# CLEAN RESOURCES FINAL REPORT PACKAGE

Project proponents are required to submit a Final Report Package, consisting of a Final Public Report and a Final Financial Report. These reports are to be provided under separate cover at the conclusion of projects for review and approval by Alberta Innovates (AI) Clean Resources Division. Proponents will use the two templates that follow to report key results and outcomes achieved during the project and financial details. The information requested in the templates should be considered the minimum necessary to meet AI reporting requirements; proponents are highly encouraged to include other information that may provide additional value, including more detailed appendices. Proponents must work with the AI Project Advisor during preparation of the Final Report Package to ensure submissions are of the highest possible quality and thus reduce the time and effort necessary to address issues that may emerge through the review and approval process.

*Final Public Report*

The Final Public Report shall outline what the project achieved and provide conclusions and recommendations for further research inquiry or technology development, together with an overview of the performance of the project in terms of process, output, outcomes and impact measures. The report must delineate all project knowledge and/or technology developed and must be in sufficient detail to permit readers to use or adapt the results for research and analysis purposes and to understand how conclusions were arrived at. It is incumbent upon the proponent to ensure that the Final Public Report **is free of any confidential information or intellectual property requiring protection**. The Final Public Report will be released by Alberta Innovates after the confidentiality period has expired as described in the Investment Agreement.

*Final Financial Report*

The Final Financial Report shall provide complete and accurate accounting of all project expenditures and contributions over the life of the project pertaining to Alberta Innovates, the proponent, and any project partners. The Final Financial Report will not be publicly released.

# CLEAN RESOURCES FINAL PUBLIC REPORT TEMPLATE

## 1. PROJECT INFORMATION:

| | |
|---|---|
| **Project Title:** | **Development of Low Temperature Stirling Engine Technology for Power Generation** |
| **Alberta Innovates Project Number:** | G2020000397 |
| **Submission Date:** | January 2024 |
| **Total Project Cost:** | $728,000 |
| **Alberta Innovates Funding:** | $200,000 |
| **AI Project Advisor:** | Susan Carlisle |

## 2. APPLICANT INFORMATION:

| | |
|---|---|
| **Applicant (Organization):** | **University of Alberta** |
| **Address:** | 10-281 Donadeo ICE building<br>Department of Mechanical Engineering<br>University of Alberta<br>Edmonton, Alberta<br>CANADA, T6G 1H9 |
| **Applicant Representative Name:** | David S. Nobes |
| **Title:** | Professor |
| **Phone Number:** | 780 492 7031 |
| **Email:** | david.nobes@ualberta.ca |

## 3. PROJECT PARTNERS

**Please provide an acknowledgement statement for project partners, if appropriate.**

*RESPOND BELOW*

The main research partner for this project is Future Energy Systems. This is a research consortium initiated in 2016 with a $75 million grant from the government of Canada's Canada first research excellence fund. The overarching goal of this consortium was to investigate the low carbon energy economy.

# A. EXECUTIVE SUMMARY

**Provide a high-level description of the project, including the objective, key results, learnings, outcomes and benefits.**

*RESPOND BELOW*

## 1. OBJECTIVE

If we consider electricity because of its usefulness, as an endpoint for any energy generation system (gas, oil, coal, solar, wind, nuclear, geothermal, etc.), there is an important feature of all of these energy systems. At some point in the energy conversion chain of any of these systems there is a temperature difference between a hot and cold heat source that sets the overall available amount of energy. A low-grade heat source is one that has only a small temperature difference. Alberta is in a unique position as it has an enormous heat source in the form of geothermal energy the covers most of the problems. Unfortunately, however, the maximum available temperatures are typically <150 °C with the majority closer to <75 °C. As most energy generation systems rely on a high temperature difference, new research is needed to understand how energy can be extracted efficiently from a low-temperature resource.

The aim of this project has been to investigate the use of Stirling engine technology, which can be coupled to any heat source, as a possible pathway to convert the low temperature difference of geothermal energy to mechanical energy and onto electrical energy. To undertake this research, a number of objectives were developed as follows:

- Develop a more inclusive mathematical model for predicting the performance of a Stirling engine operating at these conditions that include factors that are typically not found in engine models. This includes the addition of friction and output metrics such as the shape of pressure-volume (PV) loops.
- Develop an experimental test system that included a develop Stirling engine, instrumentation and an engine management system from which extensive datasets can be collected to validate developed mathematical model.
- Investigate the design of a large-scale, kinematic, low temperature Stirling engine for experimental testing.
- Given the low temperature difference available, investigate potential for scaling up the engine geometrically (physically) or thermodynamically (running at high pressure)
- Investigate how geothermal energy can be extracted from end-of-life oil wells as a potential hot source for the Stirling engine system.
- Use the models to predict engine performance for larger size engine design and industrial deployment.
- Complete an economic analysis to predict the economic potential of this technology for industrial deployment.

## 2. KEY RESULTS

Research undertaken in this project has developed a wide understanding of the Stirling engine and the thermo-physics that underpins the technology. Many interesting and scientifically important results have been developed in the research and there to be published in the output of the research in journal and conference publications as well as student theses. The most important of these results are the key findings that are:

- Heat transfer is the limiting factor for all Stirling engines. While in general analysis would highlight that a significant amount of power can be developed from a certain engine for a low temperature difference, it would not take into account the inefficiencies of heat transfer through the system. The reciprocating nature of the internal working fluid within the Stirling engine is intrinsically a laminar flow within the heat exchangers. This leads to very low convective heat transfer to and from the working fluid leading to an overall low power generation by the engine. This is true for all Stirling engines at current time whether they operate at a low temperature difference or a high temperature difference. Conventional Stirling engines operating at high temperatures >800 °C on the hot side mask this effect by using such a high temperature source. As research into heat transfer in reciprocating flows is very limited in the literature, there is a potential for addressing this limitation with new technology such as improved working fluid, the generation of large-scale flow structures to improve convective heat transfer and the optimization of the flow geometry to maximize heat transfer while minimizing flow friction.
- Physically increasing the size of the engine leads to a reduction in the power density of the engine which is not favorable design approach. An initial premise of the research was that given the low available temperature difference, physically increasing the size of the engine will allow a reasonable amount of energy to be produced. Also, the thermodynamic theory highlights that if the engine can be operated at high pressure more energy can be extracted for a given temperature difference. Both of these lead to the investigation of design and large-scale (>2m long) engine for testing the developed mathematical model. Results of the analysis however showed that the engine quickly became overwhelmingly heavy to be able to carry the pressures needed to generate a significant amount of power. An important output from the developed model and analysis was that increasing the physical size reduced the power density of the actual engine significantly. This led to the conclusion that a number of smaller engines operating at high pressure could generate more power, more economically than a single large-scale engine.
- Stirling engines can up used to generate electrical power from a low temperature source. However, the economics for generation of electrical power using this technology are not favorable. The amount of material needed to construct a large-scale engine that can produce a significant amount of power led to a high dollar value per unit of energy produced. The research had also taken the path of investigating kinematic Stirling engines for which there is a significant amount of literature available that would help allow the development of a mathematical model. These engine types are mechanically complex with the two pistons being mechanically connected (hence kinematic), leading to a large amount of mechanical friction. There is a potential for

success however through the using free piston Stirling engine technology where the pistons are not mechanically connected, reducing friction. These are also mechanically very simple but are more complex to model. Potentially, small-scale free Piston Stirling engines could operate from a low temperature difference heat source and be built economically due to their low part count and relatively simple geometry.

## 3. LEARNINGS

Fundamental understanding of heat exchanger design for reciprocating flows is limited. Indeed, there are very few publications in the literature that take on the challenge of describing heat transfer in reciprocating flows such as found in a Stirling engine. Potentially a reason for this is that there are few other technologies that have this unique flow field. The design of the heat exchanger for this flow field is one aspect of the problem. A secondary but no less important aspect is understanding the fluid mechanics of the flow field as the flow accelerates in one direction, then decelerates and stops, reverses direction and accelerates, and then decelerates and stops again. This repeating cycle of different flow phenomenon is again very unique and has almost no presence in the scientific literature. The addition of understanding convective heat transfer, the conduction of heat into the fluid and its advection away from the surface, is also complex. Our preliminary research in this area highlights there is a potential for increasing the heat transfer significantly through the introduction of large-scale flow structures such as axial or cross stream vortices. This research however is in its infancy and will require a long-term strategy to develop benefits.

Modelling of thermodynamic systems such as the Stirling engine is complex. The model needs to consider not only the thermodynamics, fluid mechanics and heat transfer but also the kinematics, dynamics and friction of the mechanical system. When modelling most mechanical engineering systems, the importance of time is usually low and can be ignored. Time-dependent systems however significantly add to the complexity as a solution must be found in every instance in time throughout a complete cycle. The PV diagram that were generated by the mathematical were an important step to understanding the engine design under development. This however, also requires the collection time-dependent data, significantly challenging giving the low time response of available sensors. The develop mathematical model, while having some limitations, has been very successful in providing guidance on the design and understanding of Stirling engine technology.

Extracting energy from a geothermal system presents its own challenges. A unique feature of Alberta is the very high number (>400,000) of end-of-life oil wells, many of which are located within a geothermal resource. Technology could be developed that would allow energy to be extracted in a useful way. An important step will be the development of a predictive model that can allow the design and optimisation of this technology. The model developed in this research project for predicting heat extraction from end-of-life oil wells takes into account many factors that are typically not included in these type of well extraction models such as the multiphase nature, multi-components of both liquids and gases, and heat transfer into the surrounding reasonable rock. The model has highlighted the importance of modelling the multiphase nature of the flow as well as the degradation of heat transfer from the reservoir rock over time. Taking this into consideration, significant heat energy can be extracted from these wells with an optimally designed counterflow system.

## 4. OUTCOMES AND BENEFITS

Some of the major outcomes and benefits of this research project are as follows:

- Model provides a better understanding and insight into the design approaches need to achieve high engine power and performance
- Physically large-scale engines do not provide a promising approach for converting low grade heat into electricity. A better approach would be to design a small-scale engine of high-efficiency that can be manufactured cheaply and used in a large array of engine sets.
- Heat extraction from end-of-life oil wells is feasible with an optimally designed system. Given the limited temperature of the available heat appropriate uses for it need to be generated.
- The research work significantly increases the fundamental knowledge in this area and a better understanding of how to model these complex thermodynamic systems.

## B. INTRODUCTION

**Please provide a narrative introducing the project using the following sub-headings.**

- **Sector introduction:** Include a high-level discussion of the sector or area that the project contributes to and provide any relevant background information or context for the project.
- **Knowledge or Technology Gaps:** Explain the knowledge or technology gap that is being addressed along with the context and scope of the technical problem.

*RESPOND BELOW*

### 1. SECTOR INTRODUCTION

Alberta is in a unique position globally as it has a significant geothermal resource that is on land and it is accessible. The majority of geothermal energy is under the ocean. Also, there is a very large number (400,000) end-of-life oil wells distributed throughout the province, many of these coinciding with major hotspots in the geothermal resource. This is mostly located along the eastern side of the Rocky Mountains. How that also has many high temperature manufacturing and industry processes from which a significant amount of heat is dumped into the atmosphere. Both of these heat sources can be described as low grade because of the low temperature difference between the heat source itself and the low temperature source which is typically atmospheric temperature. If the technology can be developed to extract useful energy from these heat sources it will doing so without adding any extra carbon to the atmosphere. Typical technology is based around the Rankine cycle that is used in the steam power plant or for low temperature application an organic Rankine cycle (ORC) where some other liquid that boils at a lower temperature the water is used as the working fluid. This technology has a lower temperature limit however typically 100 °C - 150° C whereas most of the available low grade heat is at this temperature or lower. This research investigated the use of Stirling engine technology with the aim to fill this gap.

### 2. KNOWLEDGE OR TECHNOLOGY GAPS

Despite the research undertaken, the feasibility of using Stirling engine technology at large-scale from low temperature sources is not well understood. This project will aim to address the knowledge gap by addressing the question: is it technically feasible and economically viable to use Stirling engine technology for the generation of energy from a low temperature source? The main approach for addressing this question will be the development of a mathematical model capable of predicting the performance of low temperature Stirling engines. This model will allow the thermodynamic power to be coupled to the mechanical components and the engine losses, thus falling under the category of a 3rd order model. This will be used for the design and optimization of all future development. The validation of this model is a significant component of the research work. This will be undertaken by the construction and operation of a test engine that is at a sufficiently large enough thermodynamic scale to provide meaningful results.

## C. PROJECT DESCRIPTION

**Please provide a narrative describing the project using the following sub-headings.**

- **Knowledge or Technology Description:** Include a discussion of the project objectives.
- **Updates to Project Objectives:** Describe any changes that have occurred compared to the original objectives of the project.
- **Performance Metrics:** Discuss the project specific metrics that will be used to measure the success of the project.

*RESPOND BELOW*

### 1. KNOWLEDGE OR TECHNOLOGY DESCRIPTION

The knowledge that has been developed in this project investigating the use of a low temperature different Stirling engines (LTDSEs) has been aligned with the overall objectives and developed into individual tasks. These individual tasks and the objectives are discussed below.

*Task # 1: Large Scale LTDSE Design and Build*

A large-scale Gamma (LSG) LTDSE will be built in order to prove the feasibility of the Stirling engine technology for low-grade heat recovery at a large scale. In this part of the project, the objective is to design, build and commission the LSG LTDSE. This engine will then undergo performance testing and comparison with the developed mathematical model. It is expected that this research and development will identify performance improvements in the engine that will require upgrades to specific components of the engine. The work will then design and build engine upgrades and undertake testing of the upgraded engine, i.e. Test LSG LTDSE, upgrade to LSG LTDSE and test the upgrades to LSG LTDSE. For this purpose, the following tasks will be performed:

- *Design of a Gamma LTDSE using CAD (SOLIDWORKS) with increased thermodynamic scale*
- *Assemble and test sub-assemblies*
- *Undertaking engine test study and investigating the performance of the engine under the operating conditions with comparison to the developed mathematical model*
- *Design, build and upgrade components of the engine for improved performance*
- *Undertaking engine test study and determining max performance and limitations*

*Task # 2: Thermo-fluids of Reciprocating Systems*

*This set of tasks will investigate the dynamics of the reciprocating system experimentally and theoretically for its effect on heat transfer and engine functionality. The objective of this part of the project is to study the performance of radiator and oscillating flow test setups and investigating non-standard engine mechanisms. For this purpose, the following tasks will be performed.*

- *Determining the effect of piston velocity profiles on heat transfer (thru flow radiators)*
- *Detailed investigation of the effect of the oscillating flow of the engine on heat transfer and hence energy exchange.*

- *Development and modeling of non-standard piston motion and coupling mechanisms*

*<u>Task # 3: Development of 3rd Order Model for LTDSE</u>*

*The results from the experiments, theory and analytics will be combined with the 2nd order model to develop a 3rd order predictive model of low temperature difference Stirling engine. The objectives of this part of the project are finalizing the model framework and validating the model by comparing the model predictions with experimental data. For this purpose, the following tasks will be performed.*

- *Developing the basic model framework within MATLAB, expanding the scope to include configurations that are under experimental investigation and configuring the software so that design studies for variable optimization can be undertaken.*

- *Validation of the numerics of the 3rd order, low temperature model with a standard commercial Stirling engine design software (SAGE). The software is a direct descendent of codes HFAST and Glimps developed in partnership with NASA. The harmonic analysis (using Fourier series) method used by SAGE is very efficient at solving for steady state behaviors of cyclic machines. However, SAGE has minimal inclusion of mechanism dynamics and has not been proven for low temperature Stirling engine design. The validation undertaken using Stirling engine configurations that are compatible with both software.*

- *Comparing the results collected from experiments with the model predictions*

*<u>Task # 4: Thermal Energy Transport to and from the Stirling Engine</u>*

*To allow a reasonable economic analysis to be undertaken, complete assessment of the thermal energy transport for the complete system needs to be undertaken. This work will undertake to model the performance, efficiency and cost of other important systems that include thermal energy transport from waste heat and geothermal resources to the Stirling engine and the removal of heat to a cold sink. Objectives for this part of the project include modeling the technology for extracting energy from hot thermal sources (i.e., reservoirs), investigating the methods for releasing the energy to the cold thermal sink and design of the external thermal transport model. For this the following tasks will be performed:*

- *Reviewing and modeling of suitable technologies for energy transport from the hot source*

- *Reviewing and modeling of technologies for heat rejection to a cold sink*

- *Developing a complete thermal transport model external to the LDTSE*

*<u>Task # 5: Economic Feasibility and Life Cycle Analysis</u>*

*A life cycle analysis of the engine and its carbon foot print will be undertaken in the last year of the project. The developed tools will be important for the development of an economic analysis to properly gauge risk and potential success of the technology for commercialization. The following tasks will be undertaken:*

- *Performing a life cycle analysis to estimate the carbon footprint due to using the LTDSE, especially when new materials are used.*

- *Developing an economic feasibility of the technology at a commercial scale based on experimental and model results*

- *Providing information required for developing a commercialization plan and pathway*

## 2. UPDATES TO PROJECT OBJECTIVES

The general project objectives for this research have not changed over the course of the project. With the inclusion of the support of Alberta Innovates, extra objectives were added. These was related to understanding how the Stirling engine can be scaled with the initial intent to build a geometrically large-scale engine. Design and development work in this area highlighted that the engine quickly became very heavy and outside the scope of equipment they could be handled within the available research laboratory. The objective was then altered to investigate thermodynamic scaling of the engine by running the engine at higher pressures and focusing on heat transfer as this was now highlighted as the major limitation or bottle neck in the system. This required the redesign and manufacturing of heat exchangers for the engine. The objective then focused on modelling these heat exchangers within numerical models that were available and carryout performance testing to develop a heat exchanger design approach.

## 3. PERFORMANCE METRICS

Engine operation: Two test engines were significantly investigated throughout this research project. Extensive design and commissioning work were undertaken to ensure that the engines were running reliably. This included developing instrumentation and an engine management system for controlling the engine as it was run through a performance test. Significant work was also undertaken in developing a new set of heat exchangers the low temperature engine developed on better theory and modelling for predicting the performance of the heat exchanger and overall engine. The engines performed well and as expected.

Predictive model success: The predictive model generated results that were used with a high level of confidence. Part of the project was to develop a detailed understanding of factors that influence the performance of the model. These were important as they become significant design factors. Improving the performance of the model taking these factors into account was a major outcome of this.

Scale up factors: Scale up factors were identified through the second half the project as the predictive models were used to investigate large-scale devices. Identifying specific scaling factors that were important for the overall success of this technology also included design, manufacturing, and deployment/operation costs that will drive the overall economics of the system.

Reliability engine performance data: Extensive testing of all the experimental instrumentation and test facilities was undertaken throughout the project to ensure high level of confidence and reliability in the results collected. This work was ongoing throughout the whole project as sensors needed to be regularly calibrated.

## D. METHODOLOGY

**Please provide a narrative describing the methodology and facilities that were used to execute and complete the project. Use subheadings as appropriate.**

*RESPOND BELOW*

Stirling engine simulation using 1st and 3rd order models, CFD: Thermodynamic modelling of the Stirling engine was the ultimate goal for this research project as it allowed of the design of the engine and protection of the performance of the engine at different scales. Global modelling or 1st order modelling based on nondimensional parameters provided some guideline for the expected performance of the engine. More specific modelling that included losses in the system or 3rd order modelling of the thermodynamics of the Stirling engine provided much more detail. The development of this model was a major work task of the project which was coded in Matlab. While many of the parameters could be derived from the design of the engine or collected from experimental results, some were immediately unavailable. To overcome this computational fluid dynamic (CFD) modelling was also utilized to develop the design of heat exchangers as well is provided important fundamental parameters such as the convective heat transfer coefficient for the 3rd order model.

Modelling geothermal heat extraction: Model development was undertaken in Matlab. This model is sophisticated as it needs to take into account the multiphase, multicomponent nature of the flow as well as heat transfer and the two-dimensional nature of the physics. The model was developed in such a way that the model domain can be discretized as needed for spatial resolution or solution time management. Given the geometry, an oil well up to 3 km deep, no experimental data was collected during this research project to validate the model. Instead, validation of individual components of the model was made using available data, information and models within the literature.

CAD tools for modelling and design: Standard mechanical engineering computer aided design (CAD) tools (SOLIDWORKS) were used to develop the solid models of individual components and assemblies of the Stirling engine. This allowed complex and extensive design analysis to be undertaken as well is the development of manufacturing drawings. The solid models are also used as input into computer-aided manufacturing (CAM) software to develop tool parts used in CNC machines to build components. The development of the solid models also allowed sophisticated simulations to be carried out to determine stress (FEA), heat transfer and fluid flow (CFD) at various locations within the complete engine. The simulations were important for determining the overall geometry and performance of individual components and were crucial tools in developing the large-scale engine design. Thermal transport through the heat exchangers was extensively model that combined both heat transfer and fluid flow to determine the bottle neck in heat transfer. The simulations were important part in developing a heat exchanger design methodology.

Experimental heat transfer/flow measurements: Fundamental understanding of heat transfer within the heat exchanger by convection was an important research area within this project. A separate research facility that allowed investigation of the flow within an individual heat exchanger channel was constructed. A majority of this facility was constructed using 3-D printing which allowed complex geometries to be easily manufactured. This allowed measurement of flow velocity and fluid temperature using laser based imaging techniques. Particle image velocimetry (PIV) provide high-resolution two-dimensional datasets of the velocity field throughout the reciprocating cycle of the flow. Planar laser induced fluorescence (PLIF) a two-dimensional plane of the temperature of the fluid. Together, these datasets allow the determination of the local Nusselt number which is the ratio of convective to conductive heat transfer across a boundary. This parameter is used to evaluate different potential flow fields that could be induced to increased heat transfer. Using 3-D printing, the inlet flow conditions were changed with the introduction of swirlers that would induce axial vortices in the flow, increasing the advection away from the heat transfer surfaces. This fundamental investigation is ongoing.

Experimental instrumented test engine: The development of this facility was a major task carried out throughout this project. This required the design and construction of the Stirling engines, instrumentation of the engines, development of the data collection and online analysis software for engine management, development of input controls to the engine to allow engine operating conditions to be change throughout an experiment on the overall commissioning of the complete system. This instrumented test engine facility was used extensively throughout the research project providing extensive datasets to be used to validate and develop the 3$^{rd}$ order model.

## E. PROJECT RESULTS

**Please provide a narrative describing the key results using the project's milestones as sub-headings.**

- Describe the importance of the key results.
- Include a discussion of the project specific metrics and variances between expected and actual performance.

*RESPOND BELOW*

### 1. TASK # 1: LARGE SCALE LTDSE DESIGN AND BUILD

Design and assessment of the physically large-scale engine

The development of a large-scale low temperature difference Stirling engine prototype was started in August 2020. The main objectives for this machine were to collect an extensive range of experimental data for validation of the third order model (MSPM) and to serve as a proof of concept for a low temperature engine at a scale with meaningful power output.

All stages of development were carried out, starting with a broad analysis of all feasible engine configurations, with the requirement of a kinematic mechanism to define the motion of the pistons. The primary design goals were:

- Shaft power: 100 W at 0 atm charge pressure (10x increase over previous prototypes)
- Source / Sink temperatures: 95 °C / 5 °C to use water as the heat transfer medium
- Charge Pressure: Min. 0 – 3 atm, for model validation at varying conditions
- Compression Ratio: Adjustable, to find its optimum and use as a model validation parameter
- Heat Exchangers and Regenerator: modular and exchangeable, to validate model with different heat exchanger types
- Systematically eliminate power losses from mechanical and flow friction in heat exchangers, mechanism and seals informed by earlier experimental research

A 'beta' type configuration of the Stirling engine, as shown in Figure 1, was found to be best suited. This layout features both pistons moving inside of a shared cylinder working space on a shared axis, with the mechanism connected to the piston axis on one side of the working space. A different configuration may have been chosen if a non-kinematic engine (free piston / linear actuator) was the design goal. The figures below show the solid model of the full engine in Figure 1 in a cross-section of the engine showing internal components in Figure 2 taken at the latest design stage.

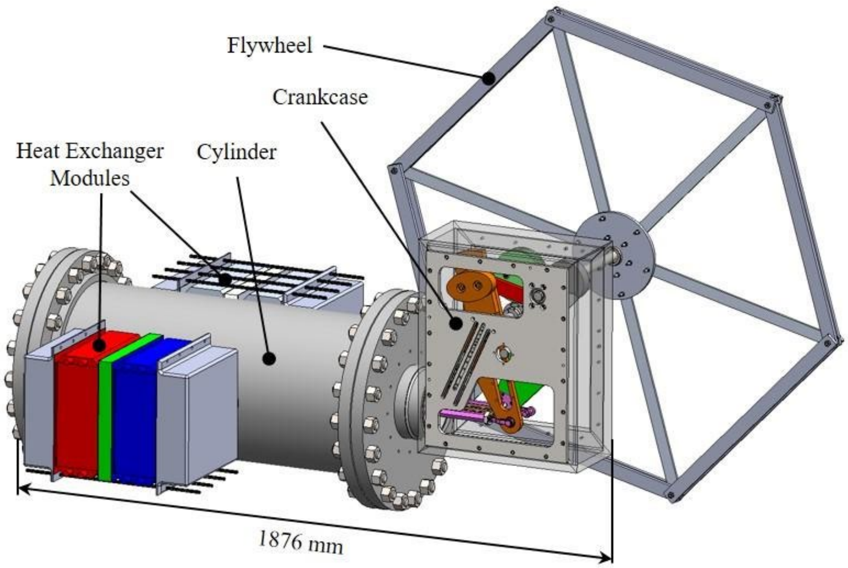



*Figure 1 A rendered images of the as-designed large-scale engine.*

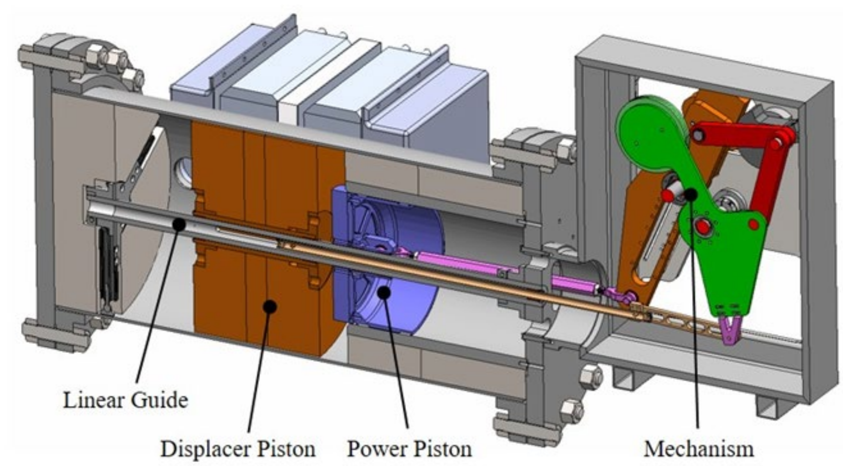



*Figure 2 A section view along piston axis of large-scale engine, showing features inside the cylinder and crankcase.*

The development process was documented in detail and comprised of the following main steps:

- Estimated size of engine volume to achieve power goal using analytical Schmidt model
- Verified performance and optimized heat exchangers using third order numerical model
- Developed multiple concepts for displacer piston, including foam, fiber-reinforced polymer, and metal, to achieve light weight and pressure resistance
- Studied heat exchanger types, developed modular heat exchangers assisted by correspondence and numerical simulations of manufacturer
- Developed novel mechanism linkage for compactness and ability to vary piston stroke

- Tested of rolling diaphragm as piston seal on small scale test rig
- Numerical stress analysis of all load bearing parts to determine shape and thickness
- Motion study on mechanism linkage to determine loads on bearings and shafts, size of flywheel
- Extensive consultation with manufacturers and suppliers to verify concepts, feasibility, manufacturability, materials, safety, component choice and design for all parts / sections
- Obtained feedback and quotes from several manufacturers for most engine sections

In September 2021, the design of the crankcase and mechanism was ready for production while the remaining sections required a few more months of work. Based on the quotes received, the overall cost for the engine including a support frame and instrumentation was estimated between $60,000 and $100,000 CAD. Through the design and development process, it was found that many components were required to be physically large in order to withstand the loads of an engine pressurized to the desired pressure. As a result of this cost estimate and the time left in the project, it was decided to discontinue development of the large-scale engine for a number of manufacturing, safety and economical reasons that were found to render the research value of a kinematic prototype at the given scale insufficient compared to cost and risks associated with it.

<u>Commissioning of the Raphael engine</u>

An important part of the redirection of the project to address the objective was the acquisition of a Stirling engine designed to run at low temperatures. This engine, designated the Raphael engine and pictured in Figure 3, consisted of the engine itself, support structures, data exposition system and a hot and cold temperature source. Upon delivery, the engine was set up so that it could be run through a commissioning phase to ensure the engine was operating properly within the design specifications of the engine.

An important consideration in choosing the Raphael engine to continue the research was that this engine was designed by a former graduate student who worked within this particular research program. They based the design of the engine on the first engine built within the research group, the high-temperature Stirling engine (HTSE), and use design principles developed within the research group to adjust the engine geometry with the aim to achieve better performance from a low-temperature heat source. The engine was also instrumented and included a engine monitoring and management software system that conformed with the approaches taken within the research group. Outputs from this engine were therefore compatible with the modelling approaches undertaken by the research group.

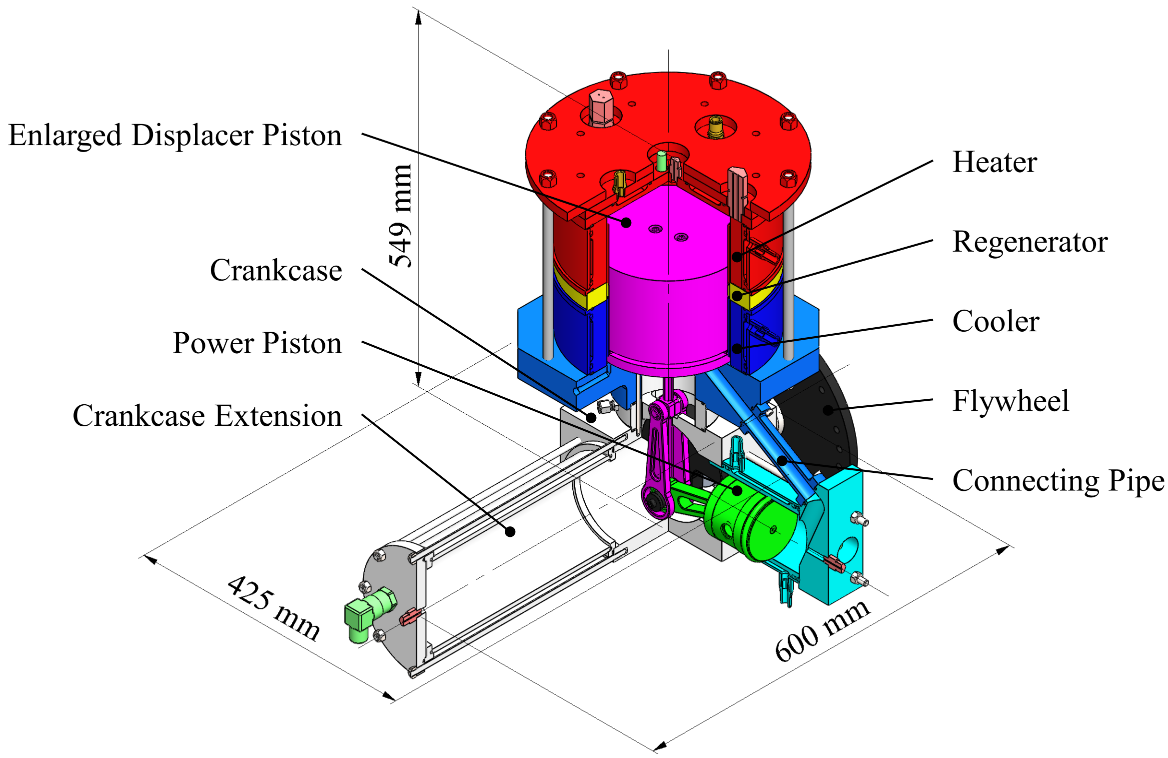



*Figure 3 An annotated section view of Raphael engine design.*

Shown in Figure 4, the experimental set-up consists of three main carts and an industrial chiller (the cold source). The main cart contains the engine, shaft power measurement system and pressure buffer tank. The instrumentation cart contains the data acquisition system, the magnetic brake control and the signal conditioner for the pressure transducers. The remaining cart houses the hot bath, cold liquid reservoir and air compressor. This Stirling engine uses dry compressed air as the working fluid. In a dedicated annular heat exchanger at the top of the displacer cylinder at the top of the engine, the compressed air is heated by a high-temperature oil that flows on the shell side of the heat exchanger. The silicone oil is heated and circulated through the heat exchanger via a hot bath. Similarly, air is cooled by a low-temperature mixture of water & ethylene glycol in another annular heat exchanger at the bottom of the displacer cylinder. The water-glycol cooling mixture is pumped from a reservoir cooled by a recirculating chiller. Measurements of temperature, pressure, crankshaft position, and torque are collected using a computer-controlled data acquisition system.

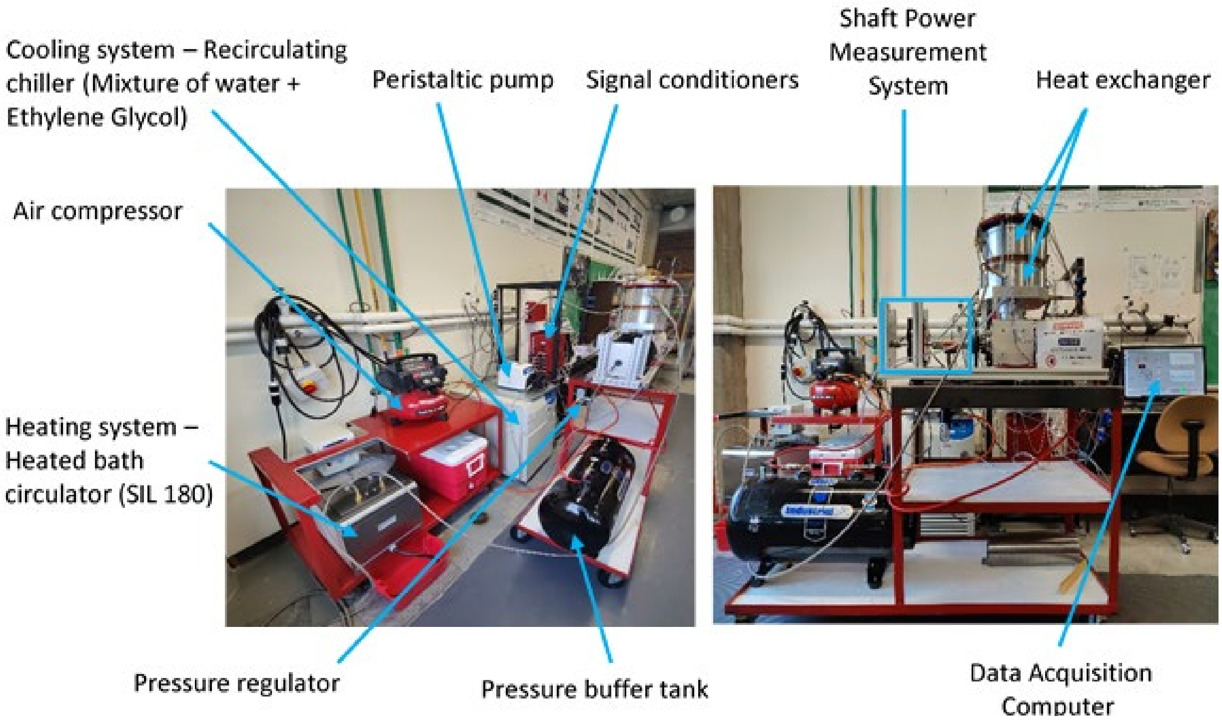



*Figure 4 Photos of the Raphael engine experimental set-up.*

The working fluid of the engine is supplied by an air compressor which feeds compressed air through a desiccant followed by a pressure regulator which allows for automated control of the pressure set-point in the engine. Following the pressure regulator, the dried and compressed air fills a buffer tank which is connected to the working space of the engine via an orifice. The buffer tank and orifice serve to isolate engine cyclic pressure changes from the air supply system and introduce pressurized air into the engine slowly. To extract shaft power, variable loads from the magnetic brake are numerically defined and applied to the engine. The temperature measurement system consists of type T thermocouples (to measure gas temperature) and resistance temperature detectors (to measure liquid temperature). The pressure measurement system includes both static and dynamic pressure transducers. The power measurement system, shown in Figure 5, consists of a torque transducer to determine the dynamic torque, a magnetic brake to apply a constant torque, and a rotary encoder to measure the crankshaft angle.

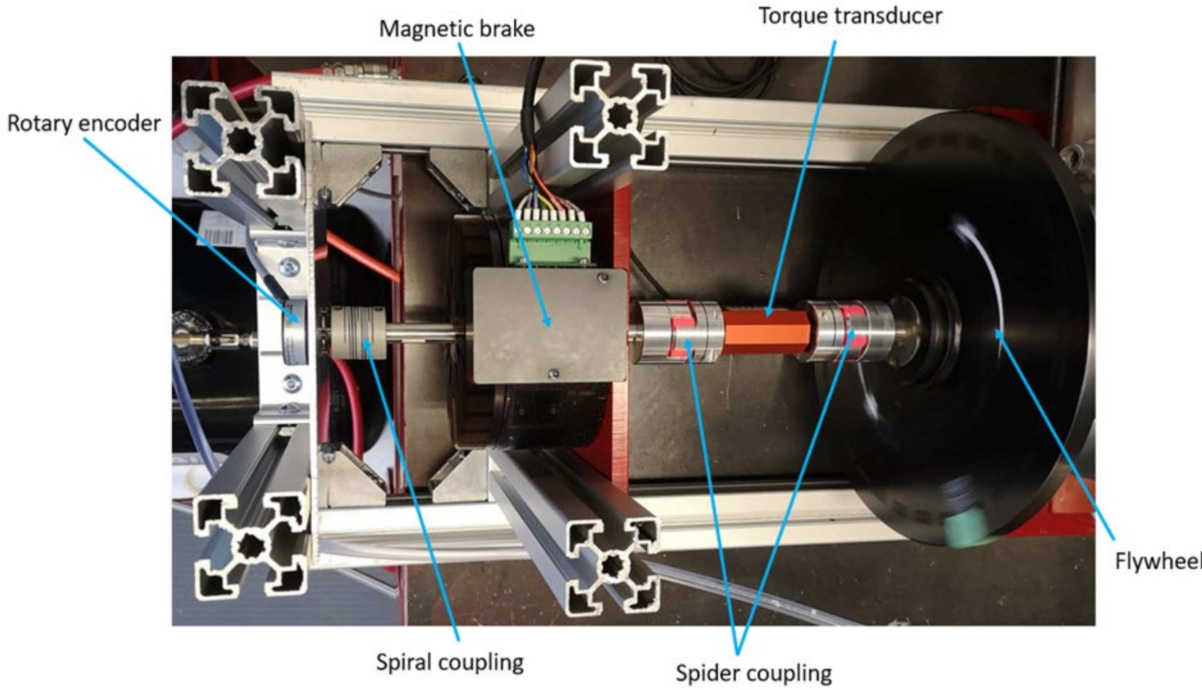



*Figure 5 Photo of shaft power measurement system.*

Raphael baseline data collection

After calibration of the sensors the engine was run for data collection at a source temperature of 150 °C and sink temperature of 5 °C, with a test at one pressure taking up to 8 hours to complete. From the measured data it is possible to calculate the indicated work of the cycle from the pressure transducer and crank angle information. The indicated work against engine speed for varying engine pressures is shown in Figure 6. This data was used for validation of both the Sage and MSPM Raphael models.

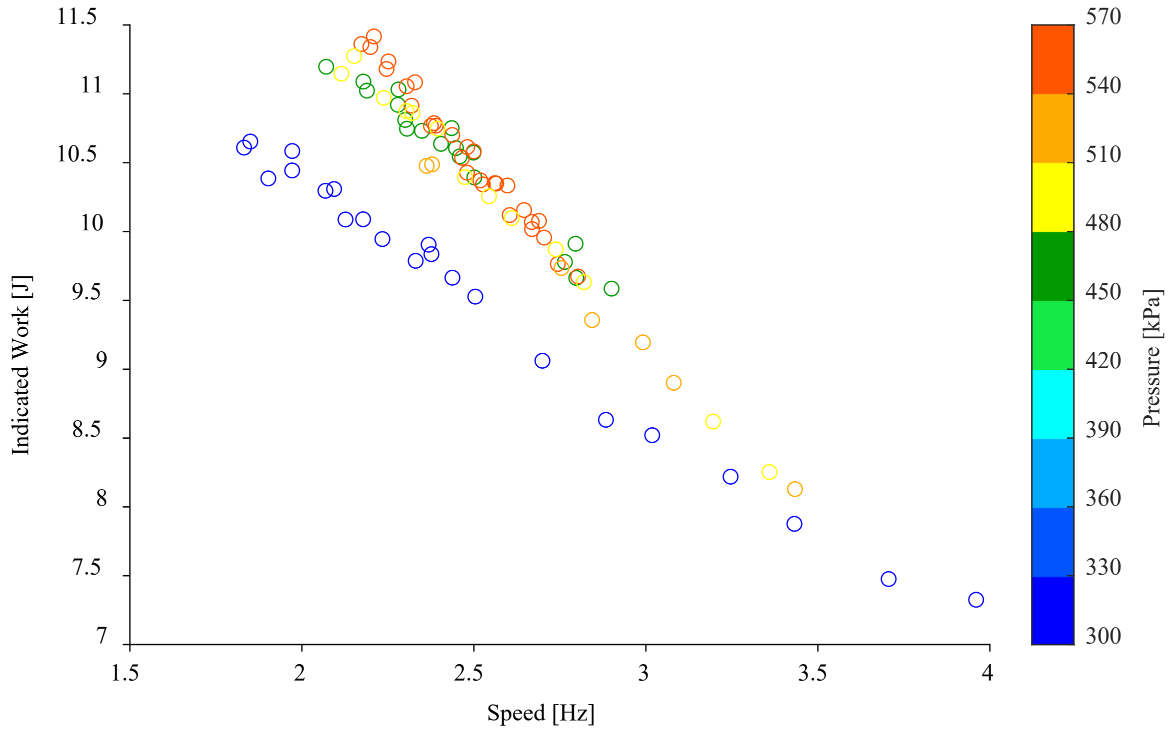



*Figure 6 Plot of baseline experimental data collected from Raphael engine after commissioning; indicated work plotted against engine speed for varying engine pressures.*

New Raphael Heat Exchanger Design and Commissioning

These baseline tests identified a bottleneck of energy exchange in the heat exchangers of the engine, with the increased pressure cases all having similar performance. This indicated that improving heat transfer in the heat exchangers would improve the engine performance. A new heat exchanger for the Raphael engine was designed using parametric Computational Fluid Dynamics (CFD) analysis to evaluate the effect of various geometric changes on the heat exchanger performance.

The air side fin geometry was changed, with varying width, length, and fin density (or gap between fins). The CFD results were used to determine the achieved gas temperatures, which were then inputted into a 1$^{st}$ order Schmidt model to determine the work output. The work due to flow friction was then subtracted in order to determine the net work. The net work was plotted for a range of fin widths and fin gaps as shown in Figure 7, and the optimum was found to occur at a fin gap of 0.75mm and a fin thickness of 1.25mm.

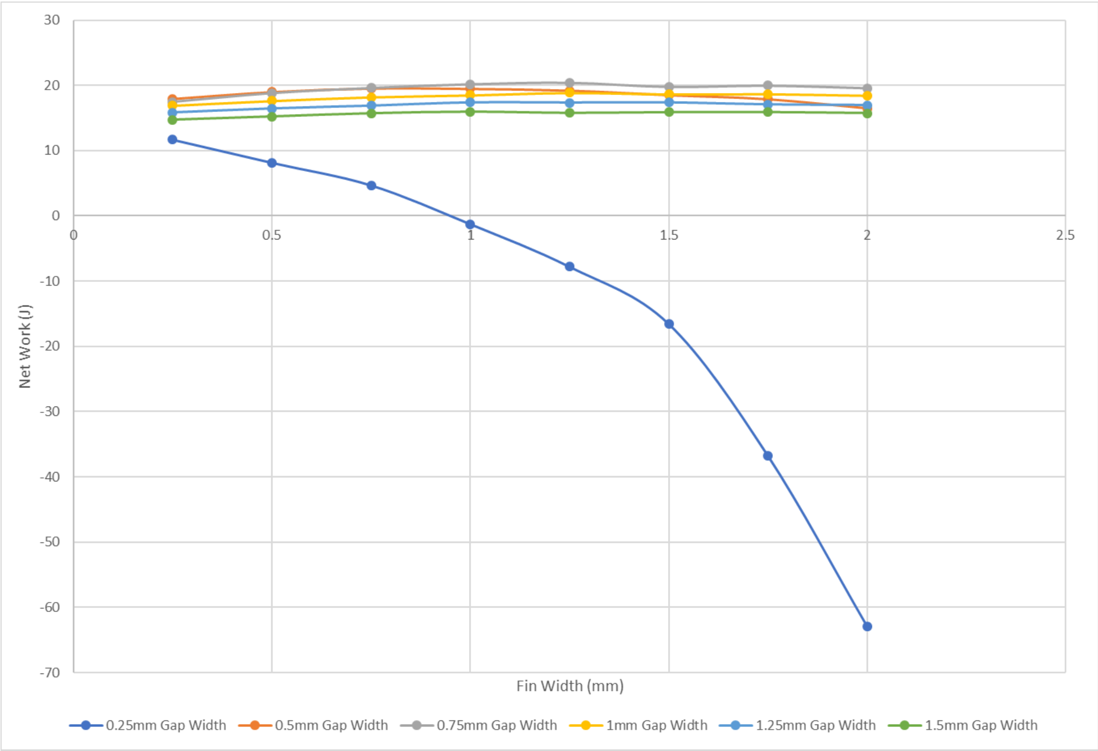



*Figure 7 Net work against fin width for various fin gap widths.*

The optimal fin length was determined using the same procedure, and it was found to be very similar to the existing fin length at 22mm as opposed to 20mm. The decision was made to keep the same fin length for simplicity.

In addition to modifying the design of the air side fins of the heat exchanger, the liquid side of the heat exchanger was modified. The existing heat exchanger had a liquid channel that had a low surface area which limited the amount of heat transferred to the engine. Liquid side fins were added in the annular channel to increase the surface area and improve the heat transfer, which can be seen in Figure 8.

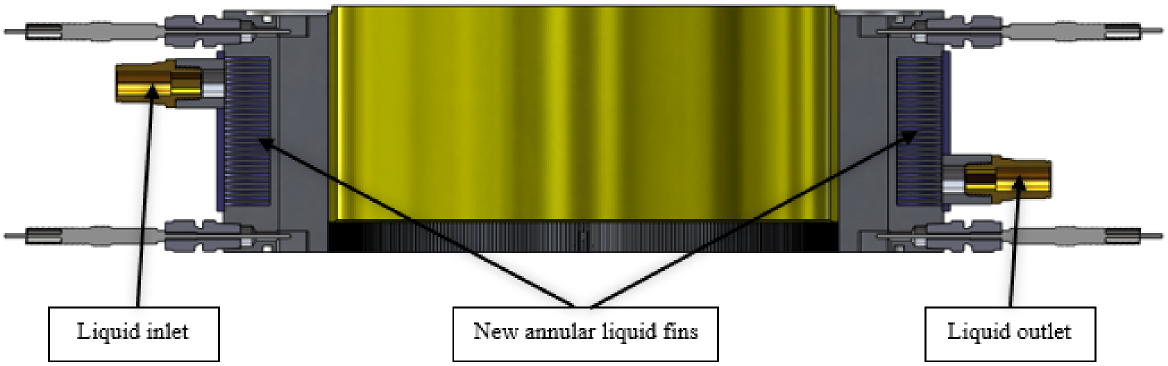



*Figure 8 Solid model section view showing the new addition to the design of liquid annular fins.*

The top plate of the engine was also redesigned. The top plate has a liquid jacket which heats the top plate – fins were added to this channel in order to increase the surface area. In addition, radial fins were added on the air side of the top plate to increase the surface area of this heating component, and allow the displacer piston to come closer to the heating plate, decreasing the dead volume. The solid model of the redesigned top plate for both the air and liquid side can be seen in Figure 9.

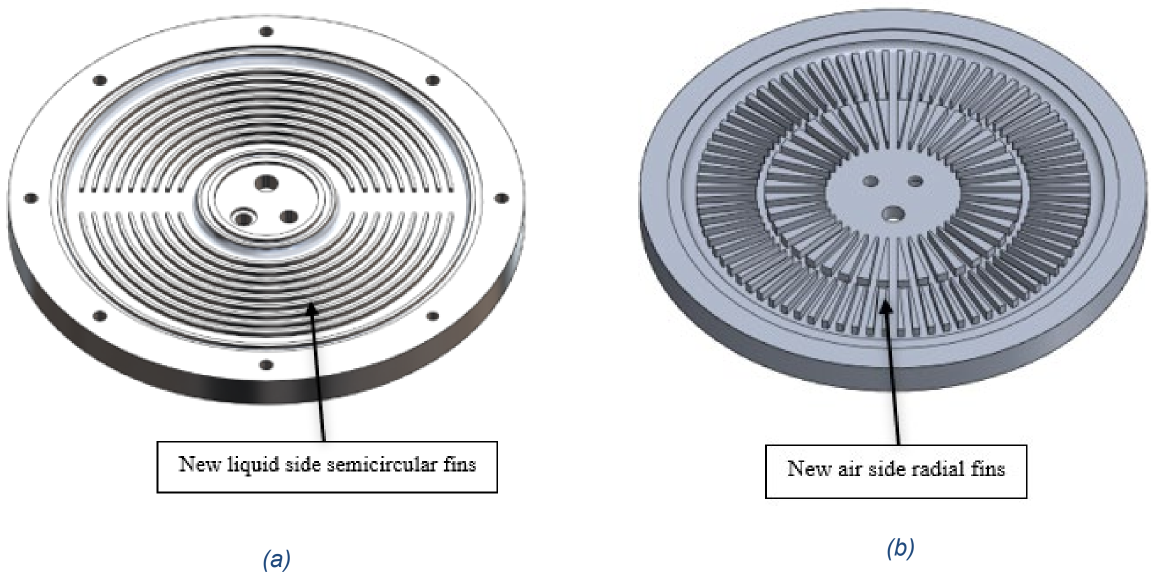
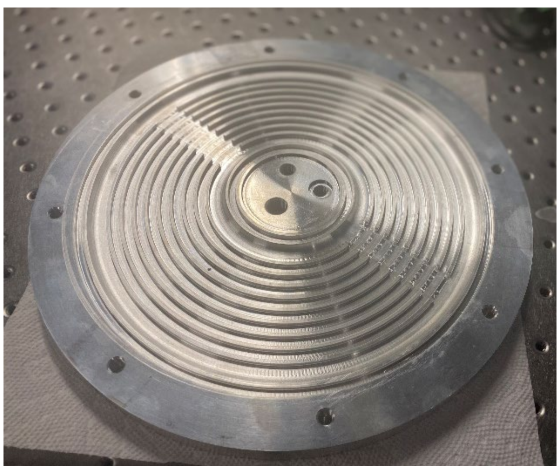


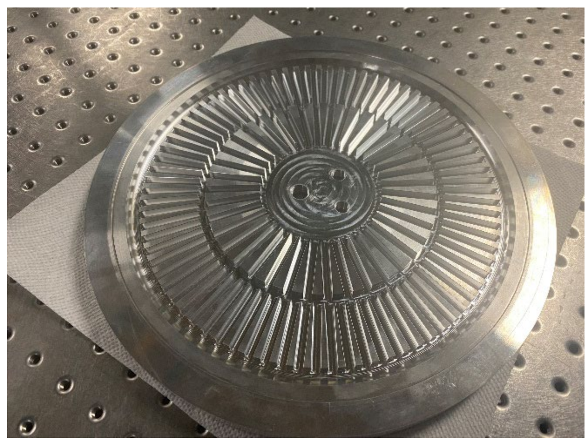

*Figure 9 Solid model of top plate (a) liquid side and (b) air side*

The design analysis culminated with the generation of a design drawing package. This was used to guide the manufacturing of the heat exchangers in the manufacturing workshop of the Department of Mechanical Engineering at the University of Alberta. The available advanced CNC machine tools such as the 5-axis HASS and wire EDM (a total of 1 week of machining) allowed the sophisticated geometry of the heat exchangers to be built efficiently. Two heat exchangers and the top plate were manufactured. The as-built heat exchangers and top plate are shown in Figure 10.

*(a)*



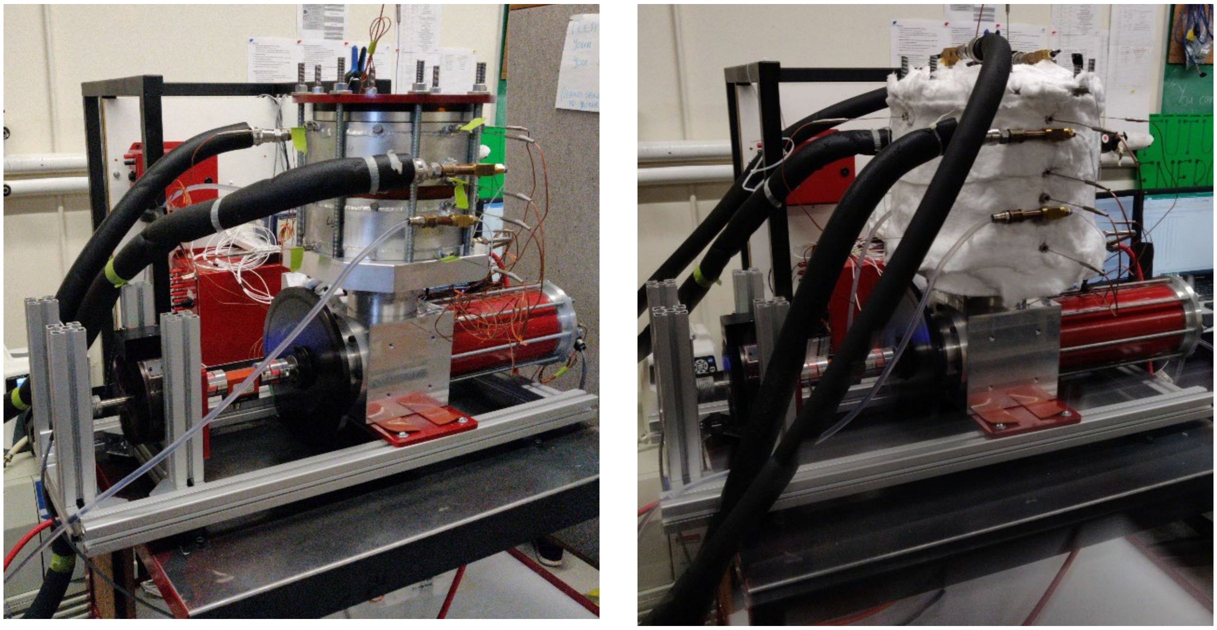
*(b)*



*(c)*

*Figure 10 Images of as-built (a) redesigned heat exchanger, (b) liquid side top plate and (c) air side top plate.*

The engine was reassembled with the new heat exchangers and either the existing or newly manufactured top plate as photographed in Figure 11, and fiberglass insulation was added around the heat exchangers to minimize thermal loss to the environment.



*(a)* *(b)*

*Figure 11 Image of (a) engine assembled with new heat exchangers and (b) assembled with added insulation.*

Heat exchanger performance characterization

Through the model validation of the baseline experimental tests, the need to quantify the heat exchanger performance was identified to allow the generation of performance parameters that can be input into the MSPM and Sage $3^{rd}$ order models. A steady state flow setup was, therefore, designed and manufactured that was able to quantify the heat exchanger performance. This setup blows air through a heat exchanger and measures the temperature and pressure at the inlet and outlet as well as the liquid temperatures. Those parameters were used to calculate the key heat exchanger performance metrics, namely, the heat transfer coefficient and pressure drop. The solid model of the setup and the as-built setup are shown in Figure 12 and Figure 13 respectively.

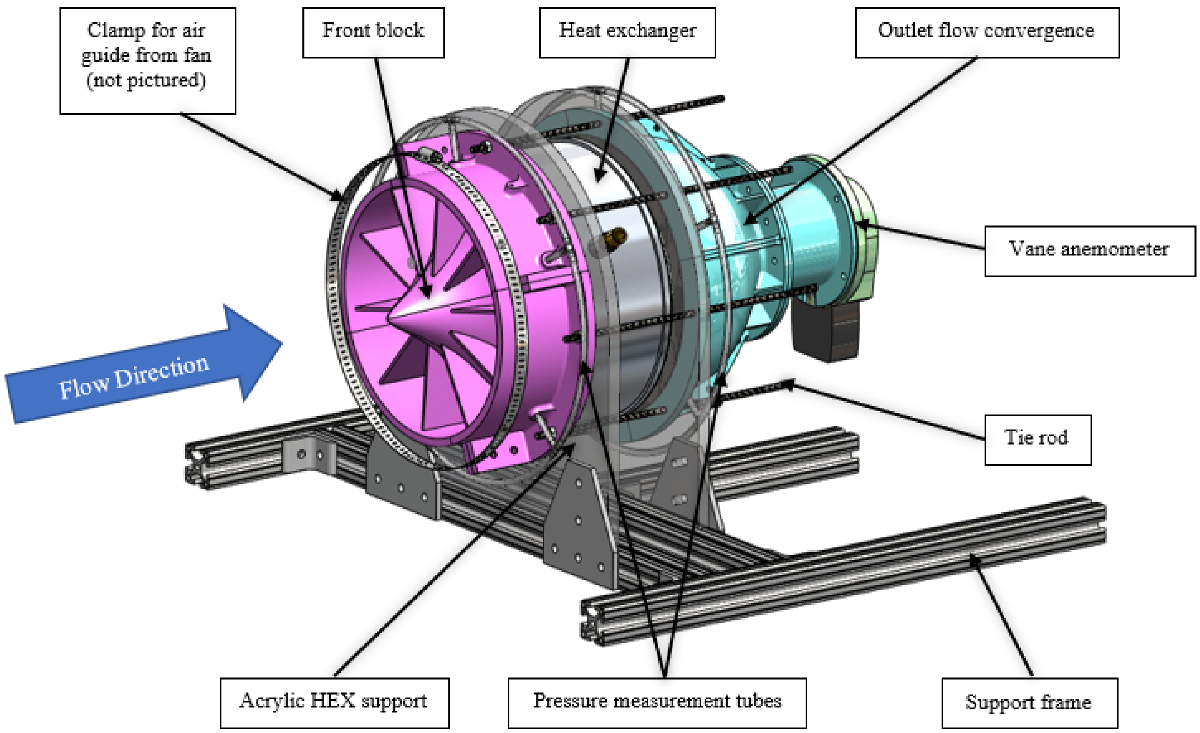



*Figure 12 Solid model of steady state flow setup for heat exchanger performance characterization.*

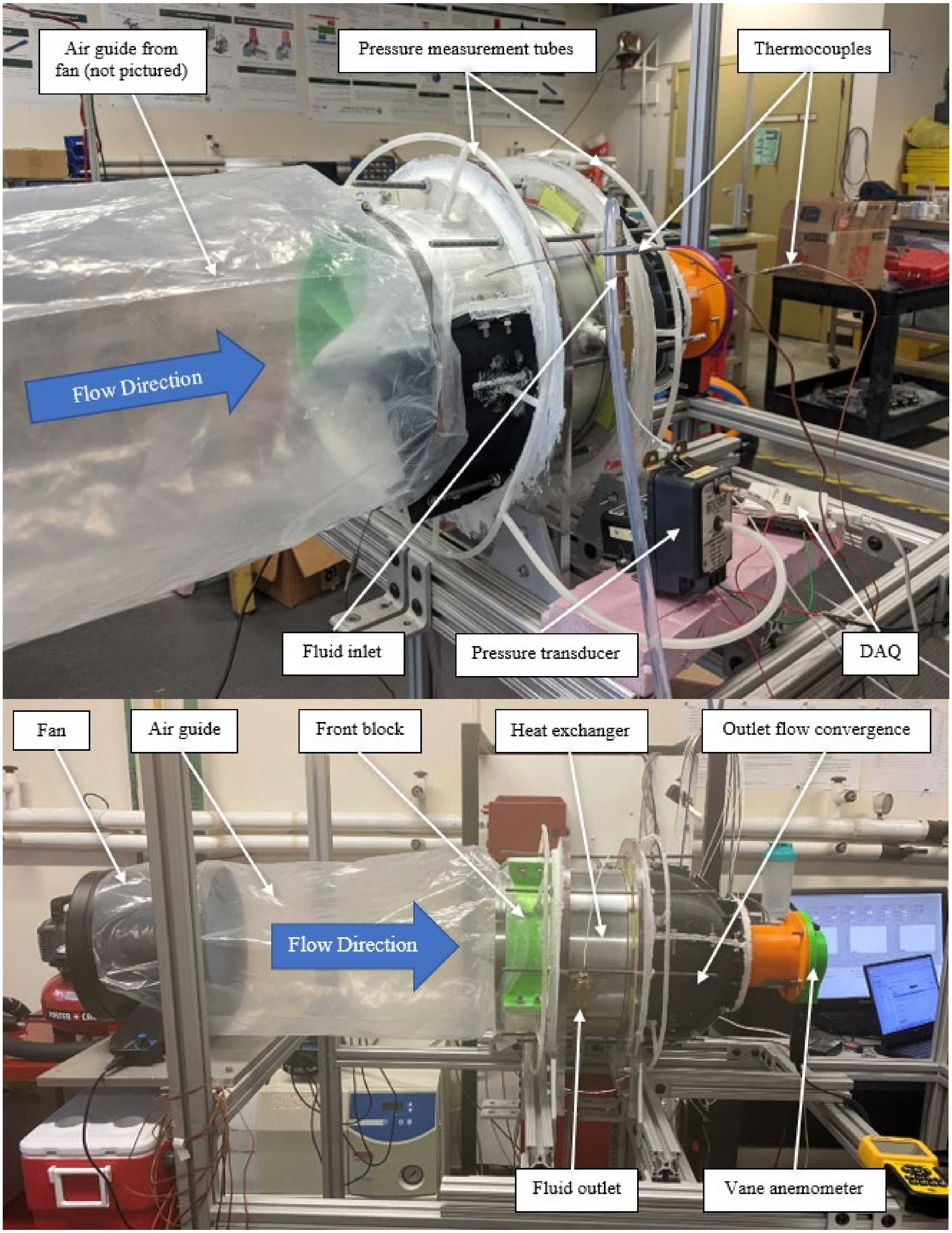



*Figure 13 Images of as-built steady state flow setup.*

To characterize the heat exchanger performance from this setup, the measured temperature and air speed data was used to calculate the non-dimensional Nusselt number (Nu) and Reynolds number (Re). The Nusselt number is the ratio of convective heat transfer to conductive heat transfer, and a higher value indicates improved heat transfer as compared to only conduction. The Reynolds number is the ratio of inertial viscous forces in a fluid, where a lower number indicates laminar flow. The Nusselt number of the various heat exchangers is plotted against the Reynolds number of the air flow in Figure 14. The plot shows that the new heat exchangers have higher Nusselt numbers than the old heat exchangers for both the heating and cooling conditions, which verifies that the heat transfer performance is improved for the new design.

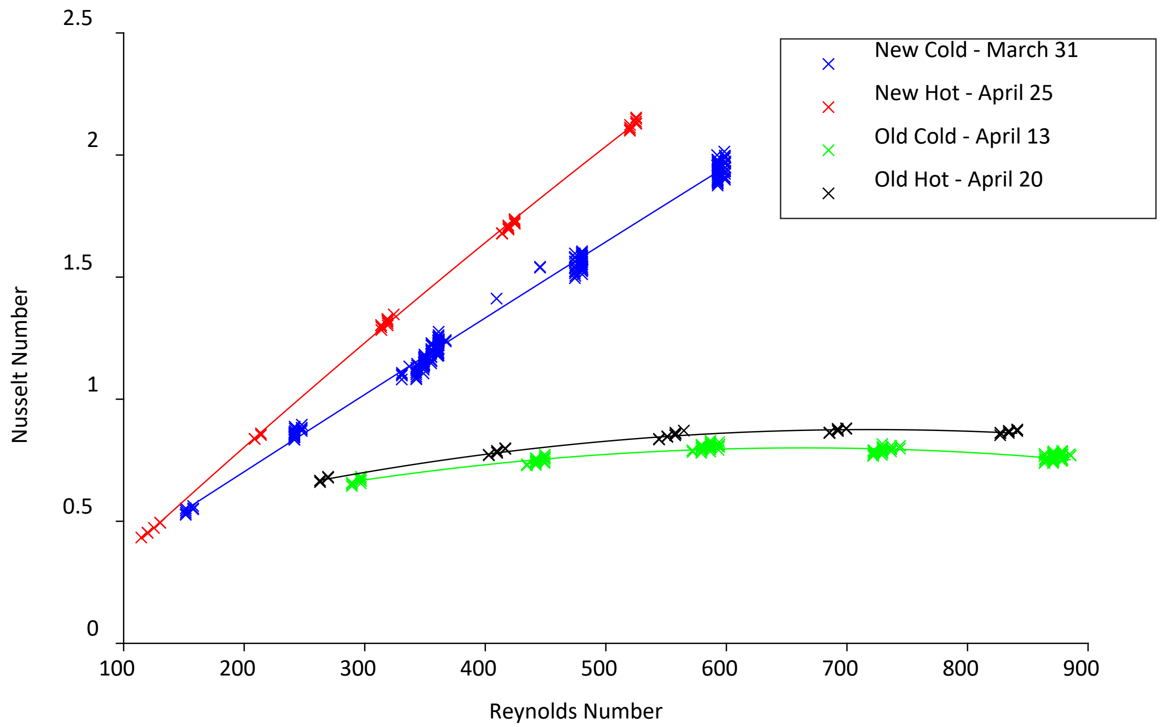



*Figure 14 Plot of Nusselt number Vs Reynolds number for different heat exchangers at hot and cold temperatures.*

To investigate the effect of the new heat exchangers on the engine performance, the engine was run with both sets of heat exchangers with the original flat top plate at varying pressures and engine speeds with a source temperature of 130 °C and a sink temperature of 5 °C. The engine was run at a lower source temperature as the heater baths were unable to provide sufficient heat input to the engine. The pressure and crank angle measurements were used to obtain the indicated work which is plotted against engine speed for the various pressures in Figure 15. There is a very clear delineation between the work output of the new heat exchangers compared to the old heat exchangers, with up to a 200% increase in the work output per cycle. In addition, the new heat exchangers show a trend of increasing work output per cycle with increasing engine pressure, which is not the case with the old heat exchangers are they are unable to provide sufficient thermal input to the increased mass of gas due to their poorer heat transfer.

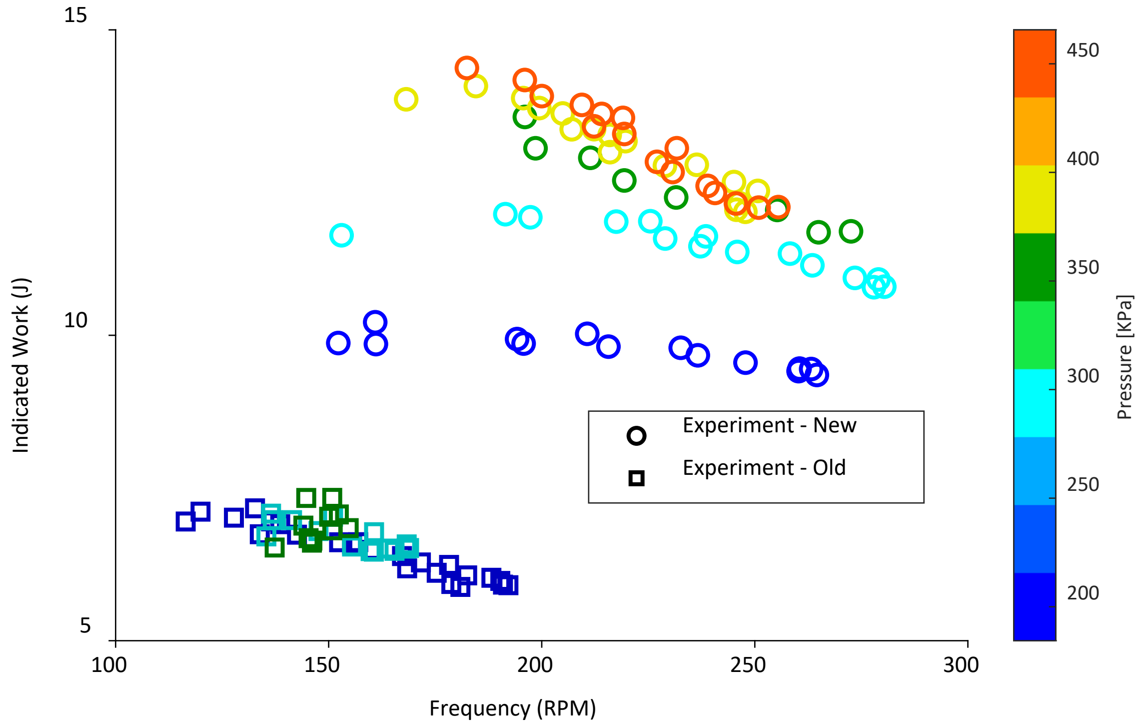



*Figure 15 Plot of experimental indicated work vs engine speed for varying engine pressures for both old and new heat exchanger designs.*

The increase in work output is primarily a result of the improved heat transfer leading to higher gas temperatures in the expansion side of the engine. This can be seen in the plot of gas temperature in the engine spaces for varying engine pressures at maximum power and maximum speed (free-running) conditions in Figure 16. The new heat exchangers in the hot space have up to a nearly 20 °C increase in gas temperature in the expansion space as compared to the old heat exchangers.

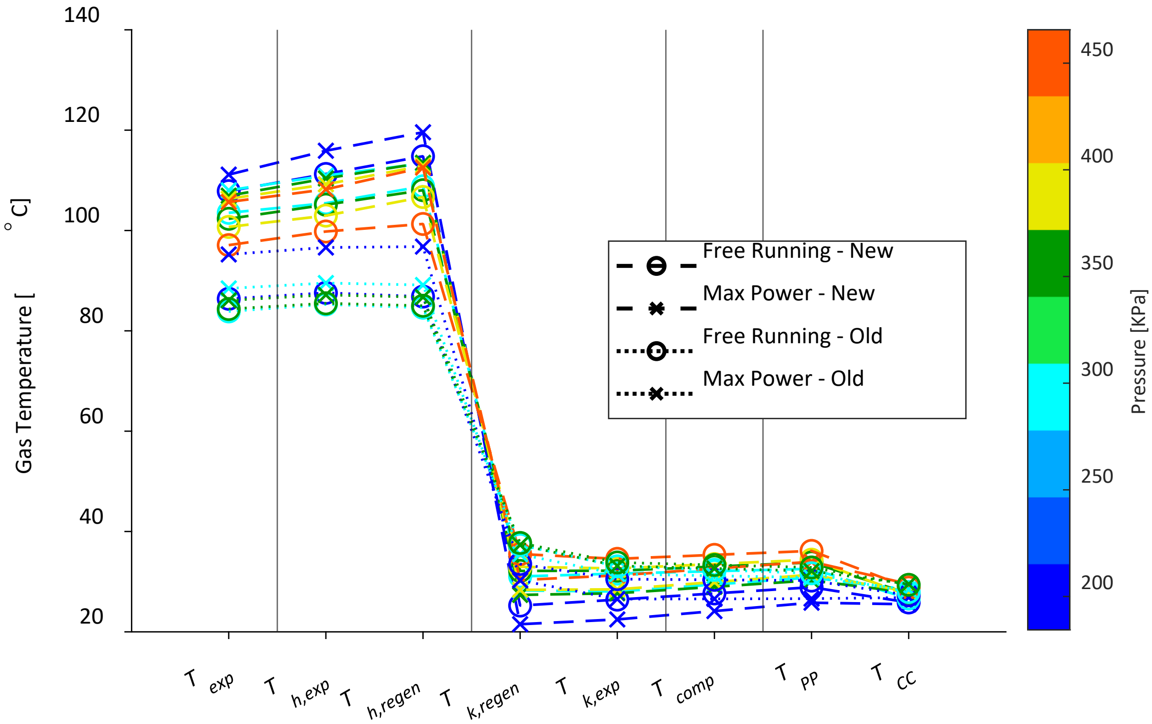
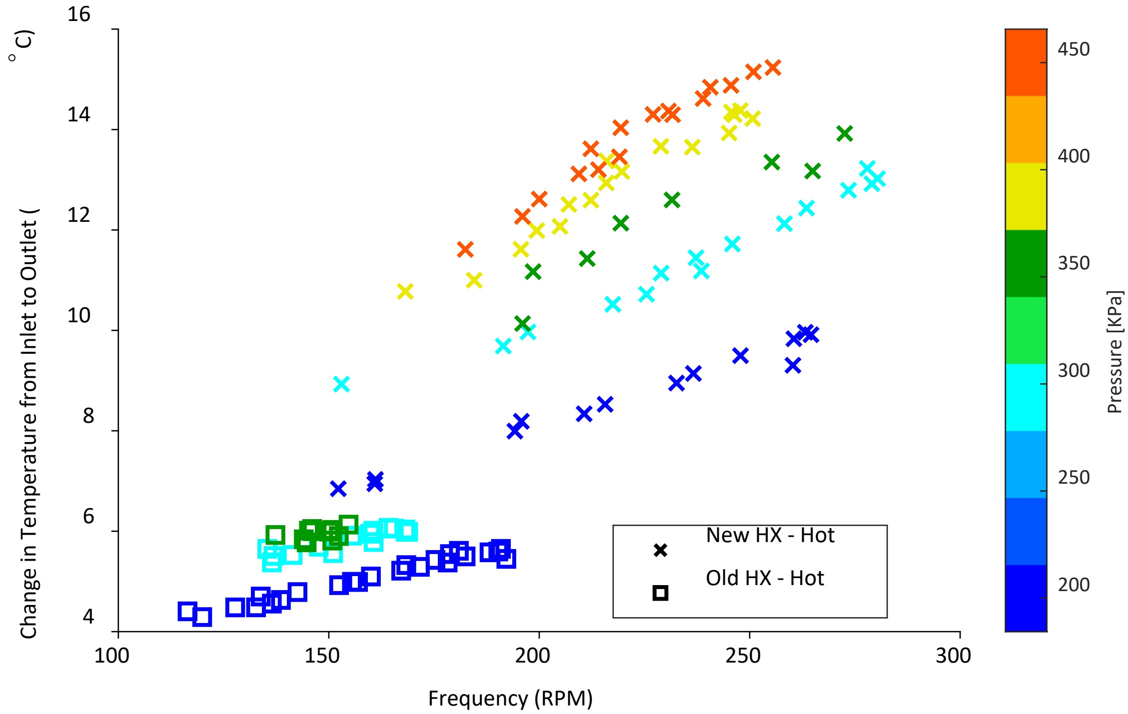
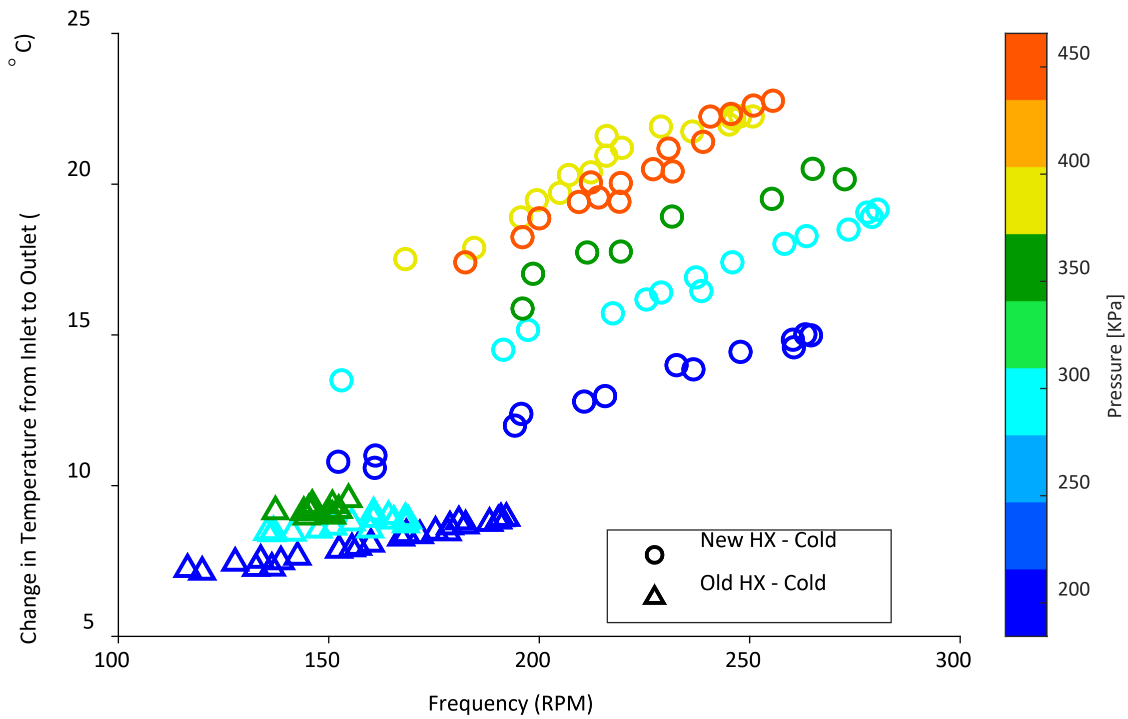



*Figure 16 Plot of measured gas temperatures for each engine space for old and new heat exchangers at both free-running and maximum power conditions.*

The primary reason for the improved gas temperatures and engine performance is the increase in heat transfer from the liquid side of the heat exchangers to the working space due to the increased surface area from the liquid side fins. This can be seen in a plot of the difference in temperature from the liquid outlet to the liquid inlet for varying engine speeds and pressure for the new and old heat exchangers, shown in Figure 17. In all operating conditions the temperature change across the liquid inlet and outlets of the heat exchangers are higher, indicating greater heat transfer rate from the liquid to the solid material of the heat exchangers. The result aligned with the expectations generated from the model verification, highlighting the usefulness of the models for predicting engine performance.




*(a)*




*(b)*

*Figure 17 Plot of difference in inlet and outlet liquid temperatures for the (a) hot and (b) cold side new and old heat exchangers for varying engine speeds and engine pressures.*

The above results do not include the finned heated displacer top plate. A shortened test was run at 350 kPa charge pressure and a source temperature of 150 °C and sink temperature of 5 °C to determine the maximum output power of the engine. This test yielded a maximum shaft power output of 29.56 W, which is a new record for the Raphael engine, and an almost double increase in power output compared to the old heat exchangers. These results strongly indicate that improving the heat transfer into the engine is crucial to improving the performance of low temperature Stirling engines.

## 2. TASK # 2: THERMO-FLUIDS OF RECIPROCATING SYSTEMS

A custom experiment was designed to investigate the physics of the heat and fluid flow of a reciprocating flow and enhance the heat transfer of the heat exchanger. A render image of the solid model of the fluid test rig, which was designed to conduct the experiments, is shown in Figure 18. Based on the designed solid model, the fluid test rig was fabricated mainly by using an SLA 3D printer. Figure 19 shows this fabricated fluid test rig alongside the optical measurement system which has been developed to apply particle image velocimetry (PIV) and planar laser induced-fluorescence (PLIF). Using PIV and PLIF, the velocity and temperature are measured, respectively. This allows the determination of important heat transfer parameters such as the Nusselt number and convective heat transfer coefficient for a reciprocating flow, something that is not reported in the literature. These are both important for use as input parameters into the MSPM and Sage 3rd order models. As can be seen in Figure 19 the measurements are done at the test section which is connected to the heat exchanger. An example of the velocity measurement is shown in Figure 20 showing the velocity evolution of the reciprocating flow at different phases.

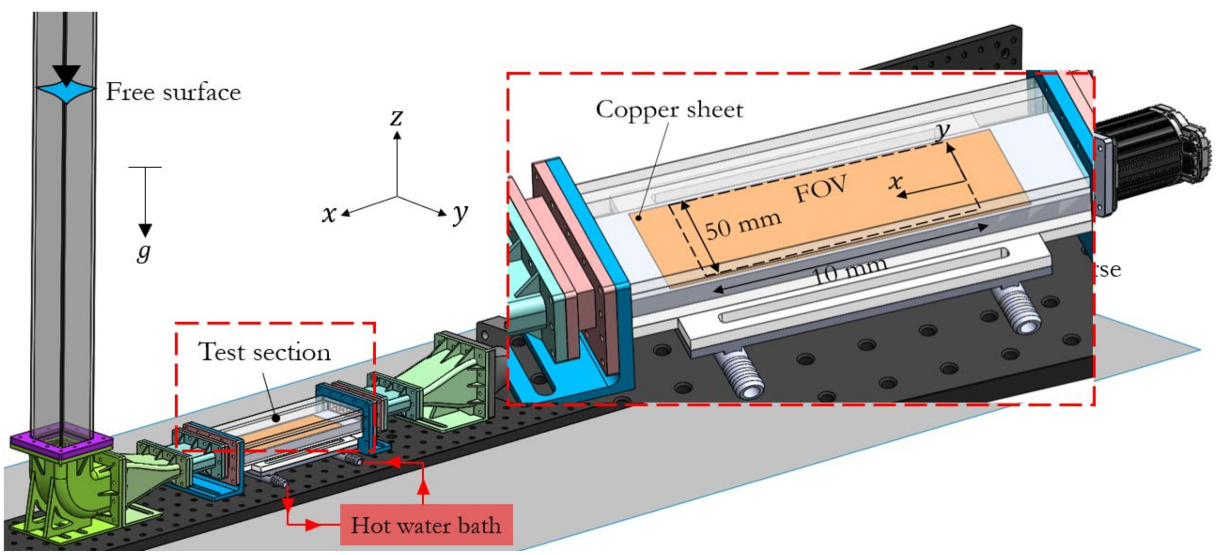



*Figure 18 Render of the fluid test rig design to generate the reciprocating flow.*

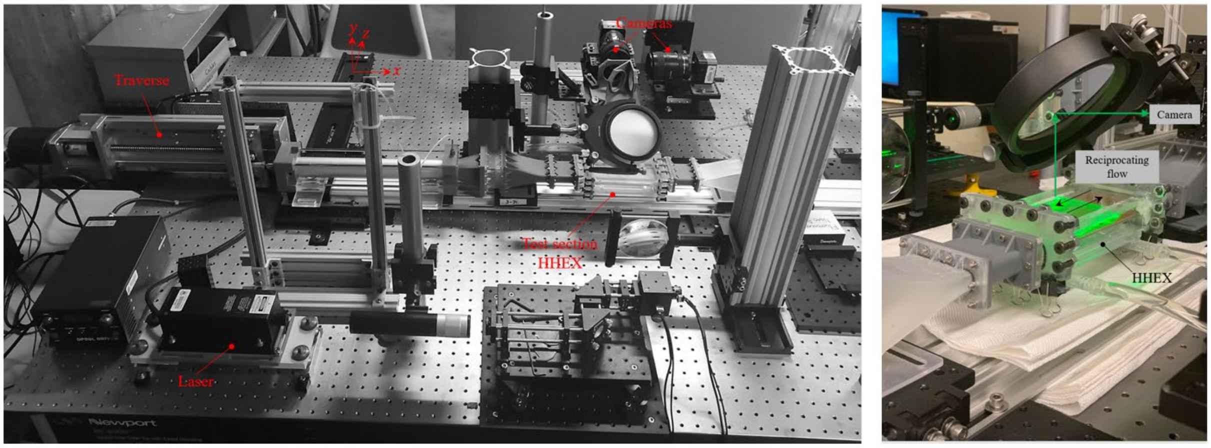



*Figure 19 (Left) Fabricated fluid test rig along the integrated optical measurement system used to apply PIV for velocity measurement and PLIF for temperature measurement. (Right) Zoomed view of the test section connected to the hot heat exchanger.*

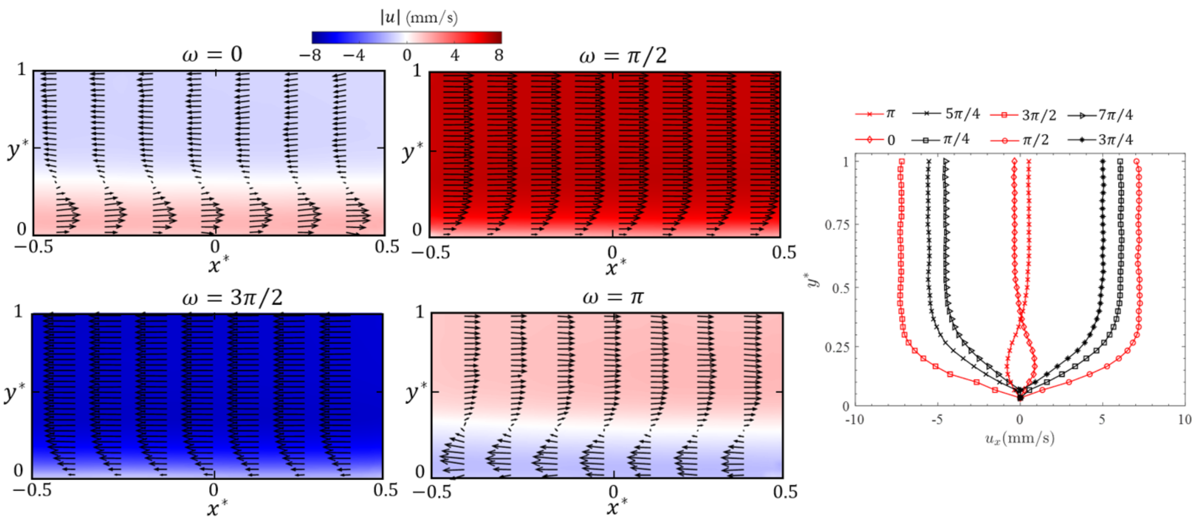



*Figure 20 (Left) Velocity field of a reciprocating flow at four different phases of a complete reciprocation motion. (Right) Velocity profile along the $y^*$ axis at eight different phases.*

To calculate the Nusselt number, which is an essential parameter for validation of numerical simulation with MSPM and Sage 3rd order models, measurement of the temperature in the fluid field is required. While in experimental works, usually the measurement of the temperature is feasible at limited number of points in the measurement domain, applying PLIF provides measurement of the temperature field of the whole flow field. This temperature measurement technique is also a non-intrusive technique, i.e., it does not affect neither the physics of the flow nor the heat transfer. For this experiment, Figure 21 illustrates the optical measurement used to apply two-colour two-dye PLIF which is a highly sensitive form of the conventional PLIF. An example of the temperature field captured using this method is shown in Figure 22. This highlights thermal plumes rising up through the light sheet.

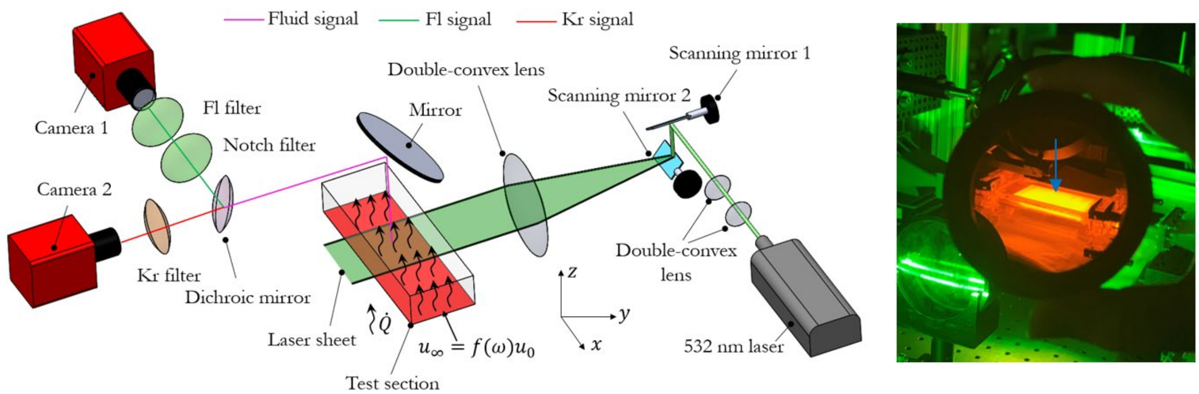



*Figure 21 (Left) Schematic of the optical measurement system designed to apply two-colour two-dye PLIF to measure the temperature field of the flow over the heat exchanger at different depth of the test section. (Right) An image of the test section during the temperature measurement by applying two-colour two-dye PLIF; The arrow indicated the direction of the temperature measurement.*

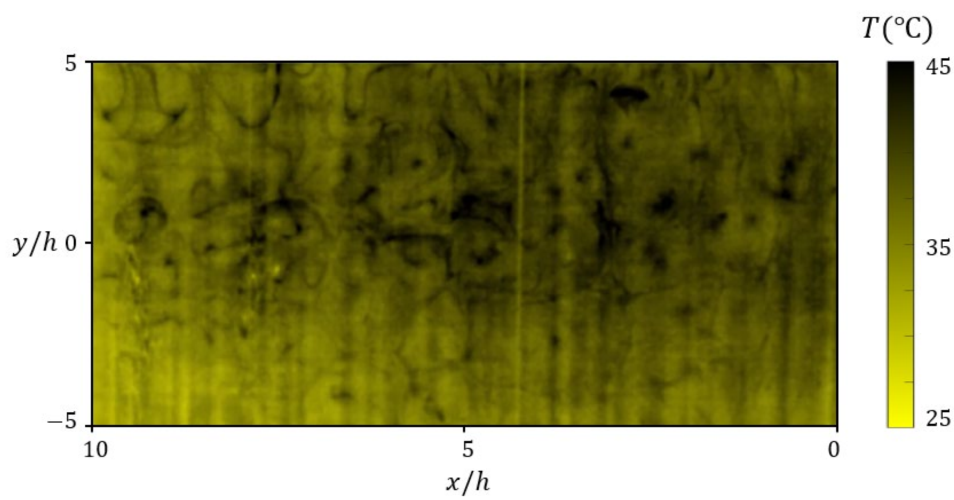



*Figure 22 Temperature field at the top of the test section above the heat exchanger.*

## 3. TASK # 3: DEVELOPMENT OF 3RD ORDER MODEL FOR LTDSE

Development of MSPM

The Modular Single Phase Model (MSPM) is a third order numerical model in MATLAB that was developed for Stirling engines by Steven Middleton until his MSc graduation in April 2021. It models single-phase fluid flow and heat conduction in any reciprocating thermodynamic machine. In the simplest case, the solver iterates to steady state, which is the state that any machine will reach once operating conditions no longer change over time. The code has been tested extensively to be stable in steady state simulations. It can also model dynamic conditions, i.e. changing conditions between engine cycles (transient) and varying engine speed during the cycle (quasi-steady), which needs further testing.

The model is two-dimensional by assuming radial symmetry and as such, all components of a modeled machine are cylindrical or annular. It has a graphical user interface and is developed specifically to predict losses present in low temperature machines. This makes it distinct from existing models by being more user friendly and open-source code. Thus, it is comprehensible and modifiable to improve its accuracy based on experimental data. It has potential to be published as a tool for researchers when validated and debugged for reliability.

Its author validated some results of MSPM with the atmospheric pressure engine the group was operating at the time (the EP-1 engine). Data from the Raphael was then used to carry out in-depth validation. Compared to 'EP-1' this engine operates at a range of 0 to 5 atm charge pressure, higher temperature difference and a wider range of speeds. It also has a different heat exchanger type, which allows it to generate data at a large number of different operating points for a broad model validation. Figure 23 below shows the representation of the Raphael engine in the model's GUI interface.

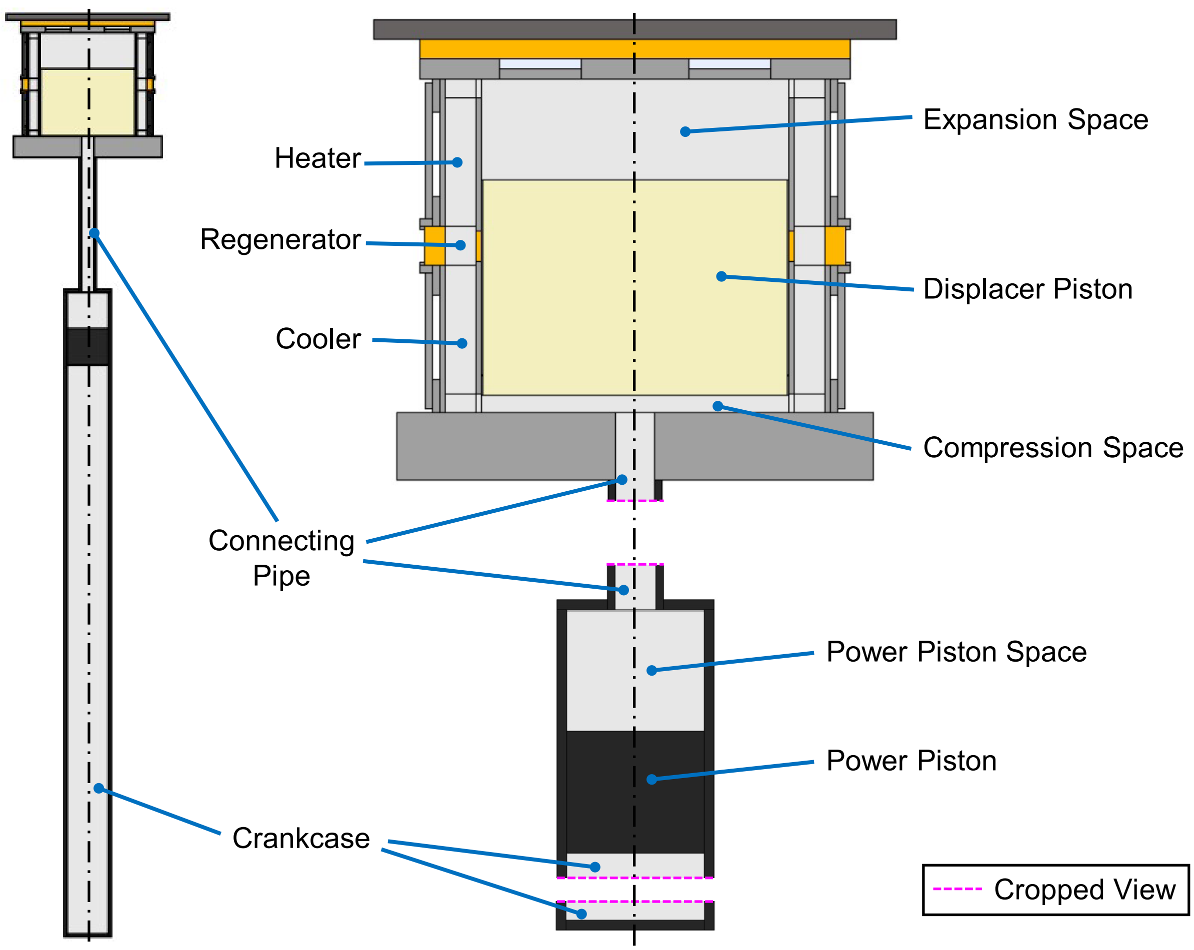



*Figure 23 Model of Raphael engine rendered in MSPM. Left: full model, center: enlarged view long sections cropped. Symmetry axis at center.*

The MSPM model code has been reviewed and some improvements and corrections implemented. Some errors were corrected that improved the thermodynamic predictions of the model. Heat transfer limitations at the heat source and sink were implemented as a manually defined heat transfer coefficient, since there was a lack in available representation of the limitations. This manually defined heat transfer coefficient was applied in the validation and found to be a significant factor for the accuracy of results. Visualization of the numerical node network (mesh) was improved, shown in Figure 24. This greatly aids the modeling process especially for more complex model geometries. The model GUI was also further improved, and the ability for model runs to be parallelized was added.

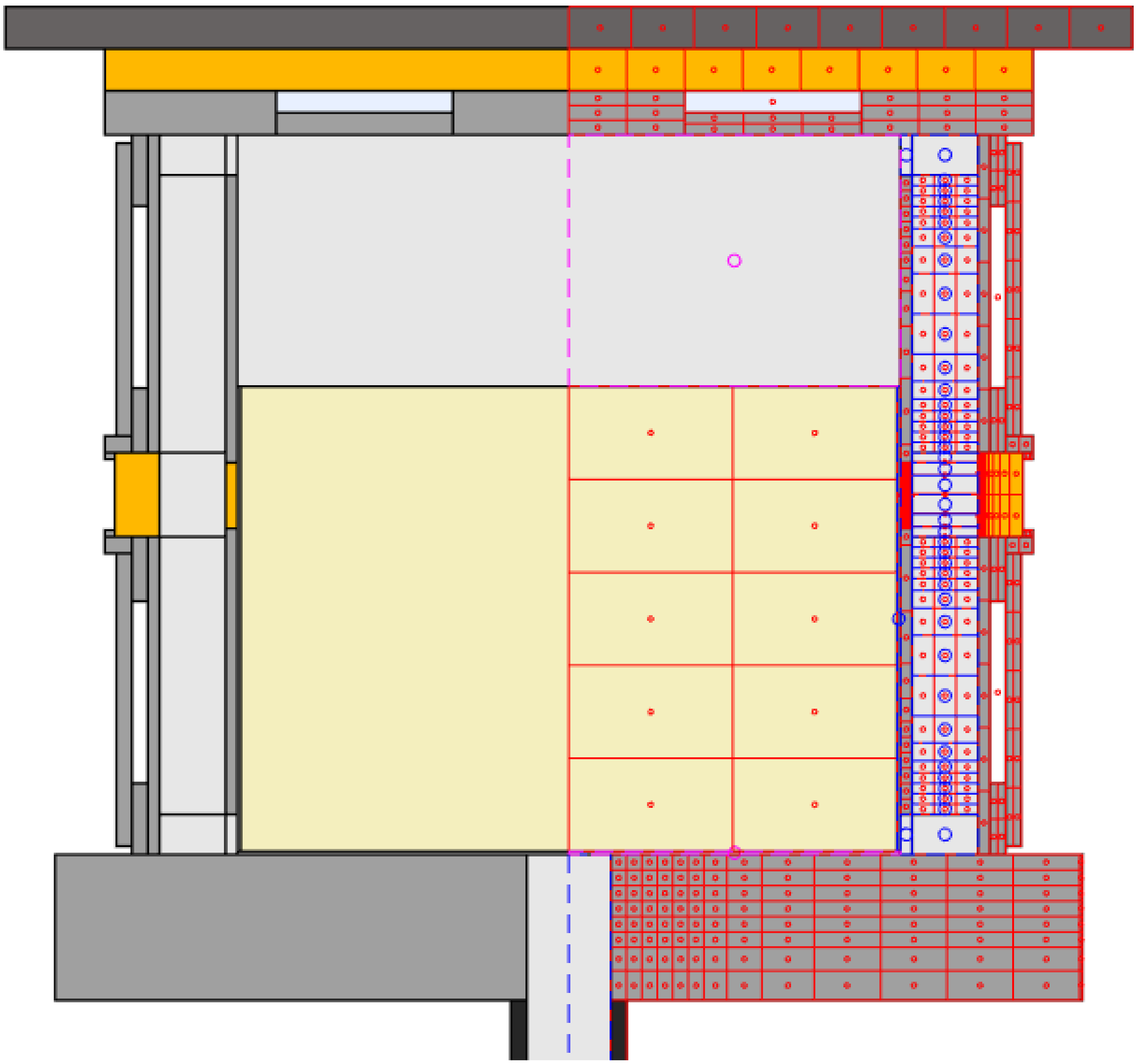


*Figure 24 Numerical mesh model of 'Raphael' as rendered by MSPM. Showing centers and bounds of gas and solid nodes.*

The experimental validation against the base Raphael data identified two model input parameters that significantly influence model predictions, yet are difficult to measure experimentally: the heat transfer at the heat source/sink and the leakage of the piston seals. The heat transfer at the heat/source sink was determined from analytical estimates as well as the CFD study of the heat exchanger performance. Four model variants (A, B, C, D) were tested that differed in these parameters. Figure 25 shows the indicated work predicted by these variants, which is the most important metric, as a relative deviation from the experimental data. The horizontal axis shows the average heat exchanger Reynolds number, representing the flow conditions in the heat exchangers.

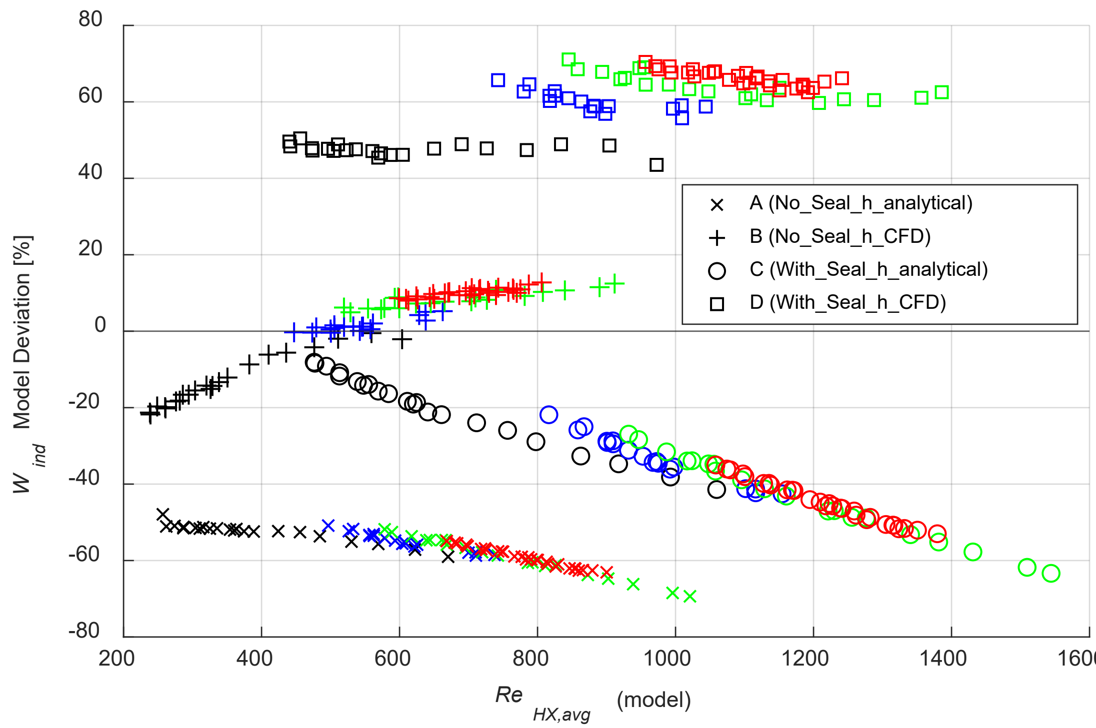



*Figure 25 Relative deviation in indicated work between model and experiment over average heat exchanger Reynolds number. All model variants A to D. Colors indicate data at different pressures. Goal is a consistent deviation around 0.*

Consistent predictions of the heat input and rejection rates within 20 % and the gas temperatures within 3 % or 10 °C were achieved, however no model variant achieved results with a consistent and small deviation in indicated work. The model results suggest that the model agreement could be improved to a reliable level by adjusting the sensitive parameters of source/sink heat transfer and seal leakage. Through experiments or other analyses, these parameters could be determined more rigorously. The key outcome of this validation is that overall, MSPM predicted the performance of the given engine well, and it shows promising potential to model future LTDSE designs, but its accuracy relies on the source/sink heat transfer and seal leakages to be well defined.

The model that was validated against the baseline Raphael data was again run to compare to the experimental results using the new heat exchangers, with the convective heat transfer coefficient being updated for the modified liquid side geometry. The plot of indicated work for both the model and experiment against engine speed for varying engine pressures is shown in Figure 26. These updated results show that the MSPM results have the same magnitude as the experimental results, however the model shows stronger dependence on engine speed than the experimental results.

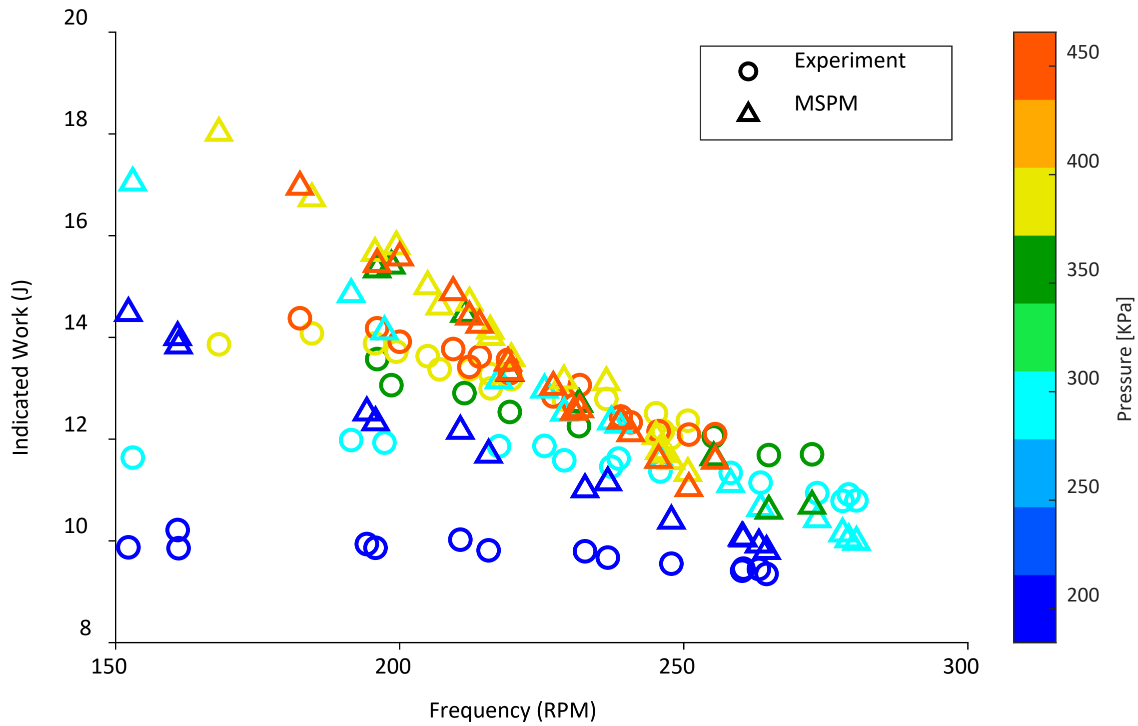
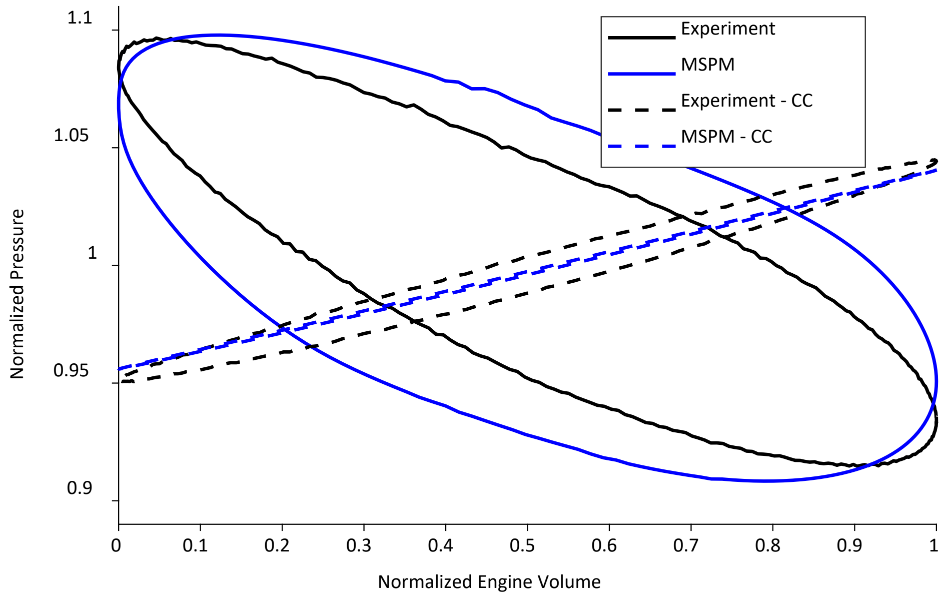



*Figure 26 Updated indicated work vs speed plot for varying engine pressures of newly collected experimental results and MSPM model results.*

The pressure-volume (PV) loops for the maximum power cases for both 200 kPa charge pressure and 450 kPa charge pressure are shown in Figure 27. In these PV loops it can be seen that MSPM has a larger indicator diagram with less pressure variation in the crankcase than the experiment. The shape of the PV diagram is strongly affected by the phase of the pressure swing, which differs between MSPM and the experimental measurement. This is particularly noticeable in the high pressure case, where the MSPM PV loop appears tilted compared to the experiment. More investigation is required into which model parameters have an effect on the phase of the pressure curve in order to improve the model output.

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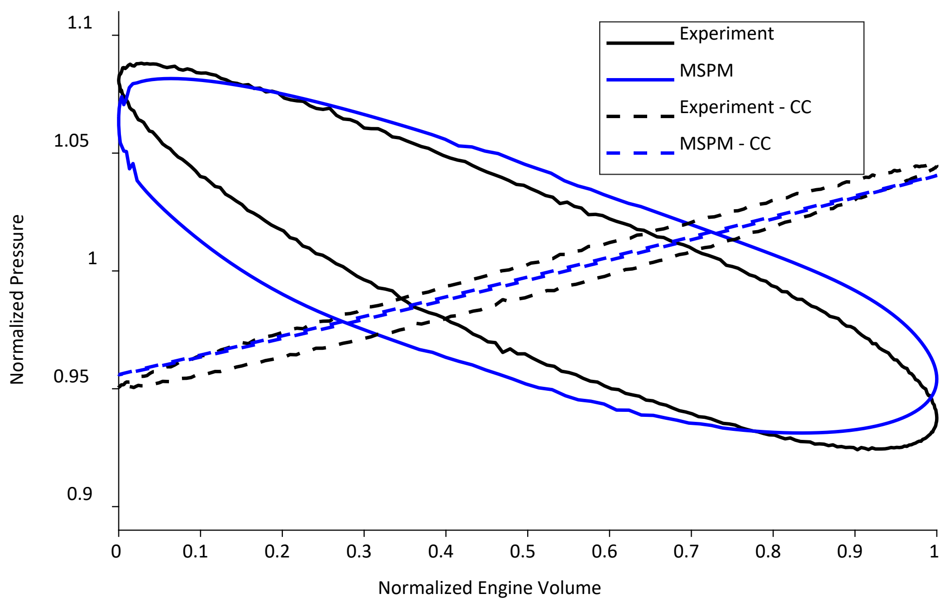



*(b)*

*Figure 27 Plot of indicator diagrams at (a) 200 kPa charge pressure and (b) 450 kPa charge pressure for the maximum power output case for experimental and MSPM results.*

An image of the model's current capabilities was gained and a range of concrete future tasks for improvement and expansion of the model were determined. These are, primarily, investigating and modeling seal leakage, expanding the variety of validation data to different heat exchanger and regenerator types as well as different working gases (helium, hydrogen), validating the mechanical model, and reviewing some assumptions the model uses.

Comparison of modelling results using Sage

The Sage model of the Raphael engine was expanded and improved. The most significant improvement was the inclusion of the liquid side thermal resistance in the heat exchanger model, as determined from the CFD studies, leading to improved gas temperature prediction. An updated schematic of the Raphael model in Sage is shown in Figure 28.

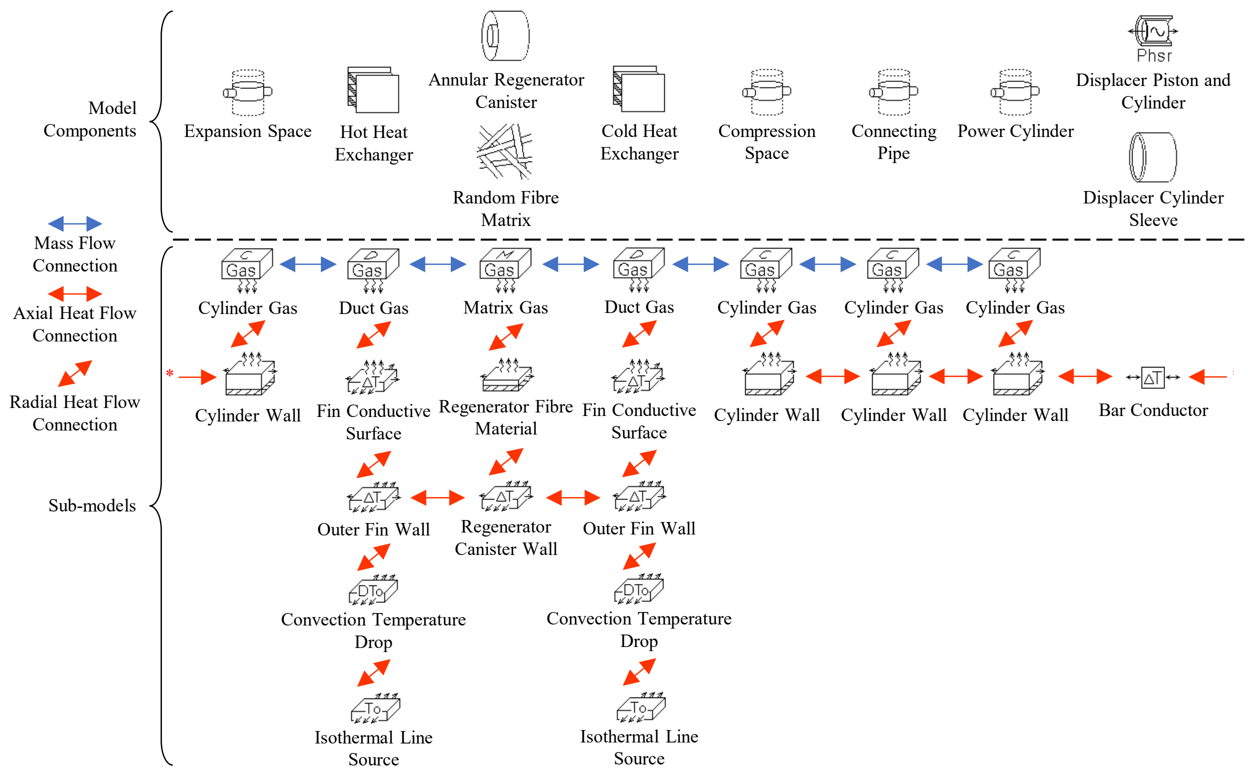



*Figure 28 Schematic of updated Sage model structure, including the liquid thermal resistance as convection temperature drop.*

With the updated model structure, the Sage model shows a reasonable agreement with the baseline experimental data. It generally agrees with the trends in indicated work output against engine pressure and speed. This can be seen in Figure 29, which plots the indicated work of the experiment and 4 different model cases against engine speed for varying pressure. Two different parameters were varied to get the 4 different model cases. The first parameter was the value of the liquid thermal resistance, with one being the direct value taken from the CFD (Orig) and one being tuned (Res) such that the expansion and compression space temperatures determined by the model agreed with the experimentally measured values. Additionally, the flow friction (FF) multiplier was varied in order to change the work output trend to agree better with speed.

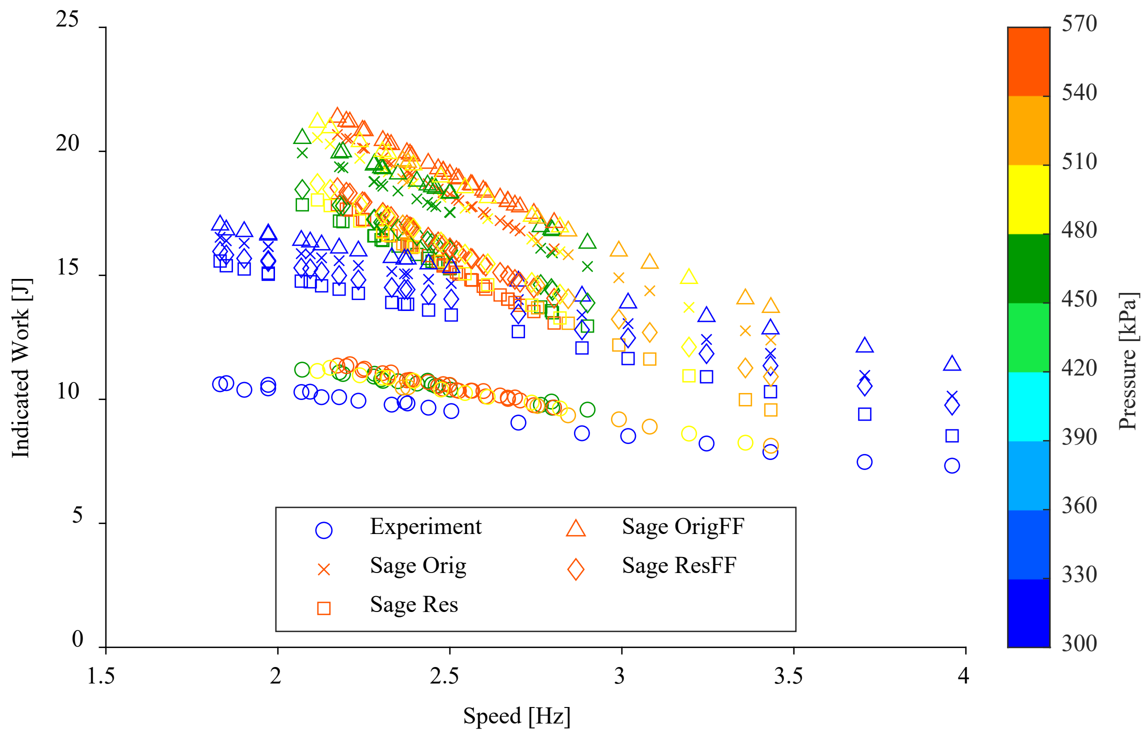



*Figure 29 Sage model results against baseline experimental pressure and speed for varying liquid thermal resistance and flow friction multiplier.*

Once new data was collected with the new heat exchangers, the Sage model was run again, where further corrections to the model were made, namely correction of the piston phasing. The plot of indicated work for both the model and the experiment against engine speed for varying engine pressures is shown in Figure 30. It is clear in the figure that the Sage model agreement is improved from the previous dataset, with the Sage data magnitude being similar to the experimental data. The dependence on engine speed is still stronger in the model than in the experiment, likely for similar reasons to the MSPM model.

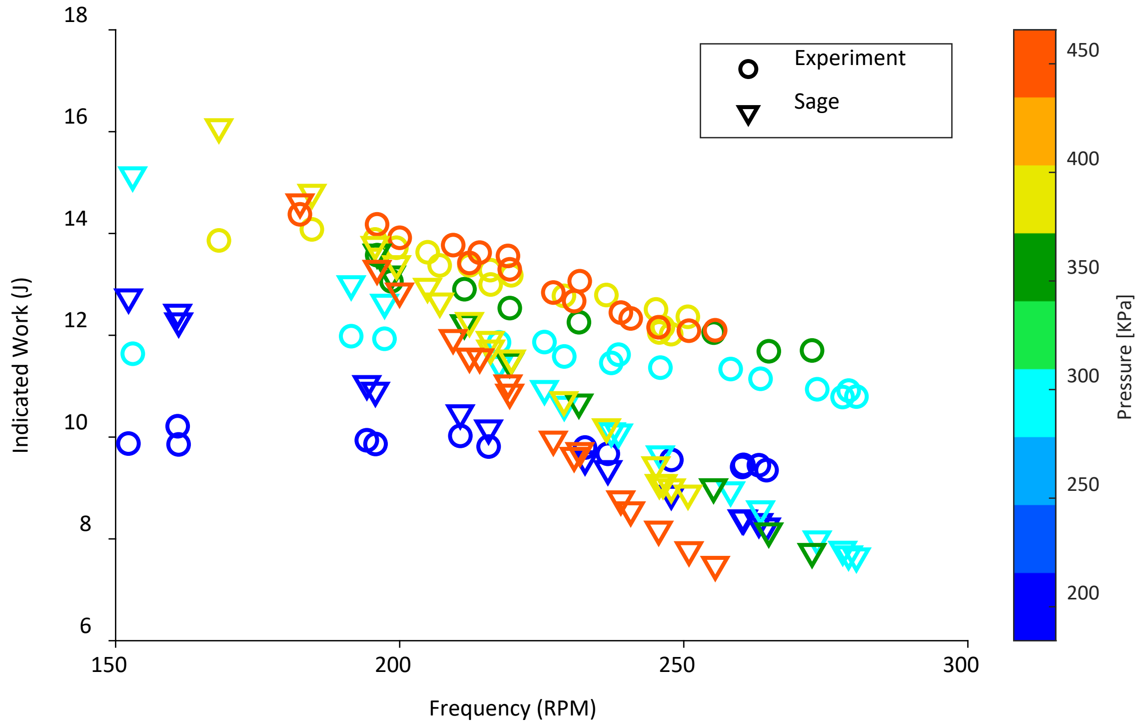
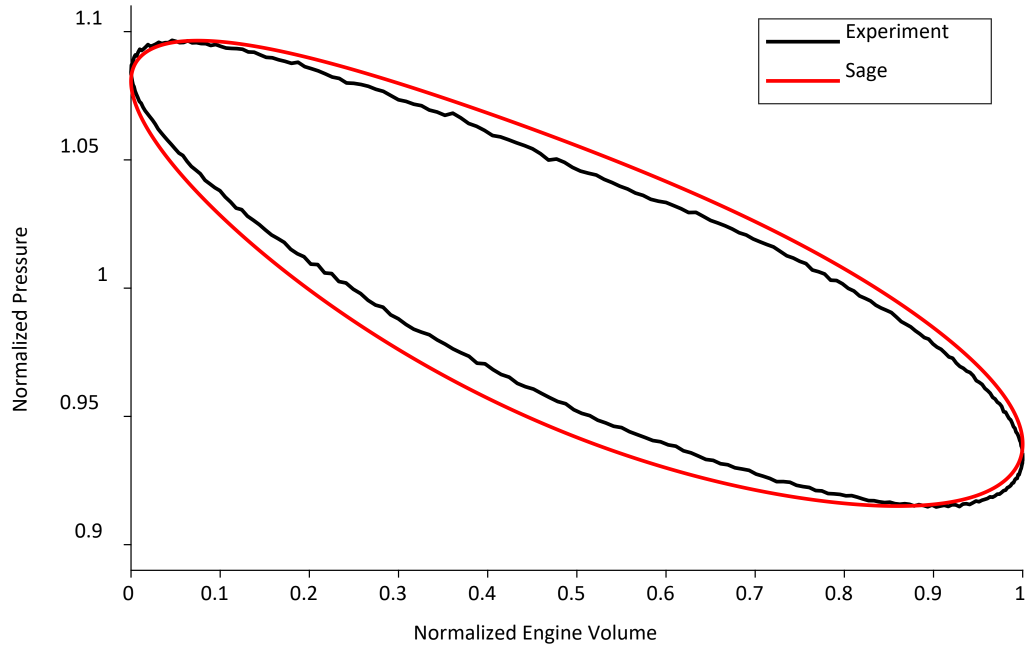
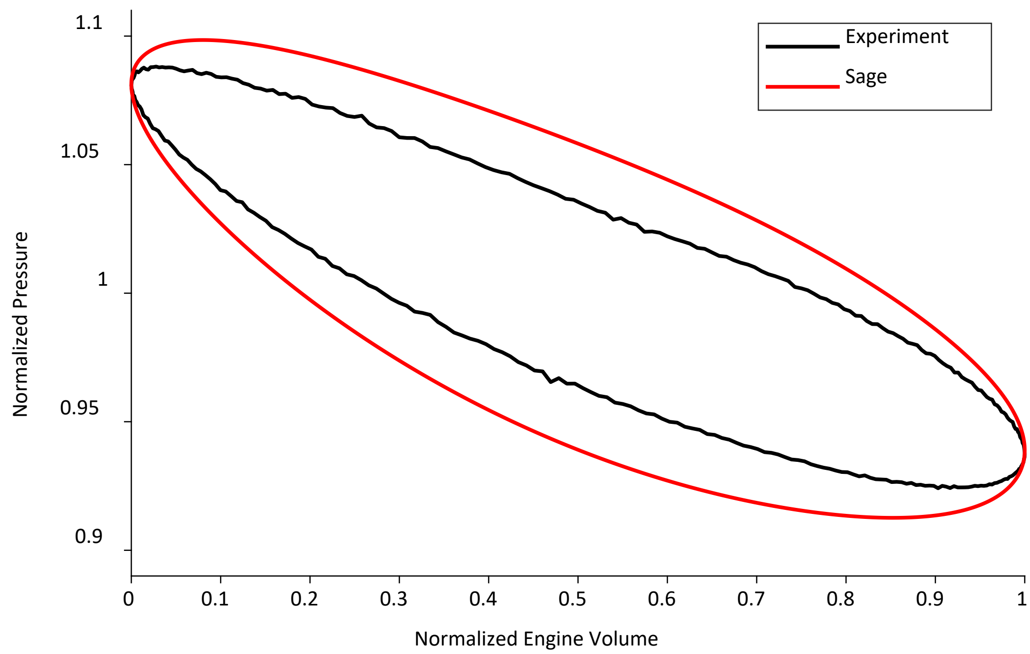



*Figure 30 Updated indicated work vs speed plot for varying engine pressures of newly collected experimental results and Sage model results.*

The PV loops for the maximum power cases for both 200 kPa charge pressure and 450 kPa charge pressure are shown in Figure 31, where it can be seen that the general shape of the PV loops is similar. The Sage model shows good agreement in PV size at low pressure, but could use improvement in the high pressure case. There is an ongoing need for better understanding of how to model the engine to produce the correct pressure swing phasing and for understanding how to best implement the liquid side heat transfer in the Sage model.




*(a)*




*(b) – something seems off with this PV loop*

*Figure 31 Plot of indicator diagrams at (a) 200 kPa charge pressure and (b) 450 kPa charge pressure for the maximum power output case for experimental and Sage results.*

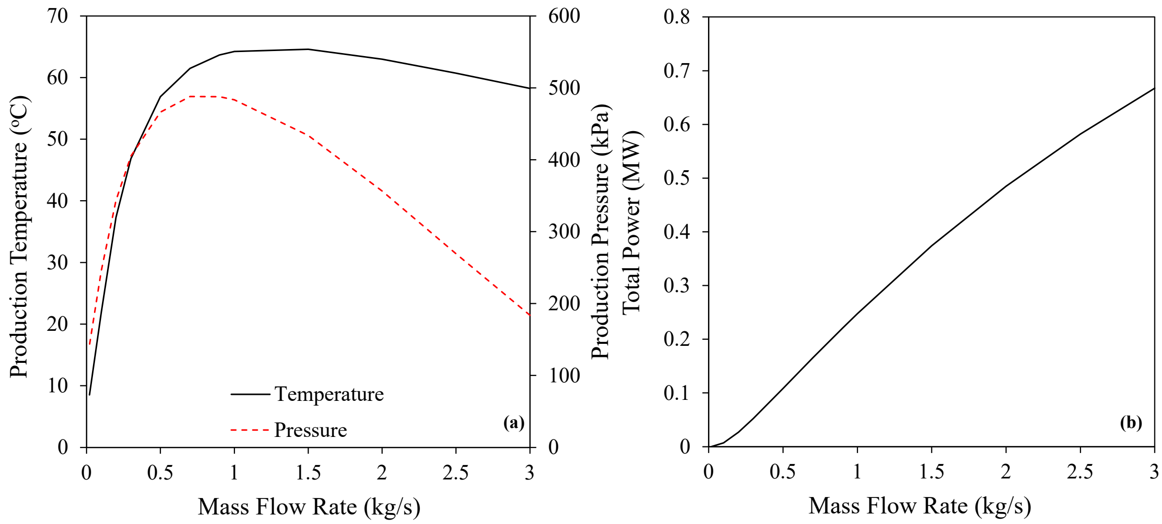
*Effect of heat exchanger geometry on output power*

The Sage model of the Raphael engine was used to investigate the effect of heat exchanger size and shape on power output. The heat exchanger aspect ratio was changed, changing the open cross-sectional area and the heat exchanger length, and the size. The indicated power output was determined for a range of heat exchanger aspect ratios and it was found that the optimum power output occurred for a heat exchanger that had a short length and a large open cross-sectional area, with the size being dependent on having sufficient surface area for adequate heat transfer to the gas. The heat exchanger design for low-temperature difference Stirling engines must balance these parameters, particularly since there is a higher sensitivity to losses at the low-temperature regime.

## 4. TASK # 4: THERMAL ENERGY TRANSPORT TO AND FROM THE STIRLING ENGINE

Oil wells at the end of their production life have the potential to be retrofitted to exploit any available geothermal energy resource, avoiding the high cost of new drilling. Two-phase fluid flow and heat transfer models are required for designing energy extraction from these wells. Our previous numerical model (Eghbali et al., 2021) for single- and two-phase fluid flow and heat transfer calculations was extended to a co-axial well. In this model, the phase equilibrium calculations for CO2-, and air-water systems are coupled with continuity, energy and momentum equations. Transient conductive heat transfer between the well and the formation was considered. The model was used to investigate the effects of single- and two-phase fluids, operational conditions, inner pipe size, transient heat transfer on the extracted power, temperature, and pressure profiles in a co-axial well system with the aim to identify optimum retrofitting design conditions for exploitation of geothermal energy.

The modeling results show that during circulation of a single- (water) or two-phase (air/CO2-water) fluid through a co-axial well (injection through the annulus), the average of the mixture density in the upward flow is less than that in the downward flow. This leads to a higher production pressure ($P_{prod}$) than the injection pressure ($P_{inj}$). $P_{prod}$ is higher for a system modelled as a single-phase compared to it being modeled as a two-phase system at a specific $P_{inj}$. As the quantity of the injected gas increases, $P_{prod}$ decreases. There is an optimum mass flow rate resulting in the maximum $P_{prod}$ and $T_{prod}$ in both single- and two-phase systems, as can be seen in Figure 32. Circulation of cold fluid through the well causes cooling of the local rock resulting in a reduction of the $P_{prod}$ and $T_{prod}$ over time. $T_{prod}$ decreases by increasing inner pipe size with respect to the well size. There is also an optimum size of the inner pipe for a specific well to achieve the highest $P_{prod}$.



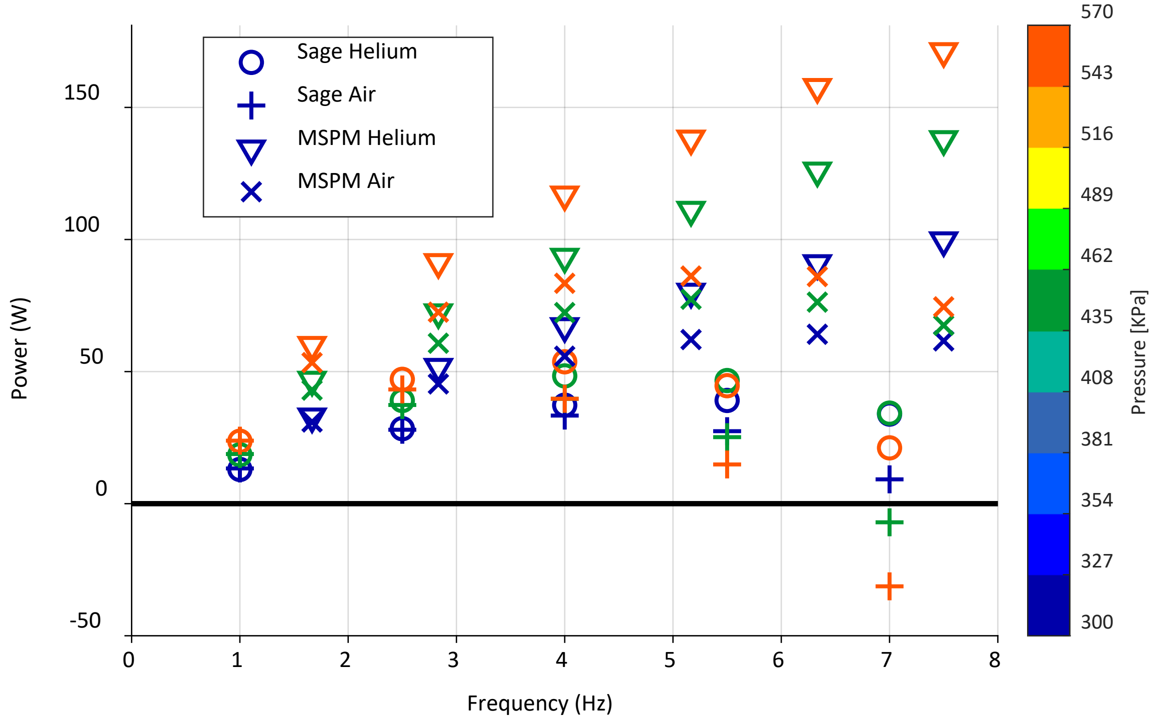

*(a) (b)*

*Figure 32 Effect of mass flow rate on (a) production pressure and temperature and (b) produced thermal power at $P_{inj}$ = 101.3kPa for a two-phase system of air-water with 0.5 wt.% air.*

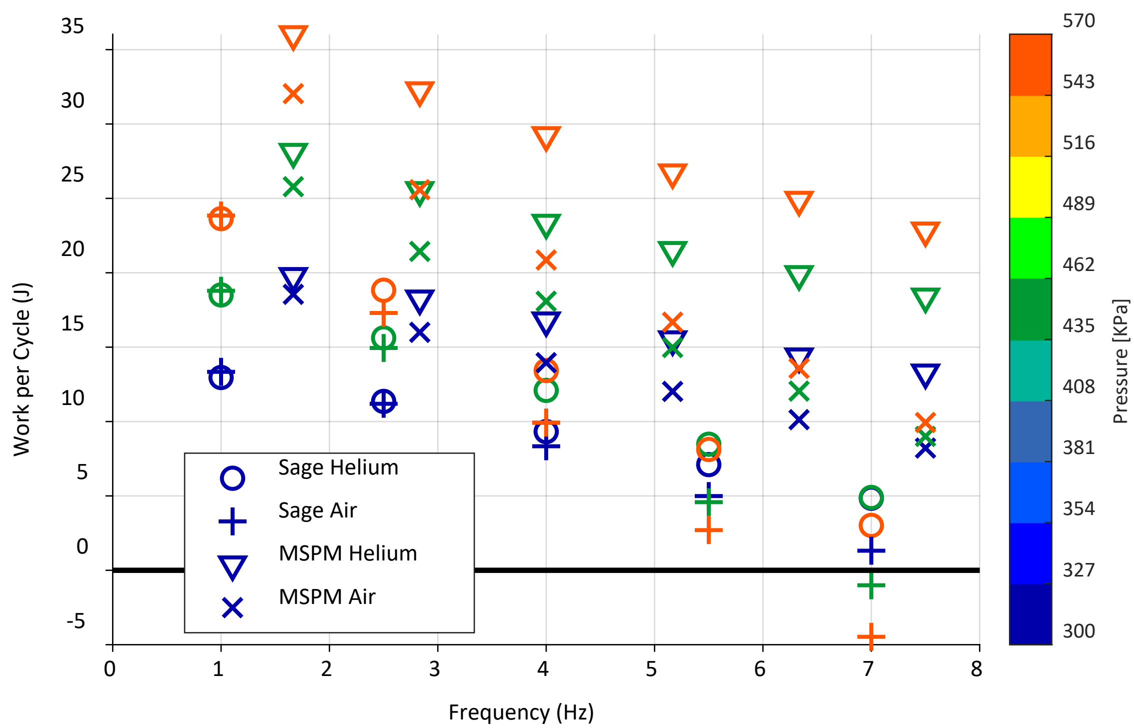
## 5. TASK # 5: ECONOMIC FEASIBILITY AND LIFE CYCLE ANALYSIS

Engine Thermodynamic Scaling

To evaluate the feasibility of Stirling engine technology for electricity generation at a commercial scale, the developed models were used to evaluate the effect of changing working fluid on the engine performance. Both the Sage and MSPM models of the Raphael engine with new heat exchangers were run with pure helium as the working fluid instead of air. The models assume an idealized condition of 150 °C source, 5 °C sink, and no convection coefficient for the liquid side of the heat exchangers (an isothermal boundary). The power output and indicated work determined by Sage and MSPM is plotted against engine frequency for the air and helium case in Figure 33. Generally, Sage underpredicts the indicated work, particularly compared to MSPM, which results in the lower peak power and downward trend as compared to MSPM. However, for both models, changing the working fluid from air to helium does not result in a direct upward shift in the curve of work or power output. Focusing on the plot of indicated work, changing the working fluid results in a change in the slope of the curve. Helium as a working fluid yields higher work output at higher engine speeds and at higher engine pressures. This result is a direct consequence of helium's decreased density, which results in lower losses due to flow friction. Thus, a LTDSE is expected to have improved maximum power output across the operating range when using helium, with the maximum power occurring at a higher engine speed.




*(a)*




*(b)*

*Figure 33 Indicated work vs engine speed for varying engine pressure for air and helium for new heat exchangers*

Experimental studies on the Raphael engine were undertaken to experimentally investigate the effect of changing working fluid from air to helium in a LTDSE. The engine setup was modified to allow for the engine volume to be purged and filled with helium, as shown in Figure 34. The engine was run at the same operating conditions for tests of both air and helium, notably at a source temperature of 130 °C and a sink temperature of 5 °C. The newly manufactured heat exchangers were used for both tests.

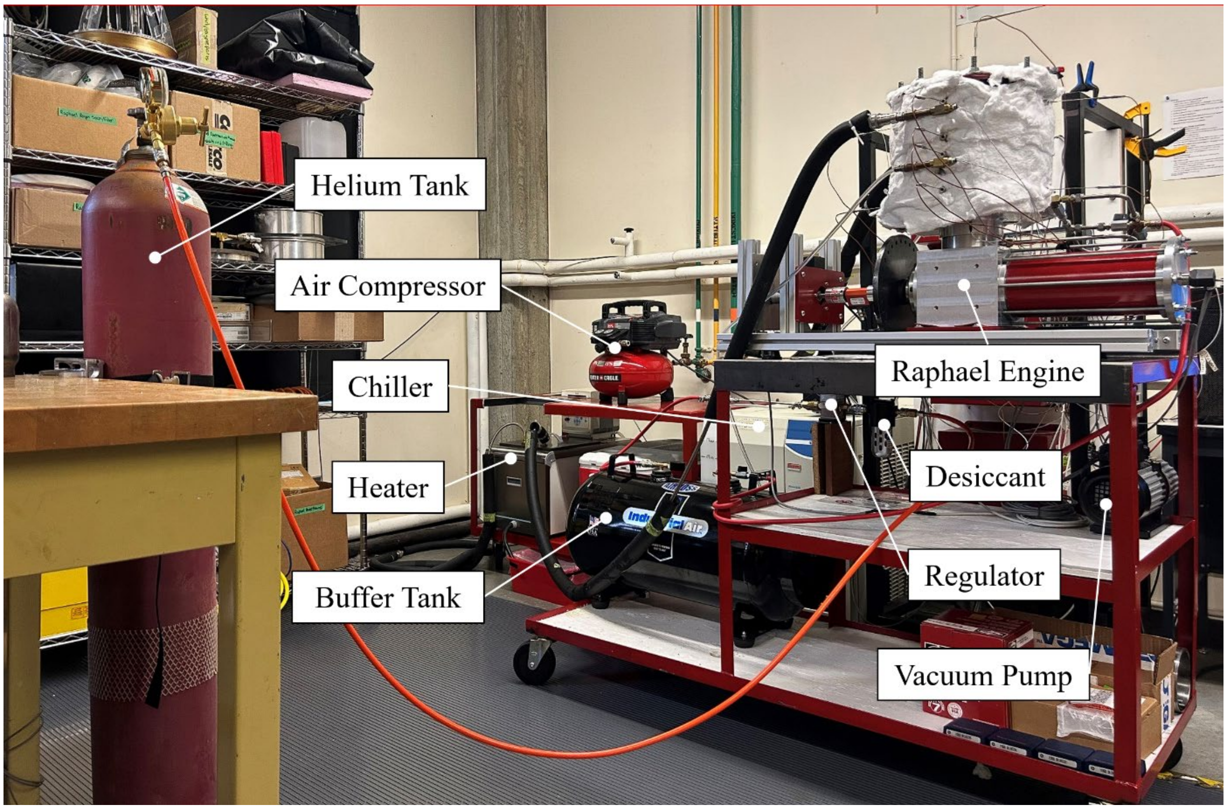
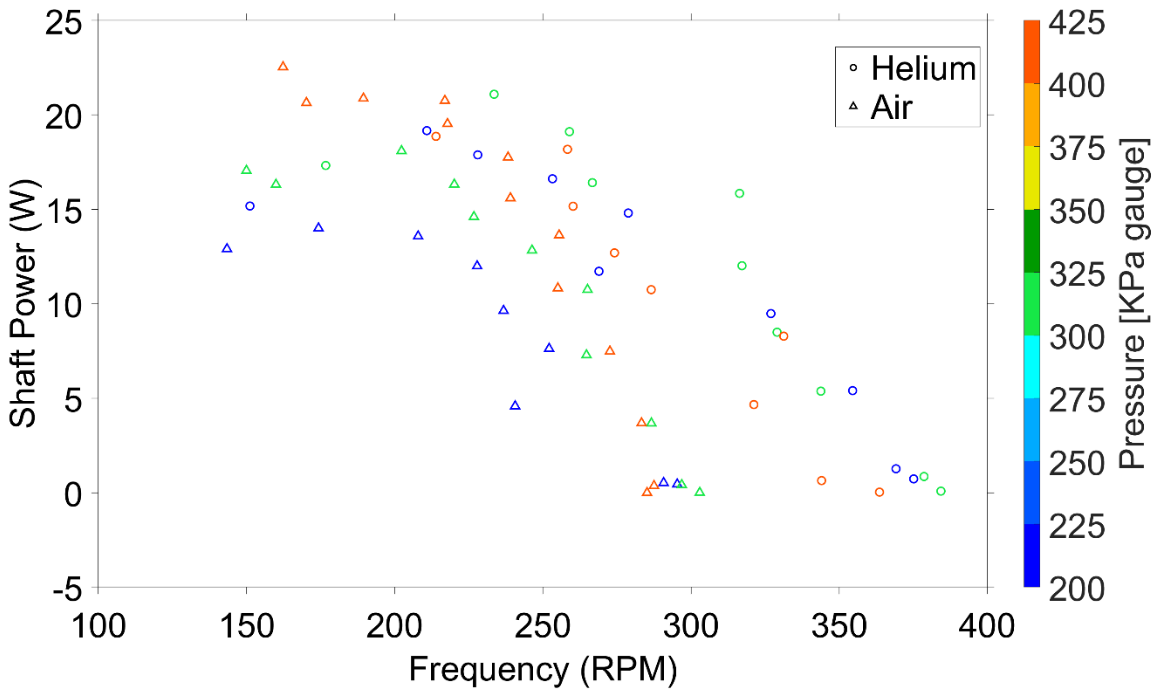
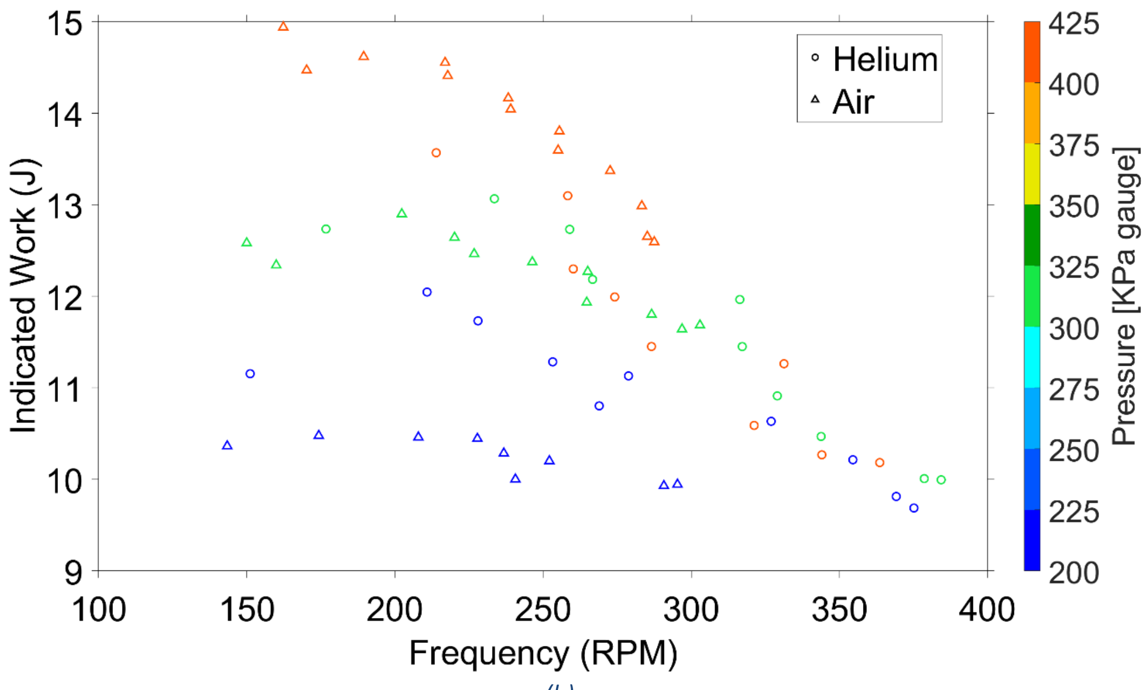



*Figure 34 Experimental setup for investigation of changing Raphael working fluid to helium.*

Two key plots were generated from the experimental investigation: a plot of indicated power output against engine speed and a plot of indicated work output against engine speed, both for a range of engine pressures. These plots are shown in Figure 35. The experimental results indicated that the influence of working fluid on the engine output power at low temperature and low speed operation is more complex than perhaps originally indicated by the models. The engine ran at faster speeds with helium as the working fluid, however it was entirely unable to run at the slow engine speeds as with air. In addition, the effect of engine pressure on output work and power output was significantly lower when helium was the working fluid than for air. The improvements in engine operating speed resulting from using helium as the working fluid do not translate into an increase in the overall maximum output power, which still occurs at a low speed, high pressure, using air as the working fluid. These results suggest there is more to investigate as to how the working fluid affects the output power of a LTDSE, and that the benefits of changing the working fluid to helium are not as pronounced in this operating range.




*(a)*




*(b)*

*Figure 35 Indicated work vs engine speed for varying engine pressure for air and helium for new heat exchangers*

Engine Physical Scaling

Initial activities associated with this task revolved around investigation of engine scaling using the MSPM model. The model was used to scale up the volumetric size of an engine from the size of the Raphael to an output power in the range of kilowatts. The model demonstrated reasonable predictions at larger scales, as power increased proportionally with volume. It was found that if only the volume is scaled, the resulting geometries to achieve 1 kW or 10 kW of power are impractical due to their large physical size. All parameters should be scaled and optimized to produce a feasible design. In particular, the heat exchangers and regenerator should be chosen to minimize flow friction and maximize heat transfer, which enables the engine to operate at higher pressure and speed, thereby increasing its power output.

MSPM was also used to estimate the power and efficiency of an existing large-scale low temperature Stirling engine. The model gave a reasonable estimate of this engine's performance, but the accuracy could not be assessed conclusively due to lack of detailed engine specifications and experimental data. This analysis showed that the regenerator plays an important role for engines even with low source temperatures, and MSPM demonstrated its ability to optimize the regenerator properties.

To further investigate engine scaling, a simplified model of the Raphael engine was scaled in different configurations. The first configuration was purely geometric scaling, where every linear dimension was multiplied by a scaling factor. The second was radial scaling, where the radial dimensions were multiplied by a scaling factor while the axial dimensions were not affected. Finally, in light of the earlier results suggesting that geometrically scaling a LTDSE results in an impractical size compared to its power output, a modified scaling scheme was used. This scheme focused on holding key parameter ratios relating to the heat exchangers constant across varying engine sizes. The selected parameter ratios were:

| | |
|---|---|
| $\frac{FA}{D_{disp}^2}$ | $FA$ = heat exchanger frontal area<br>$D_{disp}$ = displacer diameter |
| $\frac{SA}{V_{disp}}$ | $SA$ = heat exchanger surface area<br>$V_{disp}$ = displacer swept volume |
| $\frac{V_{HX}}{V_{disp}}$ | $V_{HX}$ = heat exchanger volume |

To hold these parameter ratios constant only the number of fins in the heat exchangers were changed – the fin geometry itself was held constant. For each of these scaling configurations, a scaling factor of 2, 5, or 10 was applied. In addition, when possible, a smaller scaling factor of 0.5, 0.2, and 0.1, which result in engines smaller than the Raphael, were also modelled. For each scaling factor, the operating conditions of engine pressure and speed were optimized to produce the maximum power output.

The maximum power output for each engine size determined by Sage and MSPM is plotted against the volume ratio of the engine (as compared to the original Raphael engine) in Figure 36. The results from each of the models show similar trends for the different scaling schemes, but with an offset between the models, with Sage having a more optimistic power output per volume than MSPM. The geometric scaling case yielded a linear increase in power with increasing volume, while the radial scaling showed a peak after which an increase in size decreased the power output. Interestingly, the modified heat exchanger scaling case where key ratios were held constant resulted in very little increase in power output, flatlining and then slowly decreasing with increasing engine size. In particular, it did not result in an increased power output per unit of engine volume than geometric scaling, which is not optimized for a different engine size. This suggests that controlling the heat exchanger size in scaled up engines by way of modifying the number of fins is not optimal. Once again, the need for optimizing the fin geometry at a given engine scale for improving power output is shown to be necessary, which is an intensive process both numerically and experimentally.

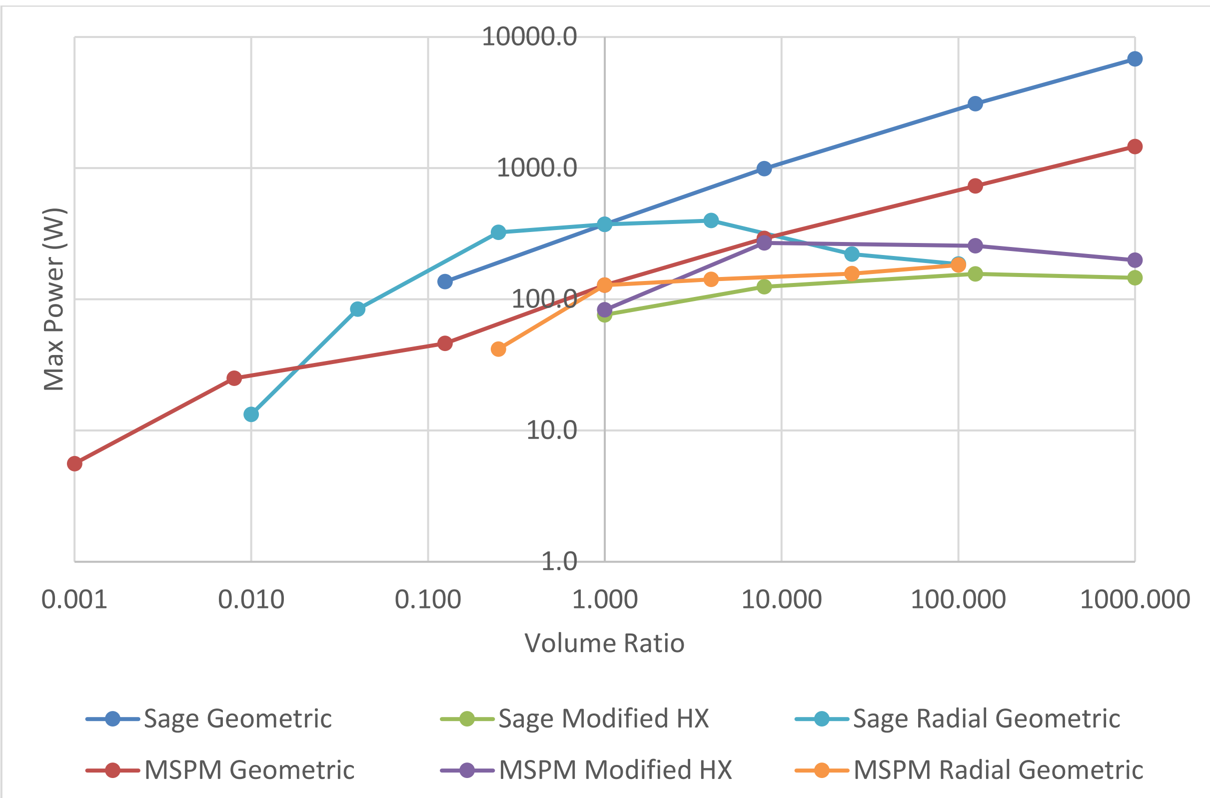



*Figure 36 Maximum power output of various engine scaling methodologies plotted against engine volume.*

Increasing the engine size generally increases the engine power output, and further optimization is required to maximize the power output of engines at this scale. Regardless of the potential for further optimization, it is worth evaluating the practicality of increasing engine scale for maximizing power output by considering power density. Power density is a commonly used metric in internal combustion engine (ICE) evaluation, defined as the power output per engine volume. Since the geometric scaling case gave the highest power output per unit volume, its power density is plotted directly against engine volume in Figure 37. A dotted line corresponding to 1 kW of total power output is plotted against engine volume to help visualize the power density of a 1 kW unit at varying sizes.

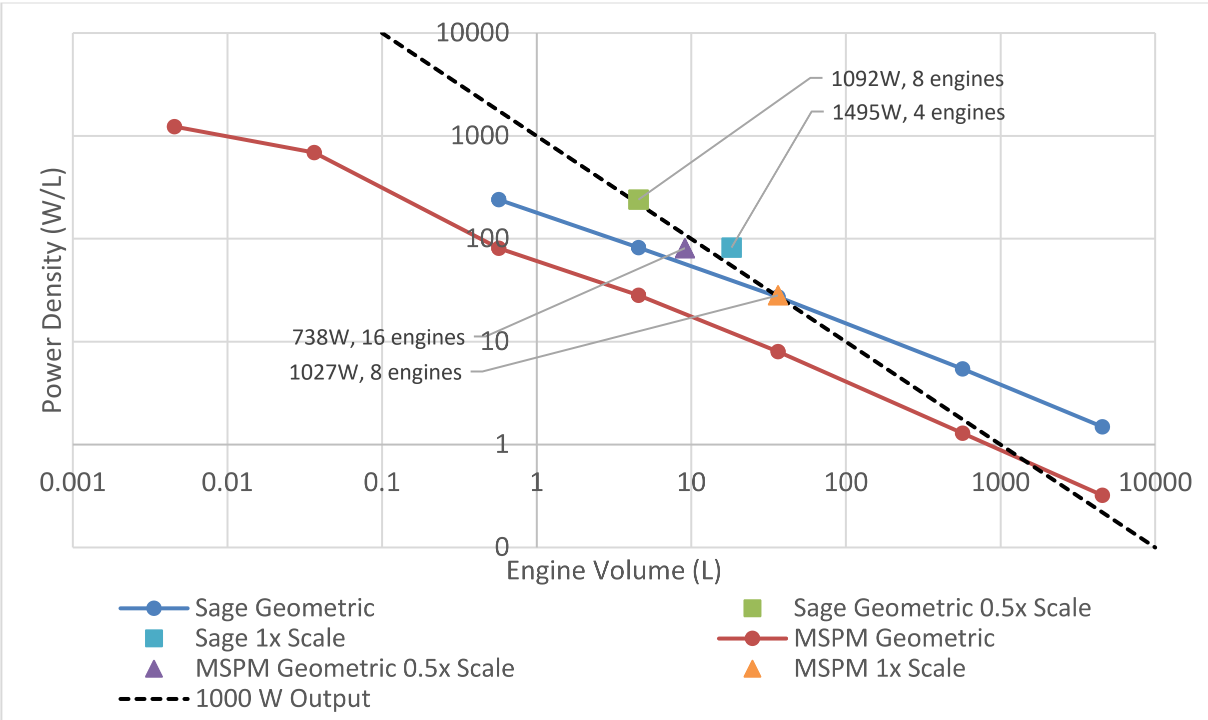



*Figure 37 plot of power density (per L) against volume ratio for varying engine geometries*

From Figure 37 it can be seen that the power density of the Stirling engine decreases with increasing size. Thus, creating a single engine unit that outputs 1 kW requires an engine size of 50 L (optimistically, from Sage results) or up to 1000 L (pessimistically, from MSPM). Larger ICEs also have decreased power density compared to their small counterparts, which largely results from necessarily slower operating speeds as a consequence of the increased inertia in moving larger pistons. This limitation is also present in Stirling engines. Additionally, in LTDSEs heat exchange is vitally important as there is limited energy available for exploitation by the cycle. However, to optimize heat exchange the heat exchanger geometry is limited by the flow characteristics. The operating speed of LTDSEs - particularly scaled up engines - is low which results in laminar flow through the heat exchangers. In this regime, increasing surface area for heat exchange is crucial, as there is no cross-stream mixing of the flow to transfer heat from the walls to the flow. Thus, the geometry is tied to the size of the boundary layer, which is small. However, this geometry leads to increased flow frictional losses. The combined effect of the increased flow losses, limited heat exchange capacity for a larger volume of air, and increased inertia and slower operating speeds results in the significant drop in power density of large scale LTDSEs.

A second observation can be made from Figure 37 of power density by plotting a select number of datapoints corresponding to multiple-engine units that output approximately 1 kW in total. By combining multiple smaller engine units, a total output of 1 kW can be achieved at a much lower total engine volume, shown clearly by the deviation from the lines predicting power density of a Stirling engine. Instead, the power density remains constant, and the power output is increased by multiplying the number of engine units. These results suggest that it is more effective, particularly for maintaining high power density, to make several smaller engines and operate them as a unit to increase power output. This comes with two main benefits: smaller overall physical engine sizes and the ability to take advantage of mechanical balancing. The engine size should then be selected to be as small as practical if the goal is to maximize power output for a given heat input and available space.

Economic Feasibility

To evaluate the economic feasibility of building a large scale engine, a simplified analysis based on the cost of total material required was undertaken. Building large scale engines would require different manufacturing techniques as the engine size increases. In addition, it is not necessarily the case that all manufacturing tolerances would increase proportionally as the engine increases, which would potentially require precision machining at a fairly large scale. To understand the economic feasibility of building large scale LTDSEs, the manufacturing variance complexities are neglected and the total material cost is considered. The material required for each geometrically scaled up engine was determined and the cost of the total required material was determined. The stock material cost for the engine is then plotted against volume ratio (compared to the Raphael engine) as shown in Figure 38. The two engine materials considered were steel and aluminum, however the two material costs are similar so the trendlines overlap.

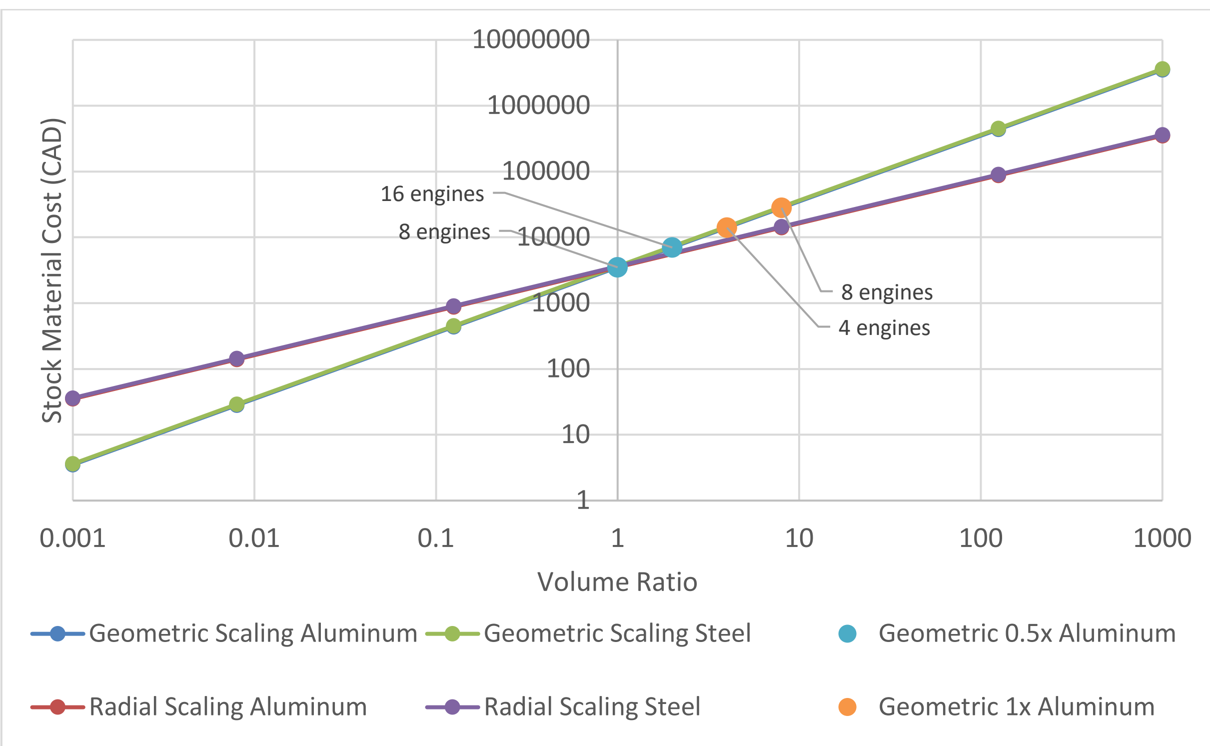



*Figure 38 Plot of engine cost (estimated) for geometric/~~radial~~ scaling, and for multiples of engine units?*

From Figure 38 it is evident that engine cost increases linearly with volume on this log-log plot, which is expected as the material required increases exponentially when the engine is geometrically scaled. The singled out multi-engine configurations that output 1 kW from Figure 37 are also plotted on the same plot, and it can be seen that they fall along the same curve of increasing cost per engine volume as the engines are scaled geometrically.

Though these configurations fall on the same curve of engine cost as the single unit, their power output is noticeably different for the same engine size and cost. To gain a complete understanding of the economic feasibility of large scale LTDSEs, the payback time for the material cost of the engines was calculated. The engine was assumed to operate for 20 hours a day, and the price of electricity was taken as the average cost in 2022 for variable rate small business from the Utilities Consumer Advocate historic rate information. The determined payback time for a selection of units that produces approximately 1 kW is summarized in Table 1.

*Table 1 Power, Cost and Payback Time for selected engine configurations with a power output near 1000W*

| ENGINE SIZE | POWER OUTPUT (W) | COST (CAD) | PAYBACK TIME (YEARS) |
|---|---|---|---|
| **GEOMETRIC SCALING 2X (SAGE)** | 989 | 27993.36 | 18.56 |
| **GEOMETRIC SCALING 10X (MSPM)** | 1464 | 3499170 | 1567.05 |
| **GEOMETRIC SCALING 0.5X, 8 ENGINES (SAGE)** | 1092 | 3499.17 | 2.10 |
| **GEOMETRIC SCALING 0.5X, 16 ENGINES (MSPM)** | 738 | 6998.34 | 6.22 |
| **GEOMETRIC SCALING 1X, 4 ENGINES (SAGE)** | 1495 | 13997 | 6.14 |
| **GEOMETRIC SCALING 1X, 8 ENGINES (MSPM)** | 1027 | 27993 | 17.87 |

An extreme divide in the payback time of single large scale LTDSEs compared to multiple units is clear from the table, with the large scale engines having an optimistic payback time of 19 years and a pessimistic payback time of over 1500 years for only material costs, making it economically infeasible, particularly as manufacturing costs have not been considered in this analysis. The payback times for multiple smaller units are feasible, ranging from an optimistic 2 years to 18 years pessimistically. It should be noted that Alberta electricity rates reached historic highs in 2022 and 2023, so the payback time would increase if electricity rates decreased in the future. In the volatile electricity market, the shortest possible payback time is most desirable.

## F. KEY LEARNINGS

**Please provide a narrative that discusses the key learnings from the project.**

- Describe the project learnings and importance of those learnings within the project scope. Use milestones as headings, if appropriate.
- Discuss the broader impacts of the learnings to the industry and beyond; this may include changes to regulations, policies, and approval and permitting processes

*RESPOND BELOW*

The key learnings for the project are outlined in the subheadings below related to the individual project tasks.

### 1. TASK # 1: LARGE SCALE LTDSE DESIGN AND BUILD

The extensive engineering design and development of the large scale engine highlighted a number of important issues. The original premise of the project was that the limitation of a low temperature difference can be overcome by increasing the scale of the engine to reduce a significant amount of power. The mechanical design of the large scale engine highlighted however that for the engine to even use moderately high pressures, the materials and volume of materials to construct the engine will lead to a very heavy engine. Importantly, the scale of the proposed engine (>1,000kg) was outside of the operational limits of the laboratory available both in terms of floor loading and the available equipment to handle heavy components.

The move away from geometrically scaling the engine to thermodynamic scaling the engine provided lots of opportunities for continued development of the technology. The low temperature engine that had been developed within the lab was capable of running at high pressure and with other gases such as Helium as the working fluid. This approach highlighted the importance of heat transfer but was not only relevant to the Stirling engine and conditions that was being researched, but also to all Stirling engines. General, 1$^{st}$ order modelling of Stirling engines highlights that significant power can be produced at high efficiency. As this does not take into account losses (i.e. friction) and potentially low performance of components such as the convective heat transfer within the heat exchanger, modelling a Stirling engine using this approach can be very limited and misleading. The design of heat exchangers with better heat transfer can significantly differently improve the overall performance of the Stirling engine.

The design of heat exchangers for reciprocating flow systems such as that found within a Stirling engine is still an area that needs to be developed. A research work has shown that using a steady-state heat exchanger performance design approach can give a good indication of how design parameters can improve or change the performance of the heat exchanger for better heat transfer. However this approach is insufficient for providing actual, quantitated value for the heat transfer performance of a particular heat exchanger. As such, further development work is needed for defining a reliable heat exchanger design approach for reciprocating flow heat exchangers.

## 2. TASK # 2: THERMO-FLUIDS OF RECIPROCATING SYSTEMS

The fundamental research undertaken to investigate the thermo fluids of reciprocating flow systems has highlighted some significant challenges. The flow field within the small and narrow channels of the heat exchanger intrinsically determine the flow to be laminar throughout the complete cycle. This highlights that heat transfer into the fluid is mostly by diffusion which is a very slow heat transfer process. If the flow could become turbulent much high heat transfer rates, at least an order of magnitude higher, could be achieved. However, it can be expected that the flow friction coefficient would also change by at least an order or two of magnitude. Approaches for developing a tabular flow without high viscous friction are very limited and are counter to the nature of the flow. Introduction of large-scale flow structures such as axial water vortices would induce cross stream transport of hot fluid from the heat transfer surface into the bulk flow. In the past, generation of these types of vortices was limited due to manufacturing limitations. However modern manufacturing techniques such as 3-D printing off an opportunity to develop technology to induce these flow structures that could drastically improve heat transfer. Research work to date has developed the tools to measure important flow components to determine the heat transfer and the influence of these large-scale structures. Research is continuing with the PhD student looking at a variety of different structure types to identify potential successes for heat transfer.**TASK # 3: DEVELOPMENT OF 3RD ORDER MODEL FOR LTDSE**

For Stirling engines operating at a high temperature difference (i.e. the hot side temperature >800 °C) any frictional losses or inefficiencies within the system can be easily overcome by increasing the temperature difference within the system. These losses and efficiencies are typically of the same order of magnitude whether running at a high temperature or a low temperature. Therefore, they become significant when considering the design of a Stirling engine operating from a low hot side temperature source. Development of the 3$^{rd}$ was crucial for this project as it allowed losses and efficiencies not typically considered (and not considered in the available commercial code, Sage) to be included within the model. The model was also constructed in an intuitive way that allowed direct feedback visually from the software in the form of temperature and flow maps in the software. This help to provide insight when developing an engine configuration. Also, the model was constructed to allow many different configurations of the engine to be modelled in a single run allowing design plots of important parameters to be considered rather than single operating points. This allows important insight to be gained, especially through the analysis of PV diagrams, allow better understanding of how different components affected the overall performance of the engine.

The developed 3$^{rd}$ order model, MSPM, was crucial in identifying that heat transfer was the limiting factor not only for the engines under investigated but for all Stirling engines. Extensive analysis using MSPM lead to the development of new heat exchanges that showed an improved performance of the overall engine.

## 4. TASK # 4: THERMAL ENERGY TRANSPORT TO AND FROM THE STIRLING ENGINE

A comprehensive model was developed to predict the thermal transport of energy from end-of-life oil wells. This model was used to investigate the design of a counterflow heat exchanger that allowed the heat exchanger fluid (water + dissolved air) to extract energy from a deep reservoir. In the work undertaken, this reservoir was as deep as 3 km. This multi-phase and multi-component flow model needed to capture the heat transfer characteristics in the rock of the reservoir and the materials of the counterflow heat exchangers, how different gasses dissolve and form bubbles based on their own physical characteristics and the effect of temperature and pressure and the general flow throughout the counterflow heat exchanger. This model also need to be to a couple throughout the complete system.

The developed model allowed many assumptions typically used in modelling these types of systems to be investigated. For example, can a single phase fluid such as water be modelled sufficiently well enough to determine the heat transport characteristics of the system compared to a multiphase model that includes the formation of bubbles. The work showed conclusively that the multiphase physics of the flow field need to be included along with the effects of heat transfer into the rock to achieve results that will describe the actual physics of the system.

Continue work using the model has highlighted that self sustained motion using the hot reservoir to drive fluid motion so that no external workers put into transporting heat from the reservoir to the surface. Also, this type of system can be used as a hydraulic compressor in excess gas is introduced into the cold fluid entering the counterflow heat exchanger within the well. The return from the heat exchanger with therefore include not only hot liquid but also high pressure gas. Both of these could be used to generate energy or used as a heat source.

## 5. TASK # 5: ECONOMIC FEASIBILITY AND LIFE CYCLE ANALYSIS

The economic feasibility of this technology was evaluated by considering only the material costs for constructing large scale engines compared to the performance improvements of small-scale engines. The modelling work highlighted that small-scale engines have much higher energy density is compared to large scale engines. Also, doing the economic analysis based on material cost provided a much more relevant understanding of the economics because material costs were readily available and the overall cost could be determined from the CAD designs generated. The economic feasibility analysis showed that it was economically more viable to generate the same amount of energy using several small scale engines compared to a single large scale engine. This was linked to the power density of the engine decreasing with increasing size.

## G. OUTCOMES AND IMPACTS

**Please provide a narrative outlining the project's outcomes. Please use sub-headings as appropriate.**

- **Project Outcomes and Impacts:** Describe how the outcomes of the project have impacted the technology or knowledge gap identified.
- **Clean Energy Metrics:** Describe how the project outcomes impact the Clean Energy Metrics as described in the *Work Plan, Budget and Metrics* workbook. Discuss any changes or updates to these metrics and the driving forces behind the change. Include any mitigation strategies that might be needed if the changes result in negative impacts.
- **Program Specific Metrics:** Describe how the project outcomes impact the Program Metrics as described in the *Work Plan, Budget and Metrics* workbook. Discuss any changes or updates to these metrics and the driving forces behind the change. Include any mitigation strategies that might be needed if the changes result in negative impacts.
- **Project Outputs:** List of all obtained patents, published books, journal articles, conference presentations, student theses, etc., based on work conducted during the project. As appropriate, include attachments.

*RESPOND BELOW*

### 1. PROJECT OUTCOMES AND IMPACTS

- Main: heat transfer, the model,

### 2. CLEAN ENERGY METRICS

*$ in Clean Technology: the funds for this project are on target*

*# of Publications: the publications generated from this project are on target and will ramp up in the remaining time. All project publications are listed.*

*# Students (MSc, PhD, PDF etc.): projected number of personnel involved in the project on target*

*Partnership agreements / MOUs?: Two companies have provided letters of support for this project*

*# New Spin-Off Companies created: Students who graduated from the project are attempting to establish a spinoff company associated with the technology. This initiative is ongoing.*

*# projected new jobs created from future deployment: These jobs have yet to be established but if the spinoff company is developed than the anticipated numbers are appropriate.*

*# projected GHG emissions reductions from future deployment (to 2030): this project is the development of the technology that will potentially achieve the GHG emission reductions as listed. A major result of this project will be determining if this is possible.*

### 3. PROGRAM SPECIFIC METRICS

*# of alternative energy technologies deployed: a major goal of this project will be the development of the design and analysis process that will allow a high energy conversion device to be developed. Work is progressing well in this direction.*

## 4. PROJECT OUTPUTS

(Co-author names that are underlined are or were students (UG, MSc., PhD or PDF) under the supervision of one or more of the academic authors at the time that any of the research was conducted.)

*Refereed Journal Publications*

J1. Saffar, Y.; Kashanj, S.; Nobes, D.S.; Sabbagh, R. (2023) The Physics and Manipulation of Dean Vortices in Single- and Two-Phase Flow in Curved Microchannels: A Review. Micromachines 2023, 14, 2202. https://doi.org/10.3390/mi14122202 (Pub, 1st Dec 2023, 33 pages)

J2. Kashanj, S., Nobes, D.S. (2023) Application of 4D two-colour LIF to explore the temperature field of laterally confined turbulent Rayleigh–Bénard convection. Exp Fluids 64, 46. https://doi.org/10.1007/s00348-023-03589-9 (Pub, 26th Jan 2023, 16 pages)

J3. Eghbali, S., Banks, J., and Nobes, D. S. (2021). A numerical study on compositional modeling of two-phase fluid flow and heat transfer in vertical wells. Journal of Petroleum Science and Engineering, 201, 108400. (accepted, 11th Jan 2021) https://doi.org/10.1016/j.petrol.2021.108400

J4. Speer, C.P., Michaud, J.P., Miller, D.A., Stumpf, C.J.A. and Nobes, D.S. (2017) Empirical Heat Transfer Correlations of Finned-Tube Heat Exchangers in Pulsatile Flow. World Academy of Science, Engineering and Technology, International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering, 11(6), 1150-1155.

*Conference Proceedings*

C1. Kashanj, S. and Nobes, D.S., (2023) Application of 3D LIF and PIV in studying Poiseuille-Rayleigh-Bénard convection, 20th International Symposium on Flow Visualization, 10 – 13 July 2023 Delft, The Netherlands. (2 page abstract)

C2. Kashanj, S. and Nobes, D.S., (2023) 'Role of Large-Scale Circulating Structures in Mixed Convection of Poiseuille-Rayleigh-Benard Convection', Proceedings of the 8th Thermal and Fluid Engineering Conference, TFEC-2013-45997, University of Maryland, USA, March 26-29, 2023

C3. Hasanovich L. and Nobes, D.S., (2023) 'Effect of Heat Exchanger and Engine Geometry on Power Output of a Low Temperature Difference Stirling Engine', Proceedings of the 8th Thermal and Fluid Engineering Conference, TFEC-2013- 45999, University of Maryland, USA, March 26-29, 2023

C4. Kashanj, S., Saffar, Y., Sabbagh R., and Nobes D.S. (2022) Calculation Of The Nusselt Number From Temperature And Velocity Data Obtained From Enhanced 3D Two-Colour LIF And 3D PTV In A Rayleigh-Benard Convection Cell. 20th International Symposium on Applications of Laser and Imaging Techniques to Fluid Mechanics, 11-14 July 2022 Lisbon, Portugal. (9 pages)

C5. Hasanovich L. and Nobes, D.S. (2021) Investigation of effect of heat exchanger size on power output in low-temperature difference Stirling engines, 19th International Stirling Engine Conference, Rome, Italy, Sep. 2021, p. 14. doi: https://doi.org/10.1051/e3sconf/202131303002. (14 pages)

C6. M. Lottmann, de Rouyan, Z., Hasanovich, L., Middleton, S.M.W., Nicol-Seto, M., Speer, C. and Nobes, D.S. Development of a 100-Watt-Scale Beta-Type Low Temperature Difference Stirling Engine Prototype, 19th International Stirling Engine Conference, Rome, Italy, Sep. 2021, p. 15. doi: https://doi.org/10.1051/e3sconf/202131308004. (15 Pages)

C7. Kashanj, S. and Nobes, D.S. (2021) Application of Simultaneous Time-Resolved 3-D PTV and Two-colour LIF in Studying Rayleigh-Benard Convection, 14th International Symposium on Particle Image Velocimetry, Chicago, USA 1-4 Aug 2021 (ONLINE) (2 pages)

C8. Hasanovich, L. and Nobes, D.S. (2021) Investigations into the effect of heat exchanger volume and geometry on low-temperature Stirling engine performance, Proceedings of the Canadian Society for Mechanical Engineering International Congress 2021, June 27-30, 2021, Charlottetown, PE, Canada (ONLINE) (6 pages)

C9. Kashanj, S. and Nobes, D.S. (2021) Investigation Into The Onset Of Turbulent Rayleigh-Benard Convection Using Time-Resolved 2-D Particle Image Velocimetry, Proceedings of the Canadian Society for Mechanical Engineering International Congress 2021, June 27-30, 2021, Charlottetown, PE, Canada (ONLINE) (5 pages)

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*Student Thesis*

T1. **Matthias Lottmann** (2022) "Validation and Testing of a Numerical Model for the Design and Up-Scaling of Low Temperature Difference Stirling Engines", Difference Stirling Engine M.Sc. Thesis, The Department of Mechanical Engineering, University of Alberta, Edmonton, Canada.

T2. **Linda Hasanovich** (2022) "Effect of Heat Exchanger Volume and Geometry on Power Output of a Low Temperature", Difference Stirling Engine", M.Sc. Thesis, The Department of Mechanical Engineering, University of Alberta, Edmonton, Canada.

T3. **Michael Nico-Seto** (2021) "Investigation of a Drive Mechanism Modification to Increase Thermodynamic Power of a Low Temperature Differential Gamma Type Stirling Engine", M.Sc. Thesis, The Department of Mechanical Engineering, University of Alberta, Edmonton, Canada.

T4. **Steven Middleton** (2021) "Stirling Engines and Single-Phase Thermodynamic Machines", M.Sc. Thesis, The Department of Mechanical Engineering, University of Alberta, Edmonton, Canada.

T5. **Jason P. Michaud** (2020) "Low Temperature Difference Alpha-Type Stirling Engine for the Experimental Determination of Optimal Parameters to Maximize Shaft Power" M.Sc. Thesis, The Department of Mechanical Engineering, University of Alberta, Edmonton, Canada.

T6. **Gabriel B.P. Salata** (2019) "Post finishing techniques to improve the functionality of 3D printed parts" M.Sc. Thesis, The Department of Mechanical Engineering, University of Alberta, Edmonton, Canada.

T7. **David A. Miller** (2019) "Experimental Investigation of Stirling Engine Modelling Techniques at Reduced Source Temperatures", M.Sc. Thesis, The Department of Mechanical Engineering, University of Alberta, Edmonton, Canada.

T8. **Calynn Stumpf** (2019) "Parameter Optimization of a Low Temperature Difference Gamma-Type Stirling Engine to Maximize Shaft Power", M.Sc. Thesis, The Department of Mechanical Engineering, University of Alberta, Edmonton, Canada.

T9. **Connor Speer** (2018) "Modifications to Reduce the Minimum Thermal Source Temperature of the ST05G-CNC Stirling Engine", M.Sc. Thesis, The Department of Mechanical Engineering, University of Alberta, Edmonton, Canada.

## H. BENEFITS

**Please provide a narrative outline the project's benefits. Please use the subheadings of Economic, Environmental, Social and Building Innovation Capacity.**

- **Economic:** Describe the project's economic benefits such as job creation, sales, improved efficiencies, development of new commercial opportunities or economic sectors, attraction of new investment, and increased exports.
- **Environmental:** Describe the project's contribution to reducing GHG emissions (direct or indirect) and improving environmental systems (atmospheric, terrestrial, aquatic, biotic, etc.) compared to the industry benchmark. Discuss benefits, impacts and/or trade-offs.
- **Social:** Describe the project's social benefits such as augmentation of recreational value, safeguarded investments, strengthened stakeholder involvement, and entrepreneurship opportunities of value for the province.
- **Building Innovation Capacity:** Describe the project's contribution to the training of highly qualified and skilled personnel (HQSP) in Alberta, their retention, and the attraction of HQSP from outside the province. Discuss the research infrastructure used or developed to complete the project.

*RESPOND BELOW*

### 1. ECONOMIC

There are two main areas that this project has developed economic benefit. These are, the training and development of HQSP in an advanced area of engineering and the development of numerical models that can be used to further develop new technology that will utilize geothermal and waste heat. The HQSP have received advanced training in engineering, fundamental physics of fluid mechanics, thermodynamics and heat transfer, design and development of complex mechanical systems, modelling of complex phenomenon in the collection and validation of models using experimental data. All of these areas are highly relevant in the Alberta engineering landscape and these HQSP will make valuable contributions in the future. The advanced modelling that was undertaken during this project included the development of a multiphase multicomponent model for predicting the extraction of heat from end-of-life oil wells and an extensive model for predicting thermodynamic cycles that is mostly focused at Stirling engines (MSPM). The model predicting heat extraction from geothermal sources will be an important tool for development of new technology that addresses a serious problem in Alberta: what to do with end-of-life oil wells? If enabling technology can be developed to allow this heat to be used both commercially and industrially, this would have a significant impact on the economics of the province. MSPM, while been used extensively for predicting the performance of a Stirling engine, can also be used or other heat engines and thermodynamic cycles. It is much more extensive than currently available models and will be an important tool for developing new technology in this area.

## 2. ENVIRONMENTAL

The development of any technology used to address environmental issues requires the development of mathematical models that can underpin the physics and be used for predictive and optimization of the design. The two numerical models developed in this project both are aimed at technologies that will have immediate effect on the environment. Whether with this is through the more efficient use of heat or the replacement of carbon based technologies for the generation of energy.

## 3. SOCIAL

In this area, the project is perhaps most beneficial in providing fundamental knowledge and understanding for entrepreneurship opportunities of value for the province. Startup companies that are aiming to use geothermal energy or waste heat will benefit from the fundamental knowledge developed in this project. As well, the numerical models that have been developed can be used to significantly underpin the development of new technology allowing startup companies to move further forward with their technologies.

## 4. BUILDING INNOVATION CAPACITY

The project, taking into account the full life of the project supported by Future Energy Systems (FES) and Alberta Innovates, has had a significant impact on the training and development of 34 HQSP. The majority of these personnel are Albertans who have come through the engineering program at the University of Alberta. Overseas students have also been involved in advanced roles undertaking a PhD and PDF positions. While the project does not move forward into the development of startup companies, these personnel have move forward in their careers working in different companies across the province. Sharing their knowledge and skills developed during the project will build capacity in Alberta through the use of advanced engineering and scientific techniques that were use during this project.

## I. RECOMMENDATIONS AND NEXT STEPS

**Please provide a narrative outlining the next steps and recommendations for further development of the technology developed or knowledge generated from this project. If appropriate, include a description of potential follow-up projects. Please consider the following in the narrative:**

- Describe the long-term plan for commercialization of the technology developed or implementation of the knowledge generated.
- Based on the project learnings, describe the related actions to be undertaken over the next two years to continue advancing the innovation.
- Describe the potential partnerships being developed to advance the development and learnings from this project.

*RESPOND BELOW*

Long-term plan for commercialization: An overarching aim of this project was to identify system solutions based on Stirling engine technology for the conversion of geothermal waste heat into useful energy. This aim is still relevant and the project has shown that Stirling engine technology could be used. However, in its current form, it is uneconomical to take this further forward. Further development and understanding in the area of heat transfer needs to be established before the technology can move forward. The long-term plan that needs to be undertaken before developing commercialization steps is to continue research to identify breakthroughs in heat transfer technology for the complex system of reciprocating working fluid in a Stirling engine.

Next steps for advancing the innovation: Next steps are all focused on conducting fundamental research in heat transfer, with a particular focus on convective heat transfer in reciprocating laminar flow systems. The PhD student who has been working on the project will continue this area until the completion of their PhD studies. To do this, they will continue to be supported by the PI of this project. Continued research in the area will require funding that allows this fundamental research to be undertaken and will be sought through application to appropriate granting agencies such as NSERC. Where possible, commercial entities and industries that would benefit from this technology development will be identified to develop collaborations. With an appropriate breakthrough in enhancing the convective heat transfer in a laminar reciprocating flow, a future project could then be developed that could develop the technology further.

Partnerships: No immediate partnerships have been identified or developed.

## J. KNOWLEDGE DISSEMINATION

**Please provide a narrative outlining how the knowledge gained from the project was or will be disseminated and the impact it may have on the industry.**

*RESPOND BELOW*

The dissemination of the knowledge gained in this project is mostly through the publication of the knowledge in general and conference papers and student theses. These documents are all listed in Section G-4 PROJECT OUTPUTS of this document.

Dissemination and impact on industry will mostly be through the training of HQPS during the project and their interaction in their future careers in local industry.

## K. CONCLUSIONS

**Please provide a narrative outlining the project conclusions.**

- Ensure this summarizes the project objective, key components, results, learnings, outcomes, benefits and next steps.

*RESPOND BELOW*

This project undertook a very challenging aim, to investigate and develop the potential of Stirling engine technology for the conversion of geothermal and low-grade waste heat from industry into useful energy. It was challenging because for the low available heat source temperatures (<150 °C) there is essentially no technology currently available. Also, while Stirling engine technology has had a long history, it is only had sporadic use and has only been commercialized in a limited number of applications. The potential of this technology has continued to be identified as promising but has been overshadowed by carbon based engine systems that had quickly proven to be reliable in providing appropriate solutions.

The main key result from the research up to this point is that convective heat transfer is the limiting physics in the conversion of a temperature difference into useful energy with a Stirling engine. The temperature difference between a high temperature source and a low temperature sink can be converted into mechanical energy with a Stirling engine which then can be used to drive an electrical generator. Fundamentally, the Stirling engine has very high promise because its fundamental Carnot efficiency can be as high as 50%, significantly higher than internal combustion engines that are at best ~25%. To achieve such a high efficiency for a Stirling engine however, requires that each individual process within the engine operated at its theoretical limit. Energy losses through friction and thermodynamic inefficiencies can be masked for high-temperature Stirling engines by running the engine at a higher hot source temperature to recover the losses. This is not possible when the available hot source temperature is <150°C, limiting the energy available for driving the engine. Of these processes, convective heat transfer from the hot source to the working fluid has been identified as the limiting inefficiency in the system. This is true for both low-temperature and high-temperature Stirling engines. It is therefore paramount that this limitation be appropriately addressed so that any Stirling engine technology can be used effectively in the future.

Extensive numerical models of the Stirling engine (MSPM) and heat extraction from end-of-life oil wells were developed during this project. These models are much more extensive than what is currently used or can be found within the literature to predict the performance of these different technologies. The learnings and outcomes from the development of these models will lead to significant benefits across different technologies. For Alberta, the development of the model for heat extraction from end-of-life oil wells will have an immediate impact on technologies that will address the large number of these wells for heat extraction. A significant benefit also from this project has been the training and experience gained by the 34 HQPS working on the project. These engineers benefited greatly through the experience that they gained on the project and they will take this forward in their future careers and impact the companies that they work for.

The next steps in this area will aim at addressing the fundamental limitation identified by this project. This being to determine how heat transfer can be enhanced in the complex flow regime within a Stirling engine. Here, the working fluid reciprocates within small channels intrinsically leading to the flow maintaining a laminar or near laminar state. Laminar flow has poor cross stream heat transfer and is avoided in all convective heat transfer systems. Further fundamental research into how the cross-stream component of convective heat transfer can be enhanced to transport heat from the surface into the working fluid needs to be undertaken before Stirling engine technology can be further developed below temperature systems.