Propulsion Thermal Management for Fuel Economy Improvement of Mild Hybrid Vehicles

By

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ABSTRACT

Over the years, reducing the emission pollutants coming from transportation vehicles has been one of the main targets. As a counter, vehicle manufacturers have been spending a lot of time in research and development for electric vehicles (EV) and hybrid electric vehicles (HEV). With the increased number of electronics, auxiliary components, design complexity and weight increase introduced to vehicles, the thermal management system (TMS) can be of great positive influence. The management system can target improvements in fuel economy, range, comfort, and safety. Its function consists of maintaining and controlling temperatures, pressures, and load ranges of the system. The focus of this thesis is to design three distinct cooling loops. The first loop is the high temperature cooling loop taking care of the engine cooling. The secondary loop takes care of the low temperature components and electronics. Lastly, the refrigerant loop which ensure drivers and passenger comfort was testing by implementing a cool down test and demonstrated the ability to follow real life results and by remaining in the set error ranges. After executing the analysis of the model, it has shown that the Low Temperature Recirculation Loop's highest exergy destruction comes from the heat sink since the battery module has a loss of about 0.16 kW. Furthermore, having investigated the electrical pumps and fan, the state of charge of the battery from its initial charge percentage to shows close to a 20% reduction of change of power by maintaining the 80 W pump around 50% activation and 20W pump around 20% activation and remaining in desired component temperature ranges.

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LIST OF ABBREVIATIONS/SYMBOLS

AC – Air conditioning

AGS – Active grill system

HTRL – High temperature recirculating loop

HVAC – Heating, ventilation, and air conditioning

LTRL – Low temperature recirculating loop

TMS – Thermal management system

VCR – Vapor compression refrigeration

WCAC – Water charge air cooler

WLTC – World harmonized light vehicles test cycle

NOMENCLATURE

A = Cross-sectional area

A_{eff} = effective area

c_p = Specific heat capacity

D = Reference length

g = Gravity

h = Convective heat transfer coefficient

h_{ref} = Reference heat transfer coefficient

h_l = Liquid phase enthalpy

h_g = Gas phase enthalpy

h_{vg} = Heat of vaporization

h_f = Heat of fusion

k = Fluid thermal conductivity

k_l = Liquid thermal conductivity

k_w = Wall thermal conductivity

$\dot{m}$ = Mass flow rate

m^n = Mass flux

Nu_l = Single phase liquid Nusselt Number

$P_{1,total}$ = Total pressure into valve

$P_{2,total}$ = Total pressure out from valve

P = Actual pressure

P_{cr} = Critical pressure

P_r = Prandtl number

P_{rl} = Liquid phase Prandtl Number

ρ_l = Liquid density

ρ_g = Gas density

q^n = Heat flux

$q^n ref$ = Reference heat flux

R_e = Reynolds number

σ = Surface tension

T_{sat} = Saturation temperature

T_w = Wall temperature

μ_l = Liquid phase viscosity

μ_g = Gas phase viscosity

V = Liquid phase velocity

x = Quality

CHAPTER 1
INTRODUCTION

1.1 Background and Rationale

For many years it has been proven that transportation of passengers and goods using road vehicles have increased pollution worldwide through emissions. In 1992 emission standards were implemented, particularly in Europe, for passenger cars and light duty vehicles [1]. These standards and regulations made it more difficult for vehicle manufacturers to achieve the new goal of not only meeting customer demands, profiting from sales but also to ensure their fleet remained within the new limitations for homologation. The initial European standard called Euro 1 as stated from above, underwent many iterations looking at improving and reducing emissions [1]. This type of regulation deals with pollutants such as carbon monoxide, hydrocarbons, NOx emissions, particulate matter, and particulate number thus, forcing automotive companies to use resources in the research and development groups to abide the regulations [2].

The burning of fossil fuels not only has an impact on local environments, but it is also a global issue. These fuels emit pollutants like carbon dioxide and greenhouse gases in our atmosphere [3]. At a local level, these emissions will affect the air quality, increase the risk of smog and surface layer ozone depletion. The results of these pollutants will lead to an impact on the local environment and health of the population.

Pollutants do not only target local areas, but this has an overall global impact. A good example of this impact is global warming, which has been experienced by and impacted everyone in the world [3]. In the United States, about 27% of greenhouse gases are from transportation alone where over 57% comes from light duty vehicles alone [4].

Due to the drastic changes required from vehicle manufacturers, it was up to them to find necessary solutions to these new limitations. This introduced many technological advancements in the increase in efficiency of the internal combustion engine (ICE) powertrain. In terms of efficiency versus area of improvement, the powertrain has a 1:1 ratio in terms of fuel saving compared to other areas of research such as aerodynamics or rolling resistance. The idea of electrification of vehicles was the next possible option in terms of benefits and attaining the new demands.

1.2 Objectives and Scope

It is well known that designing a proper thermal management system is very difficult [5]. The industrial partner Stellantis has provided both the type of mild hybrid electric vehicle (MHEV) model as well as the architecture however, an entire thermal cooling system must be designed from scratch using experimental data taken from the lab, while satisfying the given constraints. The entire TMS consists of three distinct loops: the high temperature recirculation loop High Temperature Recirculating Loop (HTRL) for the conventional vehicle, the Low Temperature Recirculation Loop (LTRL) for the Hybridization Unit (HU) unit and lastly the refrigerant circuit. Since the TMS is in relation with the powertrain of the vehicle, a selected number of components are chosen to be implemented to represent the system as shown in the diagram provided by the industrial partner. The model is firstly be designed by having each loop built separately and calibration done using experimental data for validation. Once each model satisfies the reference data, the next step is to have the each of these systems work together as a single unit where the model can undertake transient simulations from a World Harmonized Light Vehicles Test Cycle (WLTC) driving cycle. This data will be collected and an exergy analysis of each component in the HU will be accomplished alongside the HVAC model.

This opens the possibility to determine where the highest exergy destruction occurs in the system alongside exergy efficiency throughout the model. Having this in mind and from literature review, the transient model will undergo harsh environmental conditions such as high ambient temperatures to understand the response of the system. On top of this, the electric pumps influencing the HVAC heat transfer are investigated by having the simulation run from the lowest allowable setting to having the pumps and fans functions at its highest setting. From there, a selection using a matrix is developed to give a rough estimate of potential fuel savings from the TMS only in relation to reference data.

1.3 Outline of Thesis

The thesis is broken down by having Chapter 2 going over literature review where the investigation of previous methods of approach with subsequent were utilized to understand the gap in research and the great knowledge available. Following, Chapter 3 where the methodology of the project is detailed for each sub-assembly and overall design of the thermal management system. Then, Chapter 4 will explain the results and discussion of the findings from developing and designing a TMS from blank and using the industrial partners reference diagram as the architecture.

CHAPTER 2

LITERATURE REVIEW

Series hybrid electric vehicles offer an indirect power transfer from an ICE to the driving wheels. One of ICE's tasks is to transfer energy from fuel into mechanical energy. This mechanical energy is then transferred to an electric machine. The job of an electric machine can be of both a motor and generator. The ICE will be able to generate energy into the battery to supply the necessary power request from the driver. The ICE will not be able to directly provide power to the wheels.

The next option consists of a parallel architecture. This type of architecture has been distinctively categorized depending on where the connection between the hybridization unit (HU) and the e-Drive system. The categories are known as "P" allocating a specific number beside it. Firstly, we have P1 where it can be both non-co-axial and at the front of the engine or can be connected directly behind the engine onto the flywheel. Next, the P2 option where the HU is connected to the front of the transmission allowing a coupling and decoupling from the ICE. The P3 option connects the HU to the back of the transmission and the differential. Lastly, P4 is connecting this system to the other axle introducing the option of AWD.

This project consists of a mild hybrid electric (MHEV) vehicle with a P2.5 hybrid configuration with the use of a 48V battery. With this type of architecture, this HU allows the introduction to three different operations other than a standard ICE. The first option is the engine start and stop feature. After a certain amount of time stopped for example waiting for the light to turn green at an intersection, the combustion engine will turn off.

When a vehicle is idling, the engine is not operating in its most efficient operating range highly impacting the vehicles economy [5] as shown in Figure 1, this demonstrates an optimal operating line (OOL) investigated by [6]. Although most engines have different configuration, size, and performance, they will all have an OOL and as shown idling which usually occurs below 1000rpm falls below that region. The second feature of a MHEV is the ability of recovering energy while the driver is applying the brakes. As conventional vehicles use the energy transfer of a fluid to power through a chemical reaction, it is not possible to recoup some of that energy. This being only possible through a hybrid architecture (excluding some micro-hybrids) can be shown in Figure 2 and demonstrates the great advantage of unlocking this feature. The last option available in a MHEV is the electric-motor assist. This feature allows the conventional internal combustion engine to be assisted during operations like cruising and can be temporarily replaced by the e-motor for short period of times and low speeds to travel.

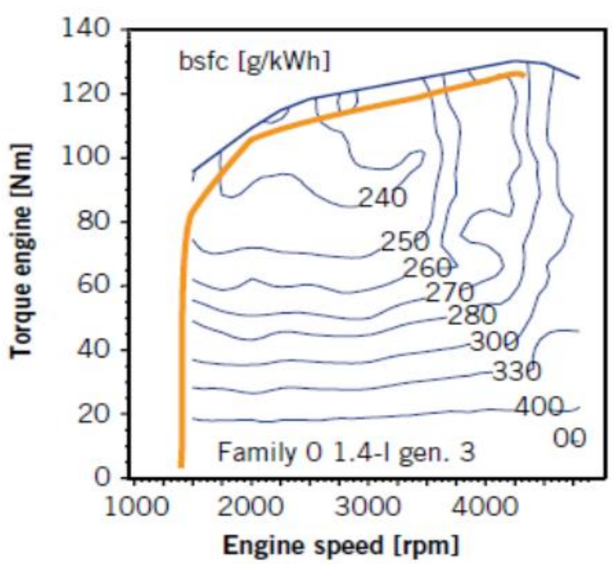


Figure 1 - Orange trace represents the engines optimal operating line in brake specific fuel consumption of the torque and engine speed specifications [5]

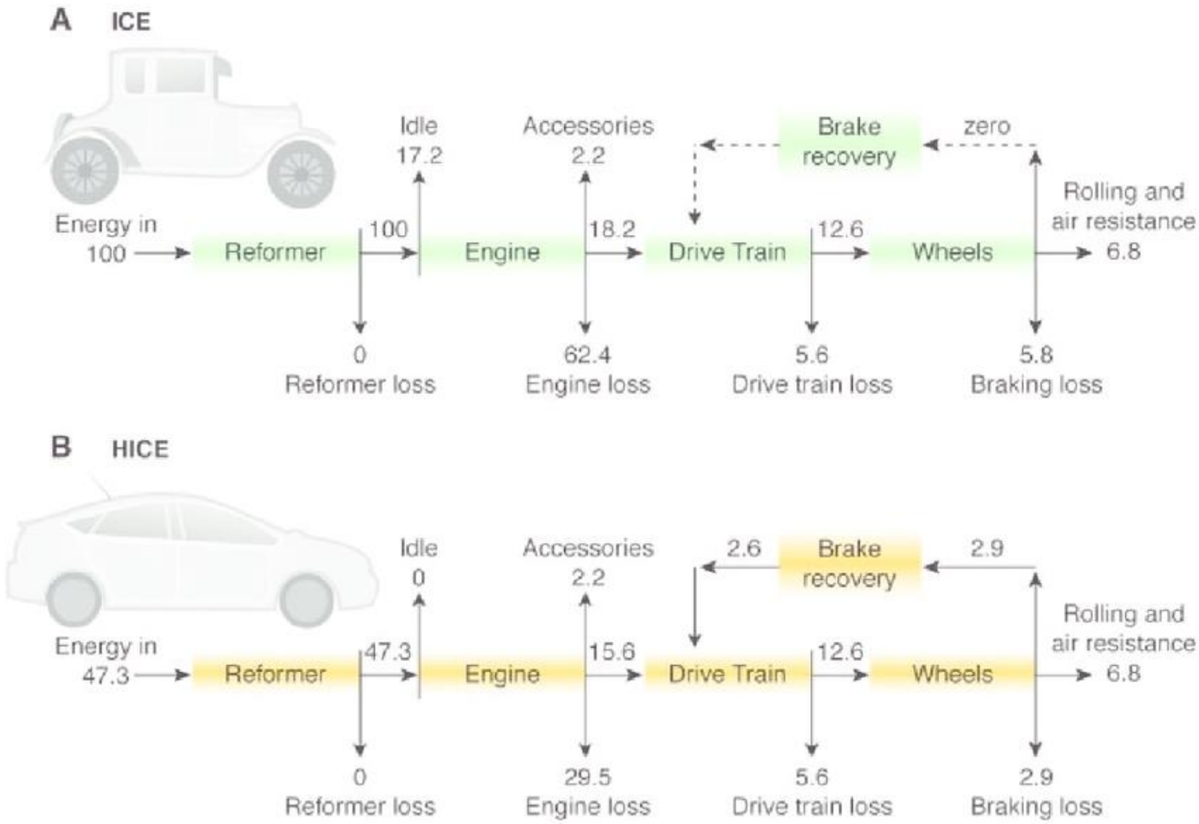


Figure 2 - Demonstrates the different energy paths of different vehicle configurations. In **A** we can see the standard conventional ICE engine, **B** the Hydrogen Internal Combustion Engine and [7]

When introducing hybrid electric vehicles there are many different options in terms of design. The first step is to define the architecture of the powertrain. The architecture can be broken up into two main concepts, which allows the ICE to provide power directly or indirectly to the wheels.

There are four different categories in which the system can be of usage. The first option is the option to run only on pure electric. With the architecture made to have a coupling/decoupling of the engine from the transmission, the engine can be fully disconnected, and the battery will provide the necessary power requested until a certain threshold. The other option is to have the ICE recharge the battery during idling or when the battery is too low to provide the necessary power request. The last two options will be to run either pure thermal meaning the e-Drive is no longer providing power to the batteries or we have the option to have the system to have a power split between the ICE and Electrification. This is when both power supplies work together to meet the requested torque from the driver.

Thermal Management System Itemization

Now understanding the possibilities and improvements, one key consideration is to understand the application of new components and their involvement from a thermal management system point of view. Thermal management systems (TMS) for conventional vehicles have been important at ensuring components such as the engine would operate at a temperature range to work at high efficiency and safely. When it comes to the hybridization unit and the components, they are not involved in the same cooling flow path. The base components of a 48V architecture are shown in Figure 3 [8] where new components involved are the battery pack, DC/DC inverter and an Electric Motor mentions that in the implementation of these new components, it is very challenging for the 12V battery found in a standard ICE vehicle to be able to operate these new components. This means that there is no risk of electric shock, and there is no need for isolation. Thorough research in the TMS has been developed by [9] where different methods are used to reduce the fuel consumption of the newly designed vehicle architecture.

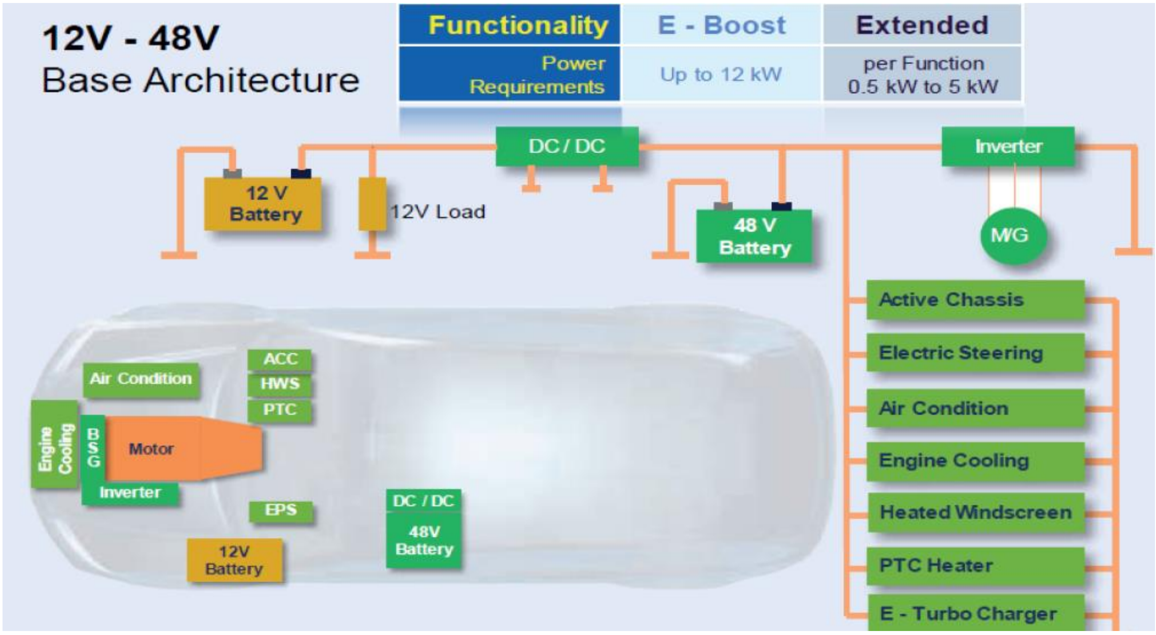


Figure 3 - Basic architecture of a mild hybrid vehicle with an implemented 48-V Battery [8]

The thermal management system required for the hybridization unit functions at much lower temperatures than the conventional ICE cooling system and introduces new potential safety concerns. The battery in this system functions in two ways, one being under charge from regenerative braking or from the ICE. The second behaviour is discharging where energy from the battery is being shared to components in the HU. A phenomenon called thermal runaway where when the temperature of the cell becomes too high, there is a release of energy and creates a short circuit which could lead to battery failure or a hazard. The cooling system of the HU has its own flow path and is not directly connected to the conventional ICE cooling system. This is due to the difference in operating temperature which the components need to be maintained. A refrigerant loop concludes the three cooling loops and allows the ability to control comfort requests inside the cabin to meet passenger and driver demands

The reason behind this is justified by having the LTRC being in a separate loop than the conventional high temperature recirculation loop (HTRL) functions using an electric pump rather than a mechanical pump. A mechanical pump is directly connected and dependent on the engine speed, meaning that there are less degrees of freedom when it comes to usability. Where for the electric pump, being independent to vehicles engine, can function and controlled as needed. Having the cabin model related to the low temperature loop does however increase the severity and importance of the cooling management system of the LTRC and could also increase the consumption depending on the request coming from the cabin.

The comprehension of the involvement of the new components and the application of a new cooling loop opens the opportunity to see what can be accomplished for this challenge. Methods of analysis for a TMS can be broken down into 4 main categories being: a battery thermal management systems (BTMS), HVAC/evaporator improvements, numerical modelling, and exergy analysis.

Starting with the BTMS, an efficient way of improving a hybrid system is by optimizing the thermal system of the battery pack. [10] investigated different types of battery material as well as an air cooled BTMS. From there, they were able to look at some potential cost reduction by also looking at environmental conditions that would put the management under high stress and ensuring no thermal runaway occurs for safety and reliability. Furthermore, another interesting approach from [11] to develop a model investigating the SOC of the battery and developing an algorithm with battery physics to not only reduce fuel economy but also understanding the aging of help prevent premature wear.

Second, one of the major components in the HVAC system is the compressor where it is the component that requests the most power demands and was analyzed by [13] where they were able to make a direct connection between fuel consumption by implementing a new 7:2 compressor architecture. This is important in understanding the potential in sizing of components which entails [13] as they undergo a full analysis in the replacement of R134a primary refrigerant to R1234yf to introduce a more environmentally friendly fluid . And lastly. Important findings from [13] who also use R1234yf as the refrigerant investigates the importance of pressure drop and the heat transfer in the evaporator being one of the most important components for efficacy in a vapor compression refrigerant cycle (VCR). They also introduce an initial understanding of the system as a whole and how a higher performance can be achieved.

Thirdly, we have numerical modelling for optimization of thermal management systems. When it comes to optimizing full thermal management system with the intent of shaving off on fuel consumption or emissions, there are many algorithms, controls or models that can be implemented. One suggestion by [14] is to simulate a vehicle's Model Predictive Controller (MPC) that is implemented in the e-motor. The functionality of this create a matrix space of dimensionless constants and the model uses this to filter and calculate the control that should be applied onto the e-motor. The results show that by only focusing on a single component, the emissions of CO_2 can be greatly reduced and they were even able to reduce their original target. Furthermore, another model which allows the involvement of an entire cooling system is a Model Based System Engineering (MBSE) with the use of other computational tools. This type of model allows the opportunity to do such model like by [15] where from the selection of components, parameters, initial rules were able to globally optimize the system architecture by having the simulation go through different configurations. This study is important as it focuses on the pump and head loss optimization as they further discuss the importance in usage but also implement this system in a transient analysis being the WLTC cycle that is used by many countries all over the world especially in the European area. This architecture optimization modelling was eye opening to the possibility and the importance of the chosen parameters as they were able to have an efficiency difference of about 69% between different configurations.

The fourth and last section of important literature is research done on exergy analysis. When it comes to doing analysis of a system consisting of a flow system, mass, energy and exergy analysis are thoroughly investigated in as follow [16] - [22]. The use of exergy analysis is based on the principle of the second law of thermodynamics and opens the option of optimizing the system where the thermodynamic book [23] are useful in exergy and energy systems and analysis which is utilized for a great detailed understanding . In many research found, most of the time the exergy analysis is done on a single component such as one by [21] where they did an entire exergy analysis on a specified automotive radiator and different percentages of brines (percentages between ethylene glycol and water mixture up to 25%). They were able to conclude that by increasing the brine concentration meaning higher percentage of the ethylene glycol that there would be a decrease in heat transfer rate as well as effectiveness. Continuing, [24] have implemented an exergy analysis on a simplified vapor compression recirculation system with the implementation of a phase change material in reducing the heat load coming from the chiller. With the findings of the exergy analysis, they were able to then find the efficiency of the system and components and using a multi-objective optimization and genetic algorithm as part of their numerical modelling were able to find a relationship between maximizing the exergy efficiency while minimizing the cost rate of the system.

CHAPTER 3

THERMAL MANAGEMENT SYSTEM MODELLING AND DESIGN

The first step in designing a thermal management system is to investigate each individual loop and understand the relation or connection between the systems. As shown in Figure 4, there are three distinct loops in the system, each denoted with an associated colour. The red loop represents the HTLR loop consisting of the powertrain components and having the highest coolant temperature of the system. The green loop consists of the LTRL for the HU cycling at lower temperatures that the HTRL. Lastly, the blue loop consists of the refrigerant loop allowing cabin comfort during high ambient temperatures. However, by closer inspection it can be seen that all three loops are in association with one another and on top of that, there is another link between the HTRL and the refrigerant recirculation taking care of the air conditioning.

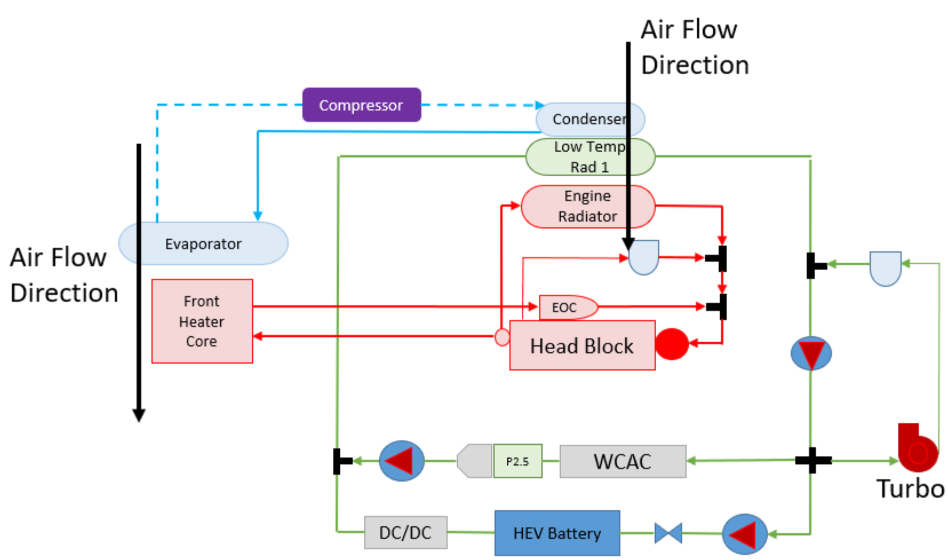


Figure 4 - Diagram of the thermal management system to be modelled and simulated. Red represents the HTRL, Green is the LTRL, and Blue is the HVAC refrigerant loop

By looking at the placement of the condenser and the radiator of the high and low temperature recirculation loop, it can be seen that air flowing towards the front fascia of the vehicle has to work through a set of series system between these components. As will be discussed in future chapters, each of these components work as a heat exchanger between their respective refrigerant and the air flowing towards the vehicle as it is being driven. As these systems work in series, this means that the heat transfer that occurs is dependent on the component preceding it.

The condenser is the component that is in direct contact with the air flow, meaning that the its performance is highly dependent on the velocity of the vehicle or the fan (section 3.3.3). The mathematical approach of the heat exchange can be further investigated looking at the work done by [25] where the authors perform a full analysis of a shell and tube condenser using the Number of Transfer Units (NTU) method. The NTU method is greatly used when designing or investigating the heat exchanger rate where information can be limited. It relies on the effectiveness of the heat exchanger, and the specific heat ratio of the minimum capable specific ratio over the maximum specific ratio. This is also used most of the time when the outlet temperature of the fluids involved are not present. The heat exchange that occurs impacts the air mass flow rate as well as the air temperature at the exit. The same principle is occurring when the new inlet mass flow rate and temperature of air enters and leaves the low temperature radiator to then flow in the high temperature radiator and finally be released to the environment.

This relation between these heat exchangers is really important as they are all interconnected to one another. This means that the cooling that takes place is impacted by this relationship of these systems. Another important point is that the refrigerant loop or the HVAC system is not always turned on. This means that the condenser in the system sometimes acts only as a flow obstruction without the presence of heat transfer. The same opportunity occurs with the high temperature cooling loop as, depending on the temperature of the coolant, the thermostat will reroute the cooling to enter the by-pass pipe in order to heat the engine as quickly as possible to the desired temperature, which will be discussed further in later chapters. The challenge of this relationship was solved using the GT-SUITE [26]. The model using the correct dimensions and configurations of all of these components were made on a 3D model and then reconfigured into a 1D model. An example of the system is shown in Figure 5 and demonstrates the flow path as well as potential heat exchange.

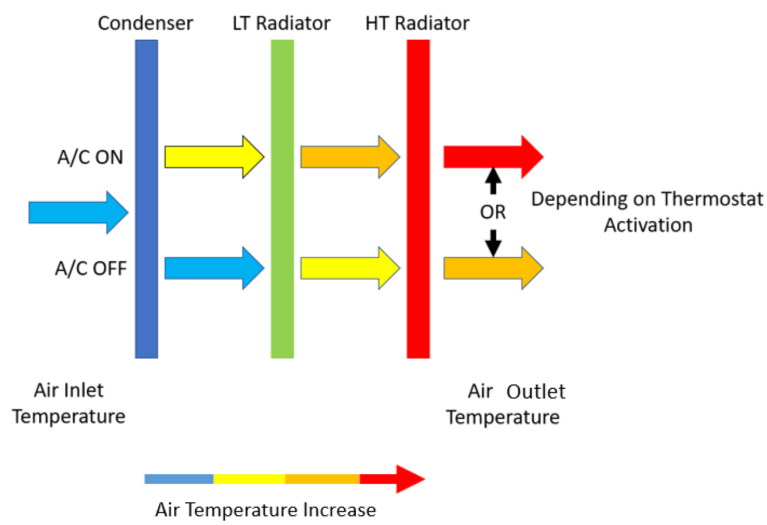


Figure 5 - Simple representation of the air flow going through the heat exchanger systems

The 1D model will also take into consideration the pressure drop on the coolant side and using data provided by the industrial partner, the model can be represented accurately with the correct behaviour.

As regard of the heater core and evaporator, a similar approach was taken into account. The collection of data of the pressure drop dependent on the volumetric flow rate of the coolant has been implemented in the model. In upcoming chapters, there will be discussion of the design and modelling of the HVAC model where results will be provided displaying the accuracy of the model.

Another component in the under-hood model is the cooling fan. Like conventional vehicles, fans are placed behind the condenser/radiator series system. There are two main options and objectives that will be considered in the design and implementation of the fan. The first one is when the vehicle is stopped, which results in no air flow in the system. For this system, having forced convection either from the vehicle in motion or using the fans increases the amount of heat transfer available increasing cooling capabilities. This could cause the cooling systems to increase temperature rapidly and falling in temperature ranges that could overheat the system. This is why the fan can then activate and simulate an artificial air flow by pulling air through the system. The second option is when the operating systems cannot maintain the coolant temperature range needed from the air flow rate alone, the fans can then activate and provoke more air flow through the series system discussed before. As these functions are similar to a pump, it can be designed by controls by the use of sensors the temperature of the coolants in the systems. This will then be working as a switch system where the fan can be turned on/off. The fan also has the potential to work at different rates and not a single speed as being another power consumer can also have an impact on the fuel consumption.

3.1. System Design Introduction

The method of approach for this project is to use a software called Gamma Technologies (GT-SUITE), which has the ability to build such thermal management system using their advanced tools. Simulations of the built system and results will also be provided by their tools. The strategy that is used for this project is to build each component individually having to deal with multiple complex components having different behaviours, usage, and importance. The industrial partner provided important experimental data for each component. These results for each component, are used as baselines. An analysis of each of the components is achieved and a calibration of the system is designed for the behaviour of the modelled components to behave as close as possible to the given data. An important aspect that is taken into consideration in the making of this model is to have it simplified without sacrificing the integrity of the behaviour of a real system. This model will allow the development of a system able output data at a faster rate than more complicated models allowing the opportunity to save time and cost from a manufacturing point of view.

3.2. High Temperature Recirculation Loop

The purpose of the HTLR is to maintain, manage and cool the components involved with the ICE which contain some of the highest temperatures ranging from 90-105 °C. This loop system consists of a secondary refrigerant known as ethylene glycol sharing a 50/50 water mixture. The coolant is used to collect heat from the components as it flows through the circuit allowing each component to maintain a certain temperature range depending on the working condition and also ensure the components work efficiently.

This closed loop system will only take care of the components which will be listed below without having any contact with other loops or components of the thermal management system.

3.3. Component Breakdown

High Temperature Radiator

- Expansion Tank

During the event of a high pressurized cooling system, excess coolant can be redirected to an external tank to prevent over pressurizing in the main system.

- Pump/Aux Pump

A mechanical pump is a component in the system allowing the motion of the coolant through the system.

- Engine

Is a mechanical component that converts chemical energy to mechanical energy allowing propulsion of a vehicle.

- Engine Oil Cooler (EOC)

This device works as a heat exchanger to preserve the life of the engine. It works by exchanging heat to maintain the desired temperature of the oil going into the engine.

- Heater Core

The heater core is the heat exchanger between the evaporator to the cabin to heat it to the temperature in demand.

As mentioned above, these components are involved throughout the circulation of the coolant. Although the components are designed to operate under high temperatures, it is important to ensure the components function at the correct temperature ranges that allow the maximum efficiency and life longevity. Having the components working in their relative operating conditions will increase the performance of the component, help decrease the fuel consumption and increase the life longevity of the component. For example, having the engine function in the correct range of temperature reduces the chance of engine overheating and seizing. Also, having the operating temperature working in too low of temperature lowers the efficiency of the combustion process and working efficiency of the engine. Therefore, having each component involved in the cycle operating at the designed temperature ranges increases fuel efficiency. The cooling loop in such a case will be more predictable to control and maintain thus reducing parasitic power consumption losses.

3.4. Working Schematic of the HTRL

The working flow of the coolant in this schematic can be explained as follow:

Starting from the inlet of the engine:

- Coolant flows through collecting heat from the engine
- at the exit there is a flow split (4-way valve)
    - Flow 1 goes towards an auxiliary electric pump
    - Flow 2 goes towards an expansion tank
    - Flow 3 goes towards the EOC
    - Flow 4 goes towards the radiator
- Cabin heater flow after the aux. e-pump allowing comfort levels in the vehicle's cabin depending on the request

- the flow returns in the flow entering the EOC and immediately returns to the engine's inlet
- Expansion tank flow has a much smaller diameter piping only to allow a pressure relief of the flow if needed
- Radiator function as a heat exchanger reducing the temperature of the coolant before returning to the inlet of the engine.

The working flow of the coolant can be done in two separate operations. When the engine is cold or during low ambient temperatures, the goal is to heat up the engine as quickly as possible to attain the engine's operating temperature. In order to achieve this, the coolant loop will bypass the radiator as shown in Figure 6 to loop back as quickly as possible.

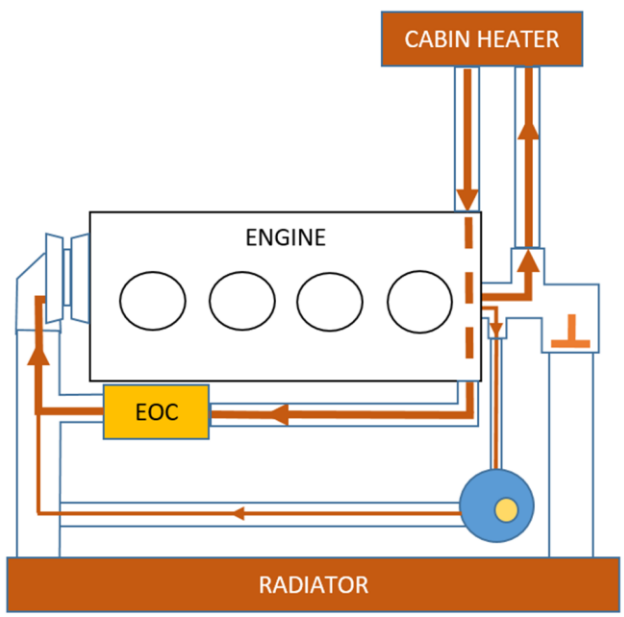


Figure 6 - Demonstration of coolant flow while thermostat is closed

Once the engine and other components have reached the desired temperatures, the next control is to manage and maintain it. This is done by having the thermostat open allowing the coolant to go through a heat exchanger radiator as shown in Figure.7. This heat exchanger will allow air from the ambient temperature to flow through the shell and tube system to cool the secondary refrigerant. The heat exchanger is dependent on the frontal area of the radiator and the speed at which the vehicle is running. This introduces a new component being the cooling fans. This component aids in the suction of airflow through the heat exchanger to meet the cooling demands. However, this component investigated later increases the power consumption and ultimately can impact the fuel economy of the vehicle.

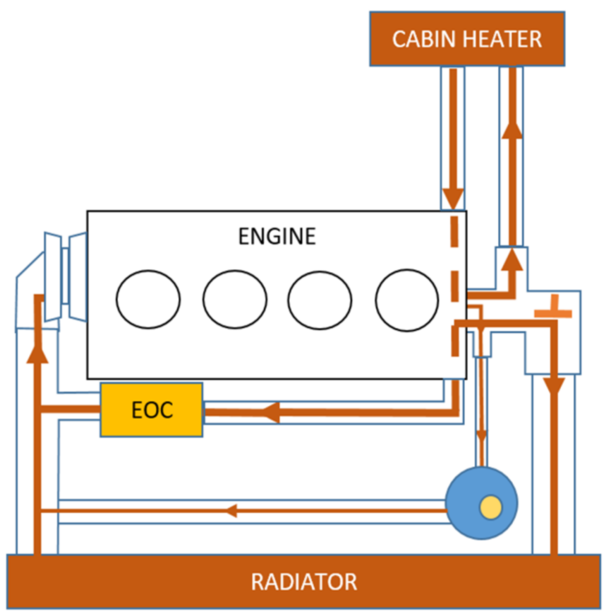


Figure 7 - Demonstration of coolant flow while thermostat is open

3.5.HTRL Design

By looking back at Figure 4, there is a need for development of this loop for further analysis. In order to achieve this, a software called Gamma Technologies (GT-SUITE) is used to build, develop and analyze this cooling recirculation loop. The first in the making of the hot temperature recirculation cooling loop is to reconstruct the given diagram in Figure 4 by understanding the structure and coolant flow directions. This information is useful in determining when the coolant is split or rejoined, ensuring that there is no mass loss in this closed loop design.

After finishing the outline, the next step of the modelling is to apply data. Due to dealing with coolant, being a fluid, and components to make up the cooling system, the method of approach is to investigate the pressure drop at each of these components. Components throughout the system will cause a pressure drop or gain depending on its features. Depending on the system demand, which in this case would be the flow rate, the pressure drop would then increase as there is an increase in flow rate. Since these characteristics are very important in the sizing of the system, it is also important to maintain consistency with the tested results from the industrial partner as shown in Table 1.

Table 1 Engine flow rate relationship with Pressure difference

Flow rate L/h	Difference in Pressure mbar
500	5.0
950	15.0
1700	50.0
2500	120.0
3500	230.0
4500	350.0
5500	450.0
7500	800.0

*Values shown are only set as an example and do not represent real experimental data

3.6. Thermostat Design

The thermostat as briefly mentioned above is used to control the flow path of the coolant to heat up the engine to the appropriate working temperature wanted and also to open access to the radiator when heat exchange is required to cool the secondary refrigerant. The way the thermostat is set up is to sense the temperature of the coolant coming out of the conventional engine. The typical engine working temperature is discussed by [27] found to be from 80 to 105˚C . Having that in mind, the sensed temperature being located after the engine will be recorded and implemented in the behaviour of the thermostat shown in Figure 8 where the initial thermostat state is set to closed for any analysis unless the analysis is specifically requested to be working under an environment where it would need to be open. When the thermostat is closed, the by-pass flow is simply a single pipe that connects where the outlet of the radiator coolant would flow. The effective area that consists of the lift position is found using the equation that considers the mass flow rate and pressure drop of between the inlet and outlet of the valve.

$$A_{eff} = \frac{\dot{m}}{\sqrt{2\rho\left(P_{1,total} - P_{2,total}\right)}} \qquad Eq.1$$

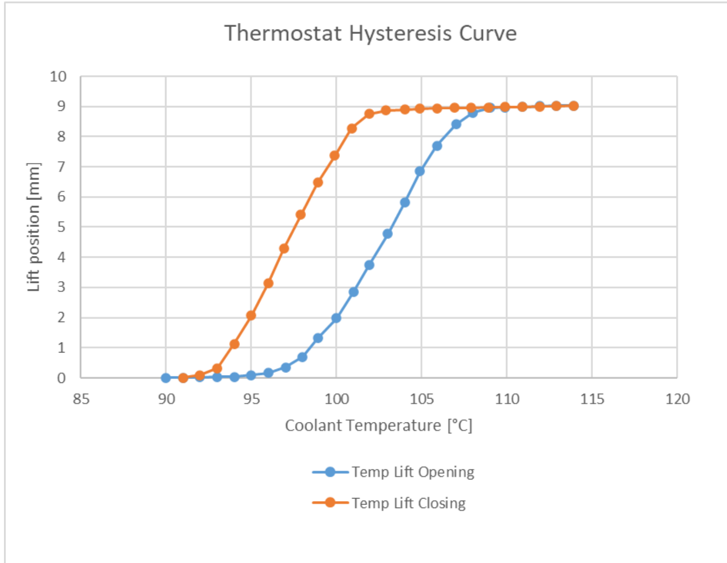


Figure 8 - Thermostat hysteresis behaviour for opening and closing depending on temperature

3.7. Hot Temperature Recirculation Loop Full Model

Now that we have had a component breakdown, have a description of important features such as the thermostat, the next step is to implement all of the components together. Having been provided the type of architecture chosen being a parameter fixed by the industrial partner, the model created was able to accomplish in Figure 9 where the same structure was recreated.

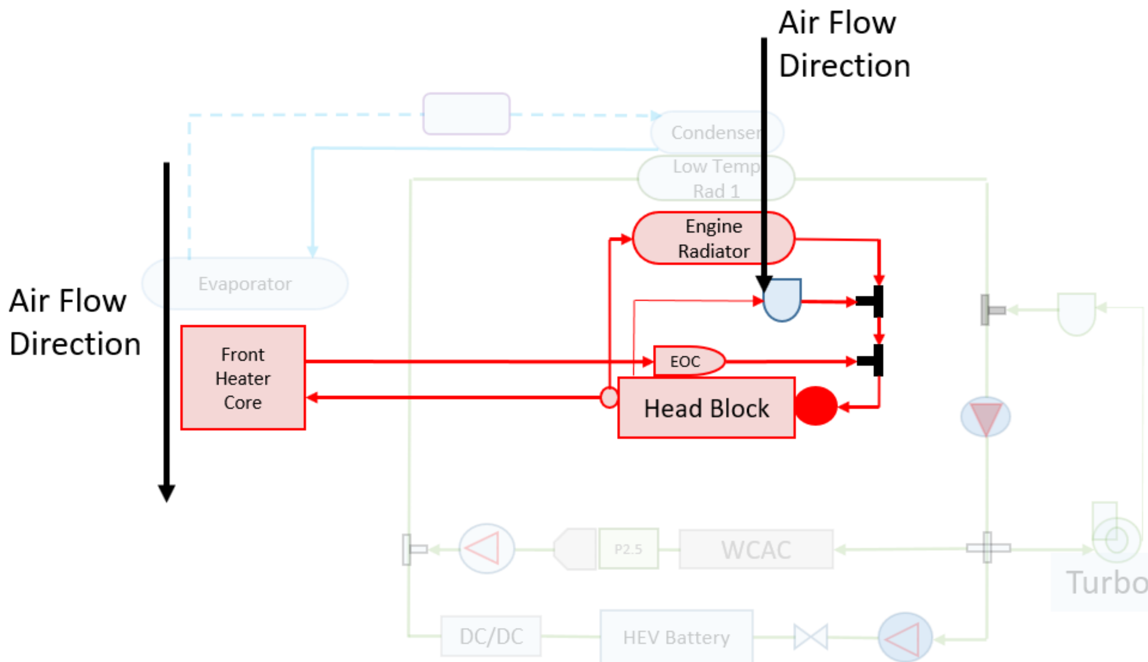


Figure 9 - Full HTLR model created on GT-SUITE involving all components and piping

Importantly, components that are not mentioned are singular pipes, flow split valves implemented in the system. As the idea of this approach is to create a model that is accurate but mostly focuses on the components themselves, pipes were only considered parameter implemented are the diameters. For example, the diameter of the piping for the radiator are 20mm, which is accurate to dimensions for this type of design and are also standard sizes that the industrial partner uses. In terms of thermal considerations, the pipes are adiabatic process and the surface finish are set to smooth removing the potential of friction. The discretization of the pipes is also taken into consideration for the implicit solver. Also, as it will be seen in the results, the exergy analysis does not consider the influence of the pipes in the system which comes in agreement with the method of design.

3.8. Validation

When it comes to validating the model, it is important to make a comparison of the results from the experiments compared to the results of the reference data provided by the industrial partner. Research of allowable errors were researched from previous analysis involving a thermal management system and can be seen in [28] the maximum allowable percentage error was about 10%. Therefore, for future validation, the data will have to be within a tolerance of +/- 10% to stay accurate and on part with other research done. The equation used to distinguish the data is found below.

$$\% \, error = \left| \frac{V_{reference} - V_{experiment}}{V_{reference}} \times 100 \right| \qquad Eq. 2$$

3.9.Low Temperature Recirculating Loop

When it comes to the low temperature cooling loop, the methodology is very similar to the one of the high temperature cooling loop. However, as previously mentioned, the system consists of components that undergo much lower operating temperatures compared to that of a conventional engine. The components involved in the hybridization unit work together and have different flow paths and pipe diameters by looking at Figure 12. The model is designed with the aid of pressure drop across each of the components with a dependency of the volumetric flow rate of the coolant.

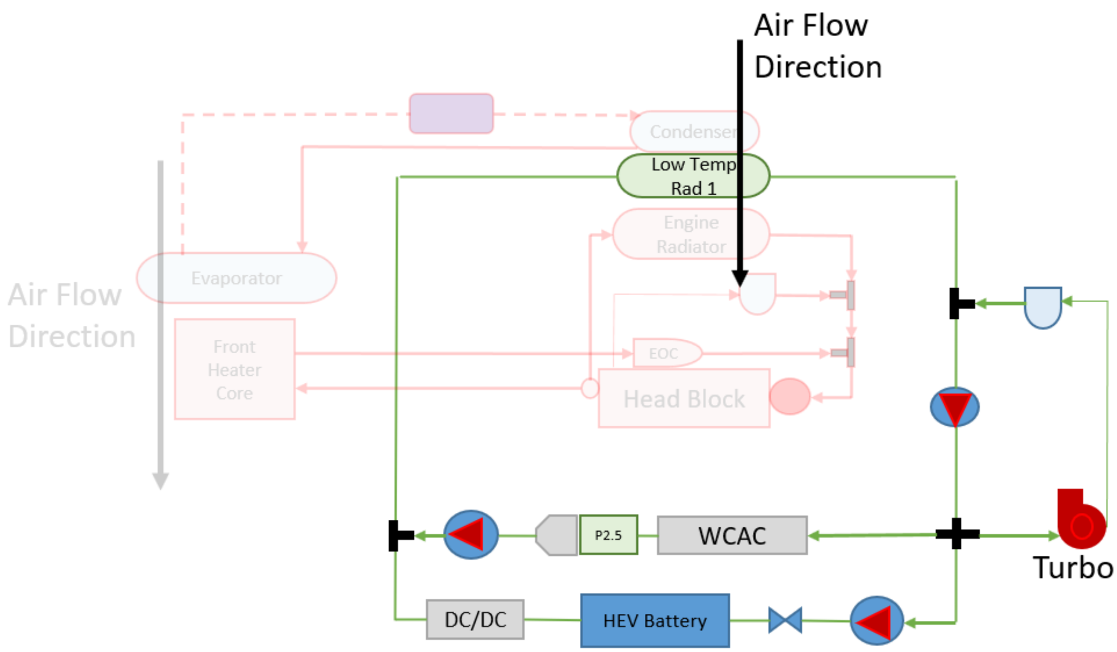


Figure 10 - Visual representation of the low temperature cooling loop and with associated temperatures of the radiator and battery pack

This cooling loop functions independently to the one of the HTLR and unlike a dependency of the engine speed, the electric pump allows for the system to behave as requested and needed. In this case, this is also why it is very important to have control of the pumps and fans as they are the key components of passage that will allow the system to be efficient and be able to satisfy the necessary cooling for each component. Similar to the HTLR, the piping is also set to be adiabatic, smooth and also various diameter sizes are used depending the component and the necessary volumetric flow rate that is required.

3.10. Battery Cooling

In the low temperature cooling loop, the battery is the component that is the primary heat source of the system similarly to the conventional engine. The operation and the direction of the flow to the battery kept some of the main principles of the engine as well. Since the battery's thermal behaviour is the element that has the highest impact on the electrification systems efficiency, life longevity and is known to be expensive, the cooling system is critical. However, it is also important to note that batteries are the most efficient at temperature ranges. The limitations which has been found in [29] when working on developing a battery thermal management system, the 48V battery which is also being used in this design has operating temperatures between -30 to 55 ˚C and promotes the highest performance when working between 25 to 40˚C. Hence a 3/2 two position directional valve system has been developed to operate the coolant flow of the system similarly to the thermostat in the high temperature loop to prevent the coolant to flow through the radiator system when the engine has not yet reached required operating temperature. Therefore, this valve specifications is provided by the supplier and can be remodelled on GT-SUITE. This valve also functions with the involvement of pressure drop and temperature. When the temperature of the battery pack is not within the range as discussed before, the coolant will then go through a by-pass system for it to recirculate through the system. Then once the battery has reached its desired temperature will there be passage to cool the battery.

It is important to note that for this model, the battery model has been simplified where it would be able to capture the heat exchange between the battery and the coolant through convection.

3.11. Further investigation of the battery model

The battery model implemented into this model has data that has been provided by the supplier where the open circuit voltage charge, discharge and internal resistance of charge and discharge has been provided in confidence. However, the generic parameters of the battery can be seen in Table where these were used for the simplified model.

Table 2 48-V battery parameters

Cell Capacity (A-h)	17.5
Number of Series Cells	12
Number of Parallel Cells	1
Mass (kg)	20
Initial Temperature	Same as ambient
Heat Transfer Area (mm^2)	240000

As mentioned above, the heat transfer is possible from convection. For this to be possible, a cooling plate for the battery model was designed and added to the model. The cooling plate component is a simple template where it uses a lumped mass of uniform temperature to be modeled. Boundary conditions were then set between the coolant passage and battery pack through the surface area. [30] went in great detail of the implementation of such component including the thermal behaviour of a battery pack. They have also mentioned different ways a cooling plate can be designed which is shown in Figure 11.

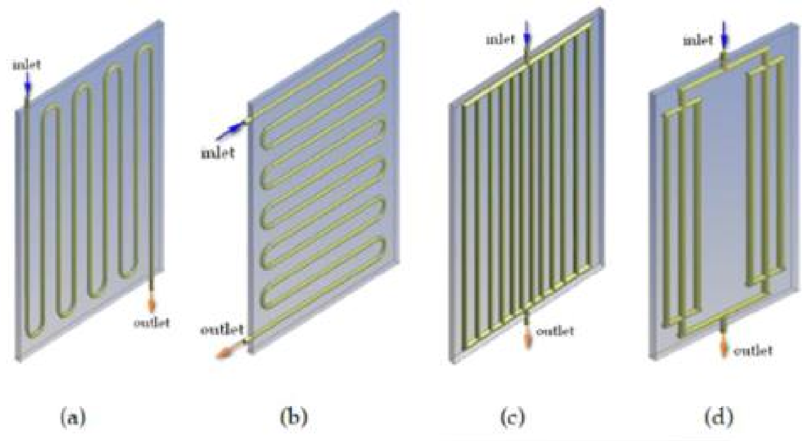


Figure 11 - Different cooling plate design possibilities depending on the users' parameters

To control the heat transfer of the battery, there were two signals involved, the first one being the temperature of the battery and the second being the state of charge of the battery. Unlike the conventional engine, the battery can be under charging or discharging meaning that the heat transfer varies depending on the response of the vehicle during operation. The heat transfer for both instances were then implemented into the model including the relationship of the pressure drop behaviour depending on the valve. During the analysis of the thermal management system, there was no powertrain involvement other than the ones already discussed. To understand how the battery behaves during operation is by being provided a map of power generation and dissipation of a transient system. As discussed in the introduction, a MHEV has multiple operating conditions and multiple ways that power is supplied or generated such as regenerative braking and so on.

3.12. Low Temperature Components

In the low temperature cooling loop there are two other components that need to be mentioned such as the turbo charger and the water charge air cooler. The turbo charger in the coolant acts as a heat source in the system meaning the coolant will heat up by passing through the piping. The turbo heat transfer map has been added to the system based on experimental data provided by the manufacturer. In order for the heat transfer to be correctly used in the system, there were two signals that allow this feature. It is well known that the turbocharger is dependent on the engine although the cooling routing is from the LTRL. This means that the first signal is the engine speed. An engine speed sensor detects at what RPM the engine is running from and secondly, the engine load will be the secondary signal. From these two, the heat transfer will be able to adjust itself accordingly even for transient systems with the use of interpolation. When it comes to the water charge air cooler, its functionality is very similar to that of a radiator. There will be a heat exchange between the coolant and air but also unlike that of a radiator the heat transfer is from the compressed air that is being generated and transferred onto the coolant whereas if it were for a coolant, the transfer comes from the coolant and is then applied onto the air. And exactly like the turbocharger, the WCAC also consists of two signals being the engine load and the engine speed.

Having the correct heat transfer going through the system is very important. But on top of the addition of heat transfer, the pressure drop of both of these components are also included in the model. This will ensure the flow rate of the coolant with respect of the correct piping diameters that the flow rate of the system is accurate.

3.13. Steady State Simulations of LTRL Based on Electric Pump Speeds

Having completed the model with the correct components and their parameters and placement in the model, the first approach in terms of validating the model was to create a system parameter to investigate if the system can properly create a correlation between experimental data and reference data given the correct parameters as shown in the table.

Table 3 Steady state input data

Ambient Temperature (°C)	20
Initial Pressure in System (bar)	1
Initial Temperature of Coolant	20
Ambient Pressure (bar)	1
20Watt Auxiliary Pump Input (%)	100
80Watt Pump Input (%)	100
Coolant	Water-Ethylene Glycol 50/50 mixture

In order to check consistency, multiple cases were run by changing three of those input parameters. Ambient temperature, and both pumps input percentage were changed as can be seen in the Table 4. This system recorded the volumetric flow rate of each components in order to ensure that the system was behaving and each components were able to change their performance while being exposed to different ambient temperatures and inputs from the pumps.

Table 4 Coolant flow rate of components with input of 20Watt from 0-20%

JE 80 Watt_13V										
Pump JE 20Watt_13V					0%			20%		
T	Temperature Liquid	degC			23			24		
					Data	Result	Percent Error (%)	Data	Result	Percent Error (%)
1	Out_Battery	L/h	PCP2	100%(13V_10A)	362	363	0	357	366	2
3	In_Turbo				150	141	6	148	142	5
4	Out 20W Pump				352	380	8	370	413	10
5	In_80W Pump				1948	2034	4	1951	2027	4
6	In-3Way-Valve				361	363	0	359	366	2
2	In_Rad LT				1798	1893	5	1803	1886	4
8	WCAC				1085	1092	1	1074	1101	2

Table 5 Coolant flow rate of components with input of 20Watt from 40-60%

JE 80 Watt_13V										
Pump JE 20Watt_13V					40%			60%		
T	Temperature Liquid	degC			24			24		
					Data	Result	Percent Error (%)	Data	Result	Percent Error (%)
1	Out_Battery	L/h	PCP2	100%(13V_10A)	330	342	4	310	329	6
3	In_Turbo				149	139	7	147	138	7
4	Out 20W Pump				496	535	8	582	640	9
5	In_80W Pump				1965	2079	6	1974	2107	6
6	In-3Way-Valve				330	342	4	311	329	5
2	In_Rad LT				1816	1940	7	1827	1969	7
8	WCAC				990	1029	4	934	989	6

Table 6 Coolant flow rate of components with input of 20Watt from 80-100%

JE 80 Watt_13V										
Pump JE 20Watt_13V					80%			100%		
T	Temperature Liquid	degC			24			24		
					Data	Result	Percent Error (%)	Data	Result	Percent Error (%)
1	Out_Battery	L/h	PCP2	100%(13V_10A)	288	310	8	288	316	10
3	In_Turbo				146	137	6	146	137	6
4	Out 20W Pump				682	693	2	682	730	7
5	In_80W Pump				1983	2121	7	1983	2134	8
6	In-3Way-Valve				287	301	5	287	316	10
2	In_Rad LT				1837	1983	8	1837	1996	9
8	WCAC				868	955	10	868	950	9

In this method of simulating, we use the same principle that we have done with the high temperature cooling loop by making a comparison using the absolute percentage error and equation. From the results of the data, we can see although some of the results seem to be on the high end of the error tolerance, they all fall within the accepted range previously discussed.

3.14. HVAC System

The HVAC model consists of the refrigerant loop system in a vehicle to allow comfort for the driver and potential passengers. This type of system is not new a new feature of MHEV as they have been implemented in vehicles for a long time. Depending on the location in the world or the option, air conditioning may or may not be present in a car. But in today’s world, it has become more of a normality and an option that is standard in most places. This system is in terms of complexity is very difficult because unlike the previous models we have been working on, this involves a two phase heat transfer system. A two-phase heat transfer system means that there is a phase change process when there is a release of latent heat vaporization. The considered refrigerant for this model is a R1234yf refrigerant. The reason why R134a is not used for this system is because it is not as environmentally friendly but R134yf is still hazardous. This system instead of building an entire model and then run a simulation from provided reference data, each of the components need to be designed independently. The reason being that from the statements mentioned above but also the geometry set up of components is very critical and can highly impact the results. In the Figure 14, we can see that the set up or implementation of this system can be very complicated as it will increase the space demand as well as it will need to interact with the entire system as a whole [31].

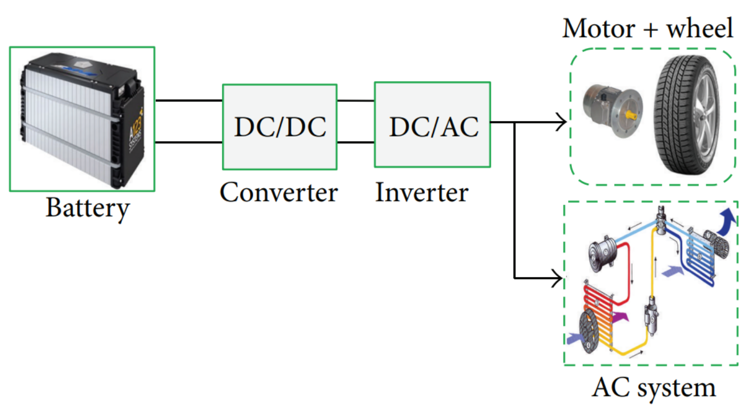


Figure 12 - Implementation of an AC system for an EV model [31]

When it comes to fuel consumption, the HVAC system is one of the primary systems that will drain significant amount of power all depending on the users end. [31] also make a comparison between the fuel consumption of a driving cycle in both situations where the vehicle completed the cycle with and without AC. We can see that the increase in fuel consumption is not nominal and cannot be overlooked as the fuel consumption ranged from 3 to 9 percent depending on the phase of AC.

Table 7 Power consumption comparison of the vehicle with and without AC

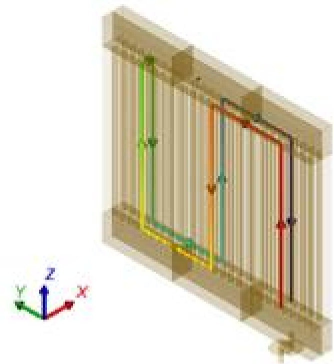
	Vehicle with AC Phases				Vehicle without AC Phases			
	2	3	4	5	2	3	4	5
Power (KW)	16.58	16.88	17.17	17.52	16.13			

3.15. Evaporator Design

Starting off with the evaporator design, it is important to notice that there are two passage ways of the evaporator. The evaporator air side where ambient air flows through and have initial pressure and temperature. Then the second passage is the refrigerant cooling. There are about four different sections which needs to be considered. The first one is the heat exchanger geometry. The evaporator is a heat exchanger with tube and fin and the parameters can be shown in the Table 9 below. The evaporator consists of multiple cores and the configuration can be shown in the Figure 15 below. The geometry and the flow path is very important as it dictates in which direction the refrigerant flows including the location of the inlet and outlet.

Table 8 Evaporator Geometry

Flow Direction	Vertical
Exchanger Height (mm)	251
Exchanger Width (mm)	212.7
Exchanger Depth (mm)	38
Material	Aluminum



-X +X

+Y/Z

-Y/Z

Flow Order	Core #1	Core #2
Pass #1	3	4
Pass #2	2	5
Pass #3	1	6

Figure 13 - Evaporator multi core flow path example

When it comes to the second section of the evaporator, it is the regarding the heat transfer correlation for the refrigerants. These equations is what will be implemented in the model of GT-SUITE to calculate the heat transfer coefficient. The Dittus-Boelter is used to define the heat transfer coefficient. The coefficient has the be implemented for both cooling and heating and can only be valid when the flow of the refrigerant is fully developed.

For single phase liquid

$$h = 0.023Re^{0.8}Pr^{0.4}\frac{k}{D} \qquad Eq. 3$$

$$h = 0.023Re^{0.8}Pr^{0.3}\frac{k}{D} \qquad Eq. 4$$

$$\left(\frac{L}{D} \geq 10\,; 0.6\ \leq Pr \leq 160\,; Re \geq 10000\right) \qquad Eq. 5$$

For single phase vapor

$$\left(\frac{L}{D} \geq 10\,; 0.6 \;\leq Pr \leq 160\,; Re \geq 10000\right) \qquad Eq.\,6$$

For the two-phase condensation the method used [26]

$$h = 0.0344 Re_l^{0.83}\left(1 + x\left(\sqrt{\frac{\rho_l}{\rho_g}} - 1\right)\right)^{0.82} \times\; Pr_l^{0.35}\,\frac{k}{D} \qquad Eq.\,7$$

$$10 < \frac{\rho_l}{\rho_g} < 2000\,; 0.01 \;< \;\frac{\mu_l}{\mu_g} \;< 1\,; 5000 \;< Re \;< 500000 \qquad Eq.\,8$$

$$0.8 < Pr_l < 20\,; 0.1 \;< x \;< 0.9 \qquad Eq.\,9$$

When it comes to the two-phase evaporation is defined when the refrigerant to be in two phase and evaporating using [26] where:

When it comes to vertical tubes, the heat transfer coefficient is N = Co

$$h_{nb} = 230 Bo^{0.5} h_l, Bo > 0.3 \;\times\; 10^{-4} \qquad Eq.\,10$$

$$h_{nb} = 1 + 46 Bo^{0.5} h_l, Bo < 0.3 \;\times\; 10^{-4} \qquad Eq.\,11$$

$$h_{cb} = \frac{1.8}{N^{0.8}} h_l \qquad Eq.\,12$$

For $0.1 < N \leq 1$

$$h_{bs} = F Bo^{0.5} e^{\left(2.74 N^{-0.1}\right)} h_l \qquad Eq.\,13$$

For $N \leq 0.1$

$$h_{bs} = F Bo^{0.5} e^{\left(2.74 N^{-0.15}\right)} h_l \qquad Eq.\,14$$

$$F = 14.7\,, Bo \geq 11 \times 10^{-4} \qquad Eq.\ 15$$

$$F = 15.43\,, Bo \geq 11 \times 10^{-4} \qquad Eq.\ 16$$

After having defined the evaporator’s heat transfer behaviour, the next phase is to model the evaporator independently on GT-SUITE which is shown in Figure 16. The parameters used for this simulation and analysis is shown in Table 10. Each of the case simulations were run in steady state but there were two parameters that were changing being the mass flow rate of the refrigerant and the air flow rate coming in the evaporator.

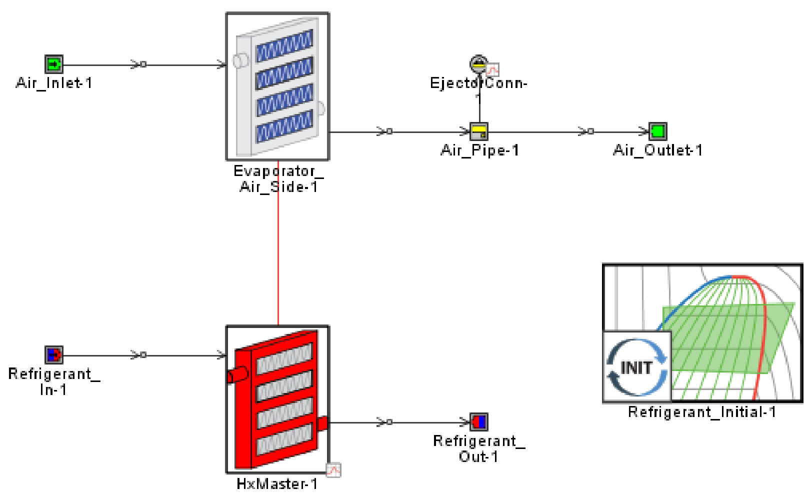


Figure 14 - Evaporator model for steady state simulation and validation

The interest when verifying the functionality and performance of an evaporator is by looking at both air and refrigerant side. A relationship between the air mass flow rate, air side pressure drop, refrigerant mass flow rate and refrigerant pressure drop is generated.

Table 9 Evaporator Parameters

Temperature out of condenser (°C)	51.5
Outlet condenser pressure (bar abs)	17
Outlet evaporator pressure (bar abs)	3.3

Overheating (°C)	5
Inlet evaporator temperature (°C)	43.3
Relative humidity (%)	19
Oil circulation ratio (%)	5

AIR MASS FLOW		
G_a (kg/h)	Results (kg/h)	Percent Error (%)
200.00	200.00	0
300.00	300.00	0
400.00	400.00	0
500.00	500.00	0
550.00	550.00	0

AIR SIDE PRESSURE DROP		
Dp_a (Pa)	Results (Pa)	Percent Error (%)
35.70	34.63	3
61.50	59.66	3
86.60	84.00	3
116.90	113.39	3
134.90	130.85	3

REFRIGERANT MASS FLOW		
G_{ref} (kg/h)	Results (kg/h)	Percent Error (%)
158.84	154.07	3
207.62	201.39	3
246.03	238.65	3
277.92	269.58	3
286.38	277.79	3

REFRIGERANT SIDE PRESSURE DROP		
Dp_{ref} (bar)	Results (bar)	Percent Error (%)
1.08	1.28	18.18
1.71	1.84	7.44
2.19	2.28	4.21
2.62	2.64	0.85
2.73	2.74	0.33

HEAT REJECTION		
Q (kW)	Results (kW)	Percent Error (%)
3.87	3.66	5.34
5.01	4.96	0.91
5.93	6.00	1.18
6.77	6.84	1.07
7.11	7.17	0.85

Figure 15 - Comparison between reference data to simulation results

By applying thermos properties and understanding the vapor compression refrigerant cycle and the data given, a relationship between the condenser input properties and the evaporator is possible with the aid of the implementation of entropy and enthalpy. And with this application, the heat rejection is also possible to be defined. Having reference data provided by the industrial partner and setting up the parameters for the simulation, a comparison was executed as shown in Figure 17. As mentioned before an absolute percentage error comparison is accomplished with the goal of having the data within a tolerance of ±10%.

The results demonstrate that under the given mass flow rates of air and refrigerant, the evaporator results are within the set tolerance. This component as mentioned before is critical because it not only is important to ensure it can handle set parameters, but also the evaporator is also in relation to cabin comfort as the evaporator will have the hot air flow through while capturing the heat and letting cool air flow through the HVAC duct system to enter the cabin. Hence doing a heat rejection analysis as shown in the Figure above ensures that this model is not only applicable for the vapor compression refrigerant cycle but when it will be involved in a combined system with the cabin model which will be later discussed, is critical.

3.16. Condenser

The next component to be investigated is the condenser which takes part of the VCRC. The functionality of the condenser is to be able to release the hot gaseous refrigerant to be condensed to really high pressure. The condenser modelling is very similar to that of the evaporator where an independent model will first be simulated and compared to reference data. The heat rejection possibilities is what will be investigated to ensure the component can behave correctly. As mentioned in the previous chapters, the condenser is part of the series system of heat exchangers with both the high and low temperature cooling radiators and the fan.

The condenser alike the evaporator when creating the model has two separate operations, one being the air side and the other being the refrigerant side. Regarding the air side, when making the model, it is only dependent on the air pressure and air temperature that channels through it. However, on the refrigerant side, there is the need to implement performance data such as geometry, materials, heat transfer data and pressure drops for both air and refrigerant sides. Some of the parameters of the geometry of the condenser can be found in Table 11.

Table 10 Geometrical parameters of the condenser

Flow orientation	Horizontal
Exchanger height (mm)	414.6
Exchanger width (mm)	580
Exchanger depth (mm)	12
Material	Aluminum

Regarding the heat transfer correlation of the condenser, the same equations and method of approach was used being equations 3 through 16. Similarly like the evaporator, for the simulation and validation, set parameters needed to be respected and are displayed in Table 11.

Table 11 Condenser simulation parameters

Inlet condenser temperature (°C)	94
Inlet condenser pressure (bar abs)	17
Subcooling (°C)	10
Inlet condenser temperature (°C)	35
Inlet air velocity (m/s)	1-5

Here below in the Table 12 we can see a comparison between the simulation of GT-SUITE [26] and the reference data.

Table 12 Condenser validation and result analysis

Refrigerant Pressure Drop			
Ref_MFR (kg/h)	Experimental Pressure Drop (Bar)	Data Pressure Drop (Bar)	Percentage Error (%)
125.00	0.19	0.19	1.20
174.00	0.35	0.35	0.00
213.00	0.51	0.51	0.00
246.00	0.67	0.67	0.31
274.00	0.83	0.82	1.02
299.00	0.97	0.97	0.09
320.00	1.11	1.10	0.52
339.00	1.24	1.23	0.67
355.00	1.35	1.34	0.55
Heat Rejection (kW)			
Air Speed (Va) m/s	Experimental Heat Rejection (kW)	Model Heat Rejection (kW)	% Error
1.00	5.9	5.28	10.44
1.50	8.2	7.44	9.27
2.00	10.0	9.30	7.00
2.50	11.6	10.94	5.66
3.00	13.0	12.34	5.09
3.50	14.2	13.56	4.50
4.00	15.2	14.63	3.75
4.50	16.1	15.62	3.00
5.00	16.9	16.48	2.46
Air Side Pressure Drop			
Mass AFR (kg/h)	Experimentl Pressure drop (Pa)	Model Pressure Drop (Pa)	% Error
1060.46	6	6.55	9.17
1590.70	13	14.12	8.64
2120.93	20	21.10	5.51
2651.16	30	29.21	2.62
3181.39	39	38.45	1.41
3711.62	50	48.81	2.37
4241.86	62	60.30	2.74
4772.09	73	72.93	0.09
5302.32	85	86.69	1.98

From the data, we can see that all of the error stays within the margins but when the velocity of the air and the flow rate of the flow rate of refrigerant is low, there is a higher percentage error compared to higher flows and velocities. A visual representation of the data can also be found below in the Figure 18 and we can see that the behaviour and the trend of the model data is close and goes in the same direction.

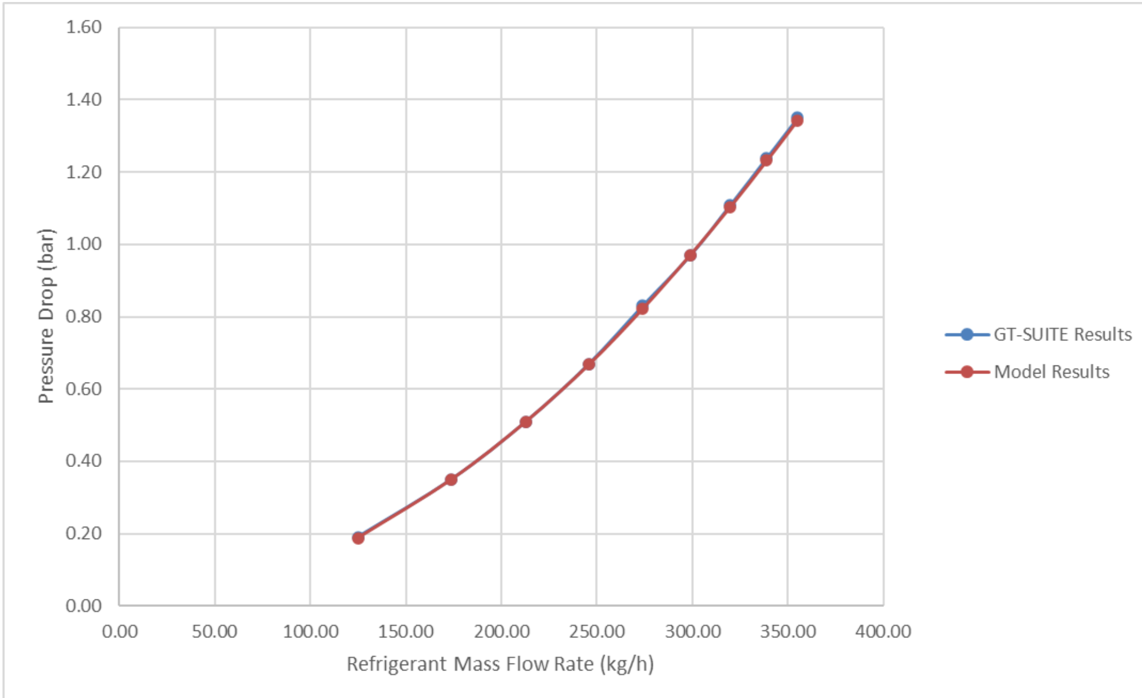


Figure 16 - Condenser air pressure drop comparison between reference data and simulation data

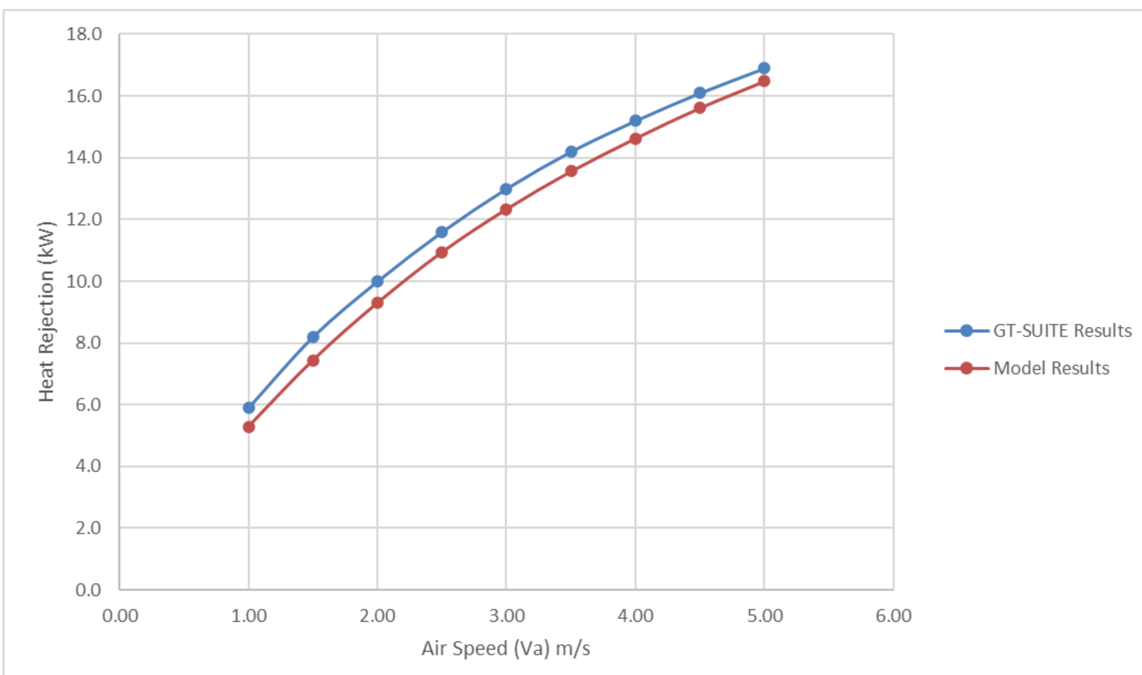


Figure 17 - Comparison of the heat rejection between reference data and simulation data

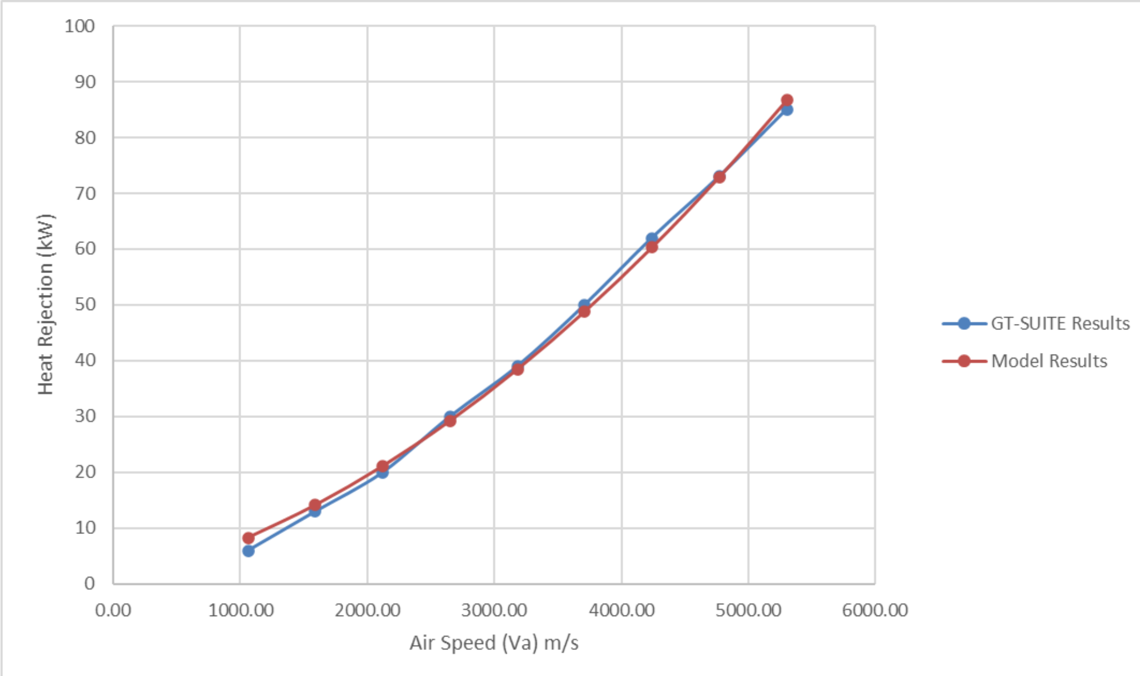


Figure 18 - Comparison between the air pressure drop between reference data and simulation data

3.17. Implementing and modelling the entire refrigerant loop

After modelling the condenser and evaporator and validating these two models, the full vapor compression refrigerant cycle. Have these two components, the compressor and a thermal expansion valve (TXV). The compressor as it states in the name compresses the refrigerant when it is in a gaseous state which will cause the refrigerant to increase in pressure and temperature. The compressor in the refrigerant cycle is the component where most of the power will be drawn in order to have the system function. The thermal expansion valve comes in right after the condenser. When it is at high pressure and hot, the expansion valve will vaporize the refrigerant with an inclusion of a temperature reduction as it flows through.

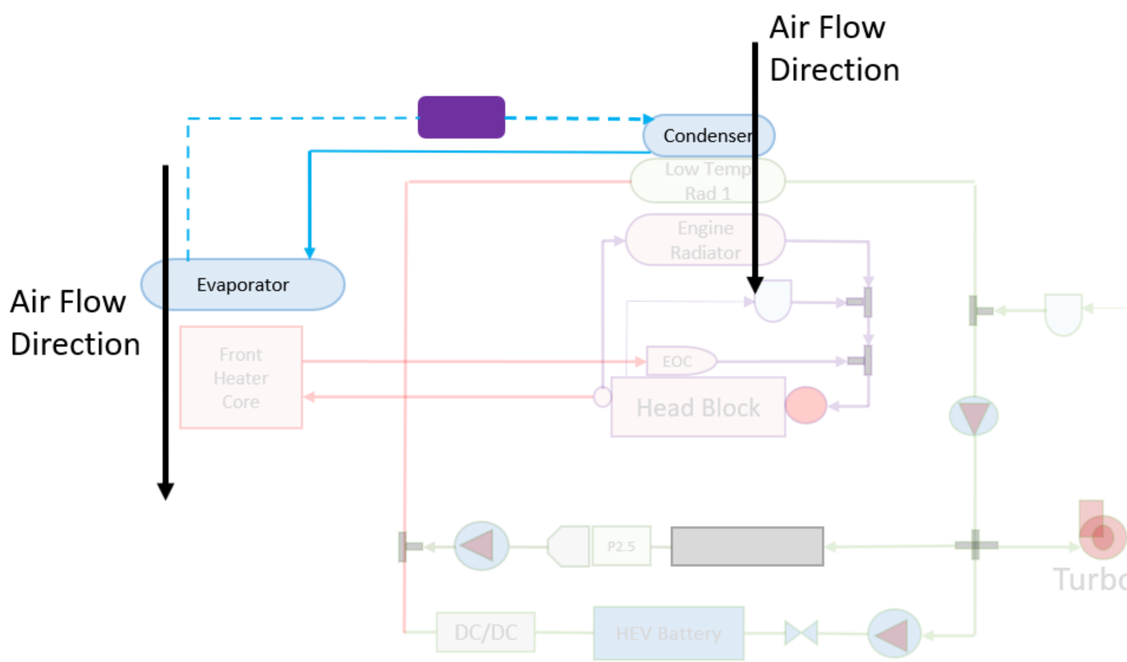


Figure 19 - Simplified refrigerant cycle model

The method of analysis for the compressor itself is by looking at the inlet and outlets also known as discharge and suction respectively. By being provided the compressor data like the speed and pressure of both the inlets and outlets, there is a lot of information that can be given such as the volumetric efficiency, isotropic efficiency, the cooling capacity, the power consumption, the refrigerant mass flow rate, and the coefficient of performance COP. The table below shows the parameters for the test that was conducted for the analysis.

From the results of running the simulation, the data follows well the reference data where the compressor can adjust itself accordingly as shown in Figure 20. What is especially important with the compressor model is the power consumption as this will later be allow a direct relation with the power consumption of the vehicle when the air conditioning of the system will be activated.

Table 13 Compressor parameters

Superheating (°C)	15
Subcooling (°C)	5
Oil circulation	5%
Ambient Temperature (°C)	20
Relative Humidity	45-85%
Pressure (mbar)	860-1060

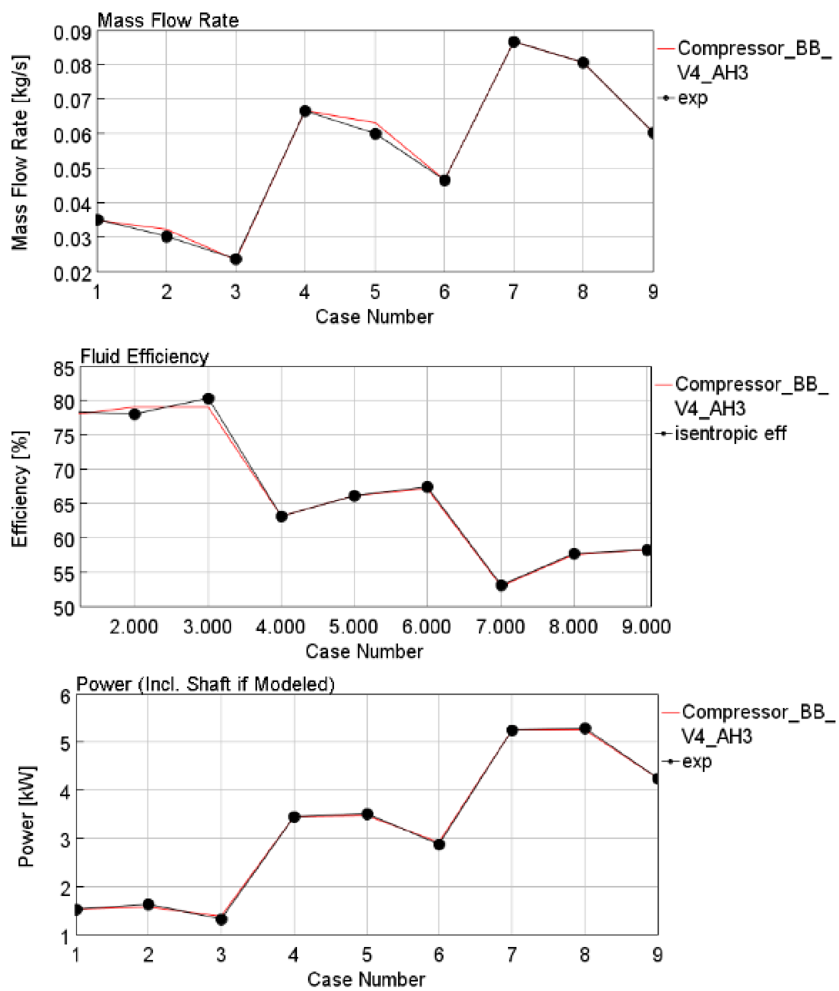


Figure 20 - Compressor simulation results compared to reference data

3.18. Cabin modelling

As discussed, the evaporator and condenser were built independently in order to do a proper simulation and comparison with the reference data, once these models were within the tolerance range of acceptance, the full VCR was designed and run, the model demonstrated that the power consumption from the compressor and that each component in the system were in agreement with one another. The next step of this modelling system is to add the cabin model. This model is designed to be as accurate as possible by gathering information about the vehicle. The cabin was modeled with cabin geometry, material and inside volume. The method of validating the model especially when involving heat transfer is to look at the cool down test. This type of analysis involves having the car "soak" meaning being exposed to an environment for a long period of time until the car has reached equilibrium. Once that time has elapse, the driver will activate the air conditioning system involving the VCR and the temperature of the cabin and the driver will be investigated. An important element of the cabin modelling is the thermal solar flux as this will act as a heat load onto the cabin. The heat transfer from the external solar flux is then transferred into the cabin and does take into consideration. It also takes into consideration the absorptivity, emissivity of main components such as doors, windows like the windshield. The results of the cabin will be investigated in the next chapter where the transient analysis of the vehicle is simulated.

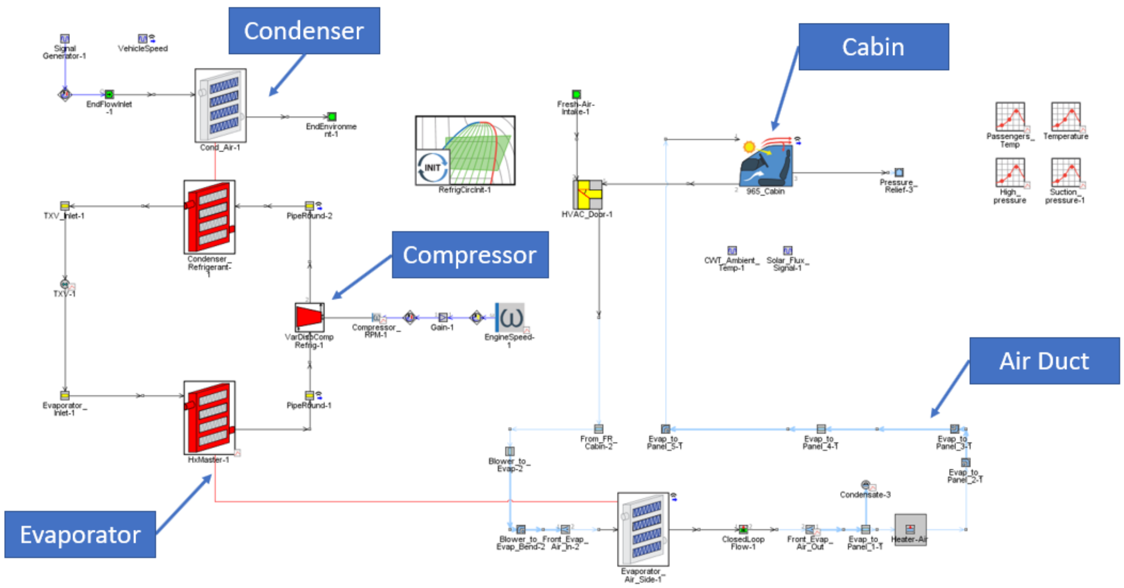


Figure 21 - Refrigerant cycle including the duct and cabin model

3.19. Full Model Building

Having created both the high and low temperature recirculation loops and the refrigerant model with the cabin implementation, the next step is to add each of these subassemblies into a single model and ensuring these models can work in harmony. As can be seen in Figure 22. the under-hood model is the main subassembly which relates all three of those loops through the series of radiator and condenser. The method of approach for a full thermal model is to implement a standard driving cycle.

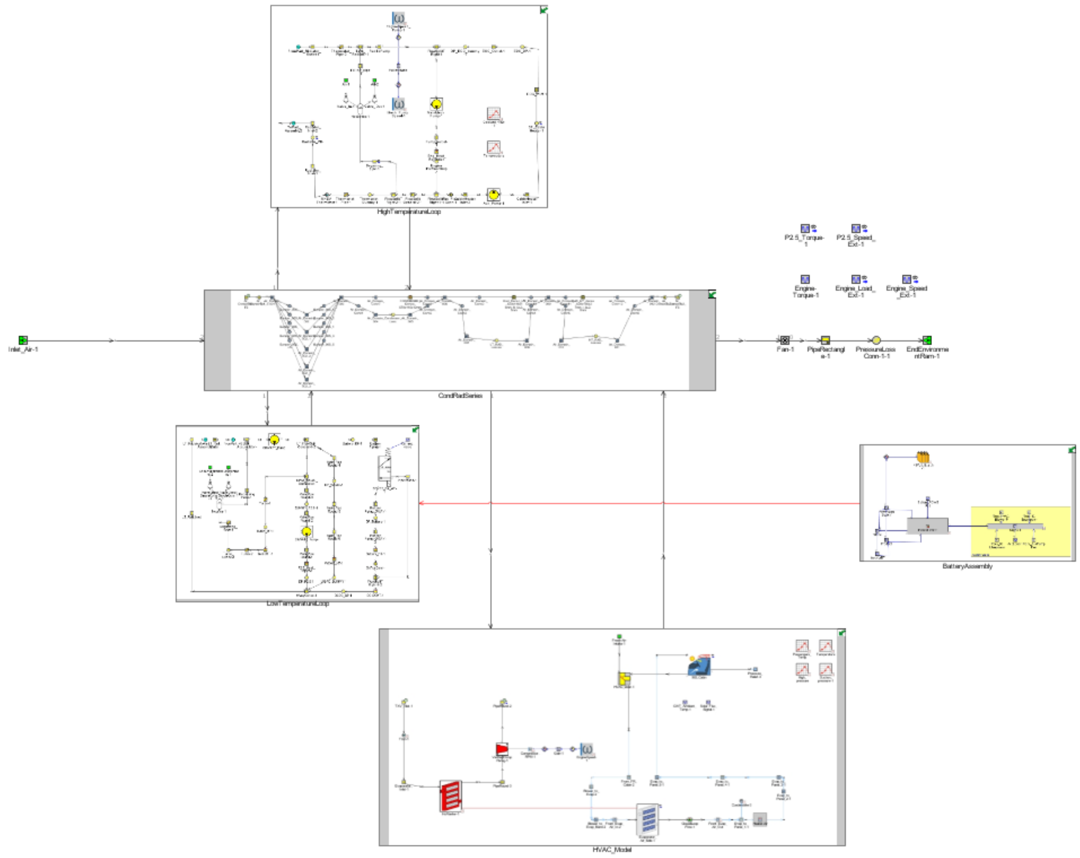


Figure 22 - Complete thermal management system of 48-V MHEV

3.20. Transient simulation analysis

The standard driving cycle is the WLTC (World Harmonized Light Vehicle Test Cycle). This cycle is mostly used in Europe and other areas around the world. This cycle can be broken down into 4 separate phases as shown in Figure 23 where different speed deviations, accelerations, braking, and top speeds take place. The idea is for this cycle to satisfy as many countries in the world as possible and in different environment such as urban and highway and lasts for 1807 seconds.

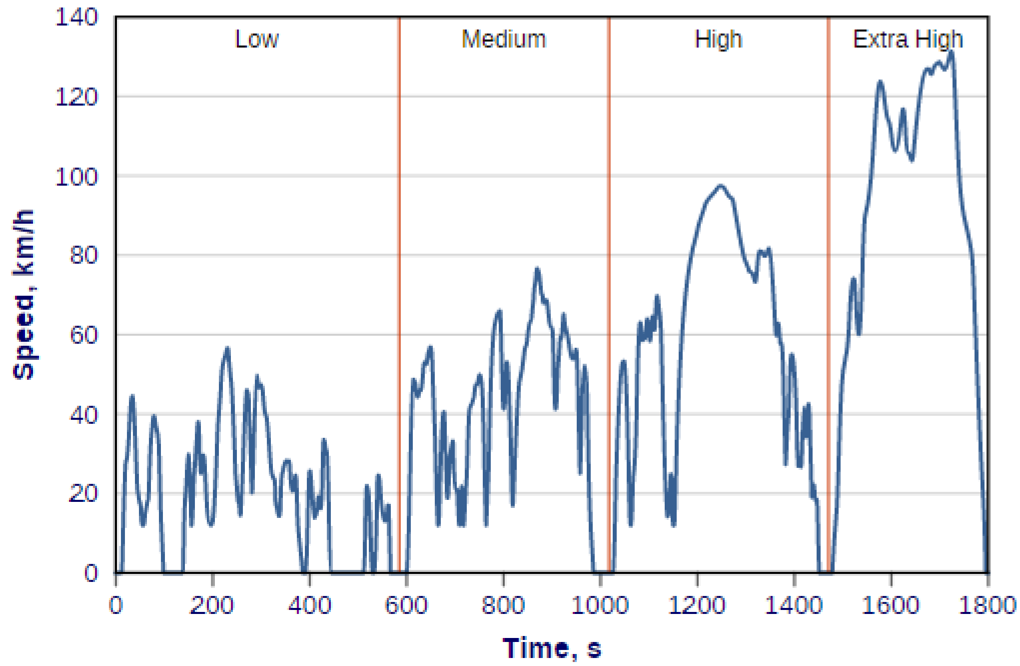


Figure 23 - WLTC driving cycle *[32]*

The main concept of validating the thermal management system designed is to set initial parameters from a transient analysis and can be compared. Firstly, looking at the high temperature cooling loop, the component of interest is the temperature of the engine, as discussed previously the engine's operating temperature where it is at its highest efficiency ranges from 90 to 105°C. As we can see from Figure 24, the designed engine coolant temperature reaches this range much quicker than the reference data and ultimately slightly increasing the performance of the engine. Once it has reached the desired range, the temperature remains relatively constant and remains in agreement with the reference data.

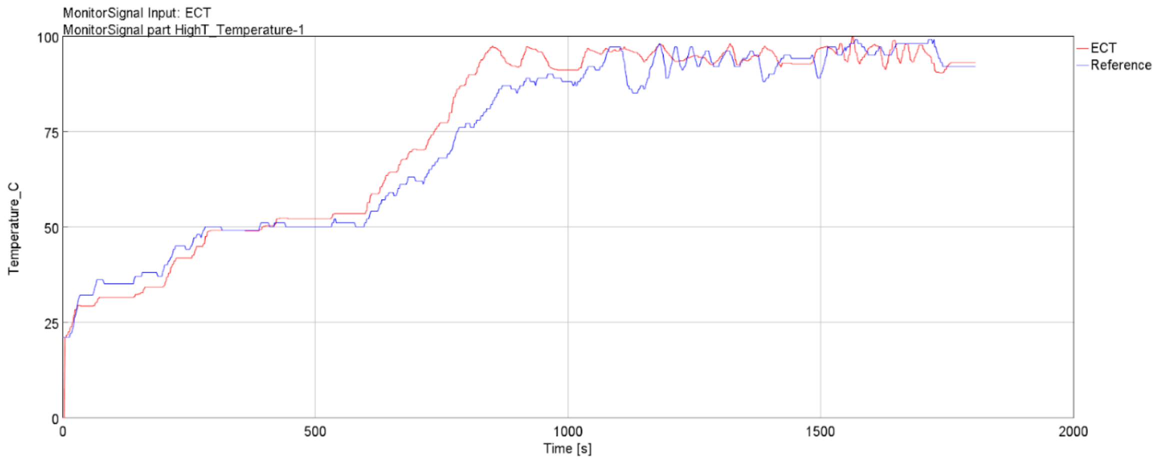


Figure 24 - Engine cooling temperature comparison during WLTC driving cycle

After looking at the engine's temperature behaviour, the next step is to loop at the low temperature radiator inlet and outlet temperature. The maintenance of temperatures in the LTRL is very important in ensuring proper efficiency, safety and performance of these components. From the Figures 25 and 26 we can see that the temperatures of both the inlet and outlet temperatures have a slightly higher fluctuations and the system during higher driving cycle like in phase 3 and 4 where the temperatures are lower than the reference data but demonstrate that the simulation is able to behave in a pattern similarly to of how the system should react the transient cycle. However, simulation limitations occurred when the implementation of an active grill system (AGS) is not available causing the divergence in the trend. A small study of this was done to imitate how the behaviour of the radiator was exposed to an AGS and can be seen in Figures 27-28 and demonstrated that the data close to 1000 seconds when AGS would be activated the temperature is closer than before.

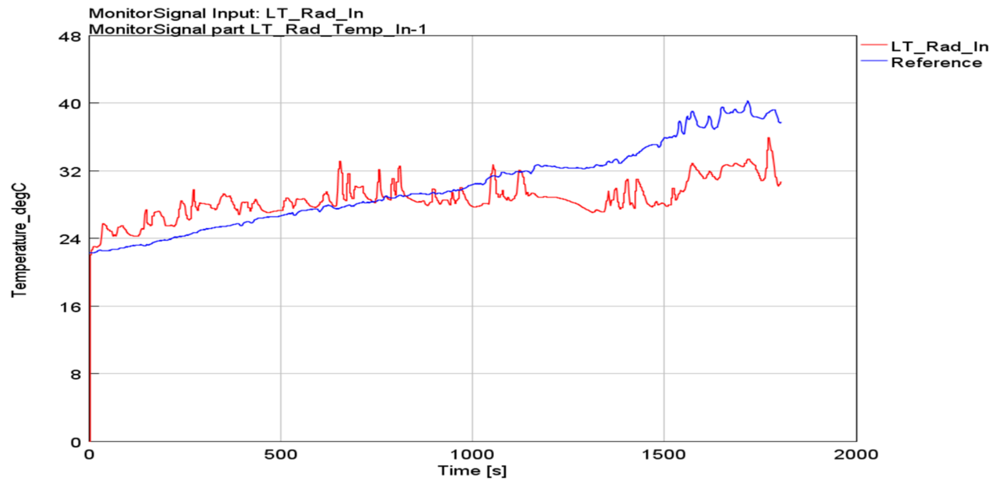


Figure 25 - Inlet temperature of low temperature radiator during WLTC cycle

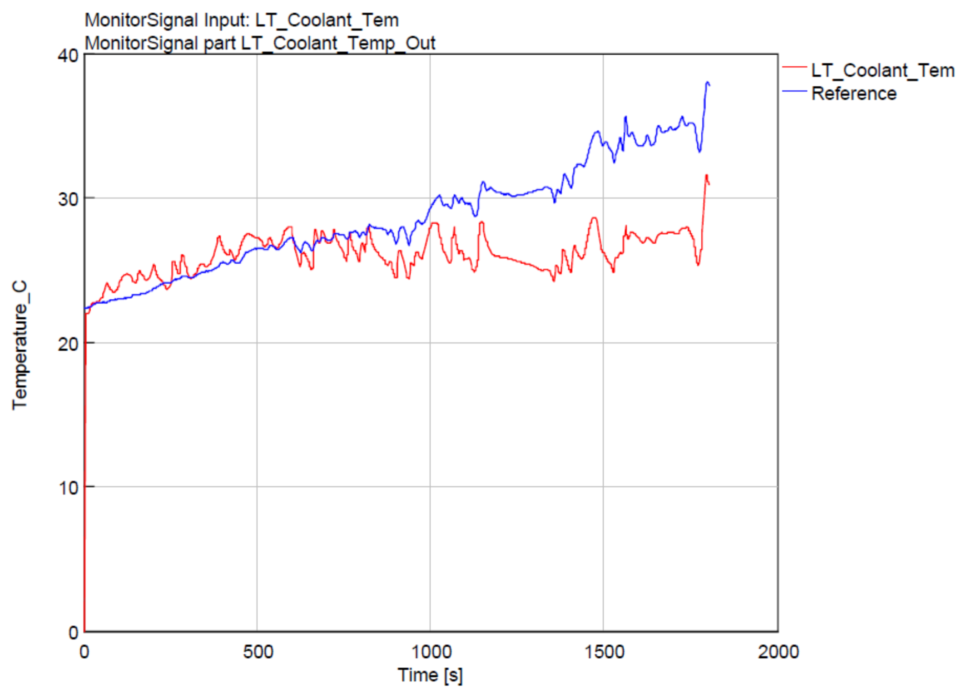


Figure 26 - Outlet temperature of low temperature radiator during WLTC cycle

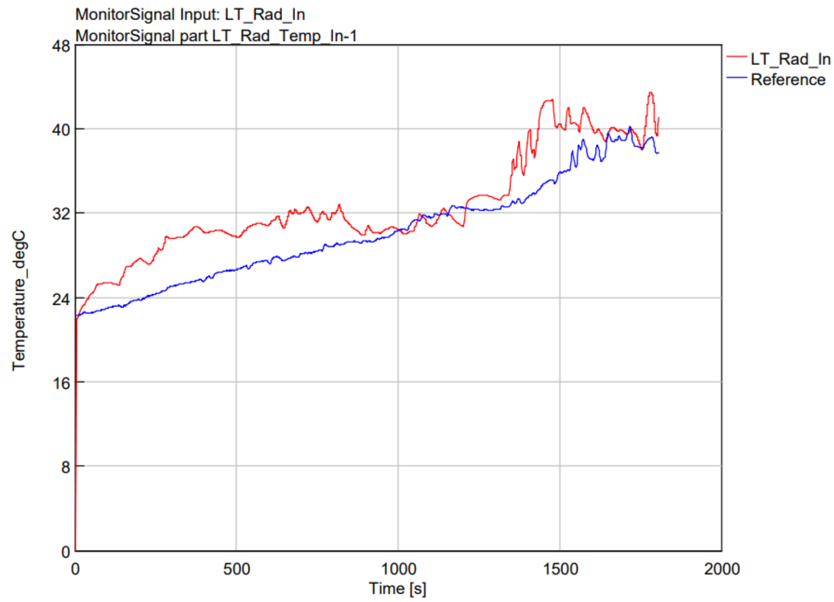


Figure 27- Inlet Temperature of Radiator with a Simple Imitation of AGS

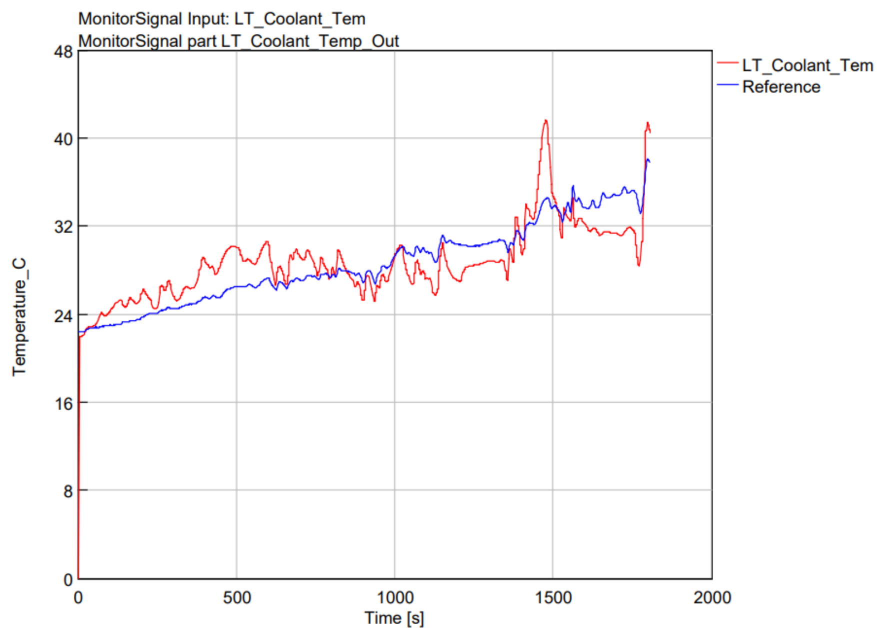


Figure 28 - Outlet Temperature of Radiator with a Simple Imitation of AGS

The next following graphs in Figures 29 and 30 demonstrates the coolant temperature at the inlet and out of the battery. Similarly, to the behaviour of the inlet and outlet of the radiator, the graphs demonstrates that the temperatures are lower especially in the extreme high velocities, while still being in agreement with the pattern and behaviour of the coolant. This means that the fluid overall for the same system is cooler which in return demonstrates the battery to have increased performance and the reduction of issues such as thermal runaway risks are much lower.

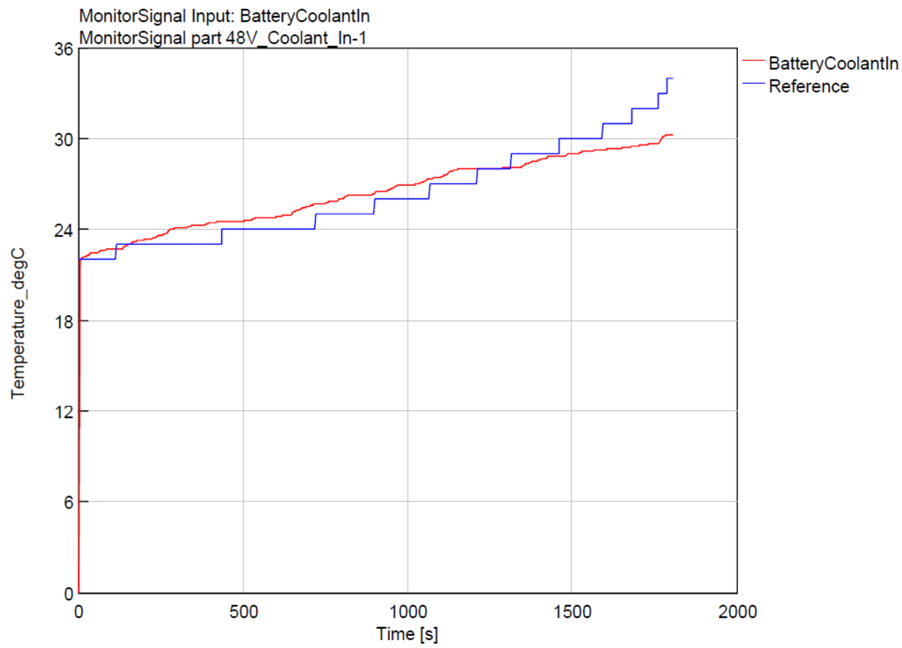


Figure 29 - Inlet temperature for battery cooling during WLTC cycle

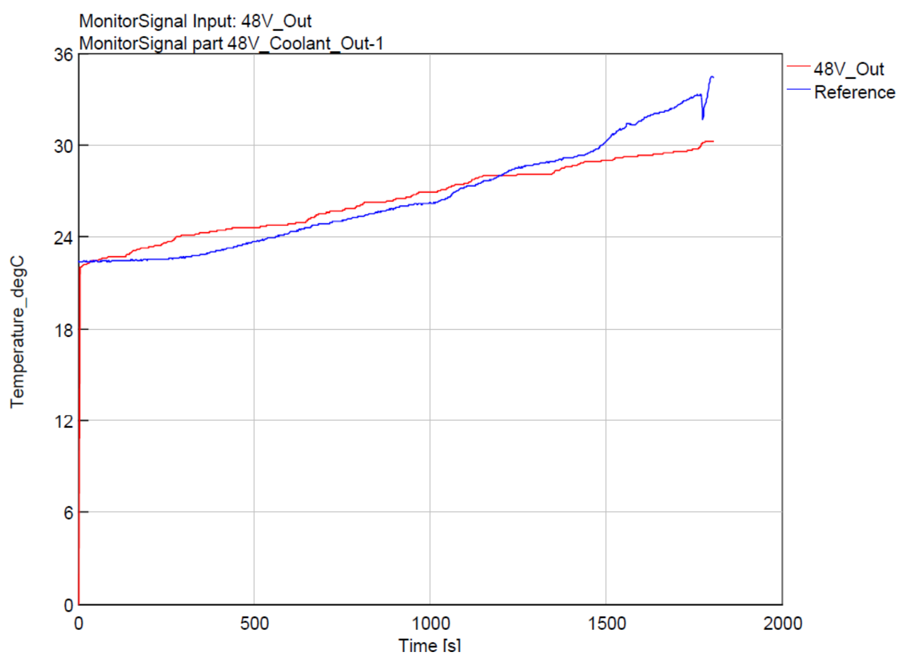


Figure 30 - Outlet temperature of battery during WLTC cycle

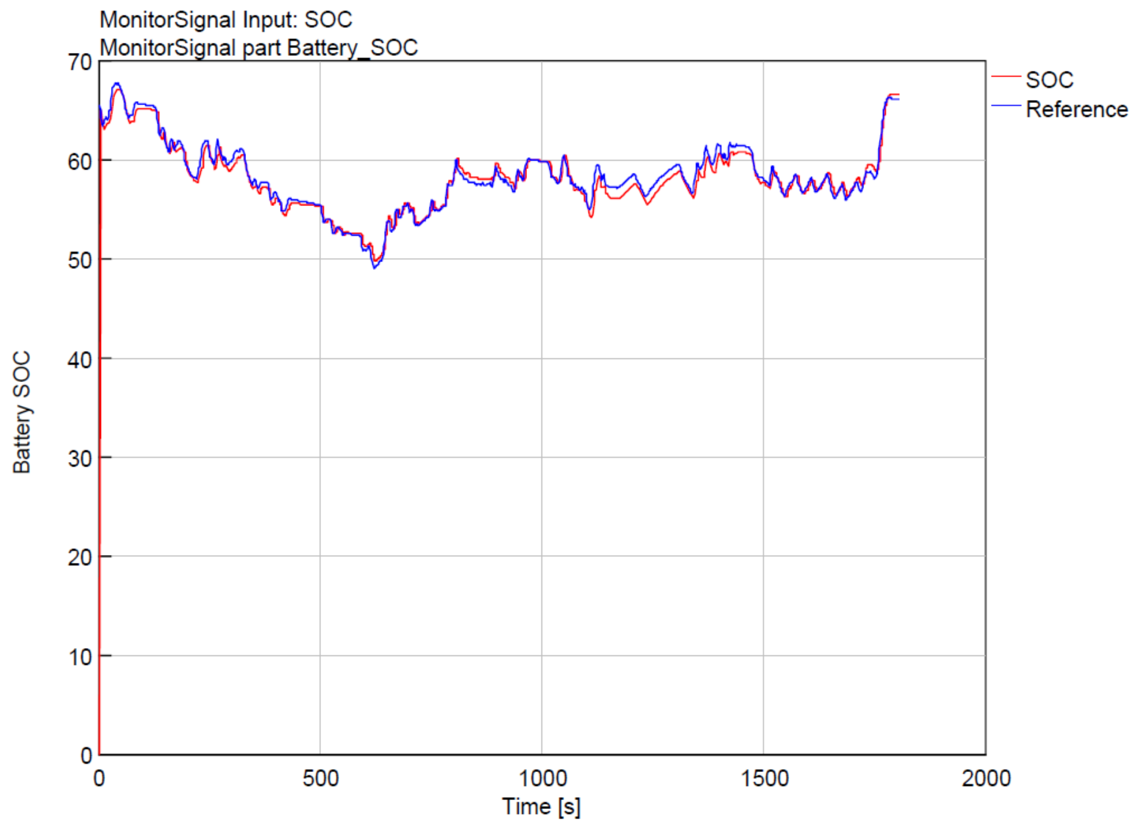


Figure 31 - State of charge of battery during WLTC cycle

The state of charge trace of the WLTC cycle demonstrates great behavioural synergy. In order to accomplish the state of charge of the battery, a model was implemented of the batteries power consumption and power regeneration from regenerative braking. From this given data, input signals of accessory loads were sent to the main power consumption and generation where both pumps in the low temperature model, in cabin accessories and the fan model were implemented to give the result shown in Figure 31. An important note is the importance of this model because from there it allowed a further analysis of the model by investigating the pumps a lot further in the LTRL which will be discussed later in the chapter.

3.21. Exergy analysis

The first method of understanding this model even further is to implement an exergy analysis on the low temperature cooling loop being the component that is newly integrated in the conventional vehicle. Deep understanding of the functionality and the understanding of the both the energy and exergy analysis can be found in the thermodynamic literature [23]. This type of application will allow the implementation of how the model performs and figure out where there may be some thermodynamic losses throughout the system. A steady state analysis of the worst case scenario was utilized as the system will be under a lot of stress and will be able to validate whether the thermal management system can withstand when introduced to harsh conditions. On top of this, the analysis will be able to give a better understanding of the efficiencies of each component involved. The method of approach is to develop a mass, energy and exergy analysis while abiding to the laws of thermodynamics. Before starting the analysis, certain assumptions which are listed below are needed to be disclaimed where some of those rules cooperate with the initial design modelled on GT-SUITE such as neglecting piping bends.

Low temperature radiator

Mass Balance $$\dot{m}_{10} = \dot{m}_1 = \dot{m}_c \qquad Eq.\ 17$$

Energy Balance $$\dot{Q}_{Radiator} = \dot{m}_c(h_{10} - h_1) \qquad Eq.\ 18$$

Exergy Balance $$Ex_{destruction,radiator} = \dot{m}_c(ex_{10} - ex_1) + \dot{m}_{air}\,(ex_{in} - ex_{out}) \qquad Eq.\ 19$$

80Watt pump

Mass Balance $$\dot{m}_1 = \dot{m}_{2s} = \dot{m}_{actual} = \dot{m}_c \qquad Eq. 20$$

Energy Balance $$\dot{W}_{pump} = \dot{m}_c(h_{2,actual} - h_1) \qquad Eq. 21$$

Exergy Balance $$Ex_{destruction,pump} = \dot{m}_c\left(ex_1 - ex_{2,actual}\right) + \dot{W}_{pump} \qquad Eq. 22$$

Condenser

Mass Balance $$\dot{m}_2 = \dot{m}_3 = \dot{m}_6 = \dot{m}_c \qquad Eq. 23$$

Energy Balance $$\dot{Q}_{Condenser} = \dot{m}_c(h_{3,actual} - h_6) \qquad Eq. 24$$

Exergy Balance $$Ex_{destruction,condenser} = \dot{m}_c\left(ex_{3,actual} - ex_6\right) \qquad Eq. 25$$

Evaporator

Mass Balance $$\dot{m}_7 = \dot{m}_8 = \dot{m}_c \qquad Eq. 26$$

Energy Balance $$\dot{Q}_{Evaporator} = \dot{m}_c(h_7 - h_8) \qquad Eq. 27$$

Exergy Balance $$Ex_{destruction,\ Evaporator} = \dot{m}_c(ex_8 - ex_7) + \dot{m}_{air}\,(ex_{in} - ex_{out}) \qquad Eq. 28$$

20Watt pump

Mass Balance $$\dot{m}_9 = \dot{m}_{10_s} = \dot{m}_{10actual} = \dot{m}_c \qquad Eq. 29$$

Energy Balance $$\dot{W}_{pump} = \dot{m}_c(h_8 - h_7) \qquad Eq. 30$$

Exergy Balance $$Ex_{destruction,pump_2} = \dot{m}_c(ex_9 - ex_{10}) + \dot{W}_{pump} \qquad Eq. 31$$

CHAPTER 4

RESULTS AND DISCUSSION

4.1. High Temperature Recirculation Results

Having implemented every component in the correct position, having experimental data for correct behaviour and setting parameters, the system was simulated. As mentioned before, the first set of analysis will be to compare experimental data provided by the industrial partner for validation. The main parameters for steady state analysis will be to investigate the coolant flow rate of the secondary at each component while also doing different case studies with incremental engine speeds starting from 900RPM up to 5500RPM. The steady state results of the HTRL can be seen in Table 14 and demonstrates that the percentage of error is below the set tolerance of ±10%. This demonstrates really how well this simplified model is able to behave like a real model.

Table 14 Steady State Results of HTRL

MHEV HT loop Coolant Flow Balancing Bench test results [l/h] -- 90 °C coolant temperature + 50/50% glycol/water Mixture + AUX Pump OFF --									
Thermostat Closed	Components								
Engine Speed RPM	CH-EOC [test]	CH-EOC [Data]	Percent Error (%)	Degassing Pipe [test]	Degassing Pipe (Data)	Percent Error (%)	HT Radiator [test]	HT Radiator [Data]	Percent Error (%)
900	235	236	0.63	31	33	5.36	0	0	0
1000	263	272	3.49	35	37	6.13	0	0	0
1500	418	423	1.19	54	56	3.76	0	0	0
2500	731	735	0.50	93	94	1.13	0	0	0
3500	1051	1063	1.16	134	133	0.87	0	0	0
4500	1446	1388	4.00	173	170	1.48	0	0	0
5500	1798	1698	5.57	215	208	3.18	0	0	0
Thermostat Open	Components								
Engine Speed RPM	CH-EOC [test]	CH-EOC [Data]	Percent Error (%)	Degassing Pipe [test]	Degassing Pipe (Data)	Percent Error (%)	HT Radiator [test]	HT Radiator [Data]	Percent Error (%)
900	190	168	11.63	25	23	6.21	638	639	0
1000	210	189	10.17	28	26	6.33	744	743	0
1500	311	283	8.91	40	38	5.47	1316	1316	0
2500	510	464	9.03	63	59	5.74	2543	2543	0
3500	700	648	7.39	84	80	4.24	3811	3775	1
4500	883	840	4.90	105	101	3.47	5223	4941	5
5500	1088	1059	2.64	128	127	1.03	6552	6228	5

From the data, it is noticeable that the data falls well within the percentage error of 10%. The data also shows a linear relationship of the coolant flow rate increase as the engine rpm increase which is to be expected as there is only one single change done to the system. On top of having the data displaying a good behaviour and relation to the reference data, it is also important to note that during the steady state simulation, the coolant flow rate remained constant. This is notable as it also demonstrates the robustness and behaves steady without any signs of instability.

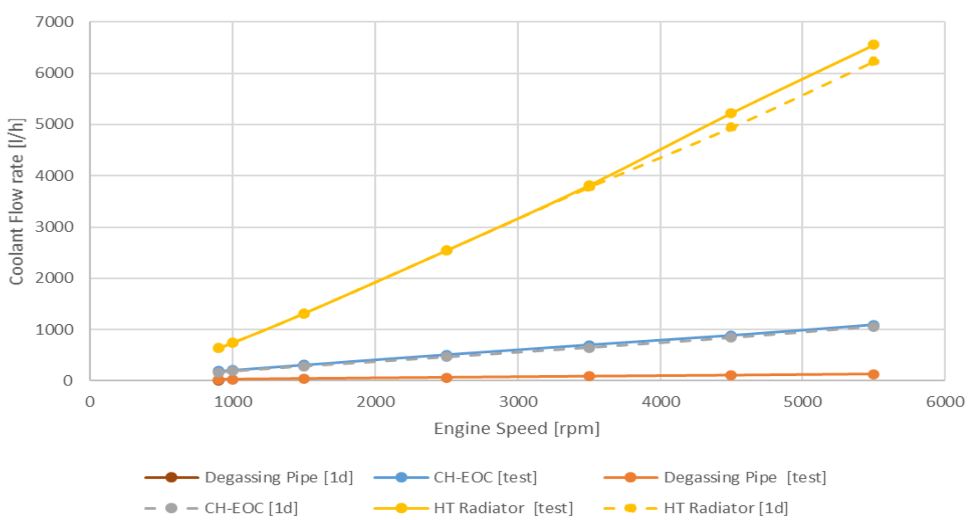


Figure 32 - Visual flow rate comparison of components of the HTRL steady state simulation while the thermostat is open

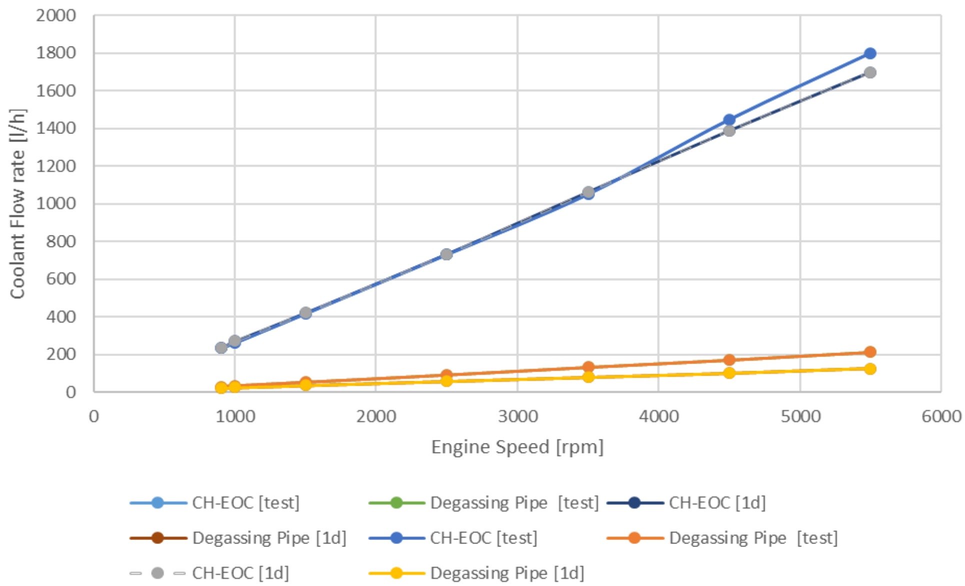


Figure 33 - Visual flow rate comparison of the HTRL steady state simulation while the thermostat is closed

In this visual representation, we can see the overlapping of most of the experimental trace over the reference data further emphasizing that under steady state, the model demonstrates the ability to reproduce experimental data and falls within the tolerances as mentioned before.

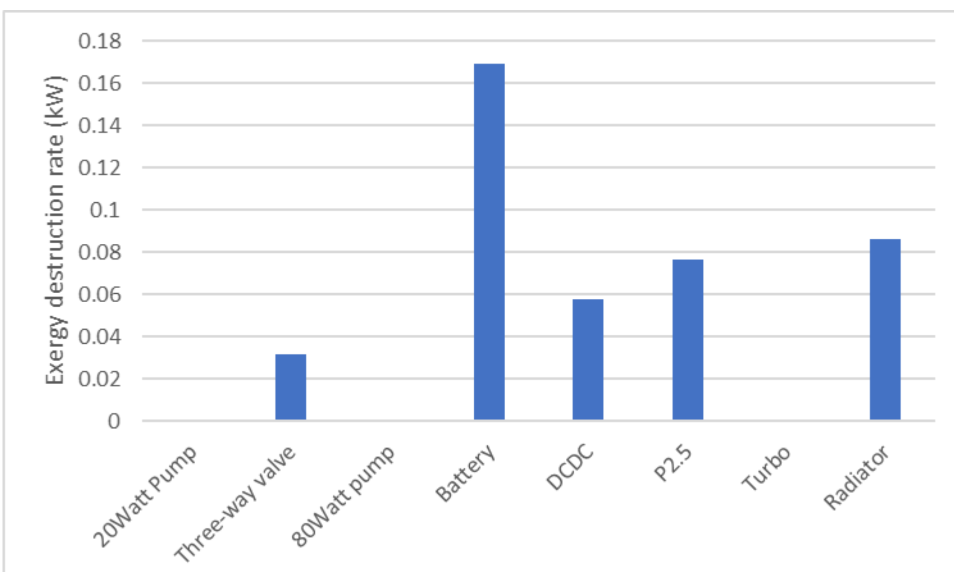


Figure 34 - Exergy destruction rate of low temperature cooling loop

From the data, we can see that the highest exergy destruction occurs at the battery. This does make sense considering as was shown earlier, the temperature difference between the coolant and battery was large so in order to reduce the losses in the battery, the next step would be to try and increase the temperature of the coolant as of right now there is high heat transfer between the two fluids. A solution to this problem could be to increase the surface area of the cooling plate that is located in order to have a higher surface area.

4.2. System based optimization

Before in previous chapters, most of the analysis done was in attempt to collect data from the model and make a comparison to real experimental data from real systems. This time, in order to have the system under different environmental stress, analysis of different ambient temperatures from 22 °C up to 40 °C was investigated. In Table 16, we can see the results of the temperature of the radiator of the low temperature with a given map that would be implemented in the WLTC driving cycle. Also, the state of charge difference from initial to final was also recorded. This helped to understand the behaviour of the coolant in terms of temperature before undergoing heat transfer in the environment and the state of charge difference allows to understand how much power consumes. The WLTC power cycle of the vehicle remains unchanged during analysis as the driving cycle does not change and it is designed to behave the same way if the same run were to be repeated.

In order to understand the involvement of the pumps which as previously discussed consume most of the power in a thermal management system a matrix was created. The matrix consists of 3 different parameters. First the ambient temperature will range between 22 °C to 40 °C as discussed and the input (percentage of activation) of the pumps has been discretized to understand the response. After running the simulation multiple times, the results can be found in Tables 17 and 18. From these results, a relationship and a target of the pump can be compared from experimental data and the results of the simulation to target at what input the pumps can be activated in order to save on power while maintaining the integrity of the thermal management system and ensuring the components work efficiently, safely, and are still within their temperature range for max performance.

Table 15 Reference data results of radiator inlet and outlet temperatures including the difference of state of charge between initial and final

		Temperature 22C			Temperature 30C			Temperature 35C			Temperature 40C		
		SOC	LT_Inlet	LT_Outlet	SOC	LT_Inlet	LT_Outlet	SOC	LT_Inlet	LT_Outlet	SOC	LT_Inlet	LT_Outlet
	80 Watt Pump (Duty Cycle)	Experiemental Data Map			Experiemental Data Map			Experiemental Data Map			Experiemental Data Map		
20 Watt Pump (Duty Cycle)	20	0.172	30.34	31.32	0.172	38.07	38.89	0.174	42.94	43.67	0.176	48.18	48.61

Table 16 Difference of state of charge between the initial state to final

ΔSOC Battery						
30°C		80 Watt Pump (Duty Cycle)	20	50	80	100
	20 Watt Pump (Duty Cycle)	20	0.122	0.137	0.183	0.240
		50	0.123	0.138	0.184	0.241
		80	0.127	0.142	0.188	0.245
		100	0.130	0.146	0.192	0.249
35°C		80 Watt Pump (Duty Cycle)	20	50	80	100
	20 Watt Pump (Duty Cycle)	20	0.118	0.133	0.179	0.236
		50	0.119	0.134	0.180	0.237
		80	0.123	0.138	0.184	0.241
		100	0.127	0.142	0.188	0.245
40°C		80 Watt Pump (Duty Cycle)	20	50	80	100
	20 Watt Pump (Duty Cycle)	20	0.114	0.129	0.175	0.232
		50	0.115	0.130	0.176	0.233
		80	0.119	0.134	0.180	0.237
		100	0.123	0.138	0.184	0.241

Table 17 Outlet temperature of low temperature radiator based on pump inputs

LT Outlet Coolant Temp						
30°C		80 Watt Pump (Duty Cycle)	20	50	80	100
	20 Watt Pump (Duty Cycle)	20	45.26	38.38	36.60	36.43
		50	42.59	42.60	36.63	36.44
		80	44.04	38.62	36.67	36.45
		100	43.94	38.90	36.71	36.45
35°C		80 Watt Pump (Duty Cycle)	20	50	80	100
	20 Watt Pump (Duty Cycle)	20	50.25	43.24	41.58	41.46
		50	47.27	47.27	41.60	41.47
		80	49.04	43.45	41.65	41.48
		100	48.96	43.69	41.70	41.48
40°C		80 Watt Pump (Duty Cycle)	20	50	80	100
	20 Watt Pump (Duty Cycle)	20	55.25	48.13	46.57	46.49
		50	51.62	51.62	46.59	46.50
		80	53.98	48.32	46.64	46.50
		100	53.84	48.53	46.69	46.50

By looking at the data, the red cases demonstrate where the SOC difference is higher than the original design and temperatures are at risk of underperforming the system. The green cases on the other hand will demonstrate where the SOC shows improvement in by having less difference from less usage and the temperatures allows the system to stay within the temperature ranges of the components for best performance. After the analysis of the matrix system, it was noticed that if the 80Watt pump has an input of 50 and the 20Watt pump is remained at an input of 20, the system would overall be in favour of reducing the power consumption of the model while still having the best performance of the cooling system compared to the original design.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1. Conclusion

In this thesis an entire thermal management system was realized from a preliminary diagram provided by the industrial partner only. With the help of background research with the strategy to target the functionality of a MHEV, different thermal management systems, and analysis such as exergy analysis were utilized to understand, research problems find innovative solutions to the problem of improving fuel economy. The provision of real-life experimental data which were used as a reference during the making and modelling of the TMS were impactful supporting elements ensuring the model functions and behaves accurately. A European standardized driving cycle being the WLTC was implemented in the full model allowing the analysis of the response of the TMS during different driving behaviours. From this, the exergy analysis of the entire system at the component level to find which exerted the highest exergy destruction or losses. Then, with these findings, further analysis of the electrical pumps and fans were controlled by changing their input levels to find lower power consumption taken from the state of charge of the battery which in parallel reduces the fuel consumption by having less power requests. Keys findings by the development of the TMS developed is the importance the findings that not all components involved in a cooling cycle are functioning at their maximum capacity due to the origin complexity of a TMS. The battery demonstrates the highest exergy destruction in the cycle which has a big impact on the reliability and safety of a MHEV. Then, by being able to investigate further electric pumps and main fan shows the relationship between activation and SOC related to power consumption

5.2. Future work

A proportional integrated derivative controller could be implemented in the model to allow higher control and adjustments of the fans and pumps of the LTRL and the main system fan to further reduce power consumption.

The model of the thermal management system can be further improved. As of now, the model is only representing a single standard driving cycle and future development and implementation of different driving standards should be implemented to understand the behaviour of the model under different circumstances and the WLTC is not used all over the world.

The battery model implemented was made to be a simple design that would allow a simple heat transfer analysis while maintaining the integrity. A more complex system where also the implementation of more powertrain components could be included to control the power output and regenerative braking depending on a driver input.

Lastly, higher controls could be implemented to have a higher level of control of the thermal management system where a potential real time adjustment could be implemented so the system could be using the optimized path as much as possible.

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