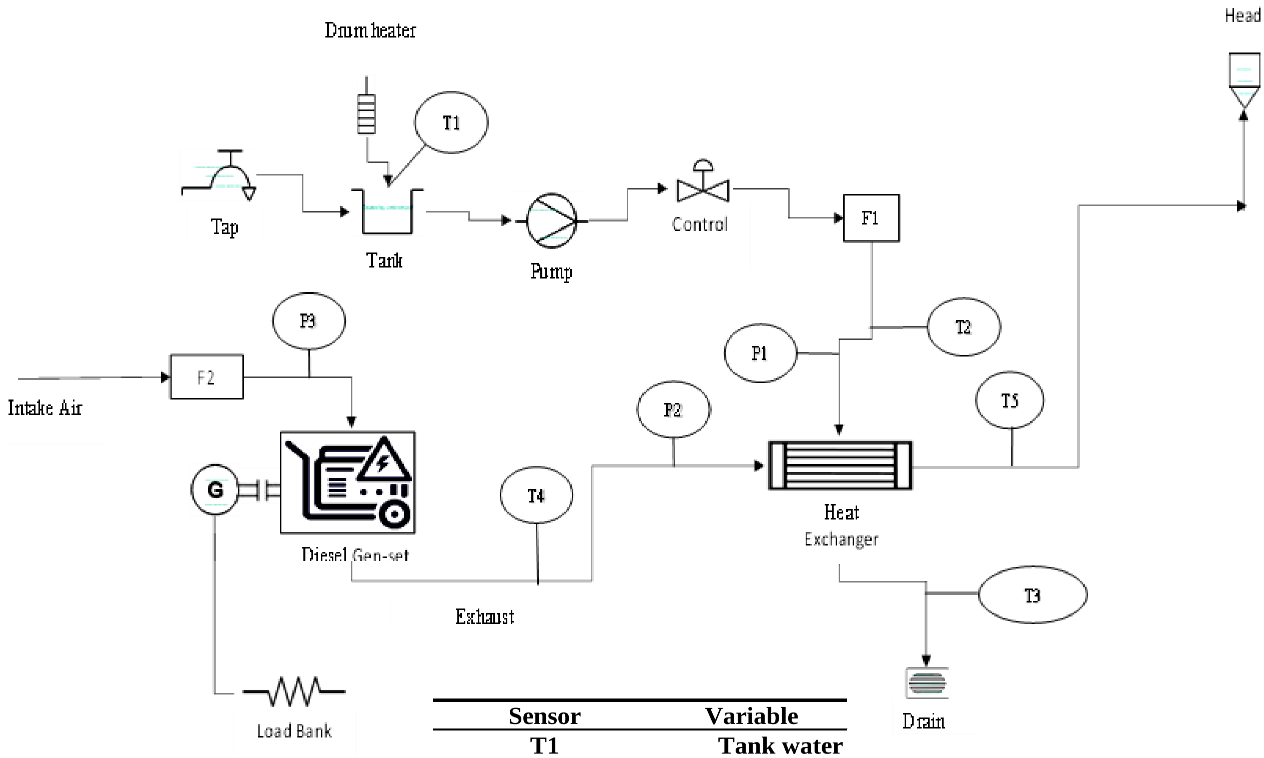
3.2 Experimental Setup

An experimental set-up was built to recover the waste heat from the exhaust of the diesel generator with a shell and tube heat exchanger. The target was to run the hot exhaust from the generator through the tube side of the heat exchanger. At the same time a flow of water would be running through the shell side, capturing the heat from the exhaust. Water was chosen as the working fluid of the system due to its availability and for keeping the system under budget. Also, as the test was conducted at The University of British Columbia at an ambient temperature of 10~15°C, it was possible to use water as the working fluid. However, in remote locations, the working fluid should have an anti-freezing property as previously mentioned.

The experimental setup had two simultaneously running, separate mobile units.

- The first mobile unit consisted of the diesel generator, a load bank to control the load factors of the generator and a shell and tube heat exchanger.
- The second unit was carrying all the necessary equipment and instrumentation to provide continuous water flow through the shell side of the heat exchanger for a certain period.

The setup (schematic is shown in Figure 3-6) was designed in a way to gather all the necessary real-time data without interrupting the process.



Sensor	Variable
T1	Tank water
T2	Inlet water
T3	Outlet water
T4	Inlet air
T5	Outlet air
P1	Water inlet
P2	Air inlet
P3	Air intake
F1	Water flow
F2	Intake Air Flow

Figure 3-6 Schematic of the experimental setup (not to scale)

After designing the setup, the following major equipment was bought:

- A DuroStar DS700Q diesel generator; the maximum power of this low-noise, air-cooled diesel generator was 5 ekW
- A shell and tube heat exchanger (Bowman Exhaust Gas Cooler: model# 2-25-3737-4)

- A Simplex portable load bank (10 kW)
- Mass flow meter (Omega FMA1845A)
- A drum heater
- K-type thermocouples with data logger
- 4 pressure gauges
- 2 mobile carts
- Piping and fittings

By using the load bank, the diesel generator was tested at various load factors (0%~100%) and the temperatures of the exhaust were logged. Both the temperature and the mass flow of the exhaust were essential to know to estimate the heat transfer between the exhaust and the water. However, due to the unavailability of suitable mass flow meters in the budget, it was decided to measure the intake air flow of the generator. Previous studies juaatified this alternative approach [42].

To measure the intake air flow, the air inlet of the generator was extended (shown in Figure 3-7) and a mass flow meter (Omega FMA1845A) with ±1.5% accuracy was installed to measure the flow. A manometer (±0.5% accuracy) was used to measure the pressure drop due to the expansion and it was less than 1 kPa at all load factors. This was reasonably acceptable for the experiment.

Later from the fuel consumption value and the air/fuel ratio of the diesel generator at different load factors (provided in the manual), the mass flow of the exhaust of the generator at different load factors was estimated.

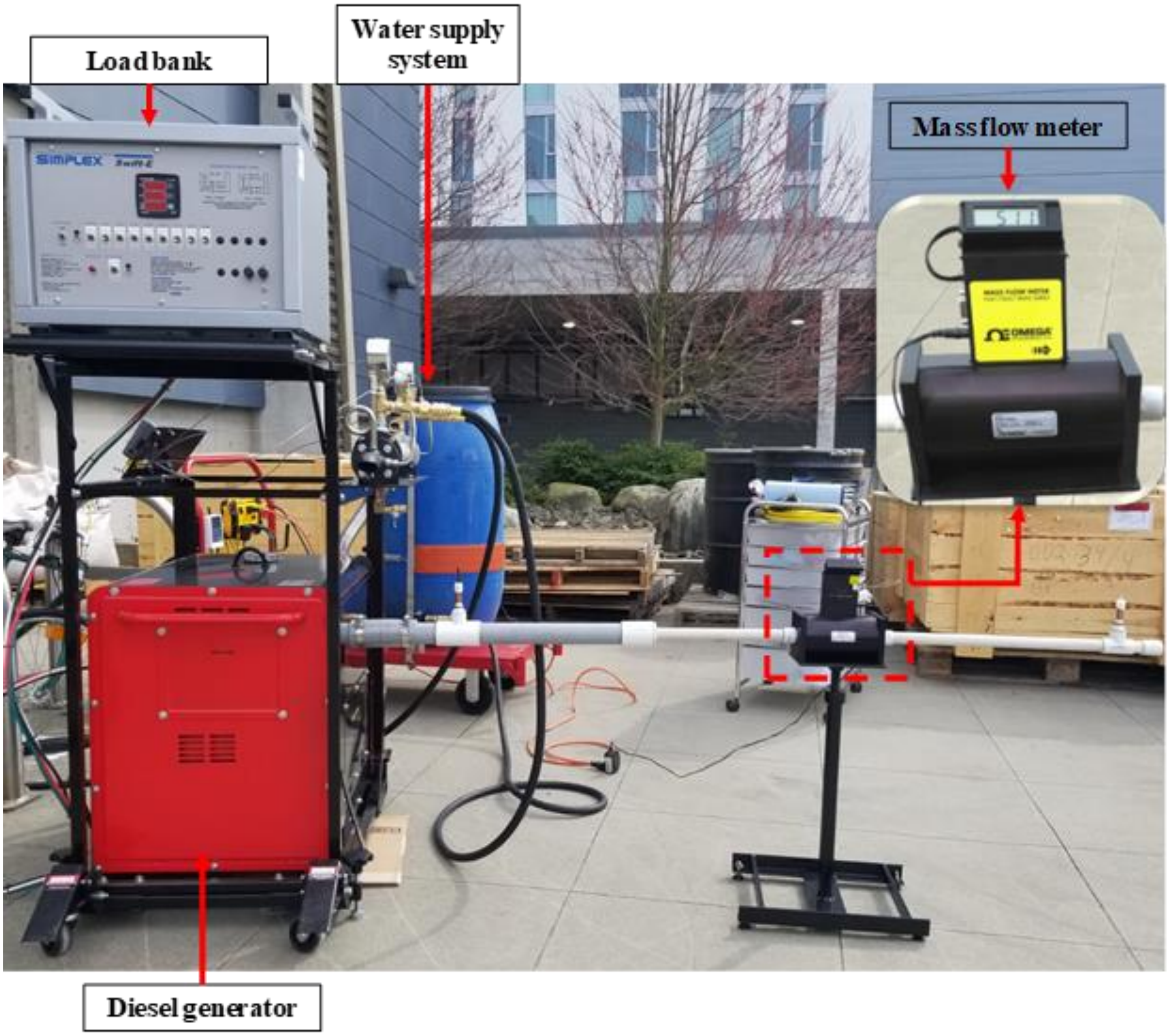


Figure 3-7 Experimental setup

As diesel engine is a compression ignition engine, the air/fuel ratio always stays in the lean zone and the mass flow of the exhaust found to be decreasing with the increase of the load factors [76]. The estimated measured values for the exhaust of our diesel generator were also in agreement with the previous findings.

The mass flow rate of the diesel exhaust at different load factors (0~100%) was estimated between 0.0121 kg/s to 0.0118 kg/s form the fuel consumption and the air/fuel ration of the diesel engine provided in the catalogue of the generator. The measured values for the intake air flow were between 0.0113 kg/s to 0.0120 kg/s. All the values are shown in Figure 3-8.

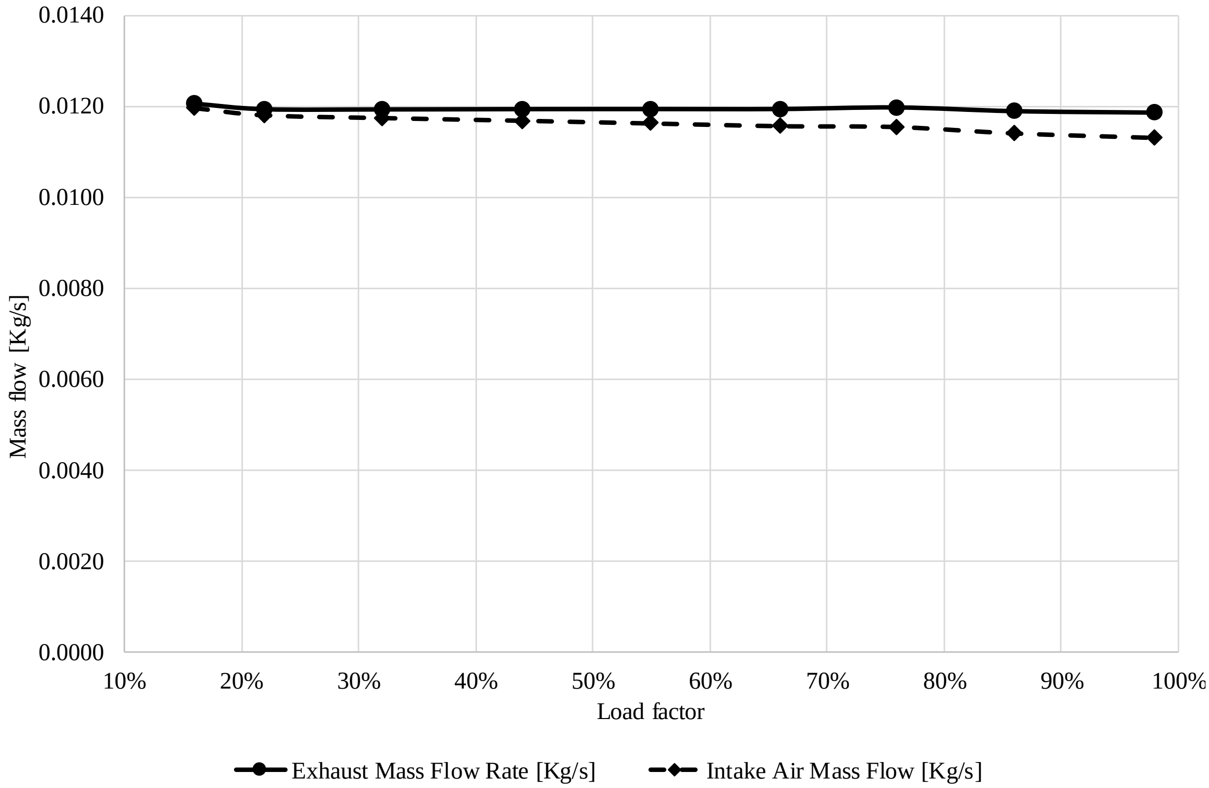


Figure 3-8 Mass flow of the intake air (measured) and the exhaust (estimated) of DS7000Q diesel generator

More details of the equipment are available in Appendix B of this study.

3.2.1 Water Supply System

The manufacturer of the heat exchanger used in the experiment warned not to use the heat exchanger without water running through the shell side of the heat exchanger. This made it necessary to ensure a continuous flow during the runtime of the experiment. To do so, a mobile cart was built consisting following equipment (shown in Figure 3-9):

- A plastic drum (size of 55 gallons) with lid necessary fittings were installed to circulate the water from the pump to the heat exchanger
- A drum heater to keep the water temperature inside drum at the required value
- A small submersible pump was placed inside the drum to mix the water for getting an even temperature distribution in the drum water
- A peristaltic pump was connected to the drum to pump the water
- DIGITEN water flow controller was containing flow and temperature sensor for real time monitoring.

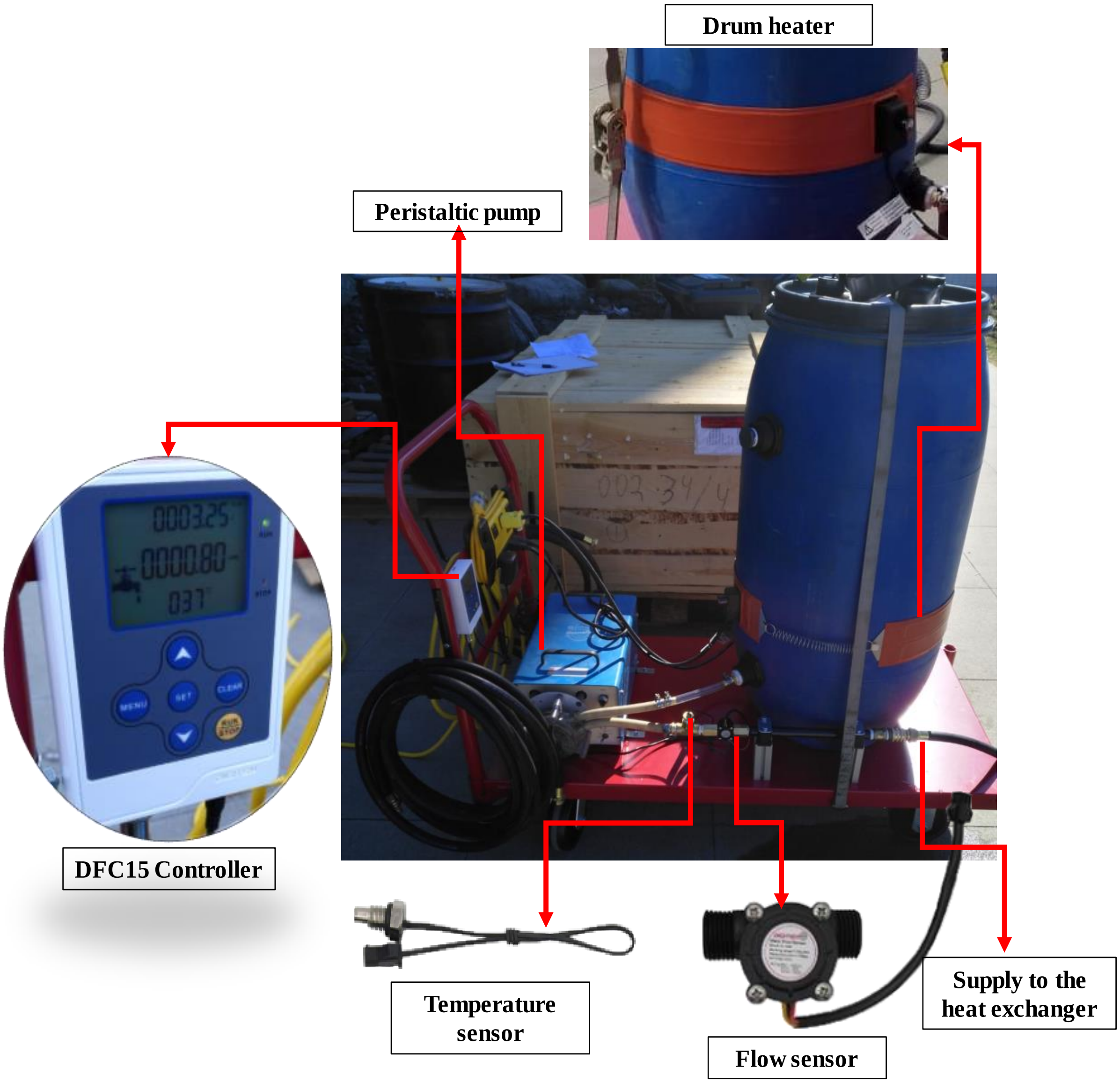


Figure 3-9 Water supply system

At first, the drum was filled with cold and hot tap water mixing to get a temperature of 45°C. Then the drum heater was used to maintain the temperature. The temperature and mass flow ensured pumping required flow rate of water at required temperature via the peristaltic pump.

3.2.2 Heat Exchanger Section

A single pass, counter flow shell and tube heat exchanger was mounted in the same mobile cart carrying the generator and the load bank. The exhaust section from the manifold was extended and connected to the tubes of the heat exchanger. The inlets and outlets of both water and the exhaust sides are shown in Figure 3-10.

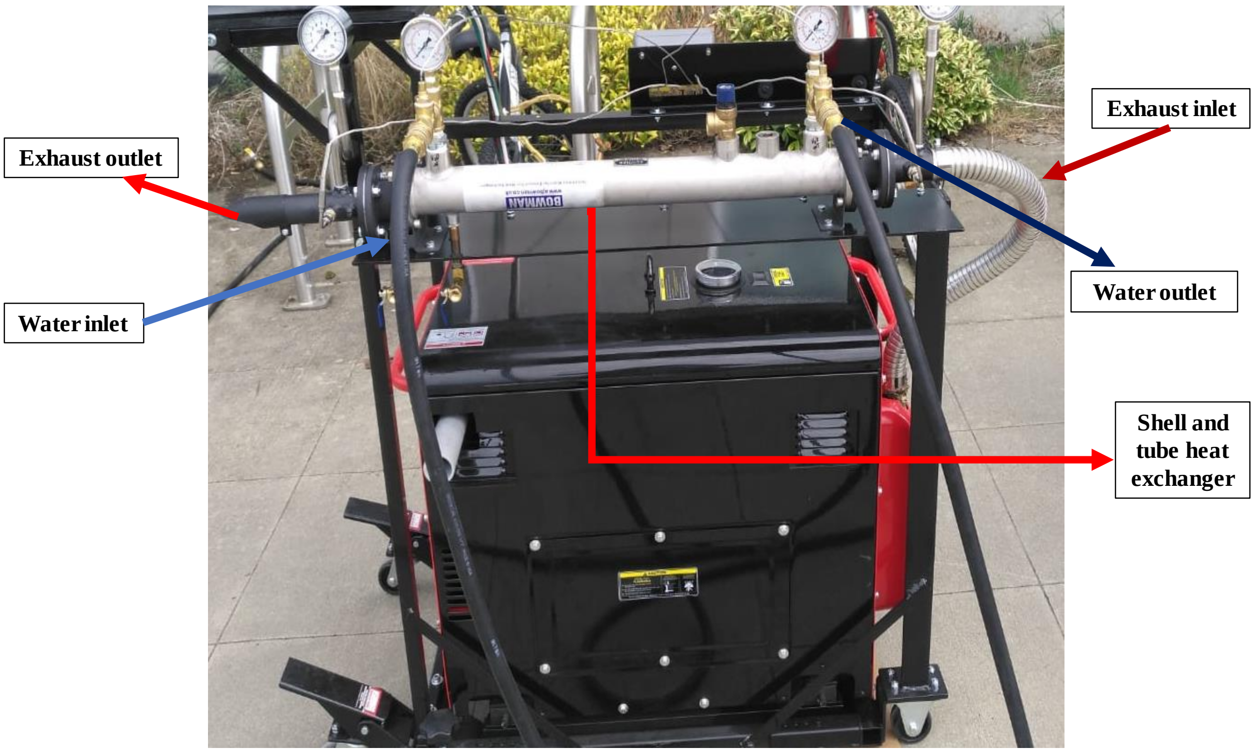


Figure 3-10 Shell and tube heat exchanger installed in the experimental setup

To monitor the pressure drop, 2 chrome plated steel pressure gauges (0-10 in. of water) with ±2% accuracy were installed in the inlet and the outlet side of the exhaust. Similarly, for the waterside, 2 stainless steel pressure gauges (0-15 psi) with ±1.5% accuracy were installed. 4 K-type thermocouples were installed in the inlets and outlets of the exhaust and water side. A channel data logger was used to monitor and store the temperature data (shown in Figure 3-11).

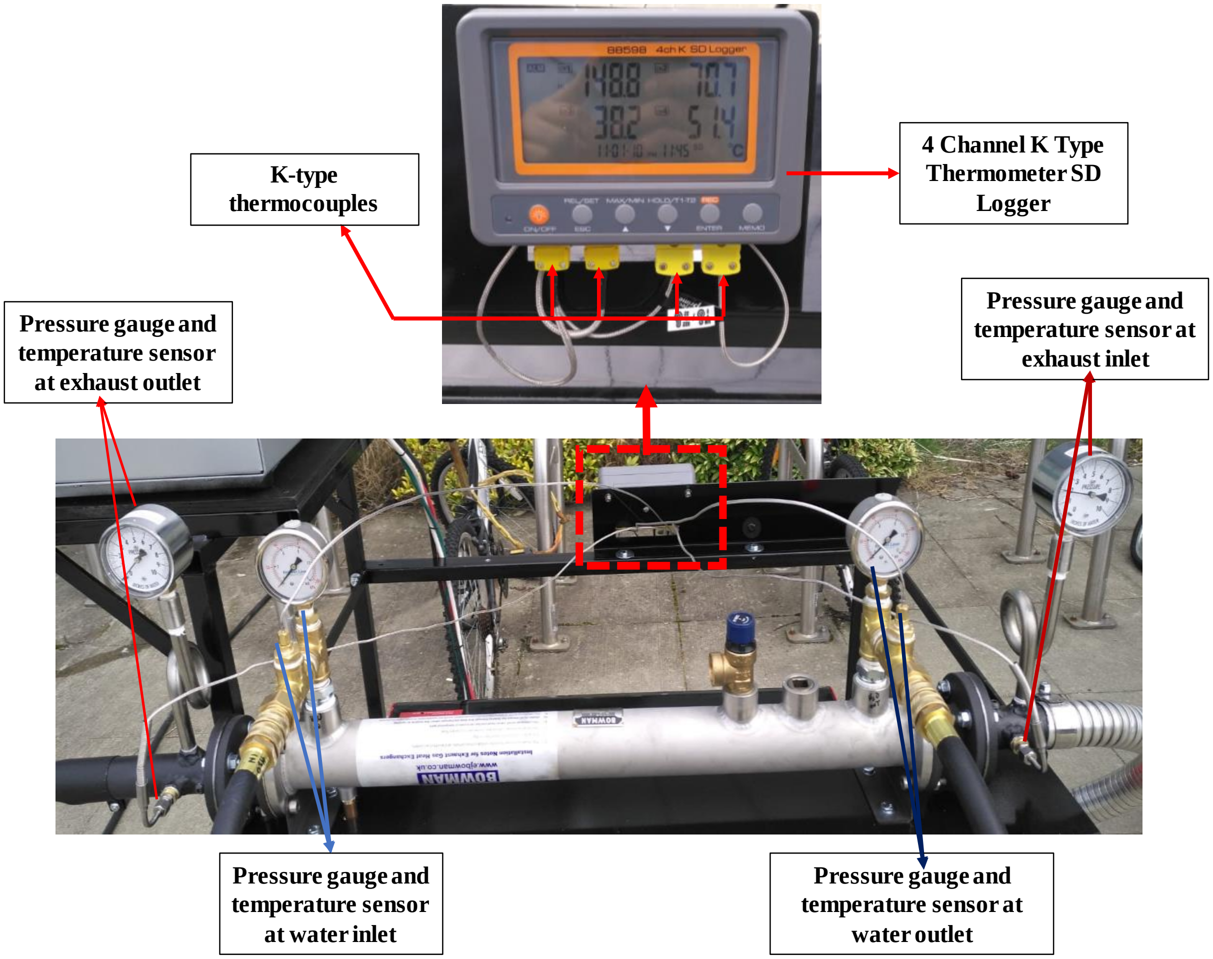


Figure 3-11 Data collection system

3.3 Numerical Model Description

To achieve satisfactory agreements between the results of experiments and simulation, the purchased heat exchanger was drawn by Computer Aided Design (CAD) software SolidWorks 2018 and later meshed in ANSYS meshing software. The fluid flow and heat transfer equations were solved via ANSYS Fluent (the CFD code is based on finite volume methods).

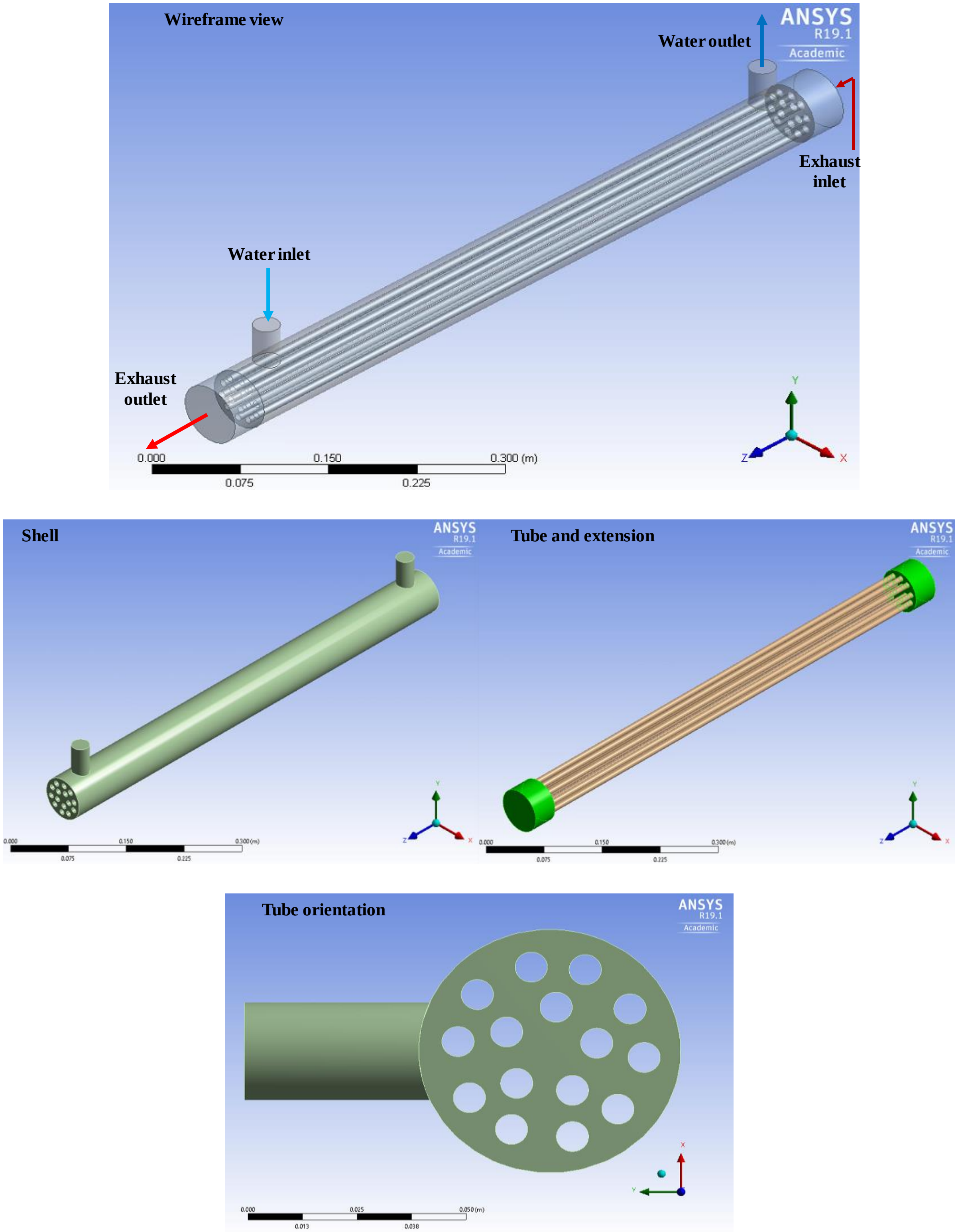


Figure 3-12 Shell and tube heat exchanger schematic

ANSYS Fluent was chosen due to its high performance in solving a wide-range heat transfer and fluid flow problems. K-epsilon (k-ε) turbulence model was selected to simulate to get the results shown in Table 3-1 at the initial level. These parameters were set based on the equations presented in section 2.2.1. The following sections contain the numerical studies conducted to get the most accurate numerical model possible which later could be validated by the experimental results. For all the simulation a constant mass flow inlet (with constant temperature) and pressure outlet at ambient temperature were used as boundary conditions for the water side. For the exhaust side, the inlet was pressure inlet with a constant temperature and the outlet was a mass-flow outlet at ambient pressure and temperature.

Table 3-1 Estimated result for the numerical model

Properties	Water	Exhaust
Mass-flow (kg/s)	0.014	0.0121
Temperature (K)	40	192
Heat flux (kW)	2.34	2.42

3.3.1 Meshing

In general, the CutCell meshing (it converts a volume mesh into a predominantly Cartesian mesh with more hexahedral elements) was chosen primarily for all the models due to its higher functionality with complex geometries. Then, different meshing schemes (based on maximum mesh size) were adapted to get a more accurate model. This way the simulation was conducted with the coarser to finer meshed models which allowed to evaluate the optimum meshing for the heat exchanger. The approach started with selecting a mesh size of 40 mm which gave a very coarse mesh with 0.18 million elements. Then the maximum mesh size was decreased to 5.76 mm, 4 mm and 0.8 mm gradually which generated finer mesh with 0.78, 2.04 and 4.3 million elements respectively.

Table 3-2 Number of elements for different mesh models

Maximum mesh size (mm)	No. of elements
0.80	4,290,179
4.00	2,037,562
5.76	776,673
40.00	180,263

Figure 3-13 shows the graphical representation of different meshed models.

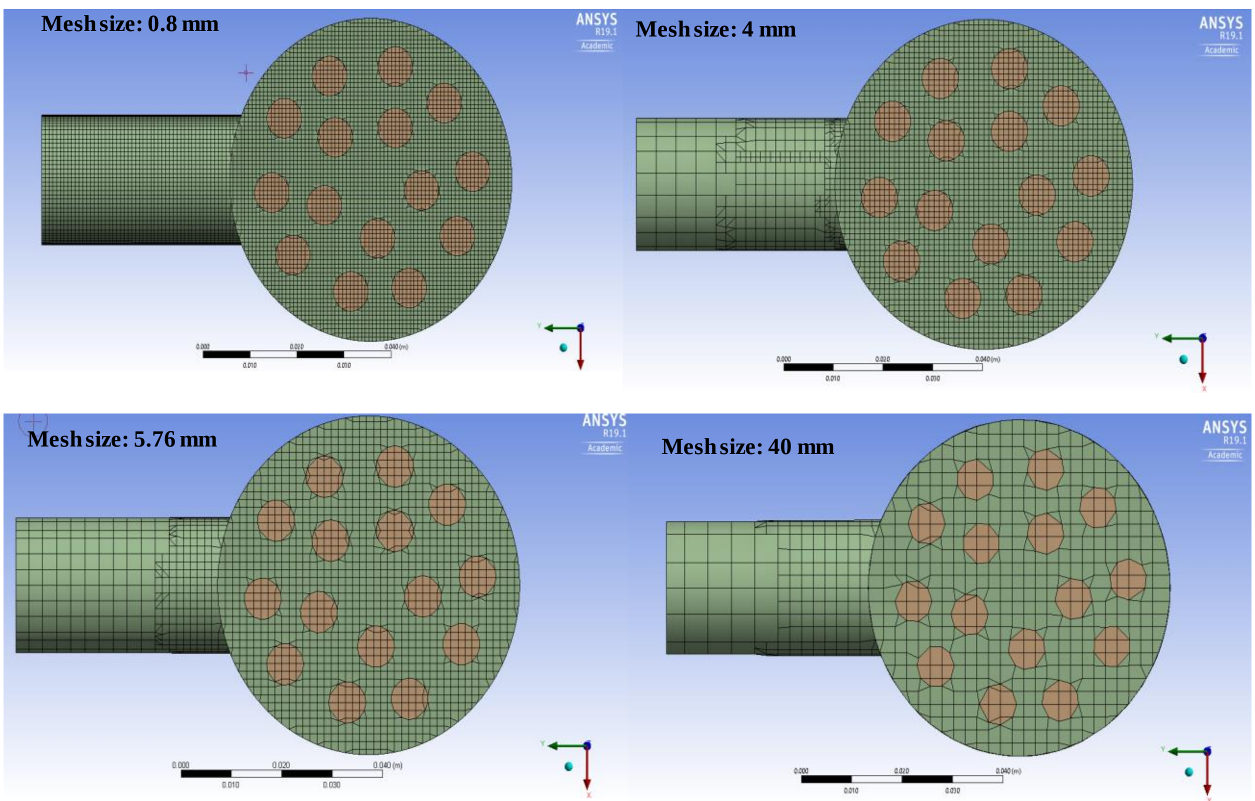


Figure 3-13 Geometrical view of different mesh sizes

The results from different meshed models showed that mesh refinement helped a little before reaching the grid independence. Considerable effects were observed up to 776,263 elements ranges. After this point, the effects were less significant in both exhaust and water side (shown in Figure 3-14). However, the final model was selected for further study with 1,988,450 nodes and 2,037,562 elements.

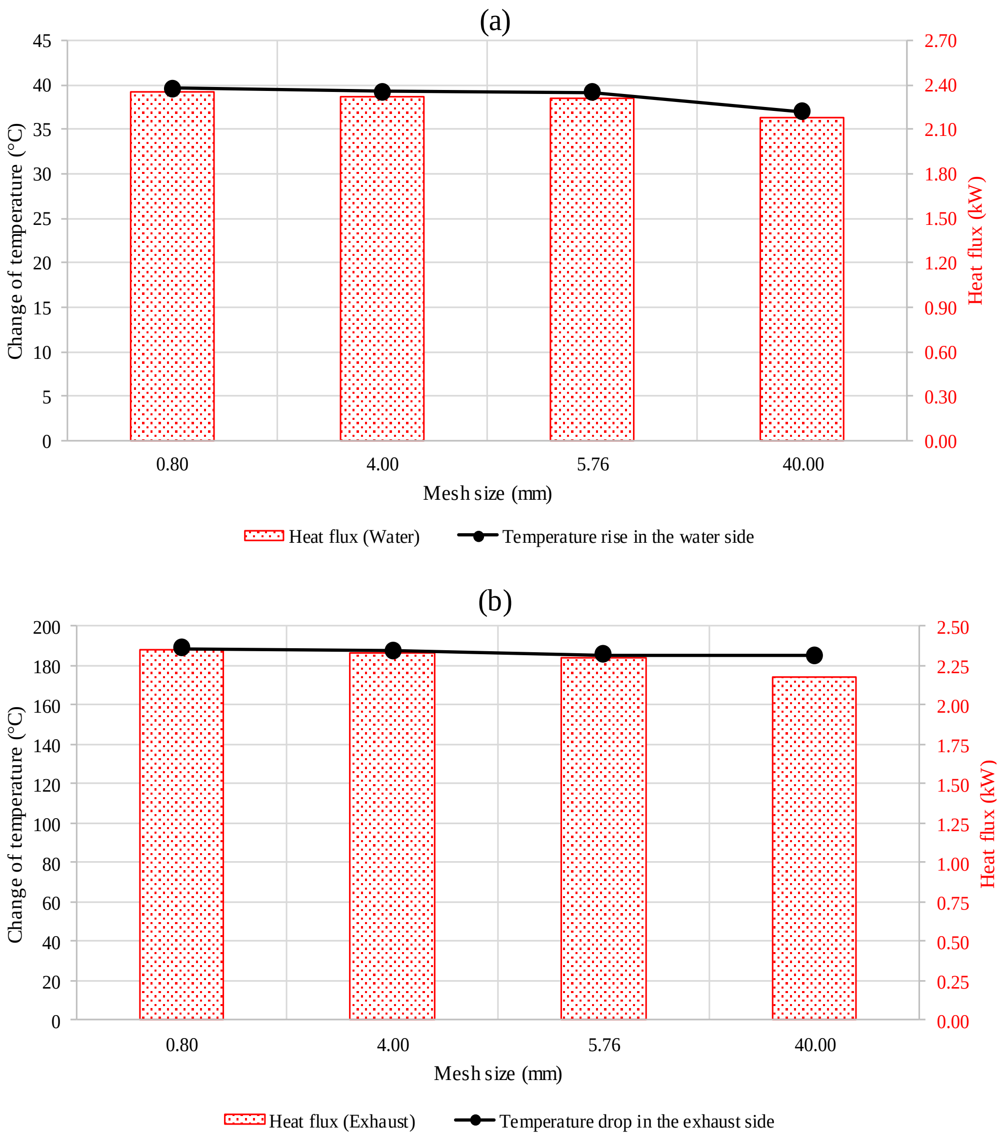


Figure 3-14 Change in temperature and heat flux for water (a) and exhaust (b) side at different mesh sizes (Temperatures and heat fluxes are shown in the left and right axis respectively)

3.3.2 Domain Length Selection

To avoid the reverse flow in the simulation and to make it more realistic, the inlet and the outlet domains for both exhaust and water side were increased (details provided in Table 3-3).

Table 3-3 Domain length for 4 different cases

Case no.	Domain extension in exhaust side (mm)	Domain extension in water side (mm)
Case 1	35	40
Case 2	45	50
Case 3	65	70
Case 4	95	100

All the 4 cases meshed with the selected settings from the previous findings (shown in 3.3.1). It was found out that minimum 35 mm of extension in the exhaust side and 40 mm extension on the water side were required to avoid the reverse flow. So, this was used as an initial point for this section of the study. Then for both water and exhaust side the domain was increased by 10 mm, 30 mm and finally 60 mm from the initial point for both inlets and outlets.

The first 10 mm increase brought the simulation results closer to the calculated values (mentioned in Table 3-1)., especially for the water side. The results for the exhaust side remained almost steady. Considering the results (shown in Figure 3-15) and the computational time, the further studies proceeded with case 2.

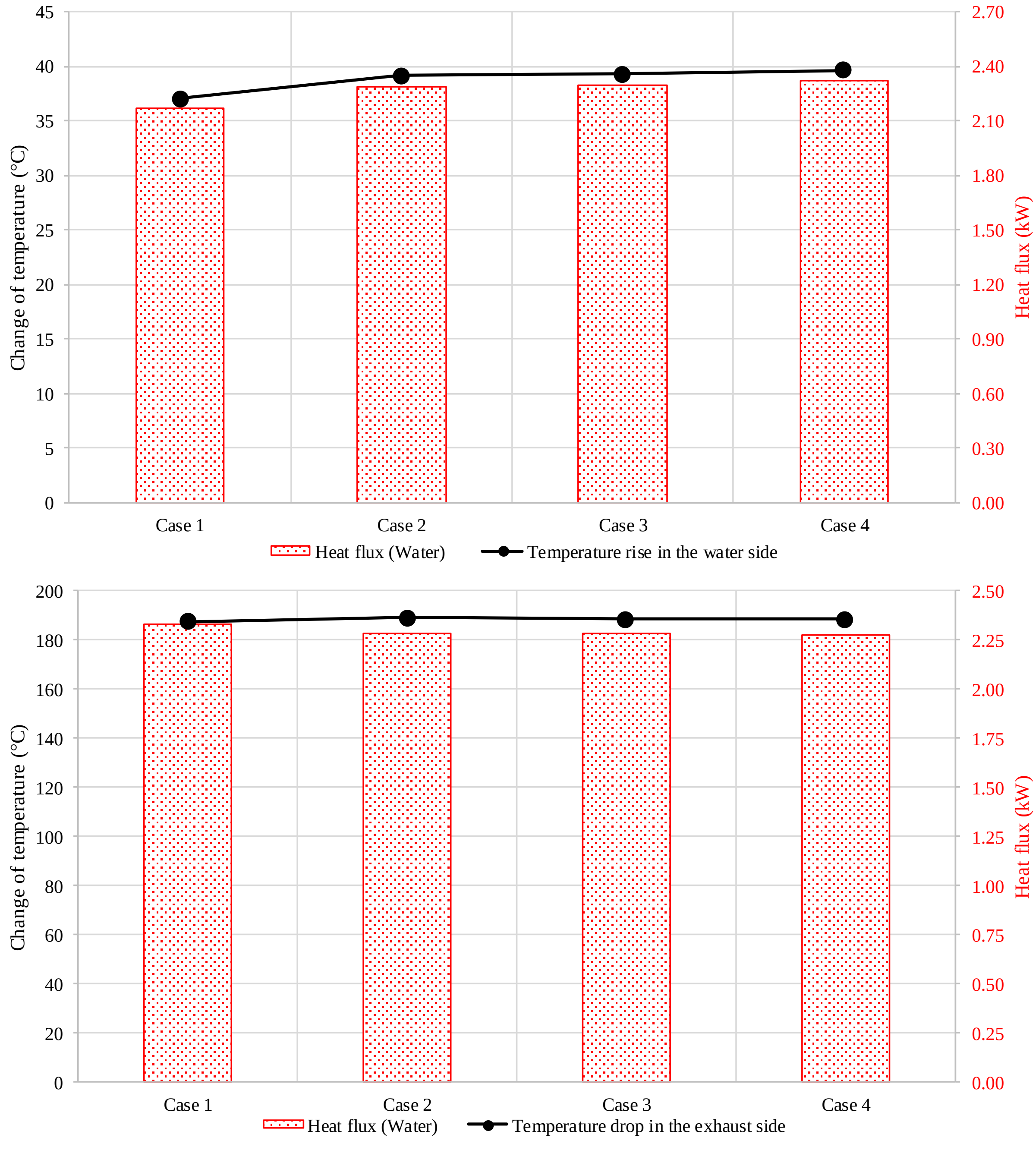


Figure 3-15 Change in temperature and heat flux for water and exhaust side at different domain lengths

(Temperatures and heat fluxes are shown in left and right axis respectively)

3.3.3 Exhaust Properties Selection

Previous studies were available where the exhaust was considered having all the properties of air constant in ANSYS Fluent simulations. However, for this study, several fluid types were considered (shown in Table 3-4).

Table 3-4 Considered properties for exhaust gas simulation

Exhaust type	Properties
Type 1	Constant properties of air on ANSYS Fluent; except ideal gas density and thermal conductivity piecewise polynomial (temperature dependent)
Type 2	Constant properties of air on ANSYS Fluent; except ideal gas density
Type 3	Constant properties of air on ANSYS Fluent
Type 4	Constant properties of air on ANSYS Fluent with a constant density of 0.7 kg/m^3

With the selected mesh and domain length (mentioned in section 3.3.1 and 3.3.2), four different simulations were rerun with the same boundary conditions (mentioned in section 3.3). However, it was found that using the ideal gas density of air brought the simulation results closer to the calculated values (mentioned in Table 3-1). Making the thermal conductivity a variable function of temperature did not have a significant impact in terms of temperature change or heat flux. However, as it required more computational time and power, further studies were conducted with ‘Type 1’ exhaust.

The results are available in Figure 3-16.

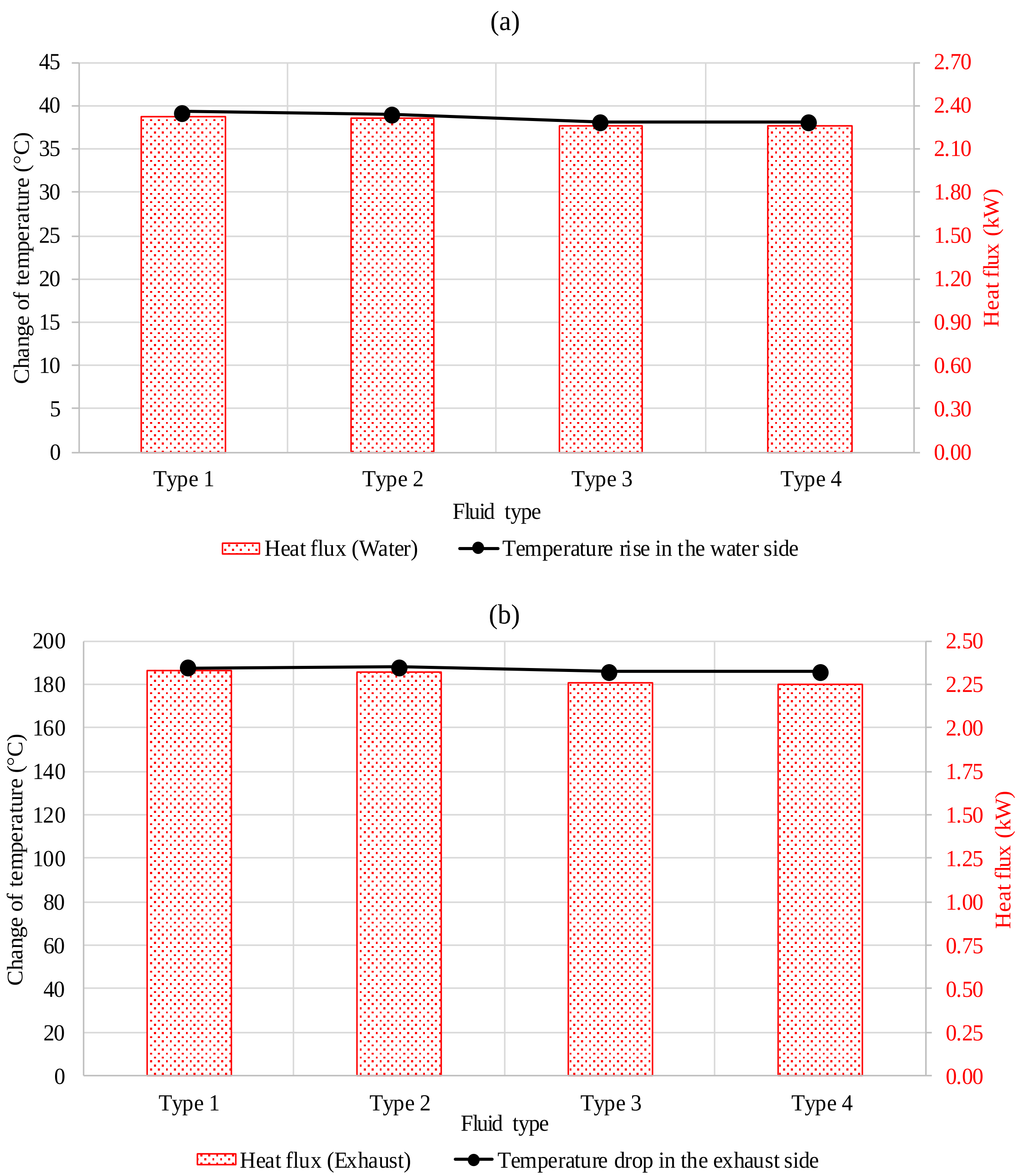


Figure 3-16 Change in temperature and heat flux for water (a) and exhaust (b) side at different exhaust types (Temperatures and heat fluxes are shown in the left and right axis respectively)

Chapter 4: Results and Discussions

4.1 Model Validation

The experiment was conducted at six different load factors (0%, 16%, 44%, 64%, 88% and 96%) of the generator. The prepared numerical model (based on the studies from section 3.3) was also run on the same load factors. As the experimental setup was lacking proper insulation, there were certain heat losses. This heat loss was calculated based on the literature [18] and added in the simulation (details are given in Appendix C)shape the simulation more realistically.

The inlet temperatures for the exhaust and the water in the experiments (shown in Figure 4-1) were logged and used in the boundary conditions in the numerical simulation. The water had an almost constant mass flow of 0.02 kg/s and the estimated mass-flow of the exhaust varied in accordance with the values shown in Figure 3-8.

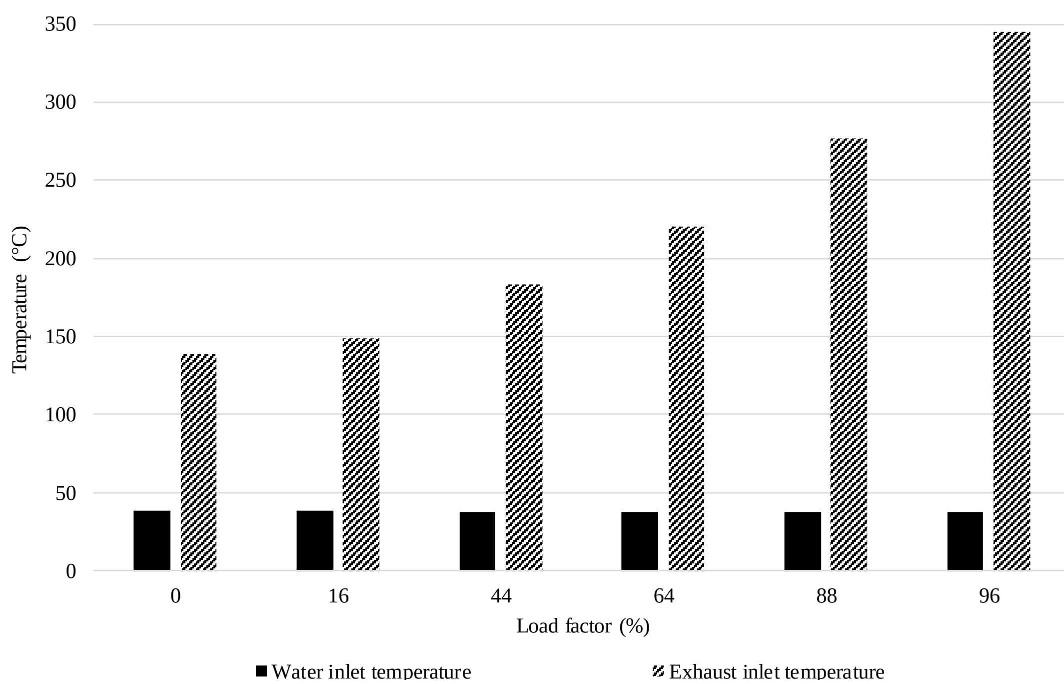


Figure 4-1 Inlet temperatures of exhaust and water

Results from the experiments and numerical simulation were gathered and plotted in Figure 4-2 for temperature change in both exhaust and the water side. It was found that the temperature of the water outlet increased gradually with the increase of the load factors. The maximum temperature was measured for water outlet was 66.1 °C while the generator was running at 96% load factor.

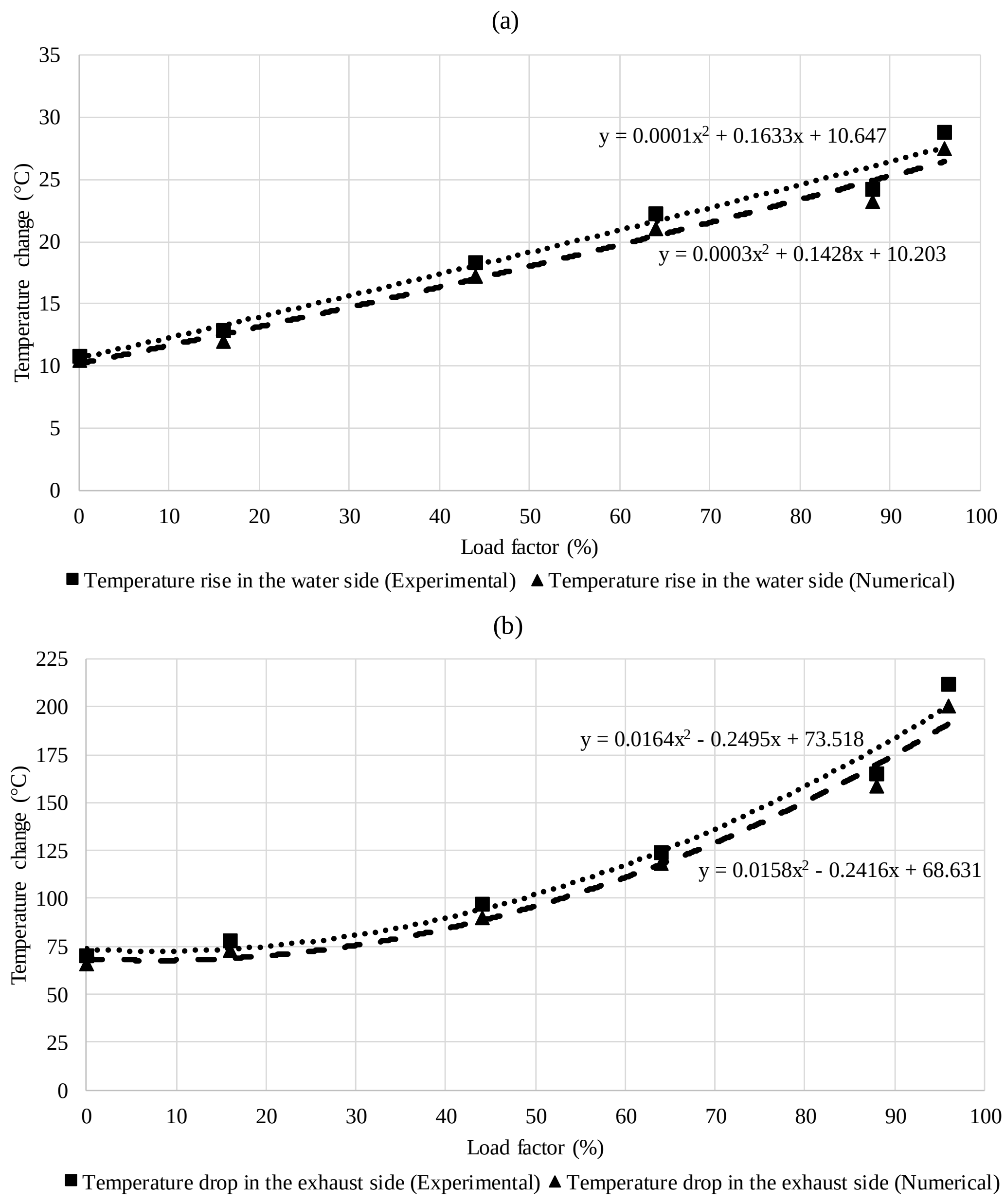


Figure 4-2 Comparison between the experimental and the numerical results of the temperature change in the water (a) and the exhaust (b) side

The temperature increase measured in the water side by 10.8 °C~ 28.8°C from no-load condition to 96% load factors. On the other hand, the temperature drop in the exhaust was also increasing with higher load factors. While the generator was operating at 96% load factor, the drop was at the exhaust side was measured by 211.8 °C.

The results from the simulations were also found in the agreement with the experimental results at every load factor. In the case of the temperature rise in the water side, the results of numerical simulations were 3%~7% behind the experimental results. On the other hand, in terms of the temperature drop in the exhaust side, the numerical results were 5%~7% behind than the experimental results at all the load factors. These values validated the numerical model in terms of temperature change.

The next parameter that was selected to validate the numerical model with the experimental setup was the heat flux in both water and the exhaust side. In the experimental setup, the heat flux in the exhaust side varied from 0.85 kW to 2.58 kW with the gradual increase of the load factor on the generator. On the other hand, the heat flux of water varied from 0.77 kW to 2.50 kW. This indicated the recovery of almost 90% of the heat discarded in the exhaust by the water even with the employment of an unoptimized shell and tube heat exchanger. The most heat losses were evident while the generator was operating at relatively lower load factors.

The results from the numerical simulations also followed the experimental results. The heat flux in the exhaust side varied from 0.80 kW to 2.44 kW with the gradual increase of the load factor on the generator. On the other hand, the heat flux of water varied from 0.75 kW to 2.40 kW. This indicated the recovery of almost 90% of the heat discarded in the exhaust by the water via the numerically modeled shell and tube heat exchanger. Plotting the experimental and numerical results gave 5%~7% difference in the water side and 3%~7% difference in the exhaust side (shown in Figure 4-3). These values validated the numerical model in terms of heat flux.

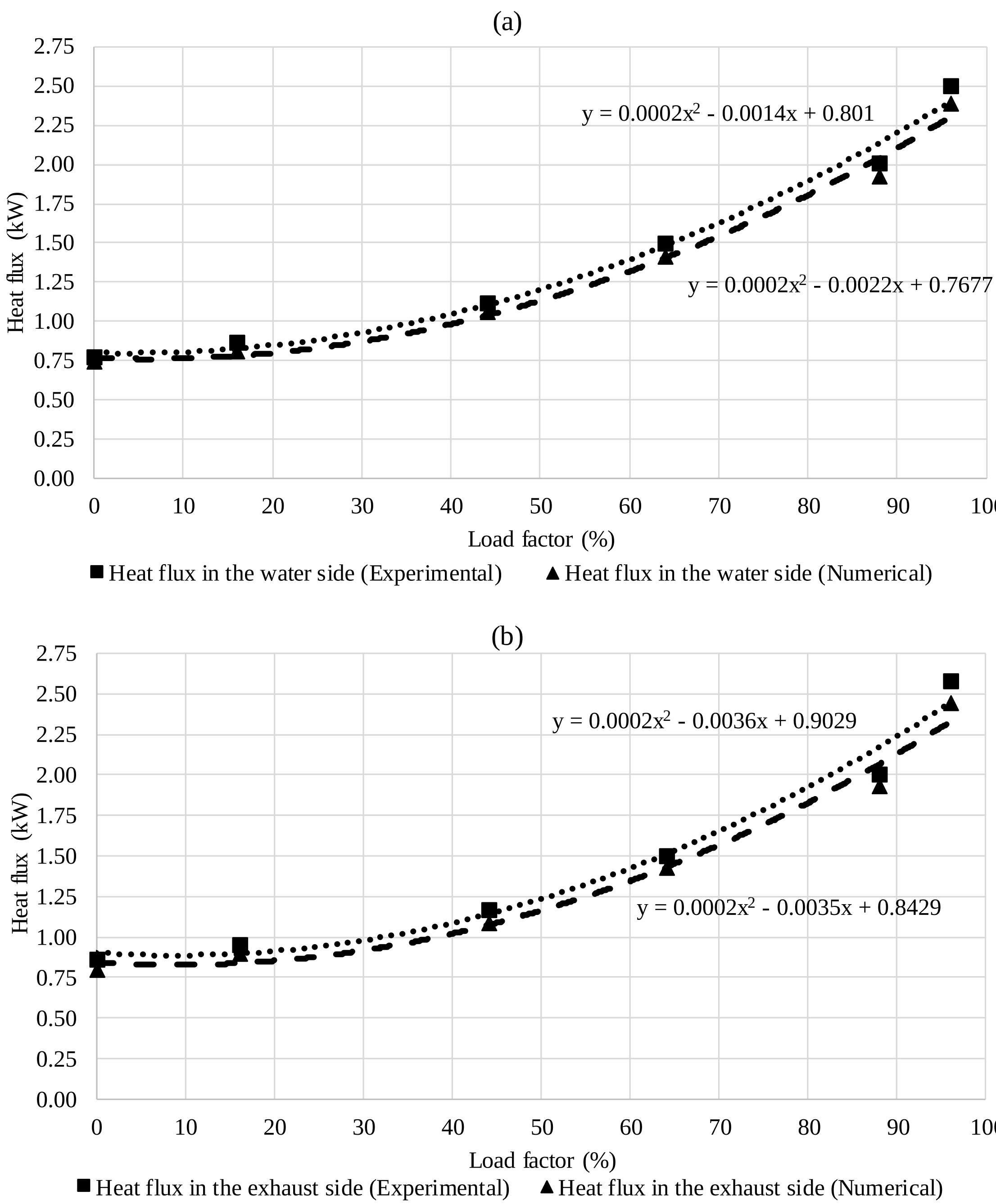


Figure 4-3 Comparison between the experimental and the numerical results of heat flux in the water (a) and the exhaust (b) side

The maximum pressure drops measured in the exhaust side was less than 2 kPa and for the water side, it was 6.83 kPa. The effectiveness of the exhaust heat recovery system varied from 63%~68% in terms of experimental result while the numerical model showed the effectiveness of 60%~64%. In both cases, the highest effectiveness was observed while the operating load factor of the generator was 66%~88% (shown in Figure 4-4).

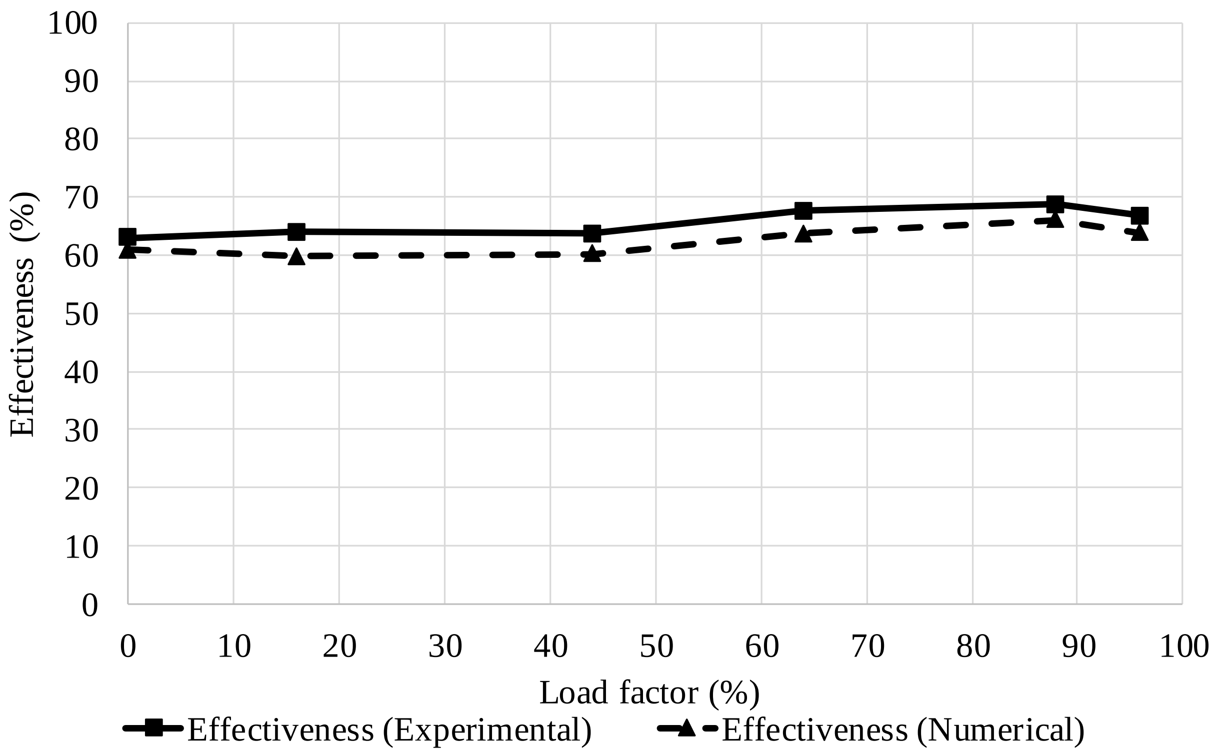


Figure 4-4 Comparison between the experimental and the numerical effectiveness of the heat exchanger

All these results from the numerical studies (validated by the experimental results) hold the necessary proof of concept based on what this diesel exhaust heat recovery system for remote mines in the cold climate regions of Canada was proposed. It also proves that even with the employment of the available market technology will bring significant savings in the remote mining operations in terms of energy and environment.

4.2 Parametric Studies

A series of parametric studies were conducted to evaluate the flexibility of the proposed diesel exhaust heat recovery system in both Case A (preheating mine intake air in underground mines) and Case B (providing surface heating) shown in Figure 3-1. These parametric studies canvass the performance of having the proposed system installed in different locations and operating conditions. For both underground and surface operations, the power generation system of the mine was considered to be designed by using certain numbers of the 1.75 eMW diesel generator (the energy analysis of this generator is available in section 3.1). A 50/50 ethylene-glycol was considered as the working fluid for the system. The system would be adaptable enough to transport the recovered heat to different applications demand.

As mentioned earlier, the shell and tube heat exchanger were chosen for the analysis due to its off the shelf availability, cost and comparatively less efficiency. All these molded the parametric studies in a conservative shape that would help to understand the performance of the system even in the worst possible cases. This system was modeled based on the applied, scholarly directives from the pieces of literature [15], [37]. All the parameters mentioned were attached to one heat exchanger only unless it was mentioned otherwise. This made the system modular that means there will be one heat exchanger attached to every generator manifold and all of which would be connected in a closed loop to a user-end heat system of choice. This would make the system flexible enough to grow with the increase of demand or availability of heating with the progress of the mine.

For all the studies, the effectiveness of the heat exchanger had been considered 61.5% which was achievable with the existing available technology and justified by the previous studies [77] (mentioned in section 2.2.3). Both propane and diesel (the primary heating fuels in Canada) based heating systems were evaluated that made the analysis on fuel and financial savings more efficient. All the parameters that could directly or indirectly effect the performance of the system were considered and analyzed in the coming sections.

4.2.1 Underground Operation

At first, a remote, off-grid underground diamond mine in the Northwest Territories, Canada was selected for the parametric studies of the proposed system in the underground operations. Table 4-1 contains the parameters of the selected mine [14], [78].

Table 4-1 Parameters of the selected underground mine

Mine parameters	
Ore production rate (Mt/year)	2.1
Annual electricity consumption (GW_eh)	161
Average power demand (MW_e)	18
Maximum airflow demand (m^3/s)	708
Intake air temperature set-point (°C)	4.0

The thermodynamic modeling of a diesel gen-set dependent power plant to power up the mine was developed based on the properties in Table 4-1. As diesel generators are standardized widely and manufactured based on common ratings and efficiency across the market, employing certain number (15) 1.75 eMW generators would still provide the reasonable values for the heat while generating power. The thermodynamic model is shown in Table 4-2.

Table 4-2 Parameters of the modeled gen-set power system

Generator parameters	
Gen-set model	CAT 3516
Engine model	3516 TA, V-16, Diesel
Gen-set capacity (MW)	1.75
Gen-set load (MW) [%]	1.225 [70%]
Average number of gen-sets	15
Max Engine Backpressure (Pa)	6,700

As different weather conditions, i.e., ambient temperatures, directly affect the number of heating degree days and consequently the heat demand of the mine, three discrete locations are selected and used all over this study, namely Northwest Territories (the original location of the underground mine), and areas in northern Quebec and northern British Columbia. These locations are shown in Figure 4-5. The weather data history from 2017 were obtained from the official source (see in Figure 4-6) and the daily average ambient temperature is used for all the intake air heating calculations and [79] for all three locations to use in analysis. The remote mines are located all over the Canada and temperature varies from one place to another. To estimate flexibility of the proposed system properly, it was necessary to evaluate the performance variation around several distinct locations. Taking an average of the temperatures of all the location might end up overestimating or underestimating the system performance.

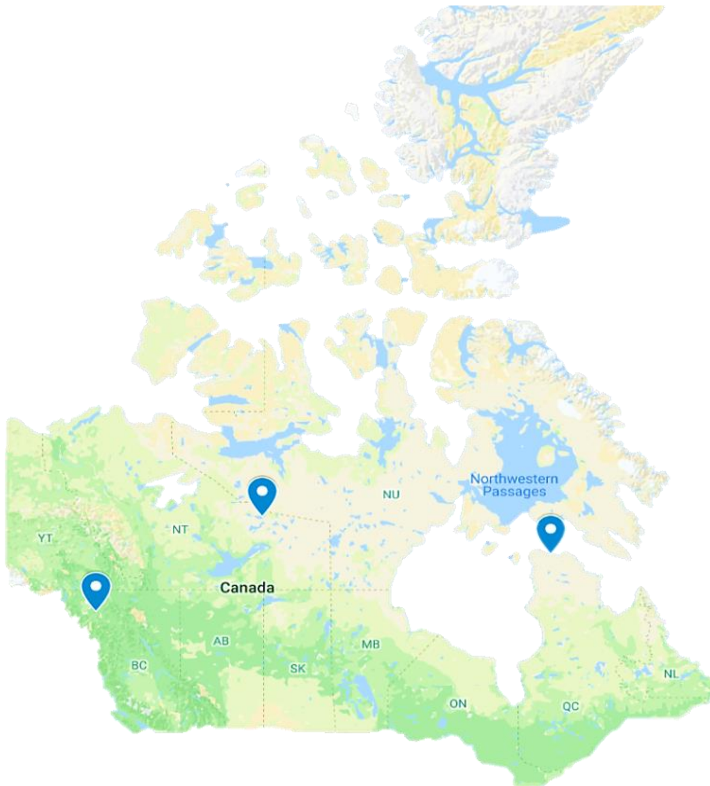


Figure 4-5 Selected location for parametric studies shown on Google map

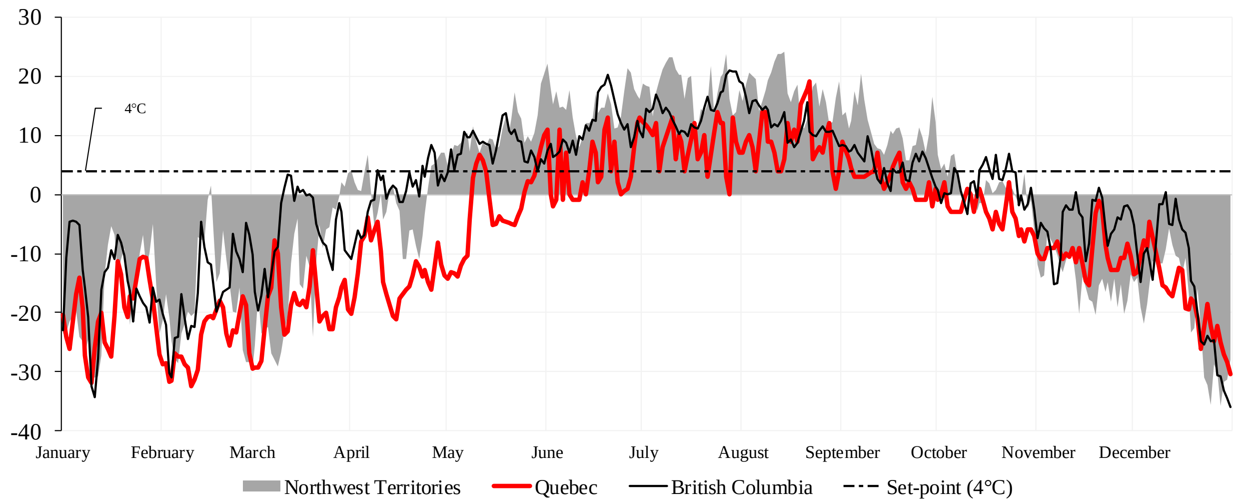


Figure 4-6 Historical weather data (for 2017) of the selected locations for intake air heating system [79]

Considering the proposed diesel exhaust heat recovery unit operating only for preheating the mine intake air, the thermodynamic parameters of the heat exchanger were evaluated from the equations shown in section 2.2.1 and shown in Table 4-3.

Table 4-3 Thermodynamic parameters of the heat exchanger (one unit per generator) for intake air heating

Properties	Hot fluid (diesel exhaust)		Cold fluid (water-glycol mixture)	
	Symbol	Value	Symbol	Value
Inlet temperature (°C)	$Th_{1,in}$	476.2	$Tc_{1,in}$	10
Outlet temperature (°C)	$Th_{1,out}$	189.5	$Tc_{1,out}$	80
Average specific heat (J/kg-°C)	c_{p_h}	1,050	c_{p_c}	3,350
Mass flow rate (kg/s)	m_h	2.33	m_c	3.0
Heat capacity rate (W/°C)	C_h	2,446.5	C_c	10,021
Pressure drop estimation (kPa)	ΔP_h	1.9	ΔP_c	70
Overall Parameters	Symbol	Value		
Glycol mass (%)	γ	50		
Maximum temperature difference (°C)	ΔT_{max}	466.2		
Minimum specific heat (J/kg-°C)	C_{min}	2,446.5		
Max. possible heat transfer rate per Hex (kW)	Q_{max}	1,140.6		
Actual heat transfer rate per Hex (kW)	Q_{actual}	701.5		
Effectiveness	ε	0.615		

4.2.1.1 Base Case

The performance of the system has been analyzed at three 3 distinct locations considering the following base operating conditions:

- The effectiveness of the heat exchanger: 61.5%
- Set-point temperature: 4.0 °C
- Maximum airflow demand: 708 m^3/s
- Average annual power demand: 18 MW

Total heat demand, amount of heat saved (heat supplied by the DEHR system after recovery) and the amount of discarded heat (displayed as negative numbers) were plotted monthly for all three locations and shown in Figure 4-7. The amount of heat in the exhaust of the diesel generator remained constant throughout the year. However, the heating demand varied on a daily basis depending on the ambient temperature. Because of this misbalance, the heat was being wasted even in those months where heat demand was not fulfilled completely.

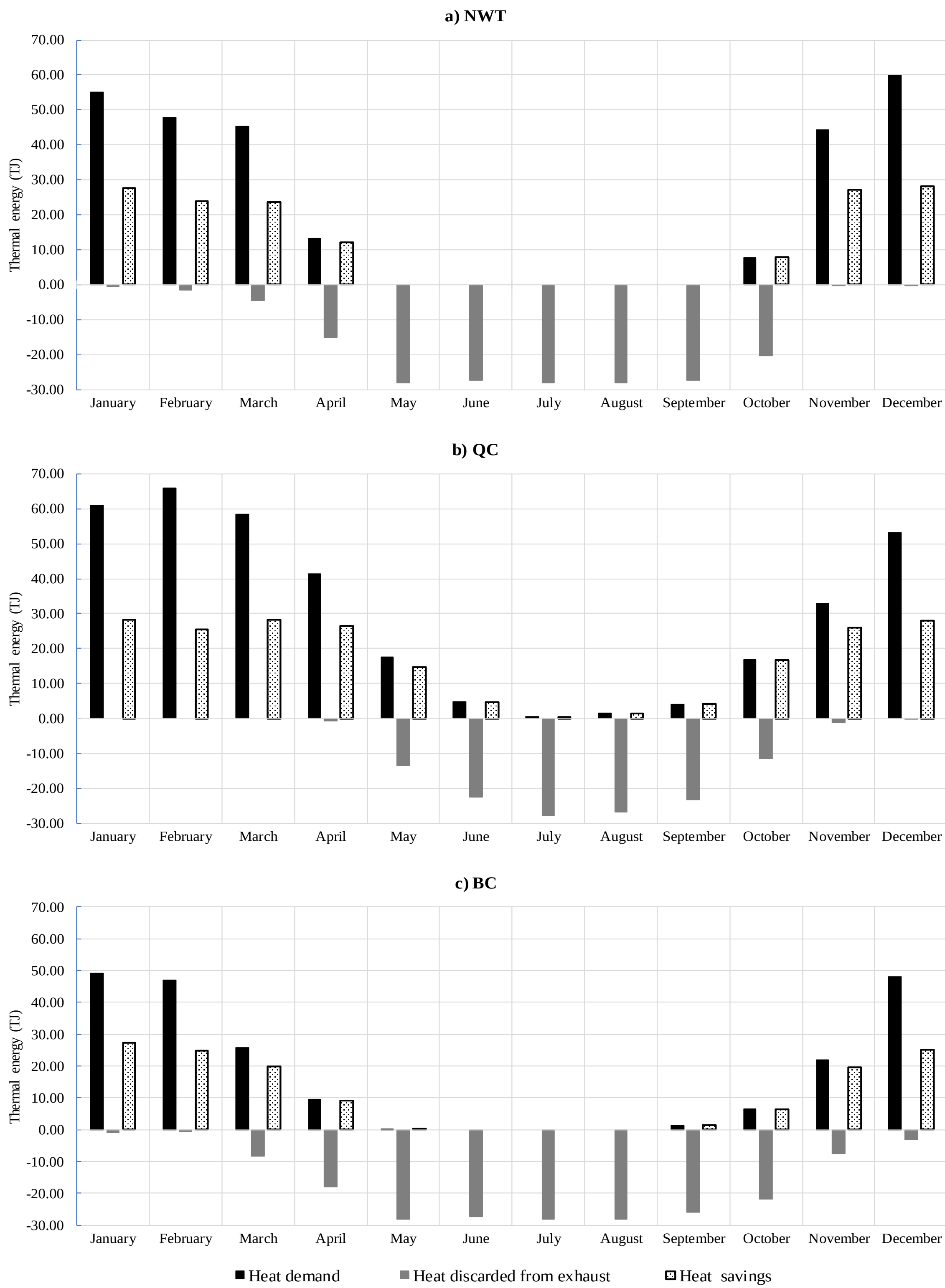


Figure 4-7 Monthly values for heat demand, heat saved using EHR and heat discarded due to the demand/supply discrepancy for: a) Northwest Territories; b) Quebec; and c) British Columbia

The proposed system was able to supply ~78% of the total yearly heating demand of the mine if the location was in BC. In case of NWT and QC, it provided ~72% and ~74% consecutively in a year. However, the system had to discard on average ~50% of the recovered heat from the exhaust in all three locations. This certainly kept the window open to reuse the heat for further applications (recommended in detail in section 5.2).

4.2.1.2 Set-point Temperature

The set-point temperature is a mine-dependent parameter that depends on several factors (mine depth, ore type, etc.). Usually, an economic value is chosen which by the aid from auto-compression becomes comfortable for the workers underground [11]. As this set-point temperature has a direct effect on the total number of heating-degree-days, it also impacts the final demand of heat of the mine.

The performance of the system has been analyzed at three 3 distinct locations considering the following base operating conditions:

- Effectiveness of the heat exchanger: 61.5%
- Set-point temperature: 1.5~6.5 °C
- Maximum airflow demand: 708 m^3/s
- Average annual power demand: 18 MW

Total heat demand, amount of heat saved (heat supplied by the DEHR system after recovery) and the amount of discarded heat (displayed as negative numbers) were plotted yearly for all three locations and shown in Figure 4-8. Having a higher set-point temperature increased the heating demand of the mine which increased the usability of system and more heat was provided and less heat was discarded.

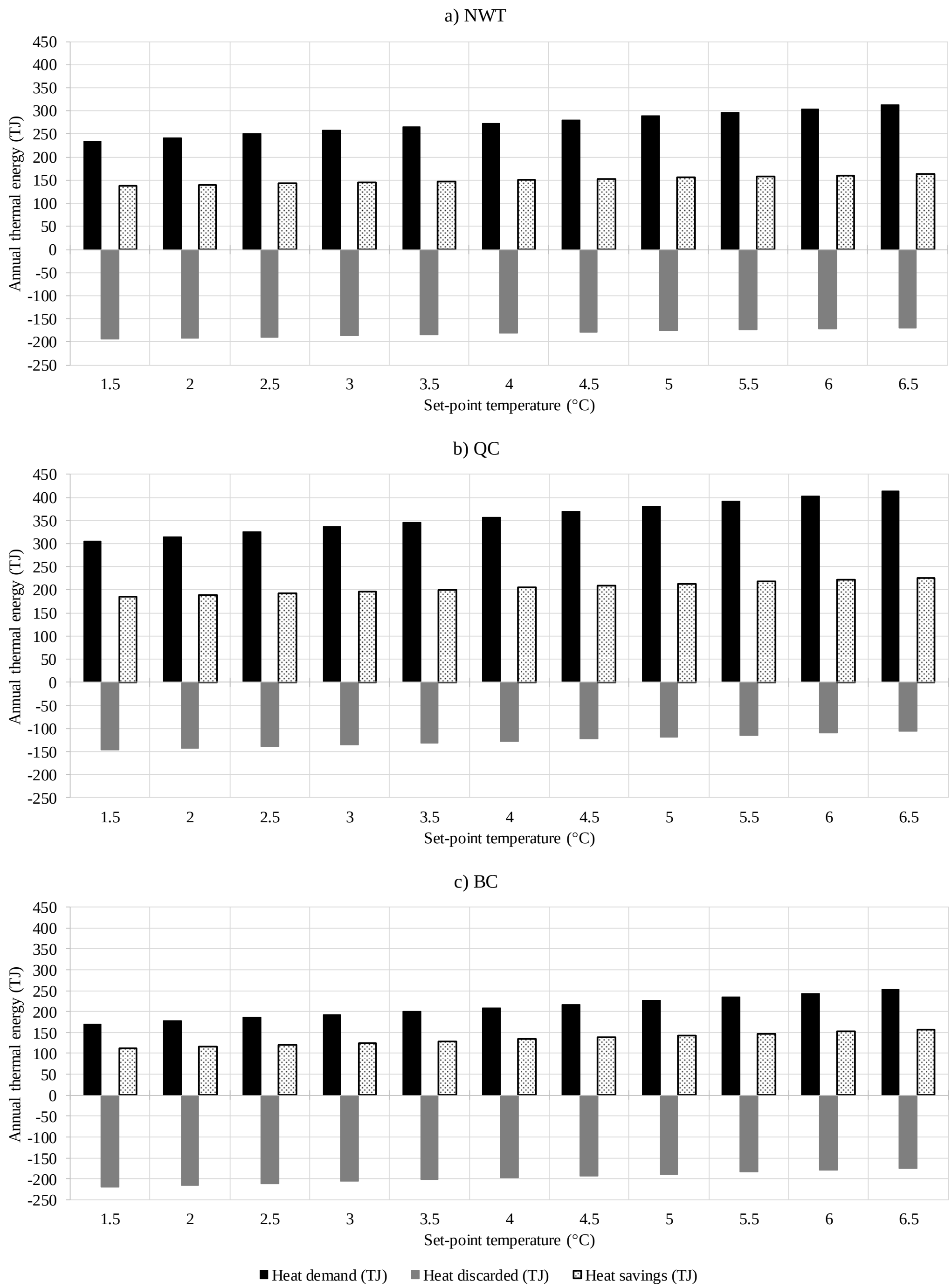


Figure 4-8 Annual heat saved, heat demand and discarded heat for the proposed EHR system on intake air heating with different set-point temperatures in a year for3 locations

In conclusion, having set-point temperatures would increase the annual heating demand as well as the annual savings from the proposed DEHR system without any additional cost. This would make the payback period shorter.

4.2.1.3 Heat Exchanger Effectiveness

The heat exchanger effectiveness selected for the base case to conduct the parametric studies was a fair but conservative one [37]. Effectiveness is one of the most significant parameters for an operational heat exchanger and generally improving the performance (or changing the type) of a heat exchanger is an attempt to increase the effectiveness of the heat exchanger [42], [80], [81]. Also, as the total heat transfer area directly impacts the effectiveness of the heat exchanger, manufacturing cost also becomes dependent on the effectiveness. This makes the choice of a balanced design of a heat exchanger which will be economical to cope-up with the operational conditions and requirements. So, it was necessary to observe the performance of the proposed system with the variation of the heat exchanger effectiveness.

The performance of the system has been analyzed at three 3 distinct locations considering the following base operating conditions:

- Effectiveness of the heat exchanger: 40%~85%
- Set-point temperature: 4.0°C
- Maximum airflow demand: 708 m^3/s
- Average annual power demand: 18 MW

Total heat demand, amount of heat saved (heat supplied by the DEHR system after recovery) and the amount of discarded heat (displayed as negative numbers) were plotted yearly for all three locations and shown in Figure 4-9.

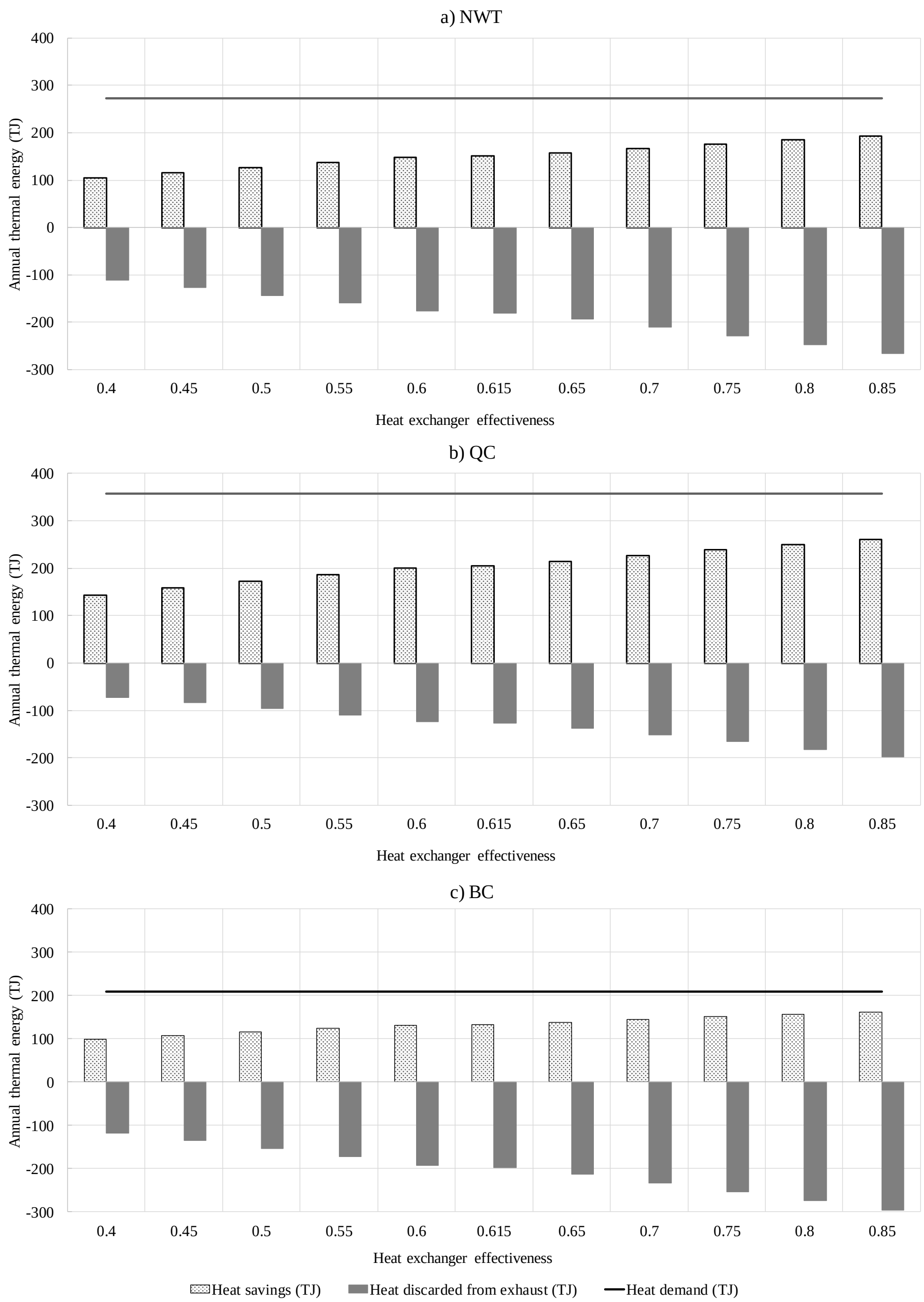


Figure 4-9 Evaluation of heat exchanger effectiveness on the amount of heat saved, and heat discarded in a year for a) Northwest Territories; b) Quebec; and c) British Columbia

Results showed improving the effectiveness from 40% to 85%, increased the heat savings by 50%~60%. However, the amount of discarded heat increased by 200%. This certainly demonstrated that though the attempt to increase the effectiveness of the heat exchanger is an emerging field, it is not as significant in the proposed DEHR system of this study. On the contrary, the attempt should be made to decrease misbalance between the heat demand and savings (recommended in section 5.2).

4.2.1.4 Air-flow and Power Demand of Underground Mines

Being an inevitable part of an underground mining operation, ventilation is between 30%~40% of the total operating cost of the mining operation. Location of the mine, type of orebody, mining methods, type of equipment, etc. control the design of the ventilation system of an underground mine. The average airflow demand for an underground mine is 100 cfm per ton of ore mined daily, while the maximum demand may reach 300 cfm/ton of ore mined daily. Large-scale underground mining methods (e.g., room and pillar and block cave methods) have comparatively lower airflow demand than the other methods [82]. All these rules of thumb made it necessary to observe the performance variation of the proposed DEHR system in various sizes and types of mining methods. Diverse values for airflow (related to the heating demand) and power demand (related to the availability of the heat in the exhaust) were chosen to conduct this parametric study.

As discussed earlier, in the base case, the power demand of the mine was 18 eMW and maximum airflow demand was 708 m^3/s. The base case was both upsized (30 eMW and 900 m^3/s) and downsized (6 eMW and 400 m^3/s) reasonably to generate 30 different combinations of airflow and power demand of underground mining operations considering set-point temperature 4.0 °C. The behavior of the proposed DEHR system was plotted for 3 different locations (NWT, BC, QC) with the 30 different airflow-power demand combinations (see Figure 4-10).

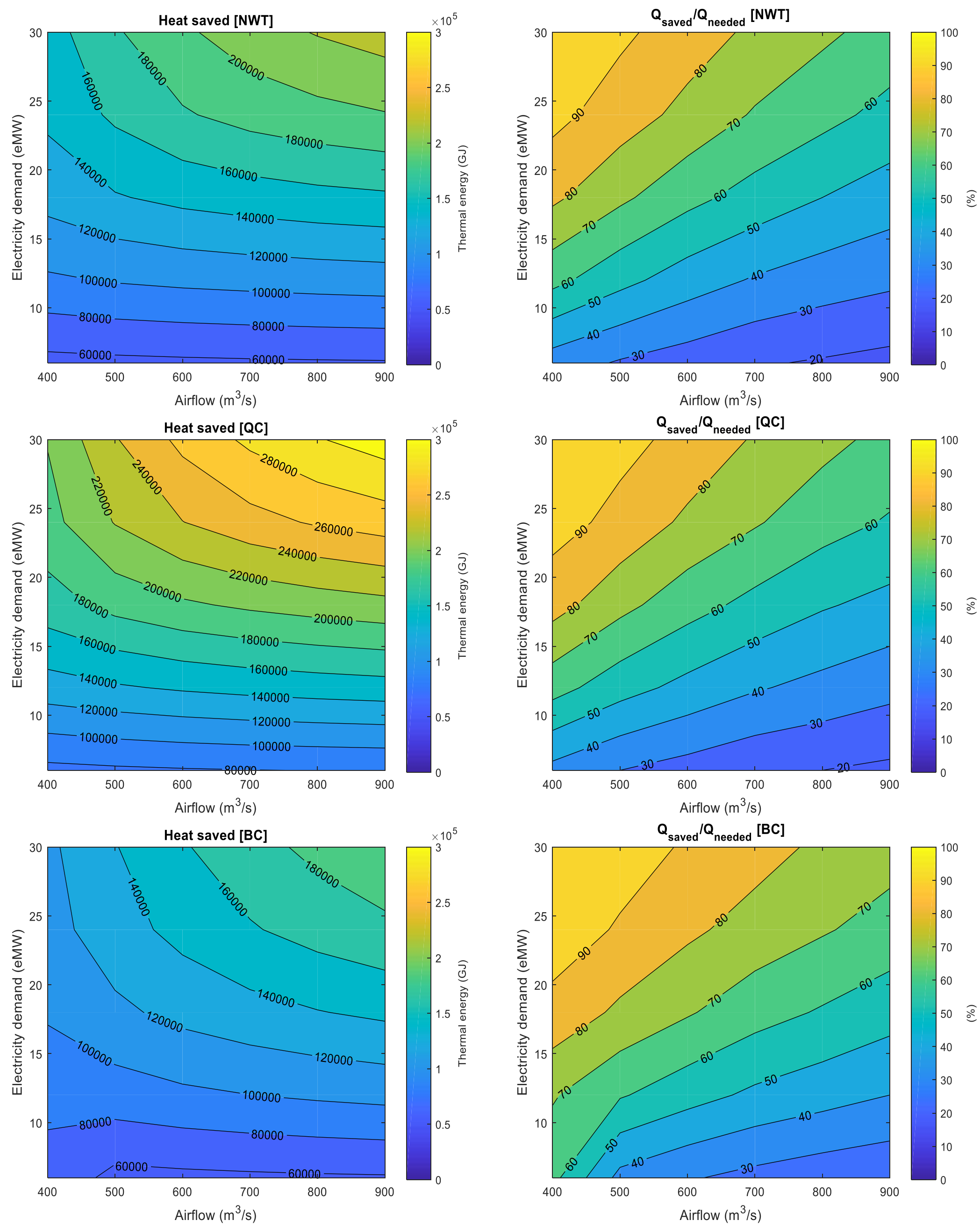


Figure 4-10 Savings in heat (recovered) and an equivalent percentage for annual supply/demand of heat in three distinct locations for varying electric power demand (related to heat availability) and airflow (related to heat demand)

Analysis of Figure 4-10 shows that the proposed DEHR system would be able to serve 65~100% of the annual heating demand while the mine had a comparatively higher power demand (20~30 eMW) with an airflow demand of 400~600 m^3/s for all three different locations regardless of the weather conditions. Because of the fewer HDD compared to the other two locations, the DEHR system served more combinations at a higher confidence level in BC. The proposed system provided the lowest heat when the power demand of the mine was as low as 6 eMW due to the low heat availability in the exhaust of the diesel generators.

The contours on the left side should be the primary focus that show the absolute values for heat savings (heat provided by the proposed DEHR system) which later translated into financial and environmental savings. For most of the situations studied, the exhaust heat recovery system likely served almost half of the total heat demand of the mine.

4.2.2 Surface Operations

To illustrate the Case B (providing surface heating to the campsites, operations and any other facilities), shown in Figure 3-1, a former remote surface mine was chosen. The operation was an off-grid, open pit diamond mine located in a remote location of northern Ontario comprising a mine office and residential buildings for 400 workers. The monthly demand for heating (for both domestic water supply and space heating) and size of the power generation system were collected from previous literature [13] and presented in Table 4-4. This allowed analysis on a monthly basis. The power system parameters were kept the same as those in Table 4-2.

Table 4-4 Parameters of the selected surface mine

Mine parameters	
Ore production rate (Mt/year)	2.1~2.5
Annual electricity consumption (GW_eh)	120
Annual power demand (MW_e)	13.8
Annual space heating demand (MWh)	2,356
Building complex capacities (employees)	400

Comparing the data from Table 4-4 and Figure 4-7, it was seen that while the surface mine required 2356 MWh (or about 8.5 TJ) of heat for both domestic water supply and space heating, the underground operation needed 200~360 TJ (depending on the location) of heat for preheating the mine intake air. This clearly indicated that the heating demand of a surface (only) operation is much lower than the underground operation even with a smaller operation. This also made recovering all the heat from the diesel generator-based power plant unnecessary to provide the necessary heating in the surface operation.

During the analysis, it was observed that heat in the exhaust from only one generator was enough to meet the heating demand of the entire operation. This decreased the number of heat exchangers to only one (in modular basis), leading to lower capital and operating cost. However, there was still 90% of the recoverable heat from the diesel generators' exhaust available which could be used in other applications (proposed in section 5.2). The thermodynamic parameters of the heat exchanger were evaluated from the equations shown in section 2.2.1 and shown in Table 4-5

Table 4-5 Thermodynamic parameters of the heat exchanger (one unit per generator) for space heating

Properties	Hot fluid (diesel exhaust)		Cold fluid (water-glycol mixture)	
	Symbol	Value	Symbol	Value
Inlet temperature (°C)	$Th_{1,in}$	476.2	$Tc_{1,in}$	30
Outlet temperature (°C)	$Th_{1,out}$	201.8	$Tc_{1,out}$	80
Average specific heat (J/kg-°C)	c_{p_h}	1,050	c_{p_c}	3,350
Mass flow rate (kg/s)	m_h	2.33	m_c	4.0
Heat capacity rate (W/°C)	C_h	2,446.5	C_c	13,427
Pressure drop estimation (kPa)	ΔP_h	1.9	ΔP_c	70
Overall Parameters	Symbol	Value		
Glycol mass (%)	γ	50		
Maximum temperature difference (°C)	ΔT_{max}	466.2		
Minimum specific heat (J/kg-°C)	C_{min}	2,446.5		
Max. possible heat transfer rate per Hex (kW)	Q_{max}	1,091.7		
Actual heat transfer rate per Hex (kW)	Q_{actual}	671.4		
Effectiveness	ε	0.615		

The monthly heating demand and supply analysis were carried for the surface application. As mentioned earlier, all the heating demand was met by recovering heat from only one generator and yet, there was still on average ~1 TJ of heat was being discarded. This certainly made the DEHR in a surface operation, a potential candidate for the combination of distinct end-users for heat. All the findings are shown in Figure 4-11 along with the temperature variation over the year on the location of the surface operation.

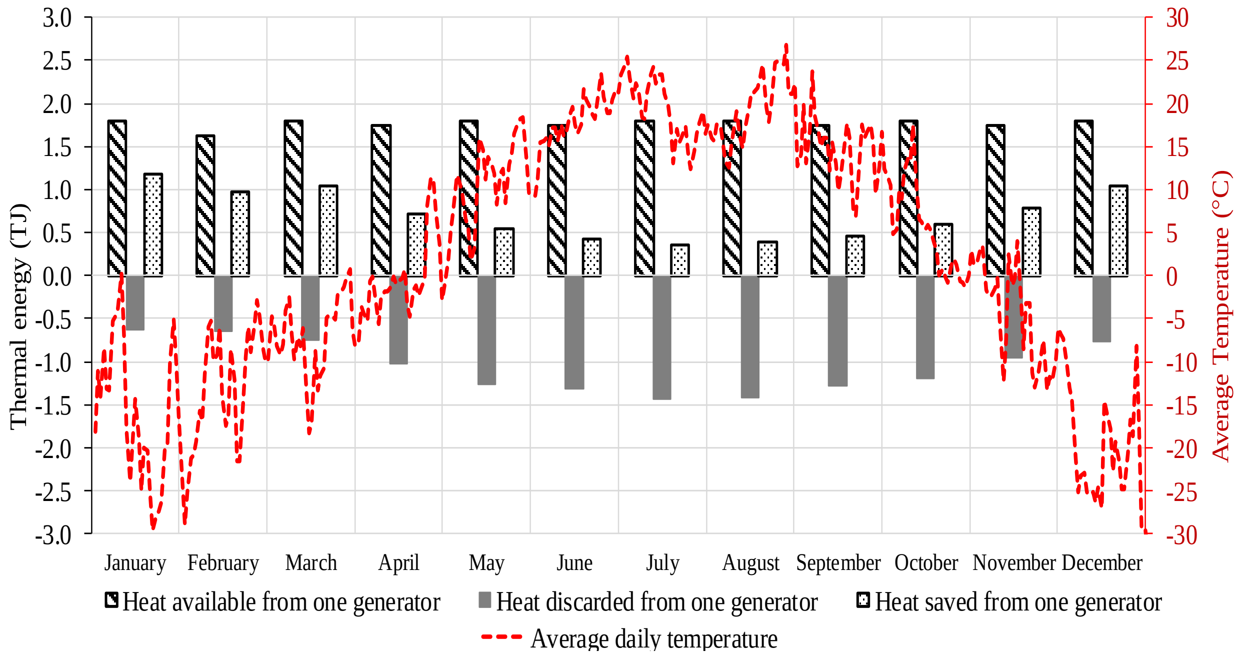


Figure 4-11 Thermal energy values for the proposed space heating system recovering heat from only one diesel generator (about 1/10 of total); bars refer to the left axis and the curve to the right one

4.3 Potential Savings

4.3.1 Environmental Savings

Marking the consumption of the fossil fuel (propane/diesel) in equivalent CO_2 in several steps of a proposed system that aims at replacing a conventional one, has been considered a justified way to evaluate the environmental benefits of the system [83], [84]. As seen from the previous observation, the proposed DEHR system would be able to supply a significant fraction of the total heat demand in almost all the scenarios. However, there would be still some amount of demand for heating unserved which will be fulfilled by burning fossil fuels (propane/diesel). Based on this, four following different heating systems were considered for the same underground mine in three different locations (NWT, BC and QC):

- Conventional diesel-based heating system
- Conventional propane-based heating system
- EHR-based heating system, aided by diesel
- EHR-based heating system, aided by propane

The amount of equivalent CO_2 was calculated for the four above mentioned heating system considering the following operating conditions and results are shown in Figure 4-12:

- Effectiveness of the heat exchanger: 61.5%
- Set-point temperature: 1.5~6.5 °C
- Maximum airflow demand: 708 m^3/s
- Average annual power demand: 18 MW

According to the analysis, the CO_2 emissions (due to the burning of fossil fuels for heating purpose) could be reduced by 3 to 5 times annually by replacing the conventional diesel-based heating system with the proposed DEHR-based heating system depending on the set-point temperatures and location. This reduction would be 2.5 to 4.5 times annually while replacing a conventional propane-based system. As the previous findings showed in case of surface operation, employment of the proposed DEHR system would be able to the meet the entire demand in case of a surface operation; it was unnecessary to compare the carbon emissions for the surface operation.

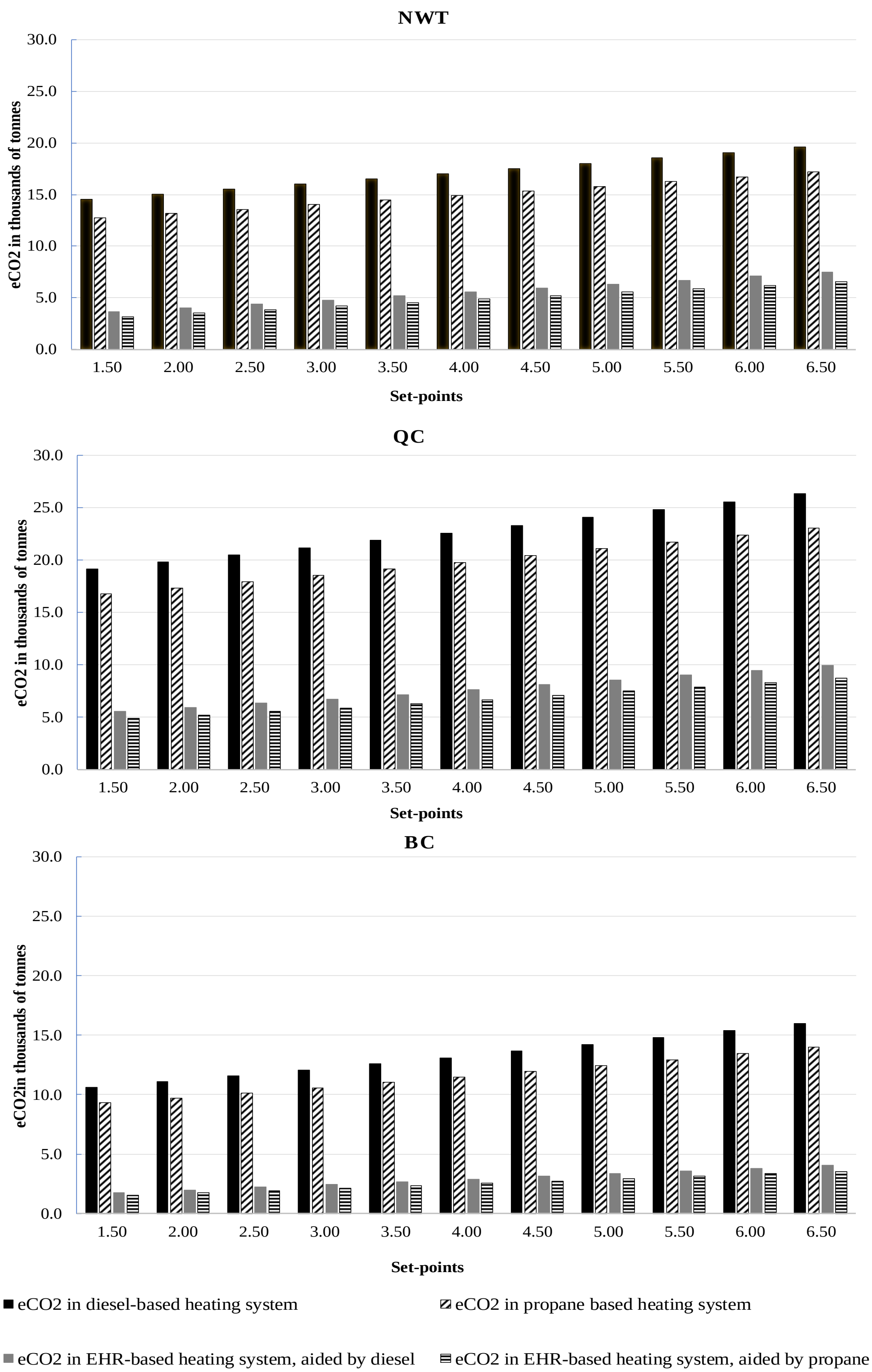


Figure 4-12 Assessment of eCO2 with or without proposed DEHR system in an underground operation

4.3.2 Financial Savings

4.3.2.1 Underground Operation

The intake air is pre-heated in an underground mine by burning fossil fuels (propane/diesel) in an industrial burner (also known as 'air pre-heater', shown in Figure 3-1). Different models of these heaters are available in the market offering the options of burning distinct types of fuels which makes it easier for the mining company to use the most economically viable option. However, all these heaters have similar operation strategy which allows considering them as equivalent.

As in remote mining operations, diesel and propane are the dominant ones; it was necessary to conduct the financial savings analysis of the proposed diesel exhaust heat recovery system by keeping both diesel and propane in consideration. To evaluate the financial justification of the model, the retail prices for propane and diesel in all the provinces and territories of Canada are shown in Figure 4-13 along with the average national price for the last 4 years [85].

For the last 4 years, the average national price for diesel ranged between 0.90 C$/litre to 1.30 C$/litre while for propane the range was between 0.50 C$/litre to 0.90 C$/litre. The most recent price for propane and diesel per litre in the four locations discussed in this study were consecutively Northwest Territories (0.60 C$, 1.39 C$), British Columbia (0.83 C$, 1.28 C$), Quebec (0.76 C$, 1.29 C$) and Ontario (0.81 C$, 1.39 C$).

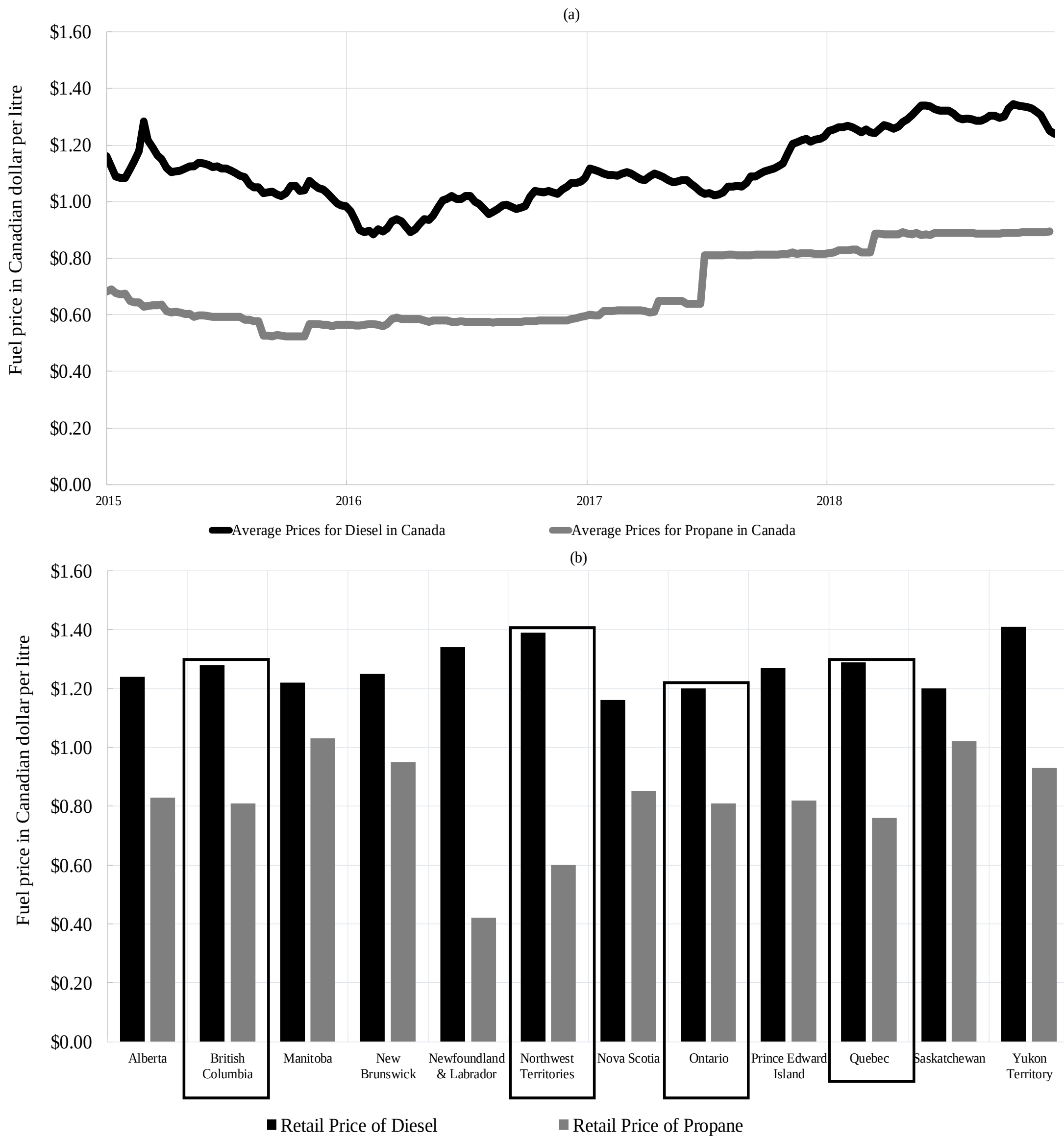


Figure 4-13 (a) Average national price for diesel and propane per litre in Canadian dollar. (b) Current price for diesel and propane per litre provinces and territories in Canadian dollar [85]

Replacing the conventional heating system (propane or diesel-based) in a mining operation with the proposed diesel exhaust heat recovery system would bring two major kinds of financial savings. The first one would be the savings of cost of that fuel (shown in Figure 4-14) which was needed to burn to generate the heat and second one would be the associated carbon tax savings (shown in Figure 4-15).

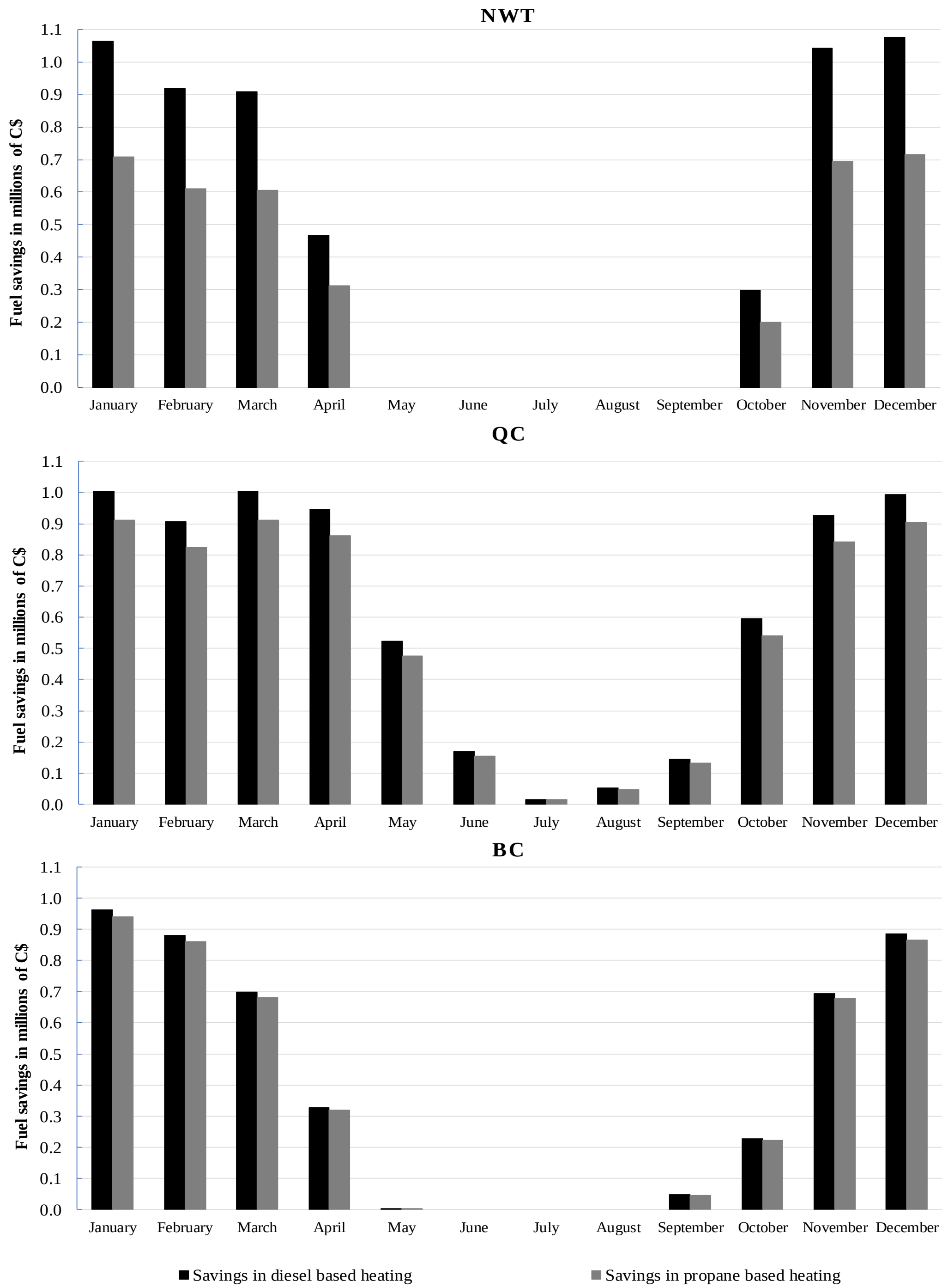


Figure 4-14 Saving in fuel cost in three different locations (NWT, QC and BC) considered for an underground mining operation with the proposed DEHR system

Figure 4-14 showed that savings from the fuel cost even reached millions in C$ in some locations for some months by replacing the conventional heating system with the proposed DEHR system. This way, the operational cost for the mines would go down drastically. Fuel transportation cost (which is higher in most remote locations), the cost for fuel storage facilities, etc. which would be decidedly less because of having the DEHR system employed were not considered in calculating the potential savings from the system.

In the case of carbon tax savings calculation, both the present and future carbon tax value were considered. The future tax will be 50 C$/tonne by 2022 despite the variation in present values from province to province [86]. This would undoubtedly increase the financial merits of employing the system in a remote mine in the future.

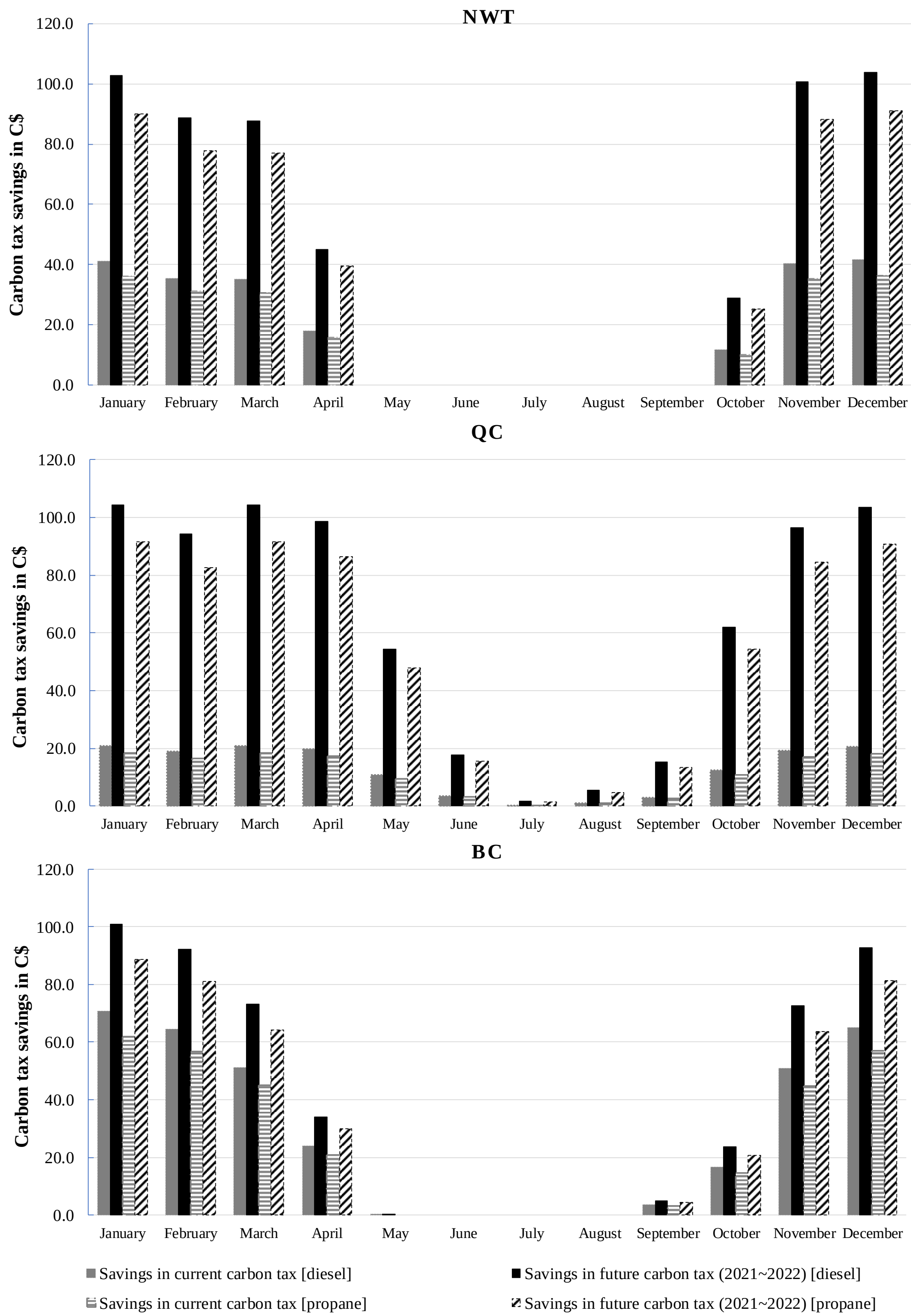


Figure 4-15 Savings in carbon taxes (for present and future values) on three different locations (NWT, QC and BC) considered for an underground mining operation

The next step was to calculate the probable capital and operating expenditure for employing the system on-site. As the system was considered modular from the beginning, the cost for a necessary number of units (which was 15 in all cases) was calculated. With 15% contingency, the capital cost was comprised with the cost for both the heat exchangers (DEHR and mine intake air heating unit) along with a reasonable estimation for piping and installation. The operating cost took account of the power demand of the heat exchanger as well as the maintenance cost. All the cost and savings were gathered in Table 4-6 estimates the payback period of the system. The calculations resulted in a very short payback period which was less than a year in all of the provinces.

Table 4-6 Payback time calculation for the proposed diesel exhaust heat recovery unit for underground operation

Province	NWT		QC		BC	
Heating fuel	Diesel	Propane	Diesel	Propane	Diesel	Propane
Peracetic Power (kW)	474.28					
OPEX (MC$)	$1.71		$1.60		$1.59	
Savings in fuel (MC$)	5.78	3.85	7.27	6.61	4.72	4.61
Savings in carbon credits (MC$)	0.21	0.19	0.14	0.13	0.29	0.26
Total savings (MC$)	5.99	4.03	7.41	6.73	5.01	4.87
CAPEX (MC$)	$1.83					
Simple Payback Time (months)	5.1	9.5	3.8	4.3	6.4	6.7

The further evaluation involved the calculation of the payback period of the system for all airflow-electricity demand combinations (mentioned in section 4.2.1.4) and shown in Figure 4-16. In almost every case in all three locations, the system would pay back even less than a year. Only a particular situation (low-price fuel, low power demand and huge airflow requirement) might make the PBP of the system unfeasible.

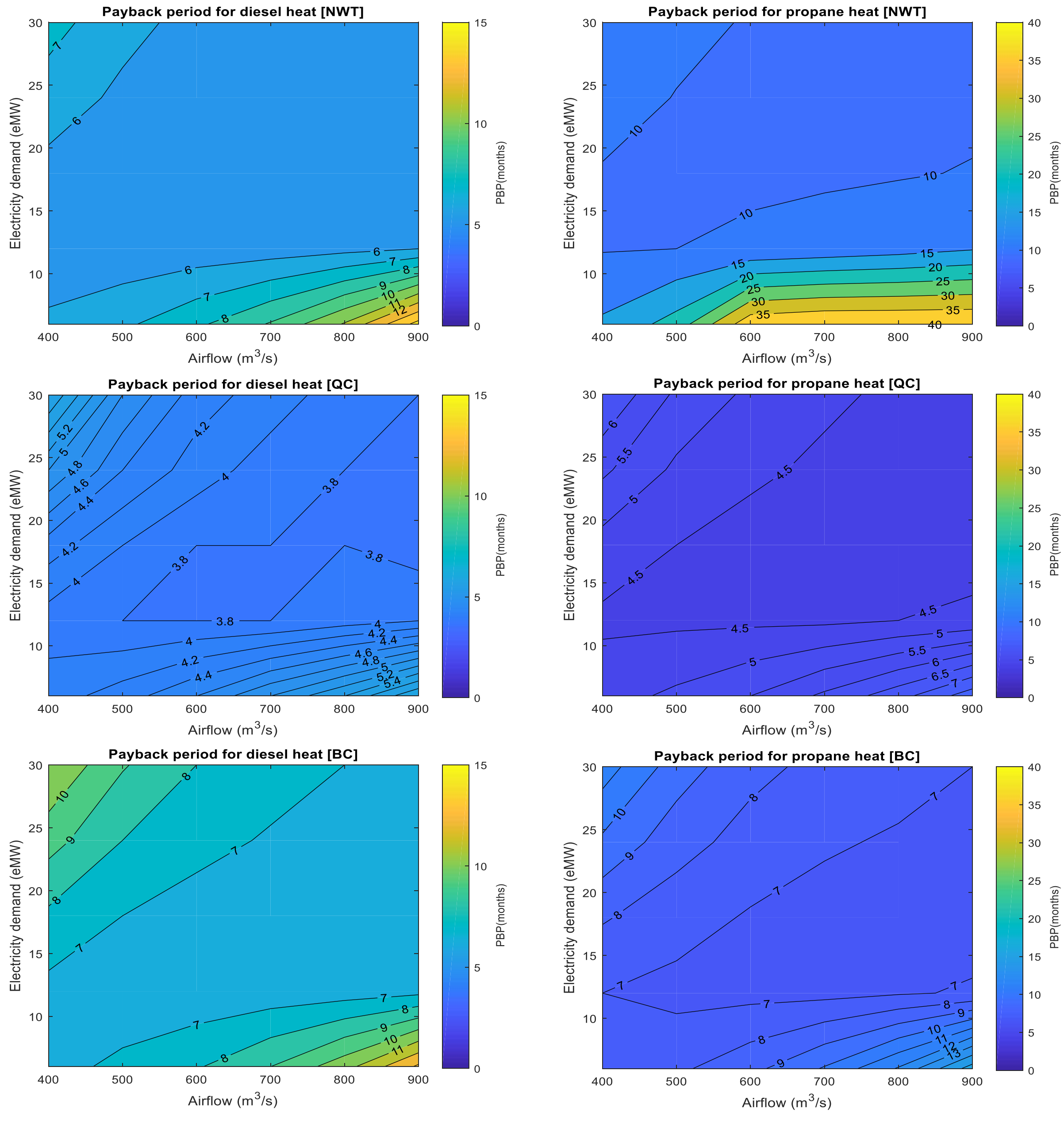


Figure 4-16 Payback periods for the proposed EHR system in mines in different locations with distinct electricity demands and airflow

4.3.2.2 Surface Operation

The financial sustainability of the proposed DEHR system was assessed in the same way as an underground operation. Due to the fuel cost of Ontario (the original location of the surface mine) at the time when the analysis was conducted, the results were found slightly different in surface operations. The savings was higher in case of a propane-based heating system than the diesel-based one (shown in Figure 4-17).

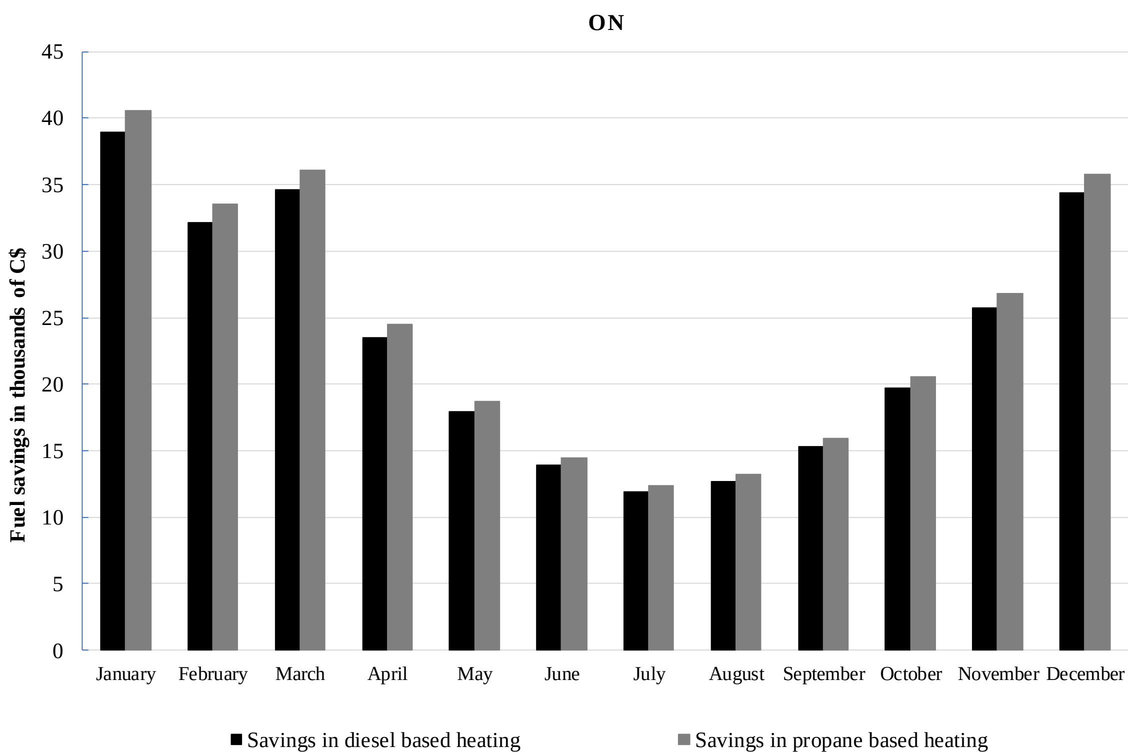


Figure 4-17 Monthly fuel cost savings in Canadian dollars of the proposed EHR system for space heating in a surface mine in Ontario

Fuel transportation cost (which is higher in most remote locations), the cost for fuel storage facilities, etc. which would be decidedly less because of having the DEHR system employed were not considered in calculating the potential savings from the system. The associated savings from carbon tax was also calculated in the same way as the underground operation and shown in Figure 4-18 which is lower comparing to the underground operation due to the lower heating demand.

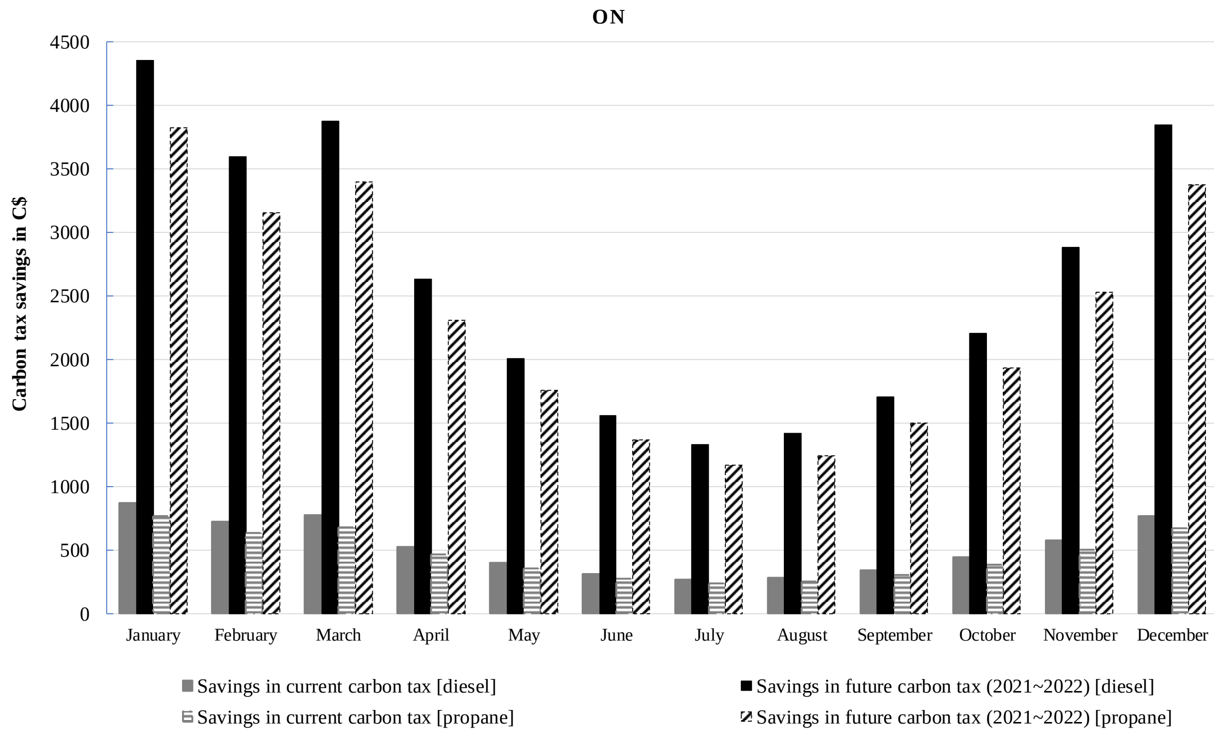


Figure 4-18 Monthly carbon tax savings in Canadian dollars of the proposed EHR system for space heating in a surface mine in Ontario

The comparatively lower value in savings might suggest the proposed DEHR system is not as beneficial in the case of surface operations compared to underground operations. However, due to the lower heat demand, the cost for a conventional heating system was comparatively small which was replenished completely by the DEHR system. Also, this decreased the required number of the DEHR units (only one) in the operation which significantly influenced the payback period. The CAPEX and OPEX were calculated in the same way as the underground operation. No cost was considered for the hydronic heating system assuming it present in the camps and other facilities.

The results (shown in Table 4-7) depicted a very lucrative payback period of fewer than 3 months. This would certainly make the system feasible for the surface mines which have a shorter mine life.

Table 4-7 Payback time calculation for the proposed DEHR for space heating in a surface mine

Province	**ON**	
Heating fuel	**Diesel**	**Propane**
Peracetic Power (kW)	7.9	
OPEX (C$)	$25,944	
Savings in fuel (C$)	$280,798	$292,530
Savings in carbon credits (C$)	$6,348	$5,510
Total savings (C$)	$287,147	$298,040
CAPEX (C$)	$ 46,853	
Simple Payback Time (months)	2.2	2.1

4.4 SWOT Analysis

SWOT (Strengths, Weakness, Threats and Opportunities) analysis has been considered one of the most widely used and functional tools in decision-making strategy. This tool was adapted in the 1950s to project different perceptions in a decision progression [87]. It has been accepted in the mining and minerals processing industry [88]. A SWOT analysis was conducted on the proposed diesel exhaust heat recovery system for remote mining operations in cold climate regions of Canada and shown in Table 4-8.

Table 4-8 SWOT analysis of the proposed DEHR system

Strengths	Weakness
• Energy savings from utilization of the waste heat • Savings in fuel costs • Savings in carbon tax • Labor cost savings in fuel transportation and storage facilities • Low CAPEX comparing to the offered savings • Reasonable maintenance cost	• Cannot supply the whole heating demand standalone • Seasonal thermal energy storage should be employed to store the discarded heat in the summer time • 'No-leakage' condition should be maintained and monitored
Opportunities	**Threats**
• Decrease the burning the fossil fuels • Reusing the heat to several other heat demanding applications • Green heating for off-grid mines • Leverage on carbon tax usage • Promotion of sustainability in remote mining operations via energy management	• Grid connection will make the system infeasible • Leakage inside the heat exchanger can contaminate the air

Chapter 5: Conclusion

This research studied the techno-economic feasibility of using a combined heat and power generation strategy to improve the energy-efficiency of remote mining operations in the cold climates such as Canada. It attempted to draw a pathway to reduce the fossil fuel consumption, carbon emissions, and carbon taxes (or to generate carbon credit revenues). The following conclusions can be drawn from this study:

- An organized overview of several strategies of recovering waste heat from the exhaust of the diesel generators was offered in brief that could be used as a stable platform for any future work on this field. A comprehensive overview of unconventional heating projects in Canadian mining showing the necessity of heating was presented in a categorized way.
- Detailed energy analysis on several sizes and types of diesel generators operating at various load factors showed that the exhaust of the diesel generator held the potential to meet the heating demands of remote mines in cold climate regions in Canada.
- An approach to recover heat from the exhaust of a diesel generator through a shell and tube heat exchanger was demonstrated numerically and validated with experimental results. The results contained proof of the applicability of the system.
- Heat transfer phenomena from the exhaust of the diesel generator to the working fluid of the heat exchanger (water) was studied. Transportation of the waste heat, study of heat, mass and momentum transfer phenomena inside the heat exchanger were studied.
- Exhaust temperature was kept high enough to avoid maintenance cost.
- Even though the heat exchanger was not optimized, the performance of the system was reliable and consistent enough to prove the concept.

- All the possible parametric studies (ambient temperatures, the effectiveness of the heat exchanger, set-points, airflow and power demand of the mine) were conducted to prove the flexibility of the system
- In most scenarios, it was found that in most cases, almost 70% of the total heating demand for preheating mine intake air in underground operations would be possible by employing the proposed system in an optimized way. In the case of surface operations, the heating demand can be fulfilled even with the recovery of the small portion of the waste heat in the running diesel generators in the mine.
- The proposed system was found to be incapable of providing all the heating demand in an underground operation standalone due to the mismatch in the daily heating demand of the mine and heat availability in the exhaust of the diesel generator.
- Parametric study on the heat exchanger effectiveness showed that instead of investing in projects aiming at increasing the effectiveness of the heat exchangers, the focus should be put in storing the discarded heat in the summer.
- The savings from the installation of the proposed system in a remote mine would save million dollars from fossil fuel cost along with a significant saving in the carbon tax.
- An elementary approach was undertaken to evaluate the operating and capital expenditure of the proposed diesel exhaust heat recovery system in remote mines in three distinct locations. Based on the savings and all the expenditures, the proposed system seemed to have a lucrative payback period.
- A SWOT analysis of the proposed diesel exhaust heat recovery system was presented based on the total study.

5.1 Core Contribution

- Detailed energy analysis on the wide range of different types of diesel generators at their different load factors was a significant evaluation of this study.
- This is one of the first studies proposing intake air heating in the remote mines in cold climate regions of Canada through the recovered heat from the exhaust of the diesel generators.
- Parametric studies showed the environmental and financial profitability of the system in the remote locations of the proposed system. These diverse studies could be used as a part of the feasibility study in the field application of this diesel exhaust recovery system.

5.2 Recommendations

- All the parametric studies pointed towards one limitation of the DEHR system which was its incapability of being a standalone source of heat in preheating the intake air in an underground mine. As it was the consequence of the mismatch between the daily heating demand and the availability of heat in the exhaust of the diesel generator. This mismatch could be minimized or even diminished by employing an optimized seasonal thermal energy storage. The author was working on such systems as an extension of this study [89], [90].
- In the case of surface operation, 10% of the recoverable heat was adequate to serve the heating demand. The rest of the heat could be used in to generate electricity through thermoelectric generators or organic rankine cycle though it would be necessary to optimize the system according to the mining demand and system efficiency and most importantly the mine life.

- The cost estimation presented in this study was rudimentary and could be used as a starting point to conduct further case specific, elaborate economic analysis.
- The proposed should be tested at pilot-scale.

Bibliography

[1] J. H. Hodgkinson and M. H. Smith, “Climate change and sustainability as drivers for the next mining and metals boom: The need for climate-smart mining and recycling,” *Resour. Policy*, Jun. 2018.

[2] Y.-T. Deng, J. Z.-C. Chang, C.-C. Yeh, S.-J. Cheng, and M. Y.-P. Kuo, “Arecoline stimulated Cyr61 production in human gingival epithelial cells: Inhibition by lovastatin,” *Oral Oncol.*, vol. 47, no. 4, pp. 256–261, Apr. 2011.

[3] World Bank, “The Growing Role of Minerals and Metals for a Low Carbon Future,” 2017.

[4] N. R. C. Jimmy Royer, “Status of Remote/Off-Grid Communities in Canada | Natural Resources Canada,” 2013.

[5] D. T. Wojtaszek, “POTENTIAL OFF-GRID MARKETS FOR SMRS IN CANADA,” *CNL Nucl. Rev.*, pp. 1–10, Sep. 2017.

[6] U.S. Energy Information Agency, “International Energy Outlook 2013,” *Outlook 2013*, p. 312, 2013.

[7] A. J. Wood and J. Wiley, “POWER GENERATION, OPERATION, AND CONTROL SECOND EDITION A WILEY-INTERSCIENCE PUBLICATION,” 2012.

[8] P. J. Balducci, J. M. Roop, L. A. Schienbein, J. G. DeSteese, and M. R. Weimar, “Electric Power Interruption Cost Estimates for Individual Industries, Sectors, and the U.S. Economy,” 2003.

[9] S. Rehman *et al.*, “Feasibility study of hybrid retrofits to an isolated off-grid diesel power plant,” *Renewable and Sustainable Energy Reviews*, vol. 11, no. 4. pp. 635–653, 2007.

[10] C. Jamasmie, “Global rough diamond production about to reach its peak | MINING.com,” 2016. [Online]. Available: http://www.mining.com/global-rough-diamond-production-

about-to-reach-its-peak/. [Accessed: 11-Apr-2019].

[11] M. J. McPherson, "Refrigeration plant and mine air conditioning systems," in *Subsurface Ventilation and Environmental Engineering*, Dordrecht: Springer Netherlands, 1993, pp. 651–738.

[12] A. E. Hall, D. M. Mchaina, and S. Hardcastle, "Controlled recirculation in Canadian underground potash mines," Elsevier Science Publishers B.V, 1990.

[13] M. Carvalho, A. Romero, G. Shields, and D. L. Millar, "Optimal synthesis of energy supply systems for remote open pit mines," *Appl. Therm. Eng.*, vol. 64, no. 1–2, pp. 315–330, 2014.

[14] A. M. Wilson and E. De Souza, "Arctic mine air heating."

[15] M. J. McPherson, *Subsurface Ventilation and Environmental Engineering*. Dordrecht: Springer Science & Business Media, 1993.

[16] K. Awuah-Offei and A. Adekpedjou, "Application of life cycle assessment in the mining industry," *Int. J. Life Cycle Assess.*, vol. 16, no. 1, pp. 82–89, Jan. 2011.

[17] C. Lin, "2008- Capture of Heat Energy from Diesel Engine Exhaust (Alaska).pdf," Alaska, 2008.

[18] Y. A. Cengel and A. J. Ghajar, *Heat and Mass Transfer, Fundamentals and Application, Fifth Edition in SI Units*. 2015.

[19] E. U. Schluender, *Heat exchanger design handbook.* VDI Verlag, 1983.

[20] V. Pandiyarajan, M. Chinna Pandian, E. Malan, R. Velraj, and R. V. Seeniraj, "Experimental investigation on heat recovery from diesel engine exhaust using finned shell and tube heat exchanger and thermal storage system," *Appl. Energy*, vol. 88, no. 1, pp. 77–87, 2011.

[21] H. E. Lambert, "Energy conservation for the mining industries," *CIM Bulletin 66 (738)*, pp.

69–74, 1973.

[22] D. G. Sims, "Energy recovery from exhaust gases," *Chart. Mech. Eng.*, no. 29, pp. 55–58, 1982.

[23] J. R. Shook, "Recover heat flue gas," *Chem. Enginering Prog.*, no. ff7(6), pp. 49–54, 1991.

[24] L. L. Vasiliev, "Heat pipes in modern heat exchangers," *Appl. Therm. Eng.*, vol. 25, no. 1, pp. 1–19, Jan. 2005.

[25] Y. H. Kiang, *Waste Energy Utilization Technology*. New York: Marcel Dekker, 1981.

[26] O. M. Al-Rabghi, M. Beirutty, M. Akyurt, Y. Najjar, and T. Alp, "Recovery and utilization of waste heat," *Heat Recover. Syst. CHP*, vol. 13, no. 5, pp. 463–470, 1993.

[27] S. H. Noie-Baghban and G. R. Majideian, "Waste heat recovery using heat pipe heat exchanger (HPHE) for surgery rooms in hospitals," *Appl. Therm. Eng.*, vol. 20, no. 14, pp. 1271–1282, Oct. 2000.

[28] F. Yang, X. Yuan, and G. Lin, "Waste heat recovery using heat pipe heat exchanger for heating automobile using exhaust gas," vol. 23, pp. 367–372, 2003.

[29] S. Du, R. Z. Wang, and X. Chen, "Development and experimental study of an ammonia water absorption refrigeration prototype driven by diesel engine exhaust heat," *Energy*, vol. 130, pp. 420–432, Jul. 2017.

[30] C. J. Chen, R. Z. Wang, L. W. Wang, and Z. S. Lu, "Studies on cycle characteristics and application of split heat pipe adsorption ice maker," *Energy Convers. Manag.*, vol. 48, no. 4, pp. 1106–1112, Apr. 2007.

[31] P. Nemec, A. Čaja, and M. Malcho, "Mathematical model for heat transfer limitations of heat pipe," *Math. Comput. Model.*, vol. 57, no. 1–2, pp. 126–136, Jan. 2013.

[32] H. J. van G. Johannes van Es, "Benefits and Drawbacks of Using Two-Phase Cooling

Technologies in Military Platforms | Electronics Cooling," *National Aerospace Laboratory NLR, The Netherlands*, 2013. [Online]. Available: https://www.electronics-cooling.com/2013/03/benefits-and-drawbacks-of-using-two-phase-cooling-technologies-in-military-platforms/. [Accessed: 17-Mar-2019].

[33] Advanced Cooling TE, "Heat Pipe Operating Temperature Range | Heat Pipe Technology," *Advanced cooling technologies*, 2019. [Online]. Available: https://www.1-act.com/operating-temperature-range/. [Accessed: 17-Mar-2019].

[34] G. Rice, "HEAT PIPES," in *A-to-Z Guide to Thermodynamics, Heat and Mass Transfer, and Fluids Engineering*, Begellhouse.

[35] C. A. Busse, "Theory of the ultimate heat transfer limit of cylindrical heat pipes," *Int. J. Heat Mass Transf.*, vol. 16, no. 1, pp. 169–186, Jan. 1973.

[36] T. Ma and Chongqing da xue. Institute of Engineering Thermophysics., *Advances in heat pipe science and technology : proceedings of the 8th International Heat Pipe Conference, September 14-18, 1992, Beijing, China*. International Academic Publishers, 1993.

[37] A. Bahadori, "Simple method for estimation of effectiveness in one tube pass and one shell pass counter-flow heat exchangers," *Appl. Energy*, vol. 88, no. 11, pp. 4191–4196, 2011.

[38] R. K. Shah and D. P. Sekulic, *Fundamentals of heat exchanger design*. John Wiley & Sons, 2003.

[39] H&C Heat Transfer Solution Inc., "Shell and Tube Heat Exchangers Construction Details," *2014*. [Online]. Available: http://www.hcheattransfer.com/shell_and_tube.html. [Accessed: 17-Mar-2019].

[40] V. H. Morcos, "Performance of Shell-and-Dimpled-Tube Heat Exchanger for Waste Heat Recovery," vol. 8, no. 4, pp. 299–308, 1988.

[41] H. G. Zhang, E. H. Wang, and B. Y. Fan, “Heat transfer analysis of a finned-tube evaporator for engine exhaust heat recovery,” *Energy Convers. Manag.*, vol. 65, pp. 438–447, 2013.

[42] S. Bari and S. N. Hossain, “Waste heat recovery from a diesel engine using shell and tube heat exchanger,” *Appl. Therm. Eng.*, vol. 61, no. 2, pp. 355–363, 2013.

[43] P. B. Surwase and H. S. Farkade, “Waste Heat Recovery From The Exhaust of a Diesel Engine Using Parallel Flow Shell and Tube Heat Exchanger,” *Int. J. Mech. Prod. Eng.*, vol. 4, no. 6, pp. 2320–2092, 2016.

[44] L. Campanile, A. ; Carlomagno, G.M. ; De Vita, A. ; Scognamiglio, A. ; Donsi, G. ; Massimilla, “SOOT REMOVAL AND HEAT RECOVERY FROM DIESEL ENGINE EXHAUST BY MEANS OF A FLUIDIZED BED FILTER/AGGLOMERATOR AND HEAT EXCHANGER,” in *International Symposium on Automotive Technology & Automation*, 1980, pp. 163–194.

[45] S. N. Hossain and S. Bari, “Additional Power Generation From Waste Energy of Diesel Engine Using Parallel Flow Shell and Tube Heat Exchanger,” *J. Eng. Gas Turbines Power*, 2013.

[46] S. M. A. Sufian, M. A. Ullah, P. Mazumder, and D. Baidya, “Design of a stirling engine to generate green energy in rural areas of Bangladesh,” in *2nd International Conference on Green Energy and Technology*, 2014, pp. 27–32.

[47] S. M. A. Sufian, K. A. Sagar, M. A. Ullah, and D. Baidya, “Harvesting electrical power from waste heat using stirling engine,” in *2014 9th International Forum on Strategic Technology (IFOST)*, 2014, pp. 343–346.

[48] J. G. Haidar and J. I. Ghojel, “Waste heat recovery from the exhaust of low-power diesel engine using thermoelectric generators,” *Proc. ICT2001 20 Int. Conf. Thermoelectr. Cat*

No01TH8589, vol. 20, pp. 413–418, 2001.

[49] D. T. Hountalas, C. Katsanos, and V. T. Lamaris, “Recovering energy from the diesel engine exhaust using mechanical and electrical turbocompounding,” *SAE Tech. Pap.*, no. 724, pp. 776–790, 2007.

[50] C. Baker, P. Vuppuluri, L. Shi, and M. Hall, “Model of heat exchangers for waste heat recovery from diesel engine exhaust for thermoelectric power generation,” *J. Electron. Mater.*, vol. 41, no. 6, pp. 1290–1297, 2012.

[51] B. Orr, A. Akbarzadeh, M. Mochizuki, and R. Singh, “A review of car waste heat recovery systems utilising thermoelectric generators and heat pipes,” *Appl. Therm. Eng.*, vol. 101, pp. 490–495, 2016.

[52] Y. Kishita, Y. Ohishi, M. Uwasu, M. Kuroda, H. Takeda, and K. Hara, “Evaluating the life cycle CO2 emissions and costs of thermoelectric generators for passenger automobiles: a scenario analysis,” *J. Clean. Prod.*, vol. 126, pp. 607–619, Jul. 2016.

[53] E. Doyle, L. Dinanno, and S. Kramer, “Installation of a diesel-organic Rankine compound engine in a class 8 truck for a single-vehicle test,” *Passeng. Car Meet.*, 1979.

[54] C. J. Leising, G. P. Purohit, S. P. Degrey, and J. G. Finegold, “Waste Heat Recovery In Truck Engines,” in *National West Coast Meeting*, 1978.

[55] E. Lodwig, “Performance of a 35-hp Organic Rankine Cycle Exhaust Gas Powered System,” *SAE Pap.*, 1970.

[56] T. Wang, Y. Zhang, Z. Peng, and G. Shu, “A review of researches on thermal exhaust heat recovery with Rankine cycle,” *Renew. Sustain. Energy Rev.*, vol. 15, no. 6, pp. 2862–2871, 2011.

[57] J. B. Heywood, “Automotive engines and fuels: A review of future options,” *Prog. Energy*

Combust. Sci., vol. 7, no. 3, pp. 155–184, Jan. 1981.

[58] J. Larjola, “Electricity from industrial waste heat using high-speed organic Rankine cycle (ORC),” *Int. J. Prod. Econ.*, vol. 41, no. 1–3, pp. 227–235, 1995.

[59] T. C. Hung, T. Y. Shai, and S. K. Wang, “A review of organic rankine cycles (ORCs) for the recovery of low-grade waste heat,” *Energy*, vol. 22, no. 7, pp. 661–667, 1997.

[60] C. Sprouse III and C. Depcik, “Organic Rankine Cycles with Dry Fluids for Small Engine Exhaust Waste Heat Recovery,” *SAE Int. J. Altern. Powertrains*, vol. 2, no. 1, pp. 2013-01–0878, 2013.

[61] M. Hatami, M. D. Boot, D. D. Ganji, and M. Gorji-Bandpy, “Comparative study of different exhaust heat exchangers effect on the performance and exergy analysis of a diesel engine,” *Appl. Therm. Eng.*, vol. 90, pp. 23–37, 2015.

[62] M.-H. Yang, “Payback period investigation of the organic Rankine cycle with mixed working fluids to recover waste heat from the exhaust gas of a large marine diesel engine,” *Energy Convers. Manag.*, vol. 162, pp. 189–202, Apr. 2018.

[63] M. Levesque, D. Millar, and J. Paraszczak, “Energy and mining-The home truths,” *J. Clean. Prod.*, vol. 84, no. 1, pp. 233–255, 2014.

[64] D. M. Doyle, “Approach to energy management at Falconbridge Nickel Mines Limited,” *CIM Bull.*, vol. 72, no. 810, pp. 82–91, 1979.

[65] A. M. JESSOP, J. K. MACDONALD, and H. SPENCE, “Clean Energy from Abandoned Mines at Springhill, Nova Scotia,” *Energy Sources*, vol. 17, no. 1, pp. 93–106, Jan. 1995.

[66] J. Raymond, R. Therrien, and F. Hassani, “Overview of Geothermal Energy Resources in Québec (Canada) Mining Enviroments.”

[67] A. E. Hall, D. M. Mchaina, and S. Hardcastle, “Controlled recirculation in Canadian

underground potash mines," *Min. Sci. Technol.*, vol. 10, no. 3, pp. 305–314, 1990.

[68] M. L. Joy and P. Applica, *Heat Pipes - Proven Versatility In Heat Transport*, vol. 71, no. 796. 1978, pp. 80–89.

[69] M. J.-G. Sylvestre, "Heating and ventilation study of Inco's Creighton Mine," McGill University, 1999.

[70] H. Dello Sbarba, "HEAT RECOVERY SYSTEMS IN UNDERGROUND MINE VENTILATION SYSTEMS AND NOVEL MINE COOLING SYSTEMS," Université Laval, 2012.

[71] L. H. Smith and D. C. Arthur, "Mine ventilation: Waste heat recovery," *CIM Bull.*, vol. 89, no. 998, pp. 126–130, 1996.

[72] C. G. Yip and K. S. Pollock, "Diavik Diamond Mine Northwest Territories, Canada NI 43-101 Technical Report," 2017.

[73] D. Diamond Corporation, "Ekati Diamond Operation Northwest Territories, Canada NI 43-101 Technical Report," 2016.

[74] C. Nwt, D. D. Johnson, and D. Pilotto, "GAHCHO KUÉ MINE NI 43-101 TECHNICAL REPORT," Vancouver, 2017.

[75] N. Peterson, "What Is The Difference Between Standby, Prime, and Continuous Power?," *Critical Power Products and Services*, 2018. [Online]. Available: https://www.criticalpower.com/difference-standby-prime-continuous-power/. [Accessed: 12-Mar-2019].

[76] C. H. G. Brito, C. B. Maia, and J. R. Sodré, "A Mathematical Model for the Exhaust Gas Temperature Profile of a Diesel Engine," *J. Phys. Conf. Ser.*, vol. 633, p. 012075, 2015.

[77] R. Thakar, S. Bhosle, and S. Lahane, "Design of Heat Exchanger for Waste Heat Recovery

from Exhaust Gas of Diesel Engine," *Procedia Manuf.*, vol. 20, pp. 372–376, 2018.

[78] G. Robinson, C. Gherghel, and E. De Souza, "Positive pressure ventilation system conversion at Diavik Diamond Mine." Airfinders Inc., Kingston, p. 17, 2015.

[79] Government of Canada, "Historical Climate Data," *Environment and Natural Resources*, 2018. .

[80] V. Mokkapati and C. Sen Lin, "Numerical study of an exhaust heat recovery system using corrugated tube heat exchanger with twisted tape inserts," *Int. Commun. Heat Mass Transf.*, vol. 57, pp. 53–64, 2014.

[81] R. Ravi and S. Pachamuthu, "Design and Development of Innovative Protracted-Finned Counter Flow Heat Exchanger (PFCHE) for an Engine WHR and Its Impact on Exhaust Emissions," *Energies*, vol. 11, no. 10, p. 2717, 2018.

[82] J. De La Vergne and S. Mcintosh, "Hard Rock Miner's Handbook," *Hard Copy Ed. CD Web Ed.*, vol. 4, no. 4, 2000.

[83] B. Bharathan, A. P. Sasmito, and S. A. Ghoreishi-Madiseh, "Analysis of energy consumption and carbon footprint from underground haulage with different power sources in typical Canadian mines," *J. Clean. Prod.*, vol. 166, pp. 21–31, Nov. 2017.

[84] H. Ferreira and M. G. P. Leite, "A Life Cycle Assessment study of iron ore mining," *J. Clean. Prod.*, vol. 108, pp. 1081–1091, Dec. 2015.

[85] N. R. Canada, "Retail Fuel Prices by Province- Energy Sources," 2017. [Online]. Available: http://www2.nrcan.gc.ca/eneene/sources/pripri/price_map_e.cfm#chartList. [Accessed: 24-Jan-2019].

[86] John Paul Tasker, "Here's where the provinces stand on carbon prices | CBC News," *CBC News*, 03-Oct-2016.

[87] D. Madsen, "SWOT ANALYSIS: A MANAGEMENT FASHION PERSPECTIVE," *Int. J. Bus. Res.*, 2016.

[88] I. E. Nikolaou and K. I. Evangelinos, "A SWOT analysis of environmental management practices in Greek Mining and Mineral Industry," *Resour. Policy*, vol. 35, no. 3, pp. 226–234, Sep. 2010.

[89] S. A. Ghoreishi-Madiseh, A. Safari, L. Amiri, D. Baidya, M. A. R. de Brito, and A. F. Kuyuk, "Investigation of viability of seasonal waste heat storage in rock piles for remote communities in cold climates," *Energy Procedia*, vol. 159, pp. 66–71, Feb. 2019.

[90] S. A. Ghoreishi-Madiseh, A. F. Kuyuk, M. A. R. Brito, D. Baidya, Z. Torabigoodarzi, and A. Safari, "Application of Borehole Thermal Energy Storage in Waste Heat Recovery from Diesel Generators in Remote Cold Climate Locations," *Energies*, p. 13, 2019.

Appendices

Appendix A Energy data of the diesel generators

A.1 Performance data of different size of diesel generators

Gen-set specification with heat rejection data:

No.	Rating Level	Power with fan	Fuel Consumption		Heat Rejection to					
			LHV	HHV	Coolant (total)	Exhaust (total)	After-cooler	Atmosphere from		
								Engine	Generator	CEM
		(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)
1.	Prime	364	940	1005	139	344	61	42	24	
2.	Standby	500	1377	1473	189	505	120	94	29	
3.	Prime	648	1708	1826	386	637	86	108	30	
4.	Prime	800	2230	2385	288	881	223	107	50	
5.	Prime	1000	2700	2888	647	1038	139	118	55	
6.	Prime	1360	3623	3872	581	1212	443	119	66	
7.	Standby	1500	3937	4211	616	1322	481	124	74	
8.	Standby	1750	4673	5000	1028	1960	321	142	86	
9.	Prime	1825	5011	5359	723	1960	567	139	86	
10.	Prime	2000	5185	5545	721	1964	514	142	94	
11.	Prime	2250	5896	6306	777	2243	690	150	91	
12.	Standby	2500	6530	6984	826	2502	786	161	107	

13.	Prime	2725	7101	7594	1229	2796	329	167	3	48
14.	Prime	2825	7101	7594	1229	2796	329	167	171	48
15.	Standby	3100	7930	8481	1355	3095	481	273	109	

(All values are rounded to the nearest integer)

Percentage of the exhaust heat in the waste heat of gen-sets:

No.	Rating Level	Power with fan	Fuel Consumption		Heat Rejection (Total)	Heat Rejection to Exhaust	% of Total Heat, Rejected through Exhaust	% of Fuel Consumption, Reject through Exhaust	
			LHV	HHV				LHV	HHV
		(kW)	(kW)	(kW)	(kW)	(kW)	%	%	%
1.	Prime	364	940	1005	610	344	56.40	36.60	34.23
2.	Standby	500	1377	1473	937	505	53.90	36.67	34.28
3.	Prime	648	1708	1826	1247	637	51.08	37.30	34.88
4.	Prime	800	2230	2385	1549	881	56.88	39.51	36.94
5.	Prime	1000	2700	2888	1997	1038	51.98	38.44	35.94
6.	Prime	1360	3623	3872	2421	1212	50.06	33.45	31.30
7.	Standby	1500	3937	4211	2617	1322	50.52	33.58	31.39

8.	Standby	1750	4673	5000	3537	1960	55.41	41.94	39.20
9.	Prime	1825	5011	5359	3475	1960	56.40	39.11	36.57
10.	Prime	2000	5185	5545	3435	1964	57.18	37.88	35.42
11.	Prime	2250	5896	6306	3951	2243	56.77	38.04	35.57
12.	Standby	2500	6530	6984	4382	2502	57.10	38.32	35.82
13.	Prime	2725	7101	7594	4572	2796	61.15	39.37	36.82
14.	Prime	2825	7101	7594	4740	2796	58.99	39.37	36.82
15.	Standby	3100	7930	8481	5313	3095	58.25	39.03	36.49

Fuel Consumption and Heat Rejection per 1 kw Production of Electricity:

No.	Rating Level	Power with Fan	Fuel Consumption		Total Heat Rejection	Heat Rejected through Exhaust
			LHV	HHV		
		(kW)	(kW)	(kW)	(kW)	(kW)
1.	Prime	364	2.58	2.76	1.68	0.95
2.	Standby	500	2.75	2.95	1.87	1.01
3.	Prime	648	2.64	2.82	1.92	0.98
4.	Prime	800	2.79	2.98	1.94	1.10
5.	Prime	1000	2.70	2.89	2.00	1.04
6.	Prime	1360	2.66	2.85	1.78	0.89
7.	Standby	1500	2.62	2.81	1.74	0.88

8.	Standby	1750	2.67	2.86	2.02	1.12
9.	Prime	1825	2.75	2.94	1.90	1.07
10.	Prime	2000	2.59	2.77	1.72	0.98
11.	Prime	2250	2.62	2.80	1.76	1.00
12.	Standby	2500	2.61	2.79	1.75	1.00
13.	Prime	2725	2.61	2.79	1.68	1.03
14.	Prime	2825	2.51	2.69	1.68	0.99
15.	Standby	3100	2.56	2.74	1.71	1.00

A.2 Performance data a diesel generator at different load factors

1750 ekw Diesel Generator's Change of Performance with the Variation of Load Level

No.	Genset Power with Fan	Percent Load	Engine Power	Fuel Consumption		Total Heat Rejection	% of Total Heat, Rejected through Exhaust	% of Consumed Fuel, Rejected through Exhaust	
				LHV	HHV			LHV	HHV
	(ekW)	(%)	(BHP)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)
1.	175	10	321	851	910	721	54.91	46.56	43.54
2.	350	20	574	1269	1357	1016	55.96	44.83	41.92
3.	438	25	697	1491	1594	1169	56.00	43.91	41.07
4.	525	30	819	1706	1824	1319	56.09	43.39	40.58
5.	700	40	1060	2131	2279	1627	55.95	42.71	39.94

6.	875	50	1299	2549	2726	1941	55.64	42.37	39.62
7.	1050	60	1542	2971	3177	2268	55.20	42.15	39.41
8.	1225	70	1785	3400	3635	2607	54.73	41.97	39.25
9.	1313	75	1907	3611	3861	2782	54.48	41.97	39.25
10.	1400	80	2030	3825	4090	2958	54.23	41.93	39.21
11.	1575	90	2276	4239	4533	3316	53.71	42.01	39.29
12.	1750	100	2525	4672	4996	3685	53.19	41.95	39.23

Change in fuel consumption and heat rejection per 1 kw production of electricity with the variation of load:

No.	Genset Power with Fan	Percent Load	Fuel Consumption		Total Heat Rejection	Heat Rejected through Exhaust
			LHV	HHV		
	(ekW)	(%)	(KW)	(KW)	(KW)	(KW)
1.	175	10	4.86	5.20	4.12	2.26
2.	350	20	3.63	3.88	2.90	1.62
3.	438	25	3.41	3.64	2.67	1.50
4.	525	30	3.25	3.47	2.51	1.41
5.	700	40	3.04	3.26	2.32	1.30
6.	875	50	2.91	3.11	2.22	1.23
7.	1050	60	2.83	3.03	2.16	1.19

8.	1225	70	2.78	2.97	2.13	1.16
9.	1313	75	2.75	2.94	2.12	1.15
10.	1400	80	2.73	2.92	2.11	1.15
11.	1575	90	2.69	2.88	2.11	1.13
12.	1750	100	2.67	2.86	2.11	1.12

Appendix B Equipment used in the experimental setup

B.1 Diesel generator

DuroStar 7000Q Diesel Generator

Generator	
Kind	Single phase
Frequency (HZ)	60
Max power (kw)	5
Max output (kiva)	4.5
Voltage (AC) V	120/240
Self-excitation	Brushless

Revolution (rpm)	3600
Voltage (DC) V	12
Current (DC) A	8.3
Optional generator grade	G1
Power factor cos	1
Steady state voltage adjust rate	-0.07
No-load waveform distortion rate	·≤10%
Insulation grade	≤15%

Diesel engine	
Mode of power	KD186FA
kind	4-stroke single–cylinder air cooled direct injection
Persistence power (KW)	6.6
Max power (kw)	7.3
Cylinder diameter stroke (mm)	86×72
Cylinder displacement (ml)	418
Cooling system	Force air-cooled

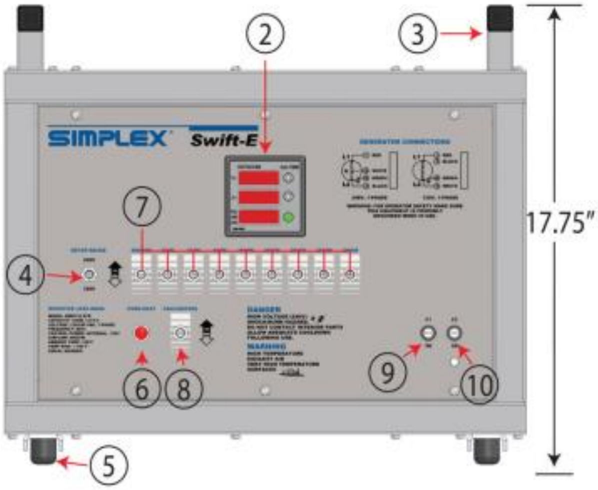
Volume of lube oil (L)	1.65
Start system	Electric start
Fuel	Diesel fuel

Gen-set	
Fuel tank volume (L)	14.5
Working way	Continuous operating for 12hours
Total weight (kg/lb.)	172/379
Over dimensions (Inch)	37.8” x 22.0” x 30.3

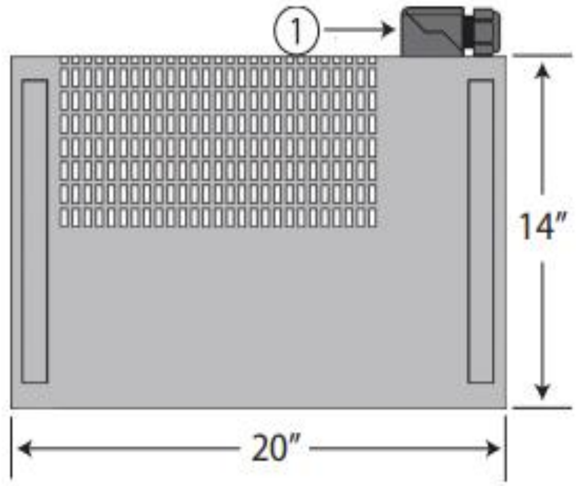
B.2 Load bank

Model	Weight	Description	Control power	Max amps at 120V	Max amps at 240V
Swift-E	45 lbs.	10KW, 120/240V, Single-Phase, 250W Step Resolution	1.33A	83.3	41.7

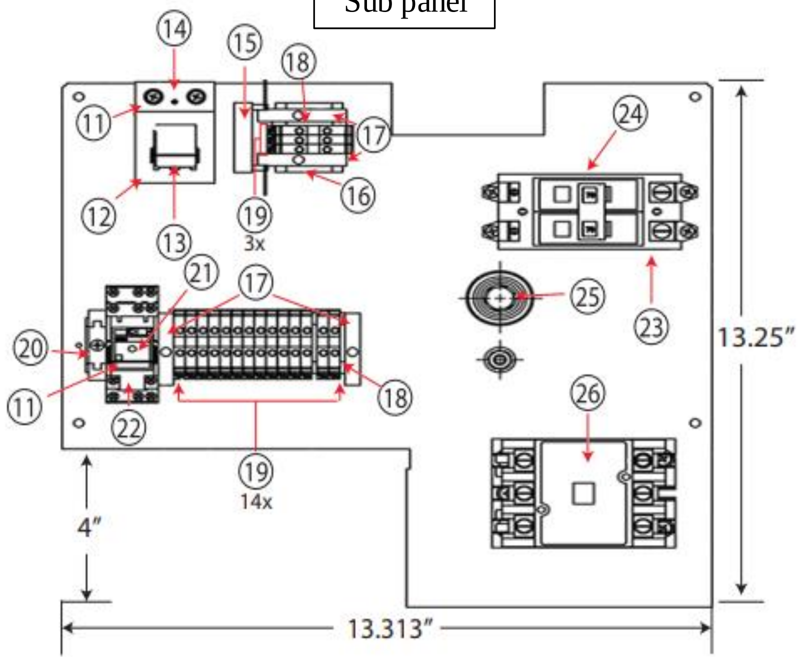
Front view



Top view



Sub panel

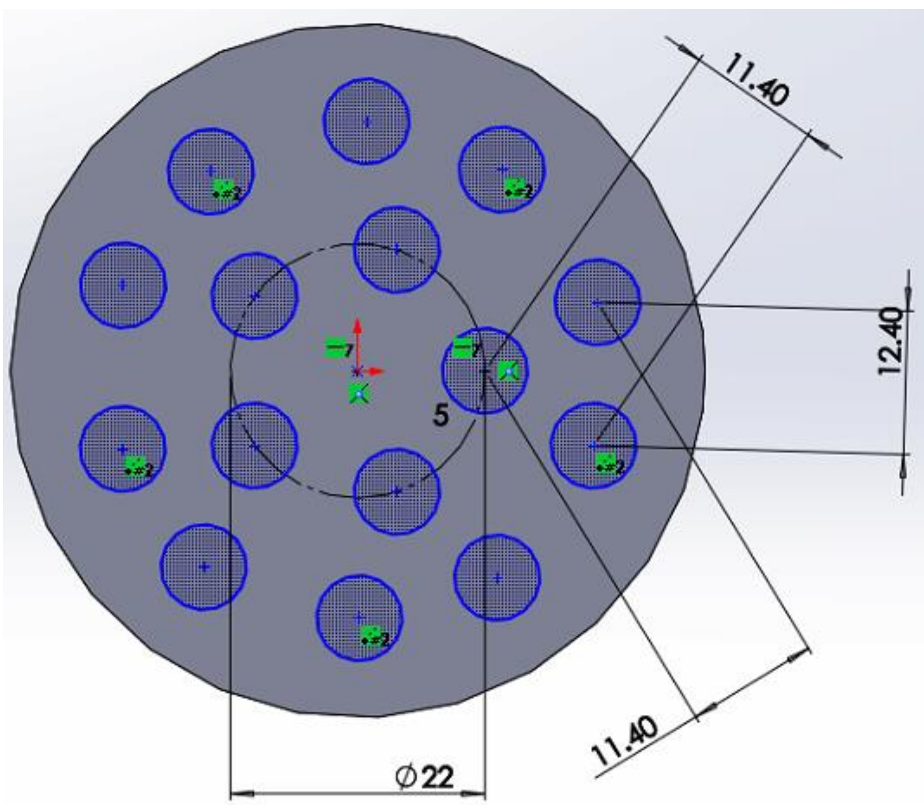


Number	Part Number	Description
1	15195030	Cable Exit, Strain Relief
2	24341000	Digital Power Meter
3	7BD215514	Handles, Cable Wrap
4	25301000	Meter Range Selector Switch
5	15303000	Rubber Feet
6	24251500	Over Heat Indicator Lamp
7	25303010	Master Load and Load Step Toggle Switches
8	25301000	Fan/Control Power Toggle Switch
9	14031000	Control Fuses 5A, 250V
10	14011000	Control Fuses 2A, 250V
11	54885650	Relay Bale
12	24885000	Relay Base Socket
13	24785300	Relay
14	50020220	Relay Base Bracket
15	25130000	Resistor
16	24892000	Din Rail, 1.75"LG
17	25678501	Terminal Strip End Barrier
18	25678502	Terminal Block End Plate
19	25678500	Terminal Block, 35A, 600V (X17)
20	24892000	Din Rail, 5.62" LG
21	24827035	Relay, General Purpose, 120VAC
22	24882100	Relay Base, 3-Pole, Screw Termination
23	12517000	Plate Mounting
24	12103025	Circuit Breaker
25	15401000	1.375" Isolator
26	13027042	Contactor, 40A

B.3 Shell and tube heat exchanger

No. of tubes	15
Length of tube	0.66 m
Tube inner diameter	0.0074 m
Tube thickness	0.0012 m
Shell inner diameter	0.054 m
Shell thickness	0.006 m
Water inlet/outlet diameter	0.0241 m

Geometrical orientation of the tubes inside the shell:



B.4 Drum heater

Model no.	Drum material	Fits drum size	Thermostat range	Volts	Watts
H-2961	Plastic	55 Gal.	10~71 °C	120	300

- Band: 4 x 64" (W x L)
- Thermostat: Adjustable from 0 ~ 10.
    - Adjusts in -12 C (11 F) increments.
    - 0= 10 C (50 F)
    - 10= 71 C (160 F)

B.5 Pressure gauges

Pressure gauge used in the exhaust side:

Part Number	KC25-10" H20
Measurement System	US
Brand Name	Kodiak Controls
Color	Chrome Plated Steel
Connector Type	Bottom Mount
Manufacturer Series Number	KC25
Material	Brass
Measurement Accuracy	2-1-2%
Model Number	KC25-10" H20
Number of Items	1
Range	0-10 IWC
Resolution	0.1 & 1 IWC
Thread Type	1/4 Npt
UNSPSC Code	41112412
Width	2.5 inches

Pressure gauge used in the water side

- Brass wetted parts for measuring non-corrosive liquid and gas pressure
- Circular dial is filled with glycerin and enclosed in a stainless steel 304 case for corrosion resistance
- Measures pressure with single (psi) or dual scale (psi/kPa)/(psi/bar)/(Hg. vacuum/kPa)/(Hg. vacuum/bar)
- Display accuracy is + or - 2.5% of full-scale value for the 1.5" (40 mm) and 2" (50 mm) gauges, and + or - 1.5% of full-scale value for the 2.5" (63 mm) and 4" (100 mm) gauges
- Lower mount or center back male connection with 1/8", 1/4", or 1/2" NPT rate with restricted orifice

Manometer used to measure the pressure in the extension of intake air system of the diesel generator:

Measures	Differential Pressure
For Use With	Air, Natural Gas
Display Type	Digital
Scale	psi, bar
Pressure range (psi)	0-30
Resolution	0.01 psi
Maximum Pressure	60 psi
For Tube ID	1/8"-3/16"
Environment Temperature Range	35° to 100° F
Process Temperature Range	0° to 140° F

Connection Type	Tube
Gender	Male
Case Material	Aluminum
Connection Material	Nickel-Plated Brass
Lens Material	Glass
Accuracy	±0.5%
Accuracy Scale	Full Scale
Accuracy Grade	Not Graded
Digital Display Type	LCD
Digit Height	3/8"
Height	6 1/2"
Power Source	Battery
Number of Digits	4
Width	2 13/16"
Tube Connection Type	Barbed
Batteries Included	Yes
Battery Size	9V
Number of Batteries Included	1

B.6 Temperature sensors

K Type temperature probe sensors:

Specifications:

- Measuring range: 0-1250 ℃
- Probe Material: Stainless Steel
- Probe Diameter: 5 mm/0.2inch
- Probe Length (Front): 80mm/3.2 inch
- Threads Size: 1/8" NPT
- Threads Lock: Adjustable Pressure Lock (Adjustable Length)
- Cable Length: 1m
- Connector: Mini K Type Connector
- Weight: 70g
- Accuracy: ± 2.2C% or ±.75%

4 channel K type thermometer SD card data logger:

- K Temp. Range: -200 to 1370°C, -328 to 2498°F / Resolution: 0.1°C/°F / Accuracy (under 18~28°C ambient temp.): ± (0.3%rdg + 1°C)
- Sampling Rate: Programmable from 1 second up / LCD Size: 47 x 104mm
- Operating Temp.: 0~50°C / Operating Humidity: <80%
- Storage Temp.: -20~50°C / Storage Humidity: <90%
- Power Supply: AA Batteries (included in the set) or 9V adaptor (not included in the set)

B.7 Water flow controller

DIGITEN water flow control LCD display:

Specifications:

- Controller Power Requirement: 12VDC
- Power Adapter: Input: 100-240VAC, Output: 12VDC, max 2A
- Adapter lead length: 1m
- Measuring Accuracy: ±1%
- Output for Solenoid valve: 12VDC, max 5A
- Temperature Sensor: 0-120℃/32-212℉, NTC3950, Accuracy: ±1℃/±1℉ thread: M8
- Max Total Volume: 999999 G/L

- Quantitative Range: 1-9999 G/L
- Flow range:1-30L/min
- Cable Length: 1m
- Operation Environment: Temperature: 0-50℃/32-122℉ Relative Humidity: <85%

VicTsing 80 GPH (300L/H) submersible pump:

Specifications：

- Max Flow Rate: 80 GPH (300L/H)
- H-Max (Lift Height): 2.6ft (0.8m)
- Power: 4 Watts
- Voltage: 110 - 120 V @ 60Hz
- Length of Power Cord: 5.9ft (1.8m)
- Dimension: 1.87in x 1.68in x 1.24in (47mm x 43mm x 30mm)

B.8 Flowmeter

Omega FMA1845A mass flow meter:

- Flow medium: Max Flow 15, 50, 100, 200 L/min, clean gases only.
- Calibrations: Performed at standard conditions [14.7 psia (1.01 bars) and 70 °F

(21.1 °C)] unless otherwise requested or stated.

- Environmental (per IEC 664): Installation Level II; Pollution Degree II.
- Accuracy: Max Flow 15, 50 and 100 L/min ±1.0% F.S.
- Repeatability: ±0.25% of full scale.
- Temperature coefficient: 0.15% of full scale/ °C.
- Pressure coefficient: 0.01% of full scale/psi (0.07 bar).
- Response time: 800 ms time constant; approximately 2 seconds to within ±2% of set flow rate for 25% to 100% of full-scale flow rate.
- Gas pressure: 1000 psig (69 bars) Max Flow 15, 50 and 100 L/min; 500 psig (34.5 bars)
- Optimum pressure is 20 psig (1.4 bars).
- Gas and ambient temperature: 32 °F to 122 °F (0 °C to 50 °C). 14 °F to 122 °F (-10 °C to 50 °C) - Dry gases only.
- Relative gas humidity: Up to 70%.
- Leak integrity: 1 x 10- 7 sccs He max. to the outside environment.
- Attitude sensitivity: Incremental deviation of up to 1% full scale from stated accuracy, after re-zeroing.
- Output signals: Linear 0-5 VDC (1000 Ω minimum load impedance) and 4-20 mA self powered sourcing type, non-isolated, (0-500 Ω loop resistance); 20 mV peak to peak max noise.

Appendix C Heat loss calculation

The heat loss from the surface of the shell of the heat exchanger was calculated with the following equation:

$$h = \frac{k}{D} Nu$$

Where, h= heat loss (W/m^{2}K)

k= thermal conductivity of air at average film temperature (average of the surface temperature and the ambient air temperature, T_f) and 1 atm pressure (W/mK)

D= diameter of the shell (m)

Nu= Nusselt number = $0.3 + \frac{0.62 Re^{0.5} Pr^{0.33}}{\left\{1+\left(\frac{0.4}{Pr}\right)^{\frac{2}{3}}\right\}^{0.25}} * \left\{1 + \left(\frac{Re}{282{,}200}\right)^{\frac{5}{8}}\right\}^{\frac{4}{5}}$

Pr= Prandtl number for air at T_f

$Re =$ Reynolds number = $\frac{VD}{n}$

V= Wind speed (m/s)

n = Kinematic viscosity (m^2/s)

Using these equations, the heat loss was found ~22 W/m^{2}K.