Virtual calibration of thermal management system using 1D simulations

Master's thesis in Mobility Engineering

Harshith Munimahadeva
Vishnu Simba Selvan Anuradha

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
www.chalmers.se

Master's thesis 2023

Virtual calibration of thermal management system using 1D simulations

Harshith Munimahadeva
Vishnu Simba Selvan Anuradha

Department of Mechanics and Maritime Sciences
Division of Vehicle Engineering and Autonomous Systems
Chalmers University of Technology
Gothenburg, Sweden 2023

Virtual calibration of thermal management system Using 1D Simulations
Harshith Munimahadeva
Vishnu Simba Selvan Anuradha

Supervisor: Mukund Rudravajhala, CAE Engineer, Volvo Cars
Examiner: Simone Sebben, Head of Vehicle Engineering and Autonomous Systems

Master's Thesis 2023
Department of Mechanics and Maritime Sciences
Division of Vehicle Engineering and Autonomous Systems
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Volvo XC40 Recharge battery pack. Source: Online, Available at https://insideevs.com/news/402530/volvo-ev-battery-pack-assembly-line-belgium/

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2023

Virtual calibration of thermal management system using 1D simulations
Harshith Munimahadeva
Vishnu Simba Selvan Anuradha
Department of Mechanics and Maritime Sciences
Chalmers University of Technology

Abstract

The integration of electrical components in Battery Electric Vehicles (BEVs) has resulted in a significant increase in the complexity of thermal management systems. Unlike Internal Combustion Engine (ICE) vehicles, BEVs require meticulous control of temperature to ensure optimal performance and mitigate the adverse effects of heat accumulation. Efficient thermal management plays a crucial role in BEV development as it directly impacts the system's overall efficiency and, consequently, the vehicle's range. Achieving precise temperature control throughout the system presents challenges that necessitate the implementation of circuits and valves specifically designed for effective thermal regulation. The optimization of thermal management in BEVs is of paramount importance, while simultaneously maintaining performance and climate control capabilities.

Calibration plays a pivotal role in achieving optimal performance in the system, ultimately enhancing the overall efficiency and range of the vehicle. Currently, the calibration process entails the availability of a physical vehicle and a dedicated test chamber. The vehicle undergoes a series of meticulously designed test cases conducted at varying temperatures. The data collected from these tests is then utilized to generate a calibrated map, building upon a base map. This iterative process may involve repeating the calibration cycle multiple times, typically around 7-8 iterations, to ensure a comprehensive and finely-tuned calibrated map encompassing a wide range of pump requests. By diligently fine-tuning the calibration, it is possible unlock the full potential of the vehicle's performance and optimize its overall efficiency.

The thesis proposal aims to accomplish calibration using 1D simulations within a virtual environment, eliminating the requirement for a physical vehicle and dedicated test chamber. This innovative approach not only expedites the calibration process but also enables automation, enhancing efficiency while reducing the likelihood of errors. One of the key advantages of utilizing virtual models is their availability years in advance, even before the physical vehicle is accessible. This advantageous time frame allows for the acquisition of calibrated values well ahead of the vehicle's actual availability, offering a significant advantage in terms of planning, optimization, and early validation. By leveraging 1D simulations, the proposed methodology revolutionizes the calibration process, facilitating faster and more efficient development.

Keywords: Thermal system, calibration, virtual calibration, 1D simulations, calibration, BEV, efficiency, thermal management.

Acknowledgements

We would like to express our heartfelt gratitude to our Supervisor, Mukund Rudravajhala and the entire CAE Thermal Management team at Volvo Cars Corporation for their unwavering support and invaluable assistance throughout the duration of this thesis project. Their guidance and expertise played a crucial role in expanding our technical skills and ensuring the successful completion of our research. We would also like to extend our appreciation to our manager, Helena Martini and our CAE Product Owner, Juan Antonio Moreno Gomez for their seamless on-boarding process and their efforts in facilitating the necessary arrangements throughout the project. Their support greatly contributed to the smooth progress of our work.

Furthermore, we would like to acknowledge the exceptional coordination and assistance provided by Yashasvi Nandivada, Jonas Karrin, and Christoffer Johnson from the thermal control team at Volvo Cars Corporation. Their collaboration and support were instrumental in overcoming challenges and achieving our objectives. Last but not least, we are sincerely grateful to Prof. Simone Sebben, Head of VEAS Division at Chalmers University of Technology, for serving as our examiner and providing continuous support and valuable feedback throughout the thesis work. Their expertise and guidance have been invaluable in shaping the direction of our research.

We would like to express our deep appreciation to all those mentioned above for their contribution to the successful completion of this thesis project.

Harshith Munimahadeva and Vishnu Simba Selvan Anuradha,
Gothenburg, June 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BEV	Battery Electric Vehicle
CDE	Common Data Evaluation
CAE	Computer Aided Engineering
EV	Electric Vehicle
TM	Thermal Management
GT-Suite	Gamma Technologies-Suite Software
ED	Electric Drive Unit
VCC	Volvo Cars Corporation
GUI	Graphical User Interface
IGBT	insulated gate bipolar transistor
CFD	Computational Fluid Dynamics
FEM	Finite Element Method

Contents

List of Figures

List of Tables

1

Introduction

Electric Vehicles (EVs) are becoming more and more common on the road, compared to a few years ago, as the transition to a pollution-free mode of transport is being popularized. They hold their advantages over conventional Internal combustion engines in terms of efficiency and pollution levels. With the increase in demand for EVs worldwide, The challenge is to cope with the change in the temperature range of an Internal combustion engine (ICE) which has a wider operating range with a Battery Electric Vehicle (BEV) which is very sensitive to temperature and has a small operational range for better performance and durability. The adaptability brings additional complexity to a BEV for its thermal management system, Hence this increases the dependence on management of the thermal system to achieve efficiency and durability.

The thermal management system of a BEV now comprises multiple pumps, valves, sensors and circuits that operate based on driving conditions, weather and state of vehicle, whose control strategy gets more complex with every additional parameter increase in the system's controls. The combinations of the different sub-systems in the vehicle allows the different circuits to be isolated from one another, depending on other factors like temperature conditions. This complex variations require proper execution for achieving highest efficiency hence the need for calibration.

The method for achieving calibration is to test the vehicle in a climate chamber with predefined condition and all possible variations within the thermal system. The data acquired from these tests are used for obtaining the calibration for flow maps of pumps in the system , which is crucial for the vehicle's optimal performance and efficiency. This calibrated flow maps are used to create the software for the car. This process has its limitations, as it requires the availability of the physical test vehicle and a test environment(test chamber). This thesis is a proposed alternative for this process where in the same tests are ran in a simulated environment and data for calibration is obtained from these simulations. From the proposed method we are able to achieve the first round of calibrations years before the actual vehicle is available.This methodology also has more benefits such as sustainability from an energy consumption standpoint.

1.1 Background

Thermal system modeling comprises several tools to design and analyze a system for any condition. The process widely used in this industry is Computer Aided Engineering (CAE), which deals with the modeling and analysis of all the physical components in a virtual/modelled environment. The crucial field in CAE for this thesis comes under the thermal analysis simulations, mainly focusing on 1D simulation in thermal domain.

One of the most popular software for modeling and simulation in 1D space for thermal analysis is Gamma Technologies-Suite Software (GT-Suite)[17]. GT-Suite also deals with all types of automotive systems along with simulation packages in-built for an effective all-in-one tool for both modeling and simulation. Previous work includes modeling the entire vehicle and its thermal management system in the virtual space in GT-Suite.

Setting up the modeling environment is a manual task, which takes a few weeks for one sub-system development. The boundary conditions, operating characteristics, and parameters are all set up manually in the vehicle model in GT-Suite. For the simulation of these models, the possible variations focused on in the thesis are pump switching, valve positions and temperature variations. Then the simulations are run and results extracted which gives the data for system calibration. For the input of the variations in the simulations the process is automated to increase efficiency and also reduce errors.

Based on previous work conducted in this domain, there is an interesting study that was done by Rask and Sellnau [1] on IC engine calibrations using simulations. The study involved the use of a spark ignition engine with variable valve actuation and timing systems that helps the engine for power, torque and emissions. Simulation models of the engine was created, with the possibility to add equipment like turbochargers and valve lifts. The use of GT-Power was prominent to accelerate the calibration process to obtain the required models. Tests on an actual engine was done to obtain base values, and the GT model was simulated to obtain similar values to the physical entity. To quickly generate and optimize calibration maps for complicated powertrain systems, simulation tools have been developed. The approach effectively provides a "Virtual Dynamometer" that may be used in conjunction with other automated online calibration procedures. The goal of this project was to speed up the generation of the calibration data set. Large databases may be required to generate accurate calibration maps due to the extremely nonlinear behavior of engine operating parameters. It is expected that future developments in computer technology would allow this virtual technique to create a vast grid of reliable data without requiring a significant amount of time. Furthermore, numerous computers can be run in parallel to increase simulation speed. The results from this study give a very detailed explanation as to how simulations can be used for analyzing a vehicle sub-system and the data obtained can be utilized for many applications like further model development, and a potential for using this in the automotive industry.

The comprehensive investigation conducted from the study [1] has provided a solid foundation for the thesis project. The extensive background research has equipped us with a strong understanding of the subject matter, enabling us to identify and address potential challenges effectively. By leveraging the insights gained from the study, we can proactively adapt the model to overcome the identified challenges and ensure a smoother progression of the thesis. This solid background knowledge not only informs our approach but also instills confidence in the feasibility and success of the thesis project. For the calibration in the thermal system the base map is calibrated to achieve a better flow map based on the test data. The calibration map data contains pump request, pressure and flow rate of the coolant within the vehicle. These are monitored and adjusted to how the vehicles are used. The calibration maps are re-run using the software created using the previous version of calibration, this repeated iteration in the process improves the system calibration by fine tuning the map data and populating it with more iterated data points for all relevant possibilities.

1.2 Aim

At Volvo Car Corporation (VCC), for the calibration of components in the thermal system, a physical car is run through a series of specific tests in a climate-controlled chamber, and the data for flow rates, pressure, and temperatures of each component and thermal circuit are recorded, and used to get the calibration values required for the vehicle. This is repeated many times until a map with almost all the relevant data points for almost all the possible operational conditions of the system are obtained. This master thesis aims to create a methodology to get the first round of calibration maps using simulation data, years before the prototype vehicle is available for testing. This data from simulation is acquired from 1D simulations run using a vehicle mode in GT-Suite. This gives a new method of performing calibration using virtual models.

1.3 Problem Statement

Currently, the calibration process for the components in the thermal system necessitates the availability of a physical vehicle and a test chamber, which typically takes approximately two months to acquire and conduct the necessary data collection for calibration. However, by utilizing GT-Suite simulations, data can be obtained years in advance, well before the physical vehicle becomes available. Moreover, the proposed method enables the calibration process to be completed at least 1.5 years prior to the vehicle launch, providing a significant advantage in overall development timeline.

1.4 Outline

The thesis comprises the following sections:

- **Chapter 1:** Provides the necessary context and outlines the scope of the thesis. It sets the stage by introducing the background information and the significance of the thesis topic.
- **Chapter 2:** Focuses on providing a comprehensive theoretical understanding of the foundational methods used in the thesis. It dives into the relevant theories, concepts, and principles that form the basis of the chosen approach.
- **Chapter 3:** Offers a detailed explanation of the methodology employed in the thesis. It provides a step-by-step description of the setup, data collection methods, tools, and techniques used for analysis. This chapter explains the method and the approach chosen and emphasizes how well it fits the needs of the thesis. It also serves as a guide for replicating the thesis.
- **Chapter 4:** Presents the results obtained from the research and conducts a comprehensive comparison between the obtained results from simulation and vehicle data. This chapter also includes detailed analysis that illustrate the findings. It critically examines the results, discusses any discrepancies or patterns observed and some corrections made to rectify them.
- **Chapter 5:** Concludes the thesis by summarizing the main findings and the workflow with the methodology for calibration.

1.5 Limitations

The validation of 1D simulation models is crucial for ensuring their accuracy and reliability. However, it can be difficult to fully validate the models against real-world data due to limited access to comprehensive and representative experimental data. This further contributes to variations in the measurements obtained from the vehicle and model when run at similar conditions. Sometimes not possible to have all the data points for all the components modeled in the system and have to be interpolated for certain regions. It is also difficult to maintain constant temperatures in the test rig, leading to certain points being questionable when comparing it to the virtual model. As a result of the mentioned differences, obtaining a precise calibration model can be difficult.

2

Theory

The simulation and calibration of the vehicle software maps using GT-Suite, Python and Sympathy for Data (platform for data analysis based on python)[18] is a step-by-step process, with the main goals of the same being:

1. Setting up the test cases using vehicle data in the GT-Suite model
2. Simulation of test cases with the GT-Suite model
3. Data analysis of simulation results using common data evaluation (CDE)
4. Calibration of the vehicle and simulation
5. Automation of the aforementioned processes using Python

The data collected from the vehicle is used with sympathy for data to get the calibration results similarly, the Complete Vehicle Thermal Model (CVTM) developed by the Thermal Management team at VCC contains all the components necessary for running simulations similar to the test conducted with vehicle. the data extracted from the simulation should be converted into a CDE acceptable format, Since Sympathy for Data was created to use with vehicle test data it compatibility should be ensured for further processing.

2.1 Thermal Management System

The thermal management system works with the convective heat transfer phenomenon, which occurs when a fluid or coolant flows through a network of pipes and valves, allows heat to be added to or removed from a system, depending on the thermal management system's temperature control strategies. This control strategy can be split among different circuits for more isolated cooling and heating paths while the vehicle is used. The system must be calibrated to ensure optimal operation and performance considering these small changes lead to greater efficiency in turn longer range. The thermal management system of a BEV is split into 3 parts, the Low Temperature, Medium Temperature and High Temperature circuits, where the flow of coolant is controlled by valves that can isolate or connect these circuits.

The behavior of a thermal management system is controlled by the valves and pump speed requests, depending on the ambient air temperature and temperature in the different circuits in the thermal management system. When there is a change in either one of the temperatures, the system is designed to maintain the temperature from overheating or freezing down. it is important the system's temperatures be maintained within allowable limits, as this can affect the overall vehicle's operating efficiency and most importantly driving range. The batteries should be maintained at a certain operating temperatures, as it is prone to heat degradation and capacity loss outside the operating temperature.

The coolant is a blend of glycol and water as this type of mixture is prone to freezing up at low temperatures and turning to slush and also less prone to evaporation at high temperatures, As a result the coolant has less viscosity variation and can handle heat exchange more effectively.

2.1.1 Thermal Circuits in an Electric Vehicle

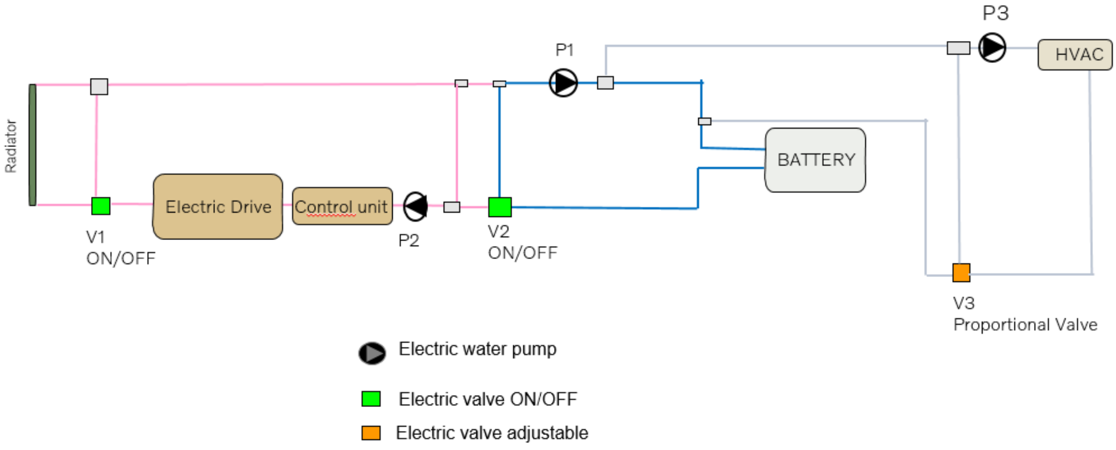

Figure 2.1: Basic circuit diagram

Figure 2.1 is a basic layout of the thermal system for which the system is divided into three different temperature circuits. This can be done to differentiate the temperature ranges among the components in the thermal system and also a very efficient way to manage these temperature ranges.

- **Low Temperature circuit (LT)**
  The low temperature circuit, highlighted in Figure 2.2, is responsible for the thermal management of the battery. This circuit contains various components which produce heat such as the battery pack and the battery management system. This circuit also houses a one-way shutoff valve that acts as a fail-safe in case of an emergency. This circuit is mostly maintained within the 30-40°celsius temperature range, this is mostly because of the optimal operating temperature range of the battery pack.

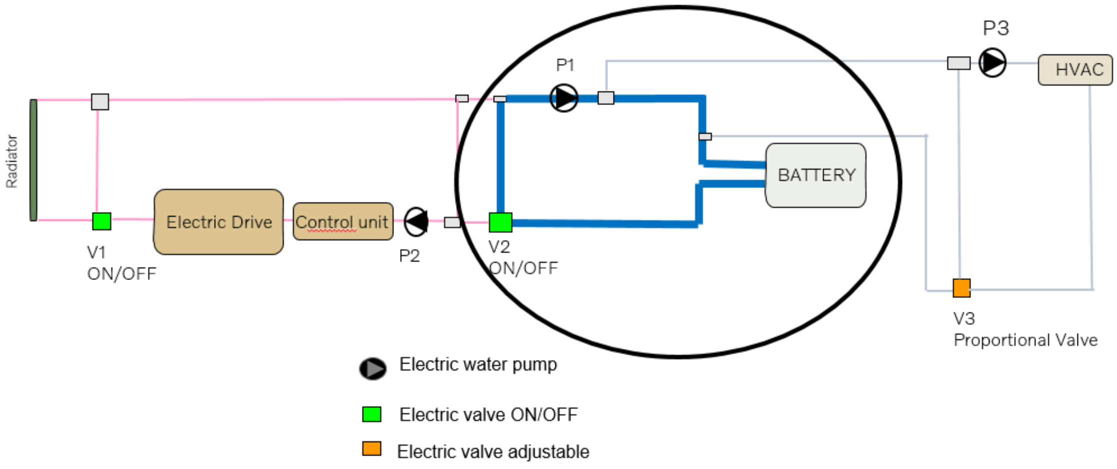

Figure 2.2: Basic circuit diagram: LT circuit.

- **Medium Temperature circuit (MT)**
  The medium temperature circuit, shown in Figure 2.3 , houses the Electric motor, inverter, charging unit, a radiator and some other low voltage electronics. In this circuit all the components except the radiator produces heat. The radiator cools down the coolant temperature using the principle of conduction and forced convection. This circuit is mostly maintained within the 40-70°celcius temperature range which is the optimal operating temperature range for the electronics and the electric motor.

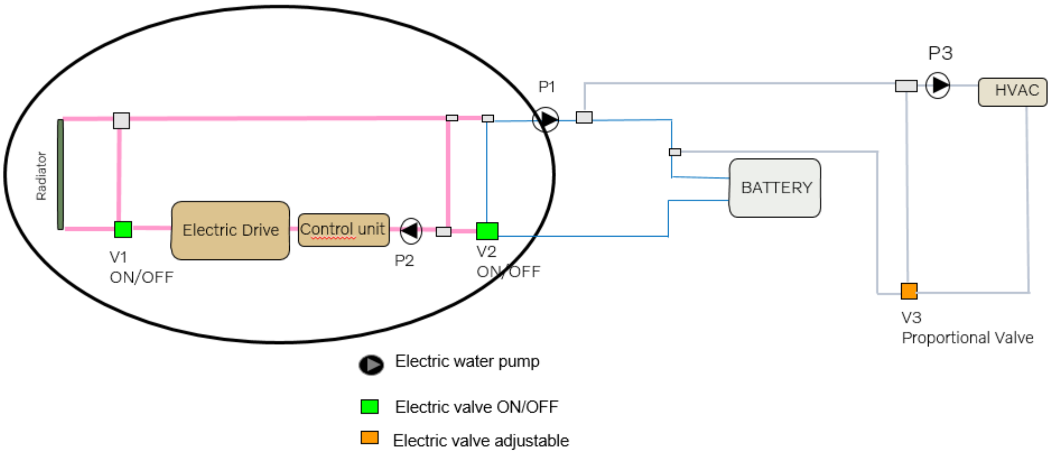

Figure 2.3: Basic circuit diagram: MT circuit.

- **High Temperature circuit (HT)**
  The high temperature circuit highlighted in Figure 2.4 handles the cabin thermal management system which is the air conditioning. This circuit contains HVAC system and a coolant to air heat exchanger. This circuit and the LT

circuit are also connected with a different medium(refrigerant) with a chiller and condenser at opposite ends. This circuit is mostly maintained within the 70-90 °celcius for optimal performance.

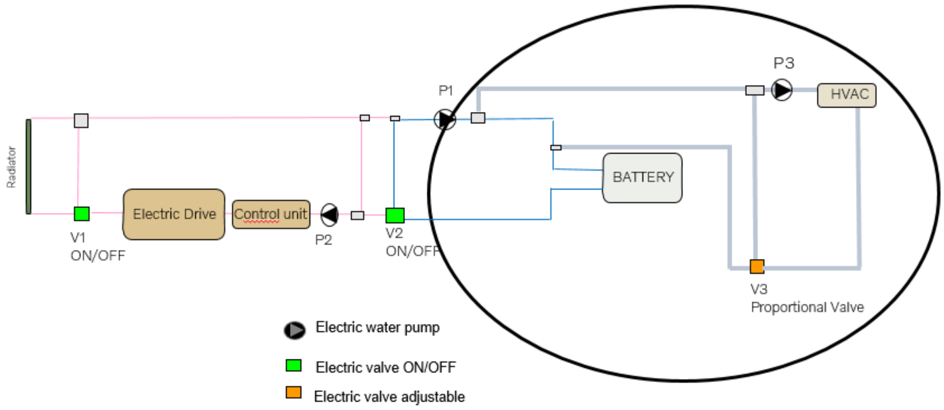

Figure 2.4: Basic circuit diagram: HT circuit.

2.2 Components in a thermal system

2.2.1 Valves

Valves are used to control the flow of coolant through them in a thermal system. The four types of valves used in the thermal system are 1-way check valve, 1-way shutoff valve, 3-way valve and 3-way proportional valve.

- **1-way check valve**
  A one-way check valve Figure 2.5, also known as a non-return valve or a check valve, is a mechanical device that allows fluid or gas to flow in one direction only. It is designed to prevent back-flow or reverse flow, ensuring that the medium flows in a single direction while blocking any backward flow. In the thermal system this valve is used as a safety valve in the MT circuit.

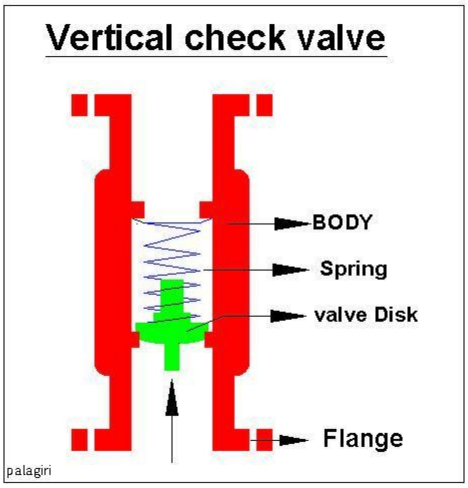

Figure 2.5: one way check valve [20]

- **1-way shutoff valve**
  Figure 2.6 is a one-way valve that allows fluid motion depending on the actuation of the valve, that is on or off [17]. In the thermal system this valve is used as a safety valve in the LT circuit.

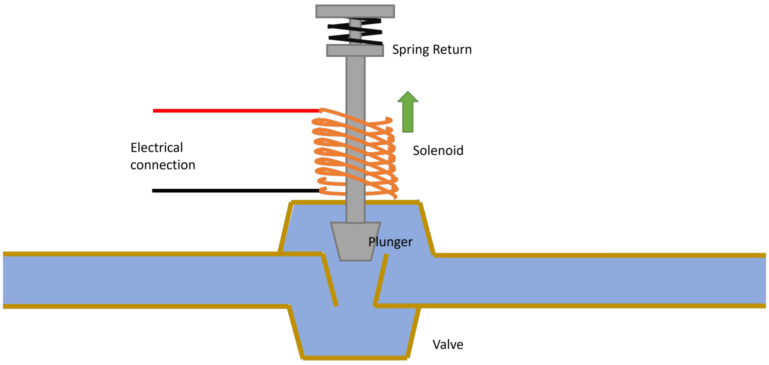

Figure 2.6: one way actuated valve[21]

- **3-Way Valve**
  Figure 2.7 is a three way valve which can let the fluid flow in 3 directions, usually it has a fixed inlet flow side and can direct full flow to one other side. This is usually used to bypass certain components in the circuit and also to either connect or disconnect two different circuits.

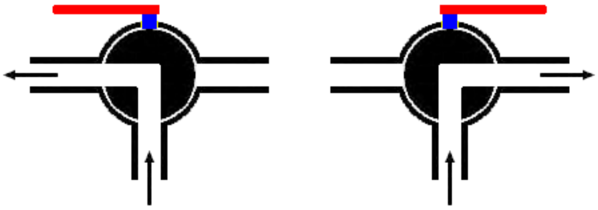

Figure 2.7: Three way valve[22]

- **3-Way Proportional Valve**
  Figure 2.8 valve similar to the three way valve can let the flow of fluid in three direction. The difference is that the flow of fluid can be split between the other two sides by a flow split mechanism controlling the amount of flow in both directions.

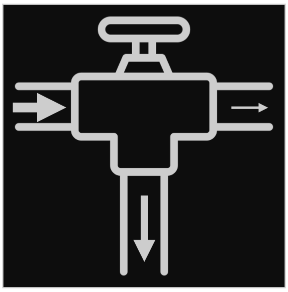

Figure 2.8: Three way proportional valve

2.2.2 Pumps

A pump is a mechanical fluid-moving device that typically transforms electrical energy into hydraulic energy[4]. These pumps are essential in a thermal system as they are the primary source for movement of coolant in the system. There are three basic types of pumps, they are:

1. **Positive displacement pump:** A positive-displacement pump Figure 2.9 moves a fluid by forcing (displacing) the volume that is trapped into the discharge pipe[6].

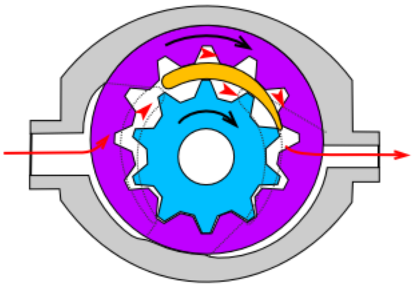

Figure 2.9: Positive displacement pump - Gear type [24]

2. **Centrifugal pump:** Centrifugal pump Figure 2.10 moves fluid by converting the kinetic energy of rotation into the hydrodynamic energy of the fluid flow.[5]

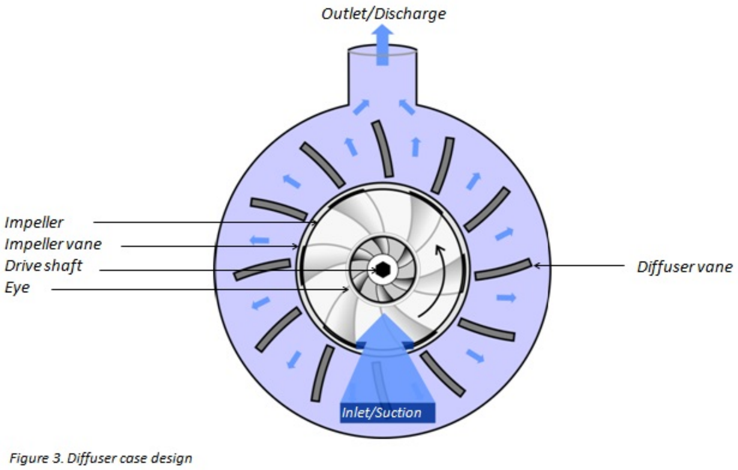

Figure 2.10: Centrifugal pump [23]

3. **Axial-flow pump:** Axial-flow pump Figure 2.11, primarily consists of an axial impeller inside of a pipe. A right-angle driving shaft that pierces the pipe or an electric motor or gasoline or diesel engine positioned on the exterior of the pipe can all be used to directly drive the propeller [7].

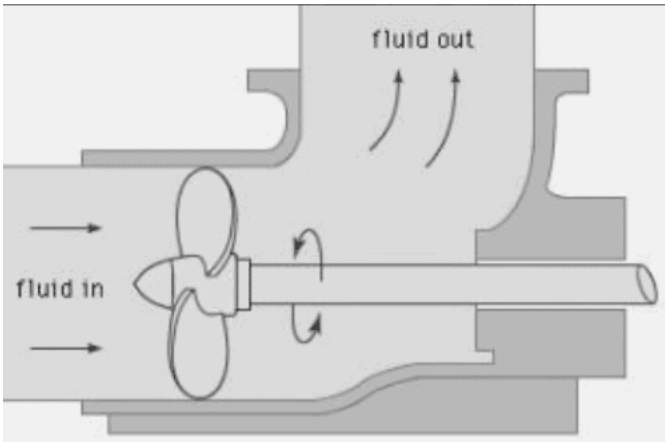

Figure 2.11: Axial flow pump [25]

The centrifugal pump is the most common type of pump used in the thermal management system in the automotive sector as this is the most convenient and effective pump to move coolant in the system with minimal losses. The centrifugal pump is often referred to as an "electric water pump" in the system.

2.2.3 Radiators

A radiator Figure 2.13 is a heat exchanger that transfers heat from the coolant to air through fins on the radiator's surface [8]. The radiator's large surface area effectively dissipates the heat absorbed by the coolant, which lowers the temperature uniformly. There are two radiators are present in the EV, One for the electric drive and another for the climate control. Airflow is provided by the vehicle when in motion or by a fan situated behind the radiators. Shutters on the front of the vehicle provide fresh air to flow through the radiators via ducts.

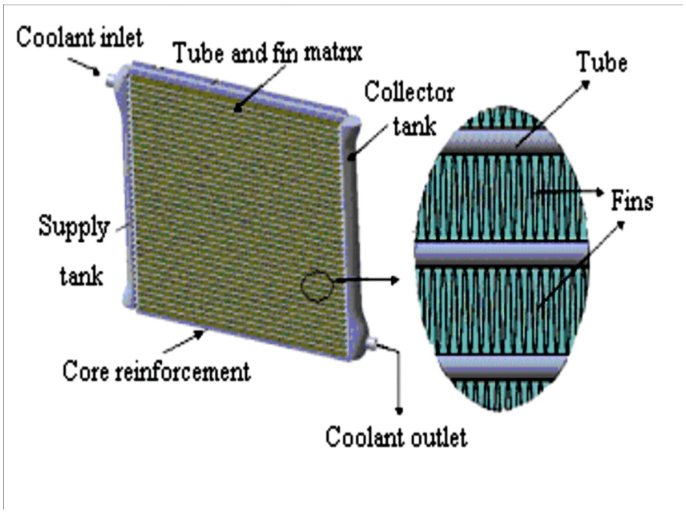

Figure 2.12: Radiator with a close-up view of the fins [26]

2.2.4 Air-conditioning system

This system is responsible for cabin climate control, which is essential for driver and occupant comfort while driving. It contains the evaporator, ventilator, water condenser and fan blowers. A water condenser is used for transferring heat from the refrigerant to the coolant in this process. The evaporator takes away the heat absorbed by the air molecules. The condenser and evaporator are responsible for maintaining humidity and temperature in the cabin. The ventilation is responsible for capturing the circulated is from the cabin and feeding it back to the circuit for heating or cooling according to driver request.

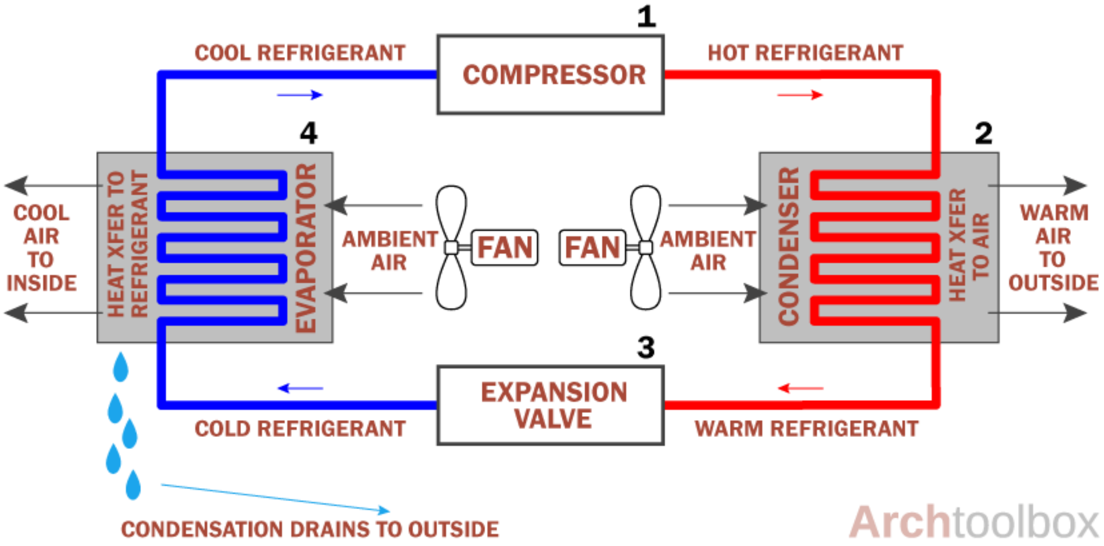

Figure 2.13: Schematic diagram of an air-conditioning system [29]

2.2.5 Chiller

A chiller is a device that uses vapor-compression, adsorption refrigeration, or absorption refrigeration cycles to remove heat from a liquid coolant.In order to remove heat from a substance or place, a chiller uses a phase changer[9]. In order to absorb heat energy from its surroundings, it works by changing the phase of a refrigerant or coolant, often from a liquid to a gas. By absorbing heat, the phase changer, often referred to as an evaporator, enables the refrigerant to evaporate, cooling the medium it comes into contact with. The refrigerant circulates within a closed system in order to carry out this operation, going through a continuous cycle of phase change, heat absorption, compression, and release.[10][11]

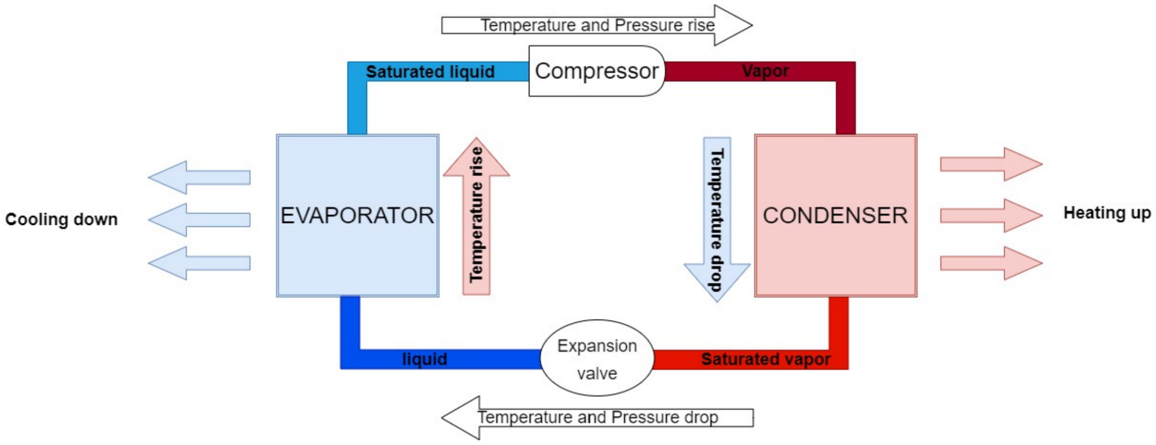

Figure 2.14: Schematic diagram of a chiller heat exchanger [3]

2.2.6 Drive system

The electric drive system is the sole responsible for propulsion of an EV. It encompasses several key elements, including electric motors, inverters, charging apparatus, and the battery. Together, these components work in synergy to propel the vehicle and enable its electric operation.

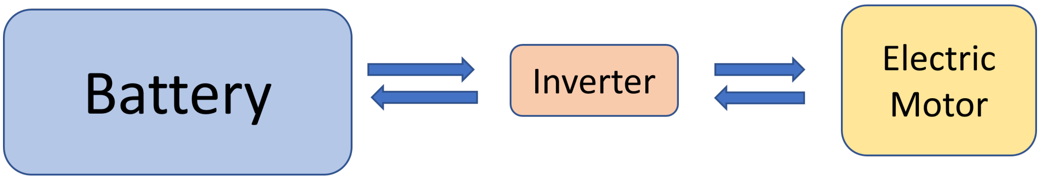

Figure 2.15: Flow of energy in the drive system

- **Electric motor**
  A machine that transforms electrical energy into mechanical energy is an electric motor. To create rotational motion, it makes use of electromagnetic principles. A magnetic field is produced when an electric current passes through the motor's coils. A force that rotates a shaft is created when this magnetic

field interacts with the magnetic field created by permanent magnets or other coils[12]. this process generates heat and need to be controlled to avoid meltdown of the machine.

- **Inverter**
  Direct current (DC) power is transformed into alternating current (AC) power using an electrical device known as an inverter[13]. An inverter's main job is to transform DC power sources into AC power. To quickly turn the DC input voltage on and off, inverters use semiconductor switches, usually transistors or insulated gate bipolar transistors (IGBT's), to produce a waveform that resembles that of ordinary AC power. Inverters frequently include sophisticated functions, such as voltage regulation, frequency control, and protective mechanisms, in addition to fundamental power conversion, to guarantee the stability and dependability of the AC power output[14]. These components are more temperature sensitive and have to be maintained at a certain temperature range (<70°celcius) to prevent wear and damage.

- **Battery**
  When needed, a battery transforms chemical energy it has stored into electrical energy [15]. One or more electro-chemical cells are arranged in a series or parallel and connected to one another. Anode (a negative electrode) and cathode (a positive electrode) are the two electrodes that make up an electrolyte in each cell. Materials that support reversible chemical reactions are used to make the electrodes. A chemical reaction that results in an electric current happens during discharge. This process transforms the chemical energy that has been stored into useful electrical energy[16]. The battery is a very sensitive component in the entire vehicle and the heat produced from batteries must be controlled as it has a short temperature range for optimal performance and efficiency.

2.3 Modeling tools

2.3.1 GT-Suite

GT-Suite [17] is a 1-Dimensional Multi-physics simulation software developed by Gamma Technologies, used in the automotive industry for modeling and simulating complete vehicles or vehicle sub-systems under any given conditions and driving cycles. GT-suite can also be used to run simulations in 3D for Computational Fluid Dynamics (CFD) and Finite Element Methods (FEM). GT-Post is used for post-process simulation data and other analysis. For the master thesis, 1D simulations are performed. The developed vehicle model is modeled using GT-Suite and tested for all varying conditions. The vehicle model is responsible for the 1D aspect of thermal behavior of the entire vehicle.

Based on previous work conducted in this domain, an interesting study [3] focused on the implementation of a vehicle model in GT-Suite for energy efficiency studies. The aim was to develop a virtual vehicle model that could accurately simulate the energy consumption and performance of the vehicle under various operating conditions. By implementing the vehicle model in GT-Suite, the thesis aimed to provide a tool for conducting energy efficiency studies without the need for extensive physical testing. This virtual approach offers advantages in terms of cost, time, and flexibility, allowing for quick evaluations of different vehicle configurations and operating scenarios.

Overall, the thesis demonstrated the value of implementing a vehicle model in GT-Suite for energy efficiency studies. It highlighted the benefits of virtual simulations in terms of cost, time, and flexibility, and it emphasized the importance of accurate modeling and validation to ensure reliable results. These findings provide a strong foundation for the utilization and implementation of GT-Suite as a modeling tool, which significantly strengthens the thesis. The comparison and analysis presented in the study highlight the potential benefits of incorporating GT-Suite into the research.

GT-Post is a post-processing application also developed by Gamma Technologies, provided as an extension for viewing the results of the simulations after downloading from a cluster or locally run cases from GT-Suite. GT-Post can also be used to review and compare results from other simulations side by side. The simulations done by VCC are sent to a high power computational cluster, a high performance computer that simulates the models as per the order of request and priority of operation. The simulations are the most time-consuming task in a calibration process. For this thesis, a simplified form of the complete vehicle model is used.

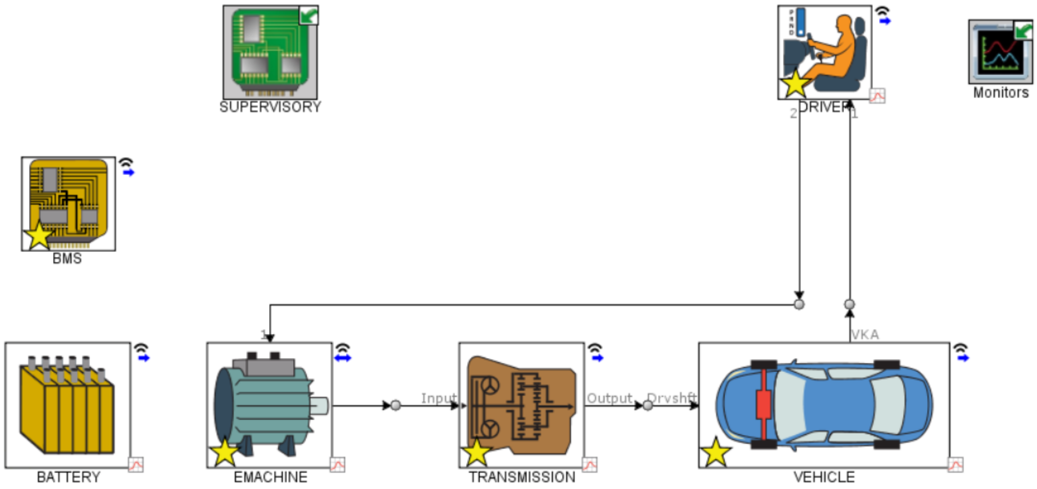

Figure 2.16: Example of an electric vehicle in GT-suite [27]

2.3.2 Sympathy for Data

Sympathy for Data is a software platform that is is used for data analysis from multiple sources and also deals with filtering and cleaning up of the data before they are compared [18]. The process flow in this software is called CDE, and will be used for the post-processing of the acquired simulation data.

2.3.3 Python

Python is an open source programming language that is widely used, and is an essential tool for this thesis to automate the workflow proposed. Python can be used for multiple applications, including automation, computation, integration and for development of new systems.

2.4 Test environment and cases

2.4.1 System model

The system model provided by VCC is an entire electric vehicle in a digital form. Complete with harnesses and cooling systems, the model is technically ready for simulations, with setting up run cases on multiple parameters. This model is constantly updated which can effects the results, hence the model needs to be updated with the latest changes. The model also contains data of the vehicle in the form of lookup tables for each component, which the component refers for operation.

2.4.2 Vehicle test cases and scenarios

The tests for the vehicle are done in a climate chamber for obtaining information about temperature, flow rates, valve openings and pump speed requests in the system. The test cases are available in an excel sheet that is used as reference for the vehicle when setup in the climate chamber for tests. The data is collected for various temperature zones varying from -24°celcius to +65°celcius.

2.4.3 Case setup using Python

The case setup in GT-Suite is a complicated process that includes setting up the pump speed requests, valve positions for every case, and there exists many such cases that are to be set up using the test cases excel. This is a time consuming process that also is prone to human errors hence, python is used to create these test cases.

2.4.4 Temperature ranges for testing

The selection of few temperatures for the testing is done to reduce the number of overall cases available for running, and then an interpolation is carried out. A minimum of 3 temperatures are needed for successful interpolation. The more the range of temperatures a vehicle is tested in, more precise calibrations can be obtained. Ultimately, It is always better to have data and information for more temperature points so that the data points are available for those certain temperatures when required.

2.5 Calibration

Calibration is the process of assessment and adjustment of a specific component or a system for deviations or errors in its functionality that has a possibility to hinder its working or operation. This is usually done to vehicle systems to check if the vehicle performs as intended. Deviations in some parameters can reduce the efficiency of the system.

Based on the previous work done in this domain [2] which explored the applications of 0D and 3D combustion modeling methods for virtual SI engine calibration. By leveraging these methods, the calibration process can be conducted in a virtual environment, eliminating the need for extensive physical testing. This approach offers significant advantages in terms of cost and time savings.

However, it is important to ensure the accuracy and reliability of the modeling techniques used. Validation against experimental data is crucial to establish the credibility of the virtual calibration process. The thesis emphasized the importance of accurately modeling various combustion phenomena, such as turbulence, heat transfer, and chemical reactions, to achieve reliable results. Although virtual calibration has its limitations, such as the need for accurate input parameters and assumptions, it has demonstrated great potential for optimizing engine performance parameters. It provides engineers with a valuable tool for exploring different calibration scenarios and fine-tuning engine parameters to achieve desired performance targets.

Overall, the thesis highlights the significance of incorporating 0D and 3D combustion modeling methods in virtual SI engine calibration. It emphasizes the need for accurate modeling and validation to ensure reliable results, and it showcases the potential of virtual calibration for optimizing engine performance.

The results obtained from this study lay a solid groundwork for the practical implementation of virtual calibration methods in the thermal system. The comparison and analysis conducted in the research underscore the potential advantages offered by virtual simulations. Thermal system calibration is done by analysing the coolant flows, valve positions, pump requests and pressure drops also its effectiveness in temperature control of the system. This process requires a physical vehicle and will take almost 2 months to get the calibration. This thesis utilizes the CVTM[19] model developed by the Thermal management team at VCC, which is a close representation of the actual vehicle and all its systems in virtual space. It is possible to obtain a base calibration of the vehicle in a few weeks and also a couple of years early than when compared to the traditional calibration method.

3

Methodology

3.1 Simulation model in GT-Suite

The CVTM was simplified with the removal of unnecessary parameters for the thesis like mass flow rate or heat rejection, for the purpose of reducing file size and run time. The required data for the thesis which are flow rates, pressure in each component in the circuit, pump and valve request signals are stored. These are achieved by given set of mathematical equations that govern the components in the circuit. The CVTM consists of all the components in the thermal system with detail such as the hose length and bend angle, which gives an exact prediction of the flow rates and pressure drops from the components. This model is chosen specifically for its simulation run time which is less compared to the whole vehicle model. The model includes any area in contact with coolant which is the main area of focus for the thesis. A series of tests were ran with the models to check combinations of the valve openings, pump speeds and temperatures are included, the data required for calibrating the components is stored and extracted.

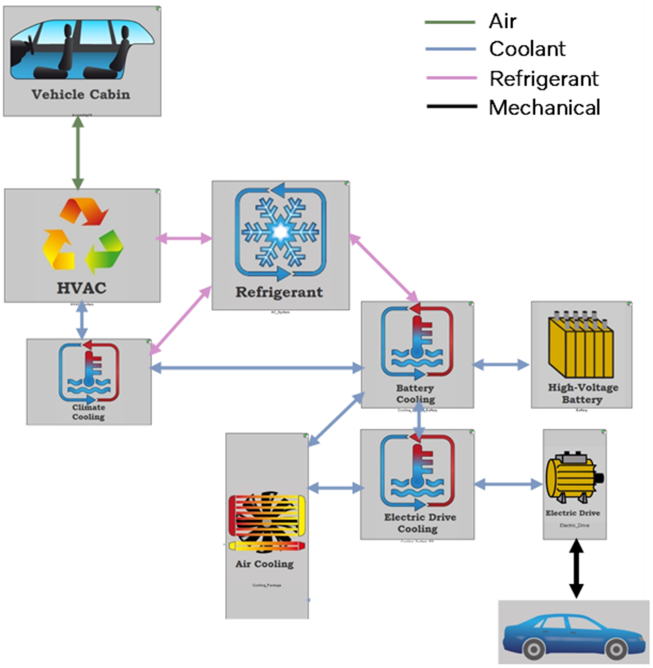

Figure 3.1: Complete Vehicle Thermal Model (CVTM)

3.1.1 Model setup

The model is updated with the exact components from the actual vehicle. The model is then updated to suit the needs of the thesis by cutting down non relevant parts. This decreased run time, reduced the file size and also very convenient if there are large number of cases.

3.1.2 Model simplification

Simplification of the model was achieved by adjusting the data storing of each component, like the unnecessary data like mass flow rate and temperature for each component were not stored and calculated in the simulations. In addition, the parameters not contributing to the end goals are also filtered out through the process, which also reduces the space occupied by the stored data files. A smaller file means faster simulation time and less data to post process. to further aid this goal the time step was increased ten times to reduced the computing time of the simulation, this does not affect the accuracy as an implicit solver is used.

3.1.3 Test runs

Using a data set from a previous vehicle test, a trial test is conducted to first check that the required results are not affected from the changes made, by comparing it with the same results from a original file . This is crucial as the process is being devised for the first time, and a good heading is important for the success of the subsequent tasks. Results from the example test runs gives an idea of how the data can be obtained and assessed based on requirements and different test cases.

3.2 Pre-processing stage

The Pre-processing stage is where the the case files are populated with the test matrix data specifically designed to operate all the valves and pumps at different combinations with different temperatures. The process involves the conversion of values in test matrix to be compatible for GT-Suite, setting up cases in .GTM file and automating the same using python. The purpose of this stage is to get the files ready to be able to simulate and get the results in Gt-suite.

3.2.1 Test matrix

The test matrix is a unique set of values, wherein it contains all the different combinations of valve positions, pump requests and temperatures of operation as shown in Table 3.1. The information contained in the matrix is usually for the entire operating range of the different components,with a wide temperature band. This broad combination of values gives a very wide spread on the flow map. This matrix can be up to 20000 cases for each temperature which is generated from varying valve positions and pump requests at very low intervals.

Variables	**Possible values**	**Increment steps**
Pump	0 to 100	1
One-way shutoff valve	0 or 1	-
3-way valve	0 or 1	-
3-way proportional valve	0 to 1	0.01
Temperature in °C	-30 to +65	1

Table 3.1: Variations for test matrix

In the system there are multiple valves and pumps of the same type, considering this along with the variations with different variables in the thermal system this only adds to the complexity of the entire matrix. The size of the entire matrix is too large.

- **Simplifying the matrix**
  Simplifying the matrix was a key part of the process as it has many benefits like reduced run time, reduced processing time and reduced file size. Therefore, to complete the simplification process, the valve and pump combinations that were not included in the controls were omitted because it was not practical to operate at those exact moments. The matrix's size was cut in half only by this. The matrix was also reduced by changing the increment steps in the test matrix as shown below.

Variables	**Old increment steps**	**New increment steps**
Pump	10	20
3-way proportional valve	0.01	0.20
Temperature in °C	20	5

Table 3.2: New variables for reduced test matrix

By doing this, the test matrix and the amount of data points collected were both significantly reduced Table 3.2. Flow of the matrix should not be interrupted because it still covers all the necessary end points and some spots in the increments, producing a map that is comparable to the one produced from vehicle but runs much faster. Its easier to add on more temperatures if time permits as it only increases the data points and it takes much lesser time to run than the previous matrix.

3.2.2 Populating the model files

The vehicle model, present as a .GTM file contain the simplified CVTM model, complete with all components and circuits. The case setup is where all the different scenarios are set for simulation like valve positions , pump speeds and temperatures. This file when run using GT-suite gives the results for all the cases after simulation in the form of .GLX files, which can be read using GT-post software.

3.3 Running of cases

The case setups are then run using GT-suite, Preferably on the cluster for more computational power. Multiple simulations can be sent over at a time and also it can be ran at time. This is part of the flow which requires the most amount of time as the simulations are calculated with multiple parameters for every time step.

3.4 Post-processing stage

3.4.1 Setting up the export file

All the information required to extract the necessary data from the.GLX files is contained in the export file, which is in the form of a .EXP type file. This file is altered to specific needs of the workflow but selecting only required data we further reduce the storage size and limit the data for required variables. This file is used as an extension/reference in the process of data extraction.

3.4.2 Data extraction and conversion for Sympathy

This is the process of extraction of results from simulations into a readable format like text (.txt) from .GLX files, which are encrypted and needs access from licence and credentials. The .txt files are then converted into an excel file with all the cases in line and in one file. This excel file created from the previous step is now converted to .Sydata file which is one of the acceptable formats of data for Sympathy for data software. The conversion is done using the Sympathy for data software with a custom flow created for this project.

3.5 Automation using Python

As observed from the test matrix that the test cases can be as much as 20000 cases, this leads to time consuming manual work and prone to errors in the entire process of achieving calibration. Automation is the solution for this case, it is much faster, accurate and runs in the background to give more freedom to the user. This process automates all the three stages mentioned above in the following steps:

- **Pre-processing:** The case setup can be a time consuming process when done manually, especially with several thousand cases with varying temperatures, many valve positions and pump requests. To ease the process of manually entering the values and also avoid errors a python script was created and used to populate the .GTM files. The code extracts these variable from an excel sheet created custom for the vehicle, hence some of the valve positions need to be converted to resemble the same in GT-suite this is done in the code as well. Then the code inputs the values into the .GTM file creating a new case for every row in the excel, also splits the file into 500 cases in each file, which was found to be optimal in the earlier stages of the project. This entire process can take about a day to do it manually and also using a GT-suite licence while doing so, This automation has reduced this time to about 5 minutes doing it without a GT-suite licence as it happens in the background. Now the files are ready to be run on GT-suite.

- **Running of the .GTM files:** Similar to the case setup a python script is developed to send the .GTM files to the cluster automatically, It is checked to see if its completed and then retrieve them is completed, which gives freedom to the user to send the files to the cluster when convenient. This method is also faster as GT-suite is opened in the background which is faster without the graphics-based operating system interface (GUI). After this process the .GLX files are stored in the folder pointed to in the code which is used for post processing in the next step.

- **Post-processing:** This process is automating using python to extract the results from .GLX to .txt format. This process happens in the background without opening the .glx file using GT-Suite while saving some valuable time in the process. The code also includes the merging and conversion of the results from several .txt files into one excel file with all the cases in the same order as the test matrix. An excel is preferred for the next step in conversion for Sympathy acceptable data. As Sympathy for data is setup for the vehicle test results the signal names are matched and replaced with the same signal names from the vehicle, this is also done in code using the dictionary excel file created which has both the signal names of the vehicle and GT-suite simulation. A final excel is obtained with the correct signal names and SI units.

- **Validation:** The Automation in each step is verified for errors. A small batch of cases at random are ran and results compared between traditional method and new python code method to further verify the process at each step of automation.

3.6 Calibration using Sympathy for Data

The code for calibration is created by the thermal software controls team at VCC in Sympathy for Data software Figure 3.2. This flow is modified to be able to receive both data from vehicle and simulation data and is compared together in the flow. This flow provides a .DCM file as the output which stores the calibrated data for different components of the thermal system. The software uses flow mapping in a cumulative process that incorporates filters, solvers, storage and plotting tools that the data is pushed through step by step, with a plot of the selected data towards the end. The process is called as Common Data Evaluation(CDE).

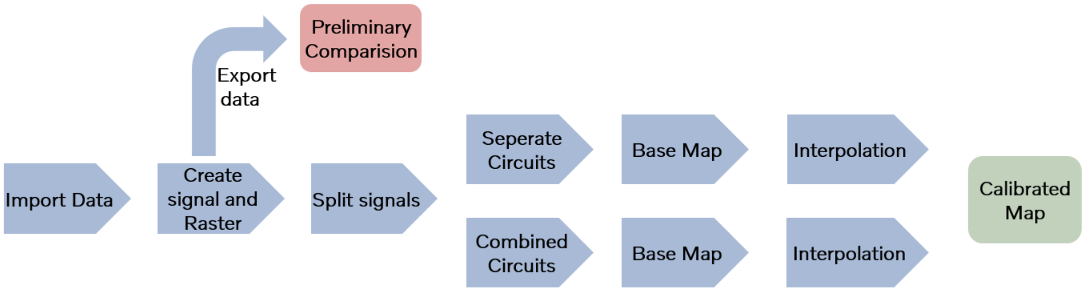

Figure 3.2: Flow in Sympathy for Data for calibration

3.6.1 Data import

The .Sydata file created is now imported into CDE along with the vehicle data which is .dat file. There are slight modifications made to the flow to read the .Sydata file as there is a differences in signal names from vehicle and simulation data. Few signals names were given alternate names from the simulation data as they resemble the same values as what the vehicle records.

3.6.2 Data comparison and analysis

The data is ran through the flow and required values like flow rates and pressure drops of each component in the system is extracted for further analysis. This can be also a validation for the GT-suite model to check how accurate the model behaviour is at different temperatures and flow rates.

3.6.3 Calibration

The calibration for each component is achieved by interpolating the values for each flow rates, valve positions and pressure drop at a time so that the map has the data to rely on for any possible combination of the these three variables. A .DCM file is a place to store all the data related to pressure drop, flow rate and pump requests for all the pumps available in the system. A base .DCM file is used for the first level of calibration or the .DCM from a similar project with almost same components as it has valuable data at certain points already optimized. The final calibration .DCM produced from the flow is then used to create the software for the vehicle which is then implemented in the car.

3.6.4 Validation of calibration

To be able to confirm that the calibration is as accurate as possible, the .DCM files are checked for the range of variations, which are expected to be within the limits. Then this can be analysed with an existing .DCM file which shows the changes made with the iteration by plotting one map on to of the other. If there are differences in the .DCM files created from vehicle data and simulation data, then the consequence of these changes can be estimated by using the .DCM files to create and test the software in the vehicle and then compare the result.

3.7 Streamlining of automation and workflow

- **Python code optimization**
  This step is essential to make all the distinct scripts developed to operate together and merge the codes where possible because the automation using Python was created independently for different stages of the workflow when required. Finally the three codes mentioned below were finalised:

  - Pre-processing
  - Running the .GTM files
  - Post-processing

  The calibration part is not included in the automation as there will variations in the flow for each vehicle and also varies on the dependencies naming each signal recorded.

- **Creating work flow and documentation**
  Since there is use of more than one software a clear workflow is required to go through the process. Each software has its own dependencies and acceptable file types. The workflow is optimized for continuous flow between two software without interruption. Streamlining of the workflow includes the documentation of the entire workflow with step by step instructions as to how to go over the entire process from data to end calibration.

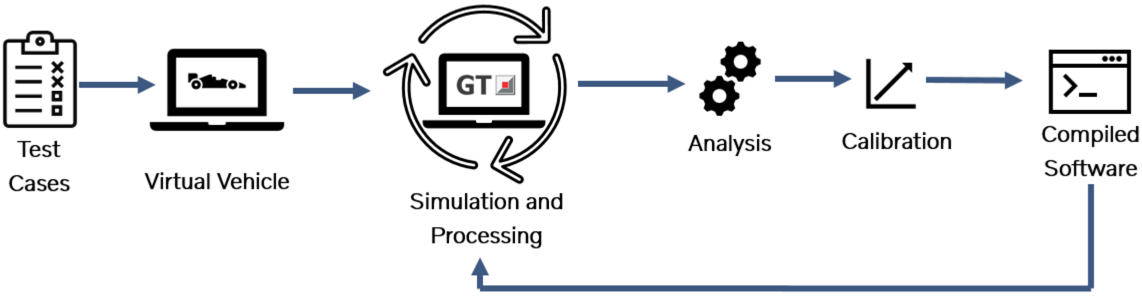

Figure 3.3: Methodology for virtual calibration

4

Results

The Result section comprises of the following steps:

- **Test case matrix**
- **Comparison of the data**
    - Flow rate comparison
    - Flow rate comparison
    - Pressure drop over the system
    - Pressure drop over individual components
- **Calibration and flow map analysis**

4.1 Comparison between simulation results and vehicle results

4.1.1 Test case matrix

In this section comparisons are made with traditional matrix and new matrix developed to reduce time and the end effect it has on the calibration maps created.

- **Traditional/Vehicle specific matrix**
  The vehicle specific matrix consists of over 17000 different cases which includes different pump requests, valve openings.These cases are activated by the by the vehicle where in the valves and pumps are activated for a particular value for each case for around 5 seconds (assumed to reach steady state).These cases are ran in a loop and the temperature is varied continuously till a desired temperature is reached and is steady for a period of time until its varied again to reach the next desired temperature. This results in many mixed points of data at different temperatures in the result file. This method will not achieve the whole matrix in one temperature due to this variation. Due to the limited time with the prototype vehicle this method is carried out so that the team can get more data points.

- **New simulation specific matrix**
  To address the issue of all data points with each selected temperature a custom matrix with about 150 cases is setup. This is achieved by lowering the increment steps in between, for both the valves and pumps. By having more temperature points, it is more beneficial rather than have many points at the

same temperature, as most of the points would repeat and only take up memory. This gives out a similar map to the one produced with the traditional matrix. The new matrix is much smaller than the traditional matrix and can be increased with points depending on the calibration level required.

4.1.2 Comparison of data

To facilitate a meaningful comparison between the data collected from the actual vehicle and the simulation data, it is essential to identify the specific region of overlap. This refers to the data set where both the test objects—vehicle and simulation—are subjected to similar conditions and scenarios. The identification of this overlapping region is a crucial initial step in the comparison process. Its purpose is to enable a comprehensive assessment of flow rates and pressure drops across various circuits and components. By ensuring that the collected data falls within an acceptable deviation range between the vehicle and simulation data, we can establish the reliability and accuracy of the simulation model. This one-time procedure contributes to validating the simulation against vehicle and enhances the overall credibility of the findings. To ensure the confidentiality of the company data, all results presented in this study have been normalized.

- **Flow rate comparison**
  To assess the flow rates within the thermal system, a circuit-by-circuit comparison was conducted, examining both the vehicle data and the simulation data separately. This analysis involved examining the flow rates of each individual circuit to determine any disparities. Specifically, the focus was on comparing the flow rates between the vehicle data and the simulation data for circuits operating independently. Notably, the comparison of Pump1(LT circuit) and Pump2(MT circuit) revealed a difference of approximately 7% between the two data sets as shown in Figure 4.1. This finding highlights the variance observed in flow rates between the actual vehicle and the simulated model, providing valuable insights for further comparisons.

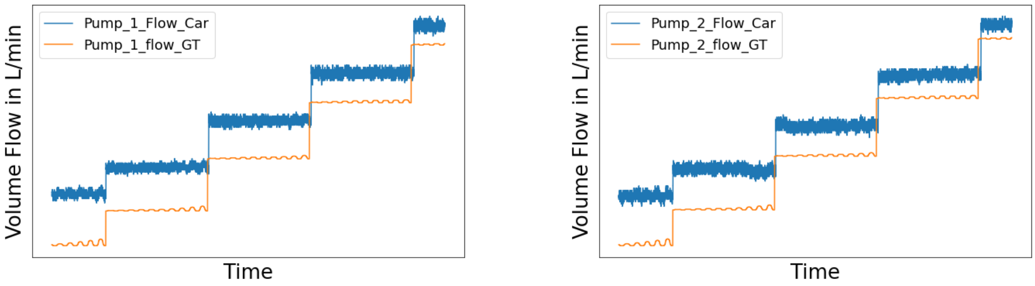

Figure 4.1: Pump 1 and Pump 2 flow rate comparison

This compared data however in the region of acceptable deviation was further analysed to find the cause of this deviation. for this the pressure drop of the system or individual circuit needed to be calculated.

- **Pressure difference analysis over the circuits**
  In order to address the discrepancies observed in flow rates between the vehicle and simulation data, a comprehensive analysis was undertaken to evaluate the pressure drop within each circuit. The calculation of pressure rise or pressure drop within a circuit is determined by analyzing the change in pressure across the circuit. Pumps play a crucial role in increasing the pressure within the system, while various components contribute to pressure reduction. The total pressure drop across the circuit is expected to equal the pressure rise caused by the pumps. This fundamental principle ensures a balanced analysis, where the cumulative pressure drop experienced by the components aligns with the pressure increase generated by the pumps.
  The comparison encompassed two distinct temperature regions: 37°C and 25°C. Remarkably, both temperature zones yielded similar results regarding the disparities in pressure drop. This examination of pressure drop provided valuable insights into the underlying factors contributing to the inconsistencies observed in flow rates, enabling a more comprehensive understanding of the system's behavior and aiding in the refinement of the simulation model.

  - **High temperature region 37°C**
    In the 37°C data in Figure 4.2, the pressure rise across the pump was calculated for each individual circuit within the system. A notable variation in pressure rise was observed among the pumps when comparing the simulation data with the vehicle data. Specifically, the pressure drop in Pump 3, associated with the HT circuit, exhibited a minimal difference of just 1% between the simulation and vehicle data. On the other hand, Pump 1 and Pump 2 displayed disparities of 6% and 12%, respectively. To understand and resolve these discrepancies, an in-depth analysis of the individual components was carried out, focusing on identifying the factors contributing to the observed differences.

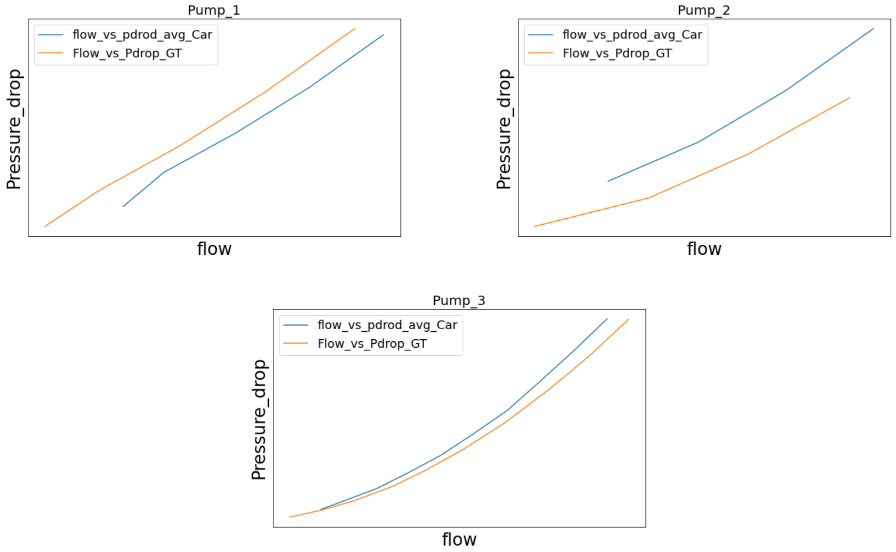

Figure 4.2: Flow rate vs pressure drop comparison within circuits.

- **Normal temperature 25°C**
  Similarly, in the 25°C data shown in 4.3, a comparable pattern was observed, with minimal differences detected in the HT circuit's pressure readings. However, notable disparities persisted in the data for Pump 1 and Pump 2. These pumps exhibited an approximate 9% difference, where the pressure rise over the pumps in the simulation data exceeded that of the vehicle data. These consistent variations in pressure drop, coupled with the discrepancies observed, prompted a more thorough investigation into the pressure drops experienced by the individual components.

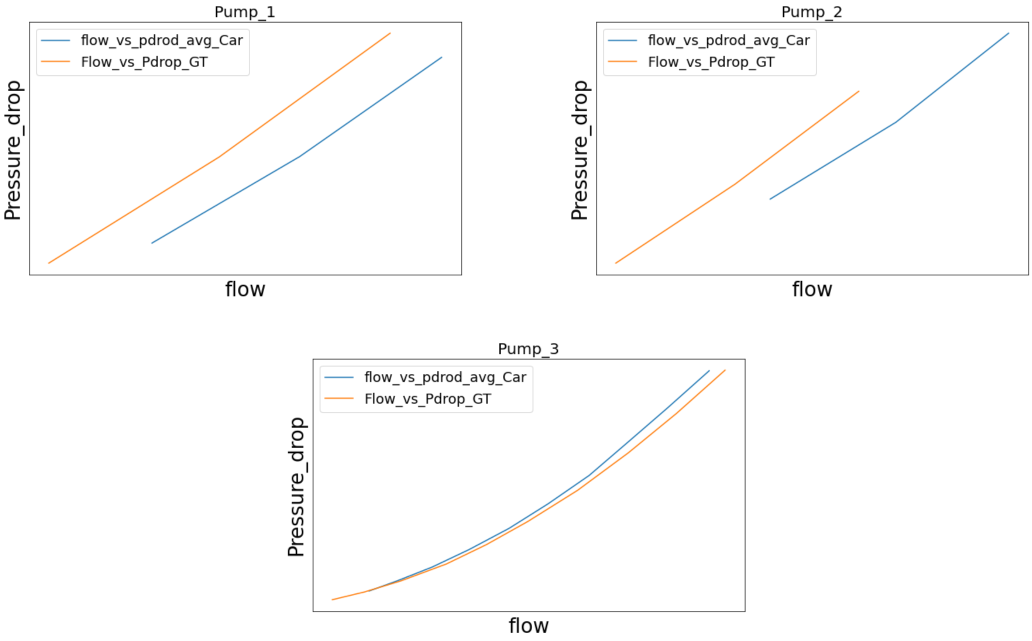

Figure 4.3: Flow rate vs pressure drop comparison within circuits.

- **Pressure drop over individual components**
  The examination of pressure drops across each component within the circuits Figures in Appendix [A] and Appendix[A.2] revealed a close correspondence between the vehicle and simulation data, except for two specific components—one from the LT circuit and the other from the HT circuit. These components exhibited significant variations in pressure drop relative to the flow rate, with an average difference of approximately 8% in LT circuit component and 15%in HT circuit component compared to the physical vehicle values Figure 4.4. Furthermore, a notable lack of parallel resemblance in the patterns further suggests that the map data provided for the simulation concerning these components requires reevaluation and updating. It is imperative to incorporate more accurate pressure drop models to ensure improved alignment between the simulation results and the actual performance of these components.

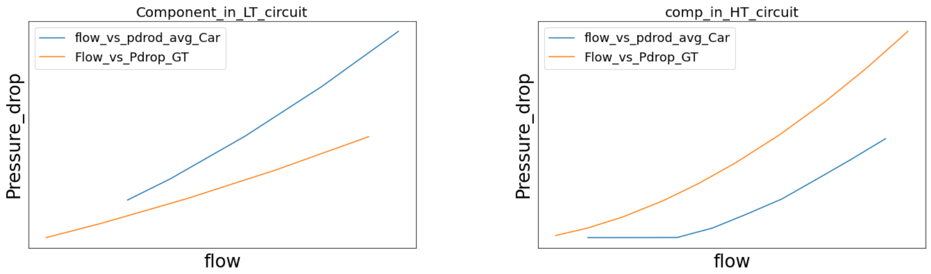

Figure 4.4: Flow rate vs pressure drop comparison for individual components

4.1.3 Challenges

During the course of the thesis, several challenges were encountered, one of which involved the variation in flow rates through proportional valves due to their nonlinear opening characteristics within the valve. Notably, the nonlinear opening behavior of the proportional valves modeled in GT-Suite differed from the actual valve opening observed in the vehicle. This discrepancy became evident when comparing the flow rates of individual components to those measured in the vehicle. To address this issue, adjustments were made to the valve modeling in order to replicate the opening behavior observed in the vehicle. By aligning the valve opening models more closely with the vehicle's actual behavior, the accuracy of the simulation was improved, enabling a more reliable comparison between the simulated and vehicle data.

- **Flow rate in valves for different requests**
  A comparison of the flow rates through the proportional valve was conducted by analyzing both the vehicle and simulation data. Notably, discrepancies in flow rates were observed at both the lower and higher ends of the pump requests, while the flow rates matched closely in the middle range. Further analysis revealed that the variations resulted from the modeling of the valve and its actual opening behavior Figure 4.5 in the vehicle under specific requests for valve opening. This observation was consistent across both the proportional valves in the thermal system. To address this issue, new values were implemented in the simulation model to accurately represent the valve opening behavior observed in the vehicle. By rectifying and refining these values, the simulation data successfully mirrored the flow rate values obtained from the vehicle, ensuring improved alignment between the simulation and the vehicle performance.

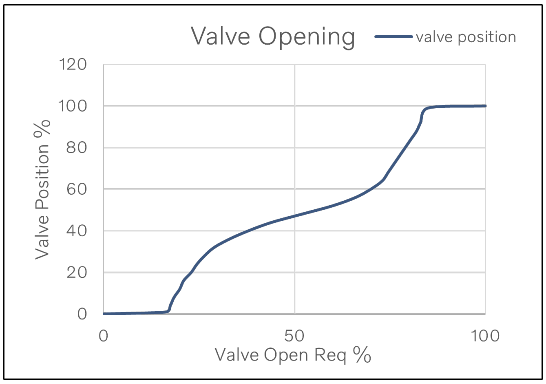

Figure 4.5: Non-linear valve actuation behaviour

- **Valve position difference**
  The modeling of the valve positions in the initial simulation was set to open from 0% to 100% based on the specified parameters. However, upon examining Figure 4.5, it became apparent that the actual valve opening in the vehicle occurred at around 17% and reached its maximum request at approximately 85%. Additionally, it was observed that the valve opening was not linear throughout its range. To address this discrepancy, the simulation model was adjusted to reflect the actual valve opening values obtained from the vehicle. These new values were implemented, and the simulation was rerun accordingly. The revised flow rate values obtained from the simulation closely aligned with the vehicle data, demonstrating a successful correction. The comparison results are presented in Figure 4.6, validating the effectiveness of the adjustments made to the simulation model.

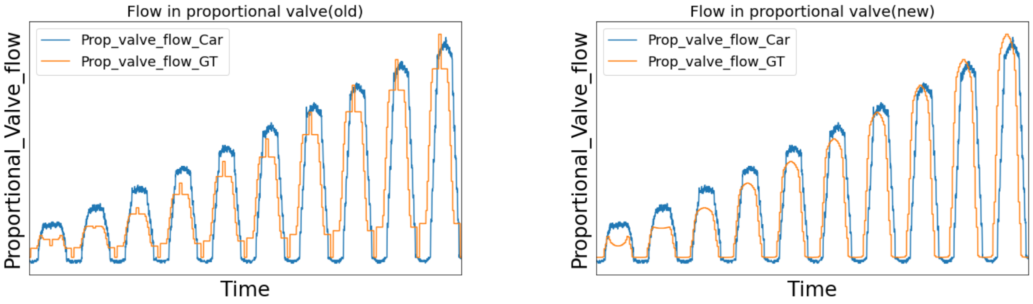

Figure 4.6: Original flow rate in proportional valve

4.2 Calibration

Calibration is a critical process aimed at evaluating, adjusting, and fine-tuning components or systems to achieve optimal operation. In this thesis, calibration focuses on refining the base maps by iteratively comparing them with test data. The objective is to derive a calibrated map that accurately determines the appropriate pump request based on specific pressure and flow rate requirements. Given the intricate nature of the circuits and components in the thermal system, a comprehensive set of maps is generated to provide more precise values for various operating conditions. This calibration process incorporates both traditional matrix data and new matrix data obtained from simulations, ensuring a comprehensive optimization approach. These calibrated maps can be utilized to develop software that can be tested on the vehicle, leading to a cyclic process of refinement and validation. This iterative calibration methodology allows for the continuous improvement of the system's performance.

- **Traditional matrix data**
  the calibrated maps using the traditional matrix doesn't match with the the calibrated map obtained with the vehicle data as shown in Figure 4.7. This could not be used to create software as it lacks the necessary data points required for most of the operation of the pump. This lead to the creation of the new matrix with all the required points necessary to calibrate the flow map with more useful data.

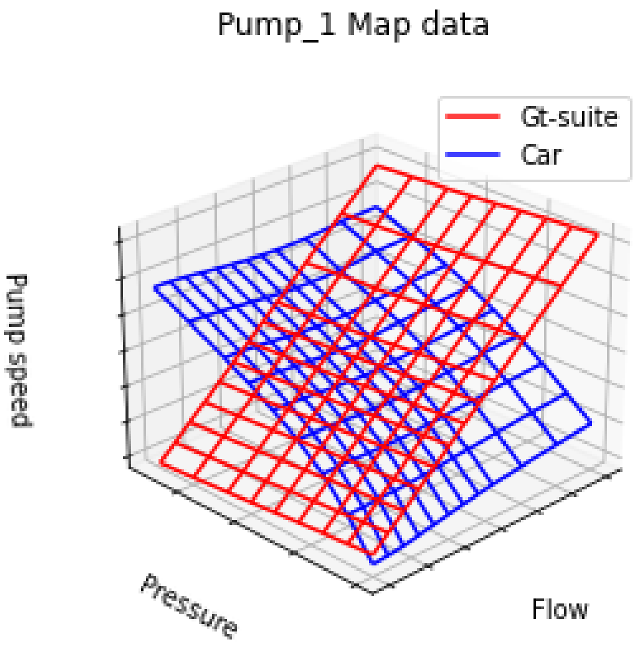

Figure 4.7: Map data created using traditional matrix in simulations

- **New matrix data**
  The matrix data utilized in the calibration process yielded an excellent calibrated map that closely resembled the map generated using the vehicle data as shown in Figure 4.8. A comparative analysis of these maps revealed an average difference of 8% at lower and higher pump requests, which aligns with the anticipated variations determined through flow analysis. An alternative approach to assess the disparities involves developing software incorporating

both the vehicle data map and simulation data map. These software can then be applied to the vehicle, enabling a direct comparison of achieved flow rates under similar operating conditions. This comprehensive evaluation allows for a robust assessment of the accuracy and effectiveness of the calibrated maps, further enhancing the reliability of the virtual thermal system's performance predictions.

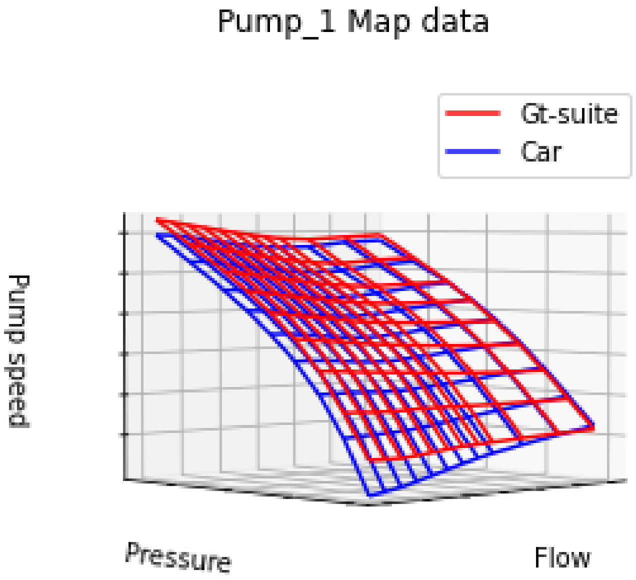

Figure 4.8: Map data created using new test matrix in simulations

5

Conclusion

In conclusion, this thesis has successfully addressed the challenges of calibration in thermal management systems by developing a streamlined workflow using 1D simulations and implementing automation. The traditional calibration method served as the basis for this study, which aimed to significantly reduce the calibration timeline and achieve calibration well in advance of the physical vehicle's availability.By leveraging 1D simulations, the need for a physical vehicle and test chamber was eliminated. This breakthrough not only saves time and resources but also provides the opportunity to refine the calibration data years before the actual vehicle is available. The calibrated map data obtained through simulations exhibited strong alignment with the map generated using vehicle data, showcasing the effectiveness of the virtual calibration process.

The streamlining of the calibration process was achieved through several key steps. A test matrix was created, and corresponding cases were configured within the GT-Suite software. The cases were then executed, and the resulting data was extracted and converted into a suitable format for calibration. The implementation of automation using Python further enhanced efficiency by eliminating manual tasks and ensuring consistency throughout the calibration iterations.The reduction in the test matrix enabled more comprehensive testing at various temperatures, resulting in a richer data set. This abundance of data points contributed to the creation of smoother curves on the calibrated map, enhancing its accuracy and reliability. The automation using Python facilitated seamless integration between multiple software platforms and different file types, ensuring a streamlined workflow and minimizing errors.

The successful achievement of calibration using 1D simulations and the automation of the process offer significant advantages in terms of time and resource utilization. The early availability of calibrated data provides improved efficiency, flexibility, and agility in the development process, ultimately leading to optimized thermal management in the final product.

In summary, this thesis project has made significant contributions to the method of calibrating thermal management systems by providing a streamlined workflow for using 1D simulations. The elimination of physical prototypes, the reduction in the calibration timeline, and the early availability of calibrated data have revolutionized the calibration process and enhanced the overall efficiency and performance of thermal management systems in various applications.

Bibliography

[1] Rask, Eric, and Mark Sellnau. “Simulation-Based Engine Calibration: Tools, Techniques, and Applications.” SAE Transactions, vol. 113, 2004, pp. 821–832, `www.jstor.org/stable/44723555`. Accessed 8 June 2023.

[2] Grasreiner, Sebastian. Combustion Modeling for Virtual SI Engine Calibration with the Help of 0D/3D Methods. 26 July 2012, `nbn-resolving.org/urn:nbn:de:bsz:105-qucosa-90518`. Accessed 8 June 2023.

[3] Theodoropoulos, Leonidas and Chithaluri, Srikar (2022). Implementation of vehicle model in GT-Suite for energy efficiency studies. Chalmers ODR. `https://hdl.handle.net/20.500.12380/304687`

[4] Submersible slurry pumps in high demand. `https://www.engineeringnews.co.za/`. Retrieved on 2011-05-25.

[5] `https://en.wikipedia.org/wiki/Centrifugal_pump`

[6] `https://en.wikipedia.org/wiki/Pump#Positive-displacement_pumps`

[7] `https://en.wikipedia.org/wiki/Axial-flow_pump`

[8] `https://en.wikipedia.org/wiki/Radiator`

[9] "Academia.edu - Share research". Academia.edu. Retrieved 24 January 2022.

[10] "Types of Chillers - A Thomas Buying Guide". `https://www.thomasnet.com/`

[11] Evans, Paul (September 26, 2017). "Absorption Chiller, How it works". `https://theengineeringmindset.com/`

[12] Faraday, Michael (1822). "On Some New Electro-Magnetical Motion, and on the Theory of Magnetism". Quarterly Journal of Science, Literature and the Arts. Royal Institution of Great Britain. XII: 74–96 (§IX). Retrieved 12 February 2013.

[13] [1] “The authoritative dictionary of IEEE standards terms,” Guide books, https://dl.acm.org/doi/10.5555/555953 (accessed Jun. 7, 2023), page 588

[14] "Inverter frequently asked questions". `https://www.powerstream.com/`. Retrieved 2020-11-13.

[15] Crompton, T. R. (20 March 2000). Battery Reference Book (third ed.). Newnes. p. Glossary 3. ISBN 978-0-08-049995-6. Retrieved 18 March 2016.

[16] Pauling, L., “15: Oxidation-Reduction Reactions; Electrolysis,” in General chemistry, New York: Dover Publications, 2005 Inc. p. 539. ISBN 978-0-486-65622-9.

[17] Gamma Technoligies, `https://www.gtisoft.com/gt-suite/`

[18] Sympathy for data, `https://www.sympathyfordata.com/`

[19] Volvo Cars, Complete Vehicle Thermal Model(CVTM) wiki. [Online]. Available: `https://intranet.volvocars.net/sites/cvtm/GT%20Suite%20Modeling%20Wiki/Home.aspx`

[20] Palagiri (2018).One way check valve. Retrieved from- `https://creativecommons.org/licenses.en`

[21] Corbett, Joey (23 November 2022). Solenoid valve open. Retrieved from- `https://creativecommons.org/licenses.en`

[22] H Padleckas (16 September 2006). 3 way valve bores. Retrieved from- `https://creativecommons.org/licenses.en`

[23] `https://www.michael-smith-engineers.co.uk/resources/useful-info/centrifugal-pumps`

[24] `https://commons.wikimedia.org/wiki/File:Gear_pump_3.png`

[25] `https://ntgdpump.com/vertical-axial-flow-pump-manufacturer/`

[26] A. Gakare, A. Sharma, and G. Saxena, "Simulation Software Based Analysis of Automotive Radiators: A Review," Zenodo, `https://doi.org/10.5281/zenodo.2563431` (accessed Jun. 7, 2023).

[27] Gamma Technologies, Vehicle Fuel Economy and Performance: GT drive+ Vehicle, 2022

[28] [1] M. Kane, "Volvo launches EV battery pack assembly line in Belgium," InsideEVs, `https://insideevs.com/news/402530/volvo-ev-battery-pack-assembly-line-belgium/` (accessed Jun. 7, 2023).

[29] `https://www.archtoolbox.com/how-air-conditioners-work/`

A

Appendix

This appendix contains extra plots and graphs which was analysed but not mentioned in the report.

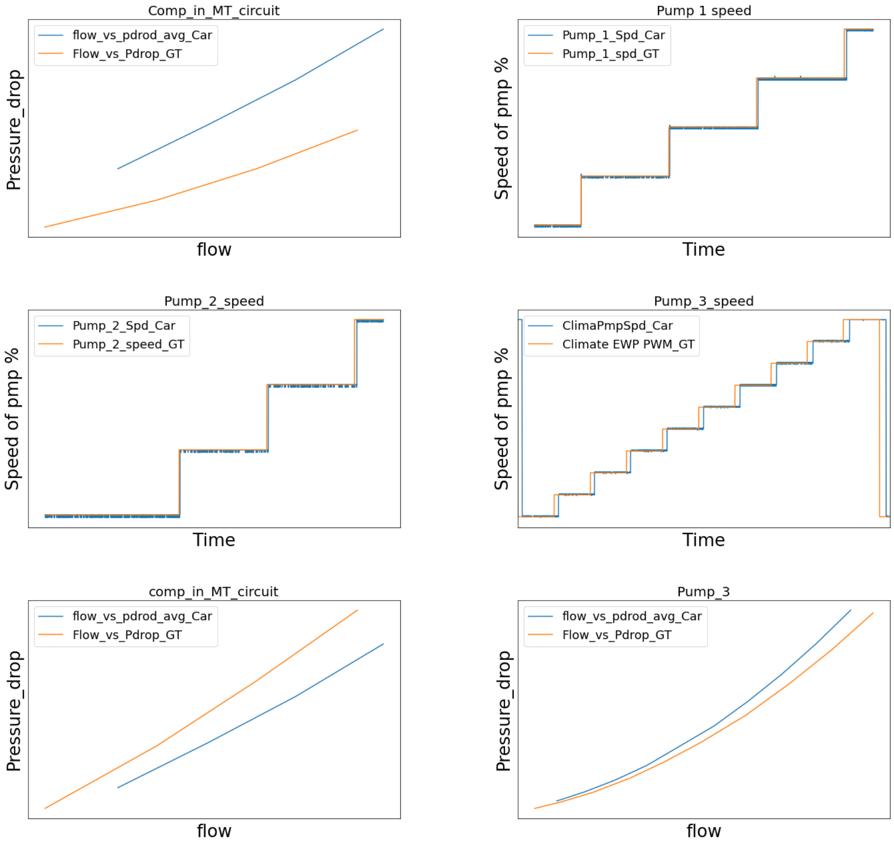

Figure A.1: Appendix for reference of all the plots analysed with 37 degree constant temperature

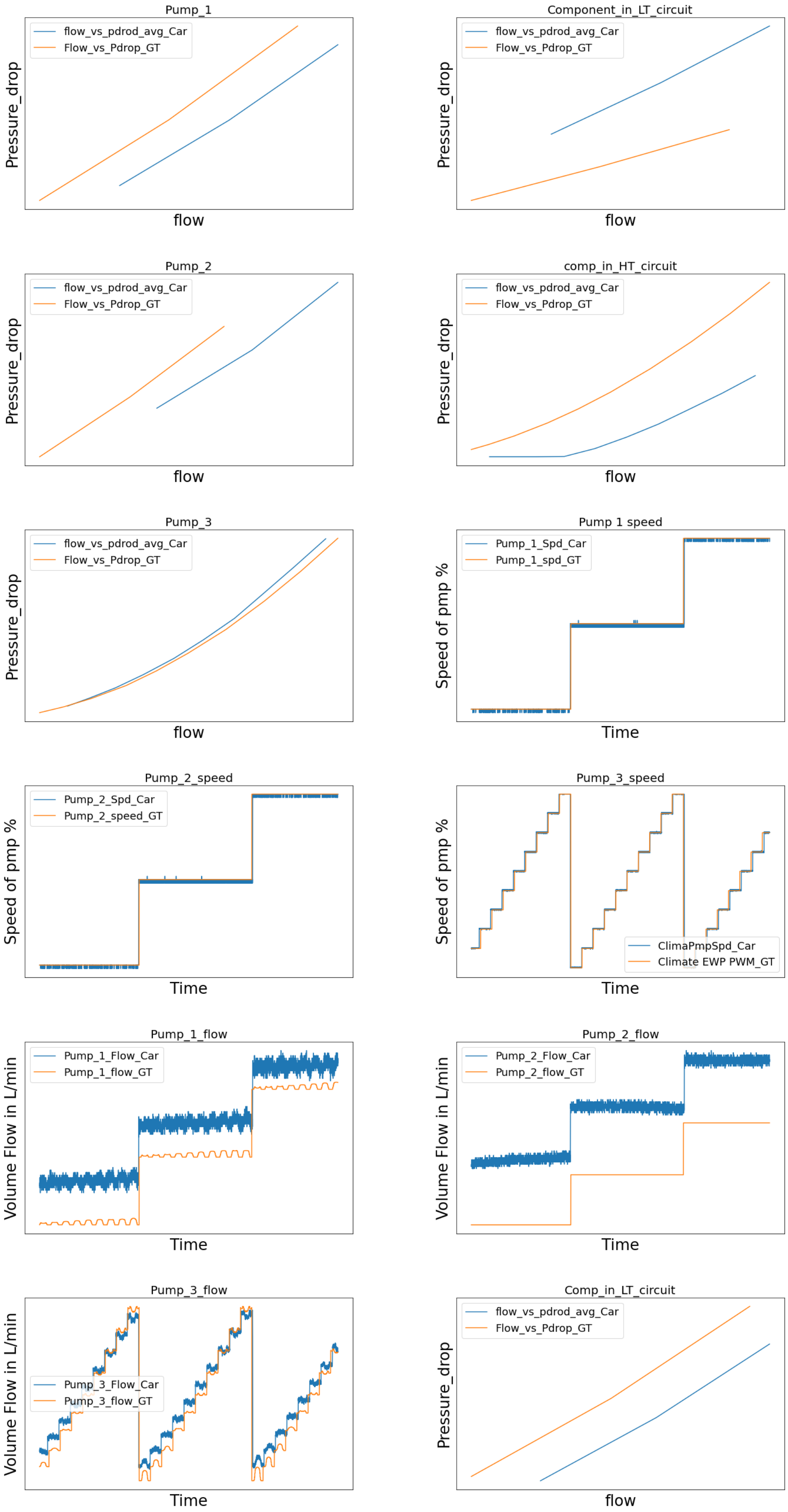

Figure A.2: Appendix for reference of all the plots analysed with 25 degree constant temperature

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se