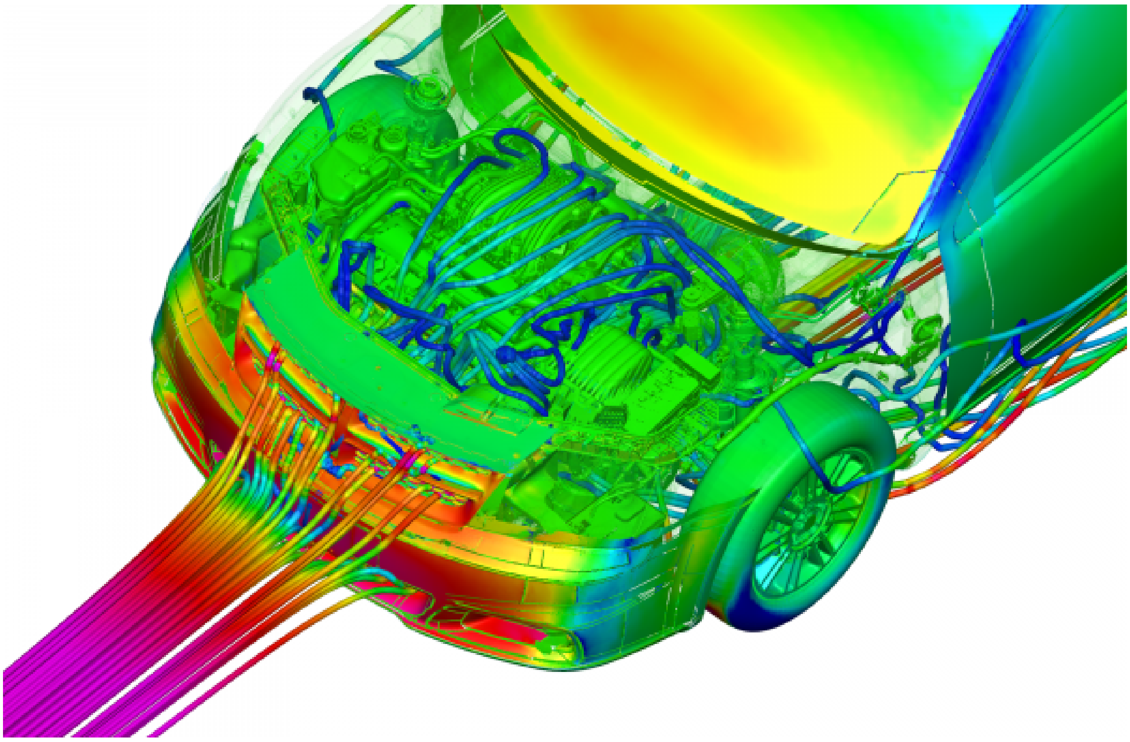

# New thermal management system for alternative refrigerants

Master's thesis in Mobility Engineering and Sustainable energy systems

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CHALMERS UNIVERSITY OF TECHNOLOGY
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# Abstract

The European Union has expressed concerns on the usage of some materials that may have a long-term effect on the ecosystem, particularly PFAS (per- and polyfluoroalkyl substances), in keeping with its continuous commitment to sustainability and the ethical use of resources. Regulations on the use of these materials, especially those containing PFAS, are being worked on by the EU.

As a company committed to sustainability, Volvo Cars is actively identifying and planning ahead for the use of substitutes in places where PFAS is utilized. The Thermal Management System is one important component that interacts with the EU-regulated refrigerant-containing refrigeration circuit. This has spurred a concentrated effort to investigate substitute refrigerants and design a suitable Thermal Management System based on them.

Keywords: Thermal Management, BEV, PFAS, Secondary Loop System, GT Suite, Full Secondary Loop.

# Acknowledgements

We extend our heartfelt appreciation to Examiner Simone Sebben for her invaluable guidance, unwavering support, and encouragement throughout this project, which empowered us to delve deeper and achieve our objectives.

Additionally, we express our gratitude to Volvo Cars for affording us the opportunity to embark on this endeavor. Special thanks are owed to our dedicated supervisor, Faruk Soydan, whose remarkable commitment, expertise, and guidance have been instrumental in our journey.

Furthermore, we would like to thank the team - Hamed Jamshidi, Mukund Rudravajhala, Babak Heydarnezhad, Rangakishen Sampath, Leonidas Theodoropoulos for generously dedicating their time to train us on the intricacies of the software.

# List of Acronyms

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

| | |
|---|---|
| AC | Alternative Current |
| A/C | Air Conditioning |
| BEV | Battery Electric Vehicle |
| CO2 | Carbon Dioxide |
| ED | Electric Driveline |
| EV | Electric Vehicle |
| GWP | Global Warming Potential |
| HP | Heat Pumping |
| HFC | Hydrofluorocarbo |
| HFO | Hydrofluoroolefin |
| HVAH | High Voltage Air Heater |
| HVCH | High Voltage Coolant Heater |
| GC | Gas Cooler |
| WCOND | Wet Condenser |
| IC | Internal Combustion |
| OEM | Original Equipment Manufacturer |
| PFAS | Per- and polyfluoroalkyl substance |
| TMS | Thermal management system |
| WLTP | Worldwide Harmonised Light Vehicle Test Procedure |

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# 1

# Introduction

## 1.1 Thermal Management System

With the ever changing world, specially moving towards sustainability, we have seen a spike to much cleaner and efficient electric vehicles. With their complex software structures and simple yet advanced mechanical components they have been proved to be more environment friendly given their resourcing and production is done in a timely manner. As the technologies and hardware implied within these vehicles are different from the more traditional IC engine vehicles, there now becomes more customers and suppliers of heat that need to be managed.

The control and management of heat produced/required by different parts of an EV, such as the motor, power electronics, battery and in some cases cabin is known as thermal management. Battery thermal management, and drive train thermal management are all included in the EV thermal management systems. [3]

Traditionally IC engines used could generate useable heat that could supply to the heating demands of the cabin. As source for heating in EVs now becomes non existent, thermal management needs to find new paths of heat transfer and not rely purely on PTC or heating applications that would consume energy from the car's high voltage battery reducing the overall efficiency and range of the vehicle. [4]

The thermal management refers to a coolant circuit used for managing thermal loads and requirements from various components that make up for the driveline, power electronics and the high voltage system of the car. This circuit in our scope, is either cooled by heat transfer with the atmosphere through the radiator or can be chilled using the refrigerant for further cooling, while also providing an option for heat pumping if required during heating mode. This makes a thermal management system very important for a vehicle as more often than not, the components used in a BEV are temperature critical.

As the electronic and mechanical components that drive an EV are now either a supplier or consumer of heat, they need to be managed extensively, thereby calling for a Thermal management system for the vehicle.

This type of a system is a link between the different components and their system and can therefore move around the heat present to accommodate the various requirements for different systems.

## 1.2 Refrigerant

The refrigerant in a air conditioning system can be used to provide extra cooling effect to the components in thermal management system when the cooling from ambient becomes insufficient. The refrigerant goes through its normal refrigeration cycle and can be used to cool a component either directly or indirectly in addition to providing the desired cooling to the cabin. [3]

Direct cooling is provided by sending the chilled refrigerant to the component and providing a means of direct heat transfer between the, while in the case of indirect cooling the refrigerant exchanges heat with the coolant which is used as a medium to transfer heat between the component with cooling requirement and refrigerant.

Refrigerant isn't only used for cooling, but can also be used for Heat Pumping as well as heating purposes, thus providing an additional supporting hand to the TMS.

Normally OEM's all over Europe have been using R1234yf which is a HFO refrigerant. HFO's are composed of hydrogen, fluorine and carbon atoms with at least one double bonded carbon atoms. This composition makes the refrigerant have negligible damage on the ozone layer or better measured with GWP of 4, which is far lesser than previously used and currently banned HFC refrigerants with GWP of more than 1300. However, the environmental hazard that arises with using R1234yf or any HFO is the presence of PFAS in them.

PFAS are a large class of thousands of synthetic chemicals that are used throughout society. They consist of Carbon-Fluorine bonds, which are some of the strongest bonds in organic chemistry, thus making them resist degradation in the environment and terming them as 'permanent chemicals.' They have been often observed to contaminate water bodies, be it surface water or ground water, thereby accumulating within the soil and cycling into our food system and proving harmful to human health.

In the automotive industry, this regulation would mean reshaping and restructuring of a lot of components and for our focus, the thermal management. Currently the refrigerant used is not only used to manage the thermal loads in the cabin through climate circuit, but it is used also used for heat transfer within the driveline and high-voltage systems as well. A change in this refrigerant would require the thermal layout to be changed in order to adapt to the capacity and limitations of this alternative.

## 1.3 Objective

The objective of the thesis is conceptualising and modelling a new thermal management system for a PFAS free refrigerant which fulfils the requirements of the temperature sensitive components in BEV.

## 1.4 Limitations

- All thermodynamic cycles are considered to be ideal.
- The system models are simulation based and no physical testing is done to verify the simulation results.
- As the refrigeration cycle is not integrated, application of heat loads and heat rejection can't be studied.
- Particular components have been simplified to have normalised pressure drops, so they do not represent the exact characteristics of the same components being developed and used within Volvo Cars Corporation.

## 1.5 Stake holders and Members

Parties involved in this project are defined in the following table:

**Table 1.1:** Stakeholder and members

| Name | Role |
|---|---|
| Volvo Cars Cooperation | Stakeholder |
| Simone Sebben | Examiner |
| Helena Martini | Engineering Manager |
| Faruk Soydan | Supervisor |
| Bhumika Dhamane | Project Engineer |
| Varun Tipnis | Project Engineer |

# 2

# Literature Review

## 2.1 Investigation

The investigation was conducted in order to garner different refrigerants that could be potentially be used as alternative to the existing refrigerants as a PFAS free substitute. Through our investigation we identified the different properties of these refrigerants, how they have a different working cycle from each other as well as from the existing refrigerant and how they can be incorporated into thermal management at different scales.

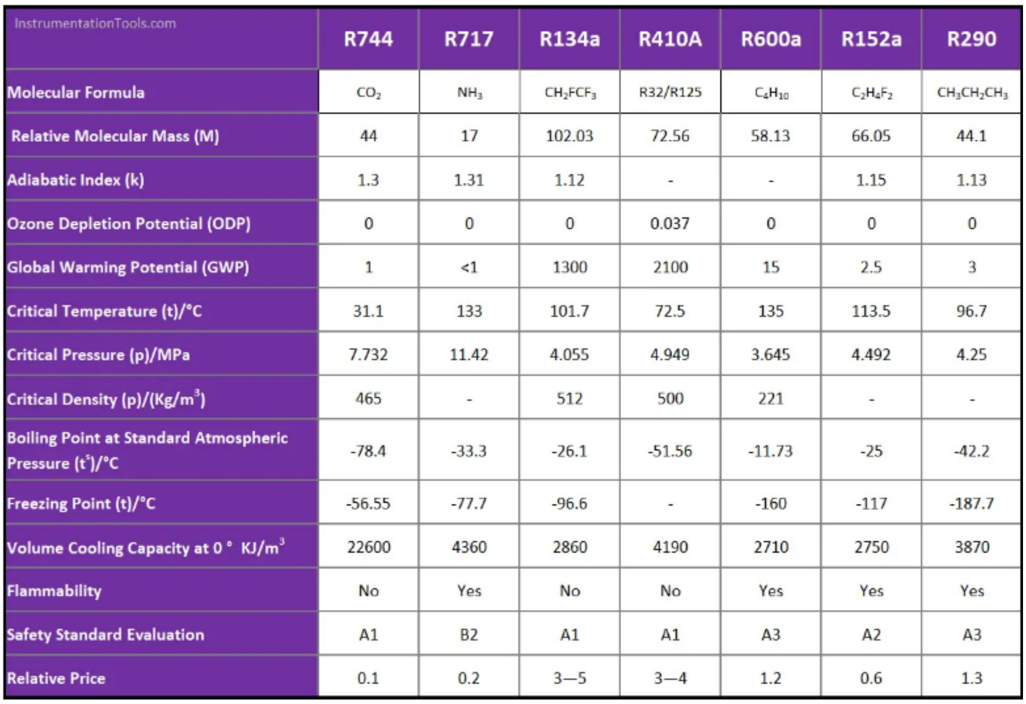
A comprehensive exploration of potential refrigerants suitable for integration into the thermal system of a car, we embarked on a meticulous journey through the available literature. The initial phase involved compiling a diverse array of refrigerants, comprising R404, R290, R134a, R22, R744 and R717. Each of these refrigerants was subjected to a rigorous analysis, meticulously evaluating their respective advantages and disadvantages across a spectrum of critical factors. These factors included the crucial considerations of GWP, operating temperature, and pressure.

Once enough knowledge was acquired regarding refrigerants, the focus was shifted to automotive thermal management. Here the task was to understand the different components in automotive thermal management systems and their interfaces with heat transfer with different assemblies in the vehicle. This study impacted how the layouts were designed in order to incorporate all the systems that required to be managed.
Following this initial phase, we engaged in collaborative discussions with the Volvo team, seeking insights and perspectives that would enrich our decision-making process. Moreover, we conducted comprehensive market research to glean valuable insights into industry trends and emerging technologies.

## 2.2 Identification of alternative refrigerant

In the preliminary phase of this research, an extensive review of available refrigerants was conducted to identify viable candidates for further study. The initial pool included a diverse range of refrigerants with varying thermodynamic properties and environmental impacts. The criteria for shortlisting were established based on key factors: GWP, cost implications, energy efficiency, market trends, and the presence of PFAS. Through a systematic evaluation, propane (R-290) and carbon dioxide (CO2, R-744) emerged as the most promising options. This section outlines the rationale behind this selection.

- Global Warming Potential: Global Warming Potentials (GWPs) are used to estimate, compare and aggregate the relative climate effects of various greenhouse gases (GHGs). They are a measure of the relative radiative effect of a given substance compared to another, integrated over a chosen time horizon.[5] Both propane and CO2 have been recognized for their low GWP values.
    - Propane (R-290): With a GWP of approximately 3, propane is an environmentally friendly alternative compared to many traditional refrigerants which have GWPs in the thousands[1].
    - Carbon Dioxide (R-744): CO2, by definition, has a GWP of 1, making it the benchmark for measuring the GWP of other substances. Its negligible contribution to global warming makes it a sustainable choice[1].



| InstrumentationTools.com | R744 | R717 | R134a | R410A | R600a | R152a | R290 |
|---|---|---|---|---|---|---|---|
| Molecular Formula | $CO_2$ | $NH_3$ | $CH_2FCF_3$ | R32/R125 | $C_4H_{10}$ | $C_2H_4F_2$ | $CH_3CH_2CH_3$ |
| Relative Molecular Mass (M) | 44 | 17 | 102.03 | 72.56 | 58.13 | 66.05 | 44.1 |
| Adiabatic Index (k) | 1.3 | 1.31 | 1.12 | - | - | 1.15 | 1.13 |
| Ozone Depletion Potential (ODP) | 0 | 0 | 0 | 0.037 | 0 | 0 | 0 |
| Global Warming Potential (GWP) | 1 | <1 | 1300 | 2100 | 15 | 2.5 | 3 |
| Critical Temperature (t)/°C | 31.1 | 133 | 101.7 | 72.5 | 135 | 113.5 | 96.7 |
| Critical Pressure (p)/MPa | 7.732 | 11.42 | 4.055 | 4.949 | 3.645 | 4.492 | 4.25 |
| Critical Density (p)/(Kg/$m^3$) | 465 | - | 512 | 500 | 221 | - | - |
| Boiling Point at Standard Atmospheric Pressure ($t^s$)/°C | -78.4 | -33.3 | -26.1 | -51.56 | -11.73 | -25 | -42.2 |
| Freezing Point (t)/°C | -56.55 | -77.7 | -96.6 | - | -160 | -117 | -187.7 |
| Volume Cooling Capacity at 0 ° KJ/$m^3$ | 22600 | 4360 | 2860 | 4190 | 2710 | 2750 | 3870 |
| Flammability | No | Yes | No | No | Yes | Yes | Yes |
| Safety Standard Evaluation | A1 | B2 | A1 | A1 | A3 | A2 | A3 |
| Relative Price | 0.1 | 0.2 | 3—5 | 3—4 | 1.2 | 0.6 | 1.3 |

**Figure 2.1:** Characteristics of the alternative refrigerants [1]

- Cost Implications : The economic feasibility of refrigerants is crucial for their adoption in commercial and residential applications. The cost considerations include the price of the refrigerant itself and any additional expenses related to system modifications and maintenance.
    - Propane (R-290): Propane is widely available and cost-effective due to its extensive use in other industries such as heating and fuel . The low cost and established supply chains make it an attractive option for many applications[6].

  - Carbon Dioxide (R-744): CO2 is inexpensive and abundant. However, systems designed for CO2 often require higher pressures and specific engineering considerations, which might increase initial setup costs but tend to offer long-term savings.
- Energy Efficiency : Energy efficiency plays a pivotal role in the operational performance and environmental impact of refrigerants. Efficient refrigerants can reduce energy consumption and operational costs.
  - Propane (R-290): Propane is known for its high energy efficiency in various applications which is about 5-12% higher than traditional refrigerants, often leading to reduced energy consumption compared to traditional refrigerants[7].
  - Carbon Dioxide (R-744): While CO2 systems operate at higher pressures, advancements in technology have enhanced their energy efficiency, especially in specific contexts like supermarket refrigeration and heat pumps[8].

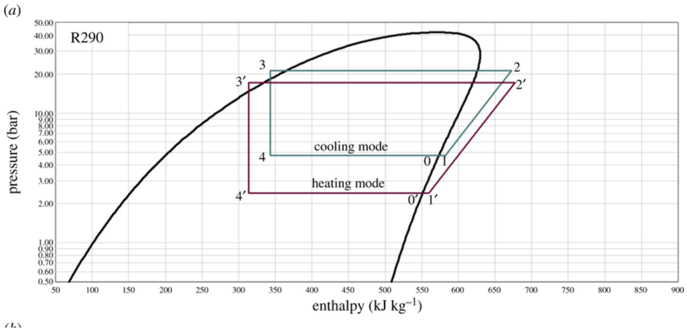


**Figure 2.2:** PH curve : R290 [2]

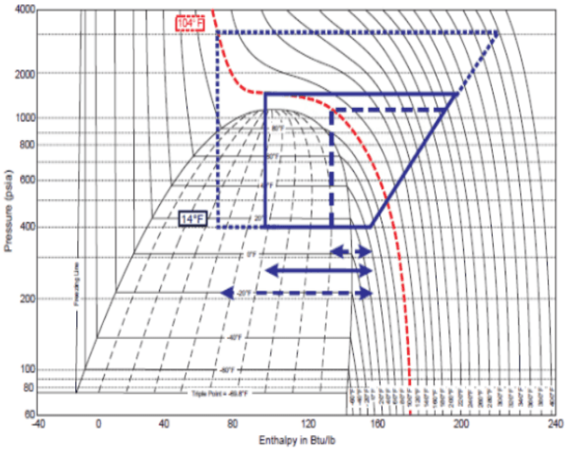


**Figure 2.3:** PH curve : R744

- Market Trends and Regulatory Compliance : Market research and regulatory trends influence the selection of refrigerants, especially with increasing global

  emphasis on reducing environmental impact and complying with international agreements like the Kigali Amendment.
  - Propane (R-290): There is a growing trend towards adopting propane due to its favorable environmental profile and regulatory acceptance in many regions.
  - Carbon Dioxide (R-744): CO2 is gaining traction in markets focused on sustainability. Its use aligns well with regulatory trends towards phasing out high-GWP refrigerants [1].
- Presence of PFAS : PFAS are synthetic chemicals found in some refrigerants. Their persistence in the environment and potential health risks have led to increased scrutiny and regulatory action [9].
  - Propane (R-290): Propane does not contain PFAS, aligning with the goal to minimize the use of these substances in refrigeration .
  - Carbon Dioxide (R-744): Similarly, CO2 does not contain PFAS, making it a safe and environmentally responsible choice .

## 2.3 Benchmarking

A comprehensive bench marking was performed to find existing solutions in automotive field. The objective was to understand how thermal management could be performed using alternate refrigerants (in our case R744 and R290). Bench marking in automotive solutions could however, only be performed for R744 solution as there are no existing Propane solutions in production. Some of the vehicles that we came across with CO2 refrigerant were: Audi E-Tron, Skoda Enyaq, Volkswagen ID series, and some of the newer electric and flagship Mercedes vehicles. Studying their layouts we figured how the components were different from a normal refrigeration cycle, and what differences existed in the interfaces between refrigerant and coolant. An outstanding difference was the Gas-cooler for CO2 that was implemented instead of a wet condenser. The existence of a Gas-cooler meant there had to be a gas to gas heat exchange for cooling of the single phase CO2 refrigerant and now the coolant couldn't be used. This created a few anomalies in the coolant circuit but through bench marking it was also identified how other OEMs found a way across it.

# 3

# Methodology

## 3.1 Thermal Management System

Requirements from Thermal Management System on component level
As discussed in the previous sections, the thermal management system in an Electric Vehicle plays a more crucial role than in traditional IC vehicles where there is only requirement for cooling of a large heat souce, i.e, the engine block.
For maintaining the life of components as well as the efficiency of the vehicle, the TMS has more functions and requirements from the components that are involved in the EV.[3]
The major components that make use of the TMS are:

- **Battery Thermal Management System**:
  Lithium-ion (Li-ion) batteries have become the dominant technology for the automotive industry due to some unique features like high power and energy density, excellent storage capabilities and memory-free recharge characteristics [4]. Unfortunately, there are several thermal disadvantages. For instance, under discharge conditions, a great amount of heat is generated by the redox reactions, and the battery temperature excessively rises.[10]
  These excessive temperature cycles have severe adverse impacts on the battery life and performance, thus requiring them to be replaced more often and proving to be a downside. Also reaching extremely high temperatures can risk a thermal incident which can prove to be fatal and very harmful to the environment due to thermal run-away.[11]
  Thus the proper heat load management of a battery system becomes a vital requirement that is demanded from the TMS. There are multiple ways of achieving this, but most common could include a plate with channels through which coolant could flow while picking up heat from the cells attached to this.[12] This thermal system maybe be able to cool the battery either passively or actively by exchanging heat with the refrigerant circuit. It could also have the functionality of creating a homogeneous temperature distribution over the cells of the battery thus improving their efficiency and life equally.

- **Electric Drivetrain and Power Electronics**:
  One of the crucial factors contributing towards the performance of electric motors is its thermal management.[13] Motor thermal management comprises heat generation, heat transfer from the generation point to the removal sys-

tems and heat removal. Heat generation is related to the losses inside the electric motors. Heat concentration can become critical to the system locally even if its small, this making heat transfer an important role player. Various solutions are available for thermal cooling system that can be employed and specifically targeted towards the major contributor of heat losses in an electric motor. Water jacket, air, glycol coolant, oil are some examples of mediums that can be used to provide thermal cooling.[14]
Miniaturization, high efficiency and compactness of power electronics have become a major as of today, which makes the thermal load a crucial issue. Excessive temperatures can cause failures and in general reduce the reliability of electronic components, particularly on power modules.[15]
This issue calls for thermal management system, that can eliminate these local heat concentrations, maintain the temperature at an optimal value and provide smooth cooling and uniformity in temperature distribution.

- **Cabin**:
  Cabin Heat Ventilation and Air Conditioning is tasked with creating and maintaining a comfortable environment for the passengers. Many external and internal factors affect the ambient cabin climate that needs to be adjusted by a thermal management system in order to maintain comfortable environment.[16] Normally the cooling is provided by the evaporative cooling of a refrigerant but in some cases such has hazardous refrigerants secondary loop is used where the cooling is done by the chilled coolant in the cabin.[17] Heat can also be provided by either coolant or refrigerant, and this heat can come from different components such as electrive drivetrain or battery instead of an extensive heating source to reduce the energy penalty.[18] The heating can also be provided by heat pumping operation for any of the components.

## 3.2 Heat Sources

EVs contain multiple electrically powered components or components which act as a resistance to flow of electricity which generate heat. When this heat is beneficial, these components can be viewed as passive sources of thermal energy.[18] The first and foremost heat producer is the electric drivetrain and power electronics. As talked about above these components are producers of heat due to the losses that prevail in them. Electric drivetrain has a lot of moving components that are in contact with each other and thus the force of friction becomes a dominant reason for energy dissipation in form of heat. The motors and power electronics also have resistance losses to the current flow and switching frequency during AC/DC power conversion. Electrical braking can be used to generate excessive heat on demand, thus serving a purpose to provide means of a on demand source as well. Battery is another major heat source in an EV. As the battery is charged or discharged, it dissipates large amounts of heat and thus acting as a good source as well. Ambient conditions around the car can be harnessed to pick up useful heat. The heat from ambient is mostly picked up during heat pumping. In some cases cabin heat is also seen as a source, although not always used it could be worth mentioning for some applications.

## 3.3 Heating and Cooling Requirements

To manage heating and cooling requirements in an EV at lower temperatures, multiple systems can be used for both the cabin and the battery. Following is a detailed breakdown of the various systems and their functions:

**Electric Drivelines**

1. Passive Cooling:
Relies on natural heat dissipation without active cooling elements. This method is typically used for managing the temperature of ED to prevent overheating.

**Heating Systems for Cabin and Battery**

1. HVCH/ HVAH:
HVCH: Uses high-voltage electricity to heat coolant, which can then be circulated through a heat exchanger to warm the cabin or the battery pack.
HVAH: Directly heats air using high-voltage electricity. This heated air can be used to warm the cabin more quickly than using a coolant loop.

2. Electric Drive Heating:
Utilizes waste heat generated by the electric drive components (motor, inverter) to provide heating. This method can be passive, where heat is simply redirected, or active, where specific components are used to generate heat intentionally.

3. Air Heat Pump:
Functions like a reverse air conditioner, drawing heat from outside air and transferring it inside to heat the cabin or battery.

4. ED Heat Pump:
The heat dissipated from electronic drive line can be captured via coolant and amplified via the refrigeration circuit.

**Cooling Systems for Cabin and Battery**

1. Active Cooling :
Active cooling or indirect cooling is used to cool down the coolant which is in turn used to cool down the Cabin and Battery. It is done by the use of refrigerants in the system.

2. Dehumidification:
While heating application in cabin, the air in the cabin becomes uncomfortable to the human skin, thus needs to be cooled a little.

### Additional Modes for Battery Heating and Efficiency

1. Battery Balancing:
A process that ensures all battery cells are at the same state of charge. During balancing, heat is generated as a byproduct, which can contribute to heating the battery.

2. Heat Pumping from Battery to Cabin:
Utilizes a heat pump system to transfer excess heat from the battery to the cabin. This process helps in maintaining optimal battery temperature while efficiently using the heat for cabin comfort.

## 3.4 Functions

### 3.4.1 Functions for lower ambient temperatures

**Table 3.1:** Status of the vehicle : Driving

| Status of the vehicle | Cabin | Battery | ED |
|---|---|---|---|
| Driving | HVCH/HVAH | HVCH<br>Nothing<br>Balancing<br>Passive cooling | Passive Cooling |
| Driving | Air HP | Air HP<br>Nothing<br>Balancing<br>Passive cooling | Passive Cooling |
| Driving | Air HP + HVCH | Air HP + HVCH<br>Nothing<br>Balancing<br>Passive Cooling | Passive Cooling |
| Driving | ED | ED<br>Nothing<br>Balancing<br>Passive Cooling | Passive Cooling |
| Driving | ED Extra Heat | ED Extra Heat<br>Nothing<br>Balancing<br>Passive Cooling | Passive Cooling |
| Driving | Lossy Mode | Lossy Mode<br>Nothing<br>Balancing<br>Passive Cooling | Passive Cooling |
| Driving | HP from Battery | Nothing | Passive Cooling |

**Table 3.2:** Status of the vehicle : Parking

| Status of the vehicle | Cabin | Battery | ED |
|---|---|---|---|
| Parking | HVCH/HVAH | HVCH<br>Nothing<br>Balancing<br>Passive cooling | Passive Cooling/Nothing |
| Parking | Air HP | Air HP<br>Nothing<br>Balancing<br>Passive cooling | Passive Cooling/Nothing |
| Parking | Air HP + HVCH | Air HP + HVCH<br>Nothing<br>Balancing<br>Passive Cooling | Passive Cooling/Nothing |
| Parking | Lossy Mode | Lossy Mode<br>Nothing<br>Balancing<br>Passive Cooling | Passive Cooling/Nothing |
| Parking | Nothing | Air HP + HVCH<br>Nothing<br>Balancing | Passive Cooling/Nothing |
| Parking | HP from Battery | Nothing | Passive Cooling/Nothing |

**Table 3.3:** Status of the vehicle : AC Charging

| Status of the vehicle | Cabin | Battery | ED |
|---|---|---|---|
| AC Charging | HVCH/HVAH | HVCH<br>Nothing<br>Balancing<br>Passive cooling | Passive Cooling |
| AC Charging | Air HP | Air HP<br>Nothing<br>Balancing<br>Passive cooling | Passive Cooling |
| AC Charging | Air HP + HVCH | Air HP + HVCH<br>Nothing<br>Balancing<br>Passive Cooling | Passive Cooling |
| AC Charging | Lossy Mode | Lossy Mode<br>Nothing<br>Balancing<br>Passive Cooling | Passive Cooling |
| AC Charging | Nothing | Air HP + HVCH<br>Nothing<br>Balancing | Passive Cooling |
| AC Charging | HP from Battery | Nothing | Passive Cooling |

**Table 3.4:** Status of the vehicle : DC Charging

| Status of the vehicle | Cabin | Battery | ED |
|---|---|---|---|
| DC Charging | HVCH/HVAH | HVCH<br>Nothing<br>Balancing<br>Passive cooling | Passive Cooling |
| DC Charging | Air HP | Air HP<br>Nothing<br>Balancing<br>Passive cooling | Passive Cooling |
| DC Charging | Air HP + HVCH | Air HP + HVCH<br>Nothing<br>Balancing<br>Passive Cooling | Passive Cooling |
| DC Charging | Lossy Mode | Lossy Mode<br>Nothing<br>Balancing<br>Passive Cooling | Passive Cooling |
| DC Charging | Nothing | Air HP + HVCH<br>Nothing<br>Balancing | Passive Cooling |
| DC Charging | HP from Battery | Nothing | Passive Cooling |

### 3.4.2 Functions for higher ambient temperature

**Table 3.5:** Functions for higher ambient temperatures

| Status of the vehicle | Cabin | Battery | ED |
|---|---|---|---|
| Driving | Active Cooling | Nothing<br>Active cooling<br>Balancing<br>Passive cooling | Passive Cooling |
| Parking | Active Cooling | Nothing<br>Active Cooling<br>Balancing<br>Passive cooling | Passive Cooling |
| Parking | Nothing | Nothing<br>Active Cooling<br>Balancing<br>Passive cooling | Passive Cooling |
| AC Charging | Active Cooling | Nothing<br>Active Cooling<br>Balancing<br>Passive cooling | Passive Cooling |
| AC Charging | Nothing | Nothing<br>Active Cooling<br>Balancing<br>Passive cooling | Passive Cooling |
| DC Charging | Active Cooling | Nothing<br>Active Cooling<br>Balancing<br>Passive cooling | Passive Cooling |
| DC Charging | Nothing | Nothing<br>Active Cooling<br>Balancing<br>Passive cooling | Passive Cooling |

## 3.5 Conceptual Designing and Shortlisting

The first phase of the project after literature review was to apply the acquired knowledge from different literature and inspiration from the bench marking. After considering and listing down the various functions and requirements that our layouts had to satisfy, we began conceptual designing several options for the two refrigerants based around their refrigeration cycle.

Some important theories we learnt along the way so as to create a layout with minimized energy penalty and for it to be technologically feasible were:

- To always have a path for the coolant to reach the radiator in any case. This is an important factor in order to have a means for heat dissipation in the coolant side.
- The flow path for coolant must be modular such that the radiator can be placed after the ED circuit or the flow would be able to bypass it or even return to the ED circuit via the radiator.
- Never have pumps working against each other. Pumps that work against each other cause instabilities and unpredictability of flow in the circuit and can re route the coolant flow in an undesired manner.
- As the energy of operation of a solenoid valve is higher than a proportionality valve, avoid using one way solenoid valves unless necessary.
- The cost of a 3 way and a 4 way valve are not too far apart, so visualise the benefit in using a 4 way valve in place of a 3 way valve to maximize operational conditions for a fraction of a cost increase.

With the learning in mind to minimize the energy penalty and make a technologically feasible layout that could be versatile to fulfill the requirements set by us, we proposed a few layouts.

The list of functions and requirements was then prioritised to what could be the most critical operations that need to be performed and the operations that could be left out. This helped us compare the layouts against the functions list and further shortlist the ones that could not satisfy the high priority operations.

The remaining layouts after shortlisting were then finally proposed to our supervisor where his experience came into play and helped us identify the inefficiencies and in-capabilities of the layouts. During this phase of the project, we were also made to show the flow routes of our layouts for various applications to satisfy the scenarios that had incurred during live testing of the cars. Based on all of the discussions regarding the layouts, we could finalise 2 layouts from the shortlisted ones to be simulated. These had 1 layout for the CO2 refrigerant and other for Propane.

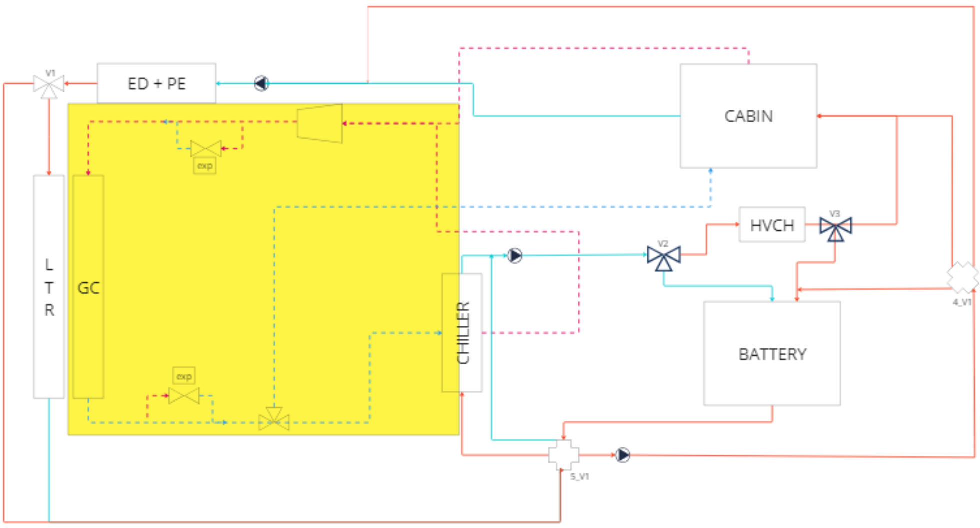


**Figure 3.1:** CO2 Layout

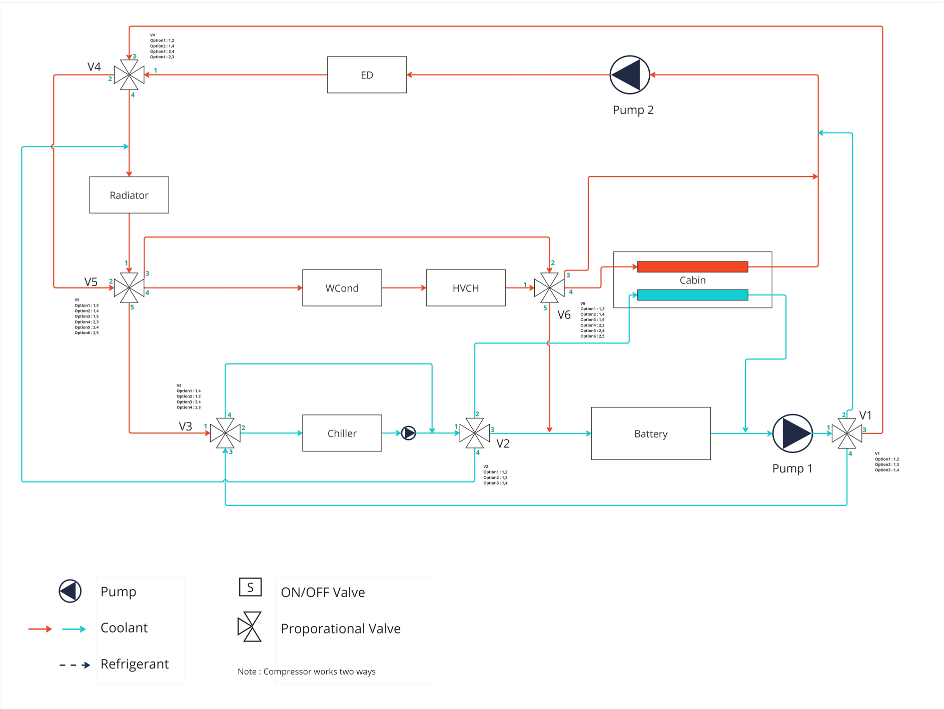


**Figure 3.2:** Propane Layout

### 3.5.1 Summary of the Layout structure

A brief discussion about the structure of layouts will be presented in this section. From all the mentioned functions, both the layouts were capable to meet the necessary requirements in a TMS. In addition, CO2 layout was able to satisfy approximately 85% of the total functions listed while Propane could satisfy 78% from the same function list.

**Table 3.6:** Summary of layouts

| CO2 | Propane |
|---|---|
| 3 Pumps | 3 Pumps |
| 3 two way valves | |
| 3 four way valves | 4 four way valves |
| 1 five way valves | 2 five way valves |
| 1 Interface with refrigerant (Chiller) | 2 Interface with refrigerant (WCond and Chiller) |

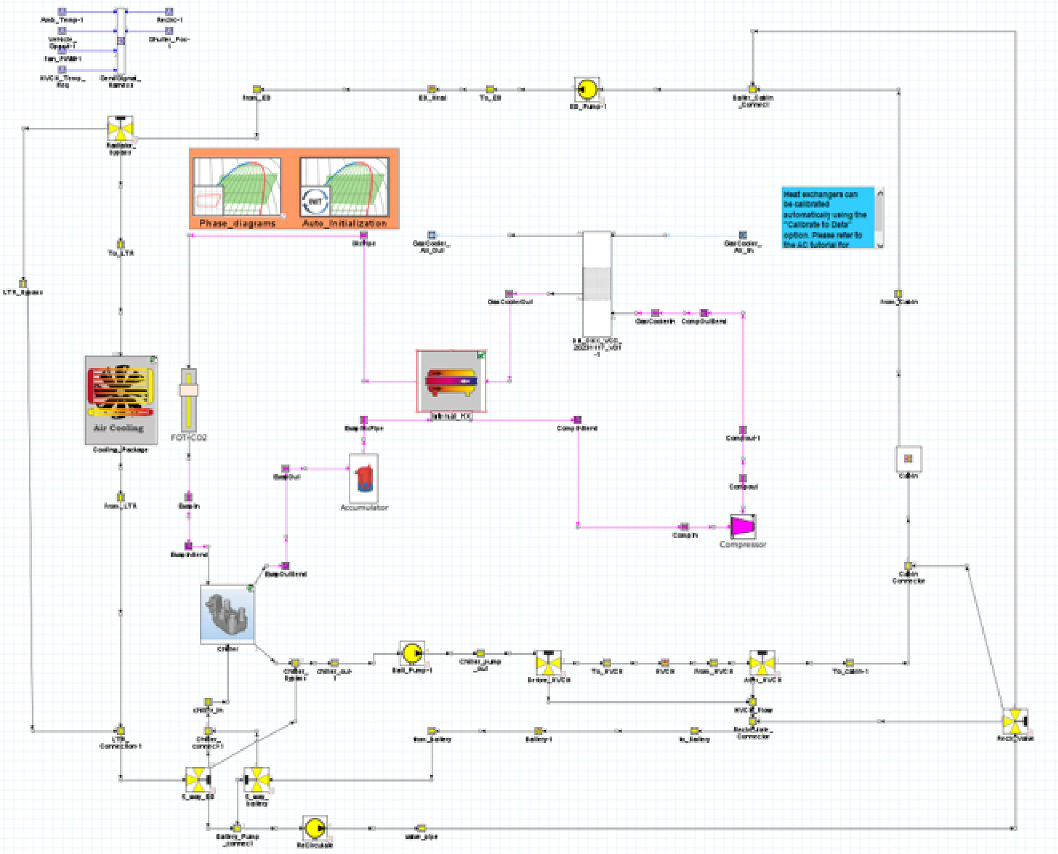
## 3.6 Introduction to GT Suite & Modelling in GT

### 3.6.1 Introduction

GT-SUITE is the industry-leading simulation tool with capabilities and libraries aimed at a wide variety of applications and industries. It offers engineers functionalities ranging from fast concept design to detailed system or sub-system/component analyses, design optimization, and root cause investigation.[19] For the purpose of this study, GT Suite has been loaded with thermal and flow library apart from the custom library of VCC. These libraries have contained all the blocks and functionalities that would develop the thermal management systems that are targetted to be simulated and studied in 1D.

### 3.6.2 Modelling in GT Suite

Following on the conceptual designing phase, the shortlisted layouts are modelled on GT Suite utilizing both, the data available from Volvo Cars' component library as well as the GT Suite library. Simplification of a few components is done in order to make the simulations faster to fit our timeline. Through simplification, we have made redundant the extra component data that we don't need to assess and doesn't relate to the goal and scope of our thesis. The simplification has also allowed is to protect Volvo Cars' internal data by generalizing the properties of the said components. It is also made sure that the simplification is not done to an extent which will deviate our analysis results from standard values yielding unrealistic results, thus maintaining the sanity of our simulations.



Heat exchangers can be calibrated automatically using the "Calibrate to Data" option. Please refer to the AC tutorial for

**Figure 3.3:** GT model: CO2

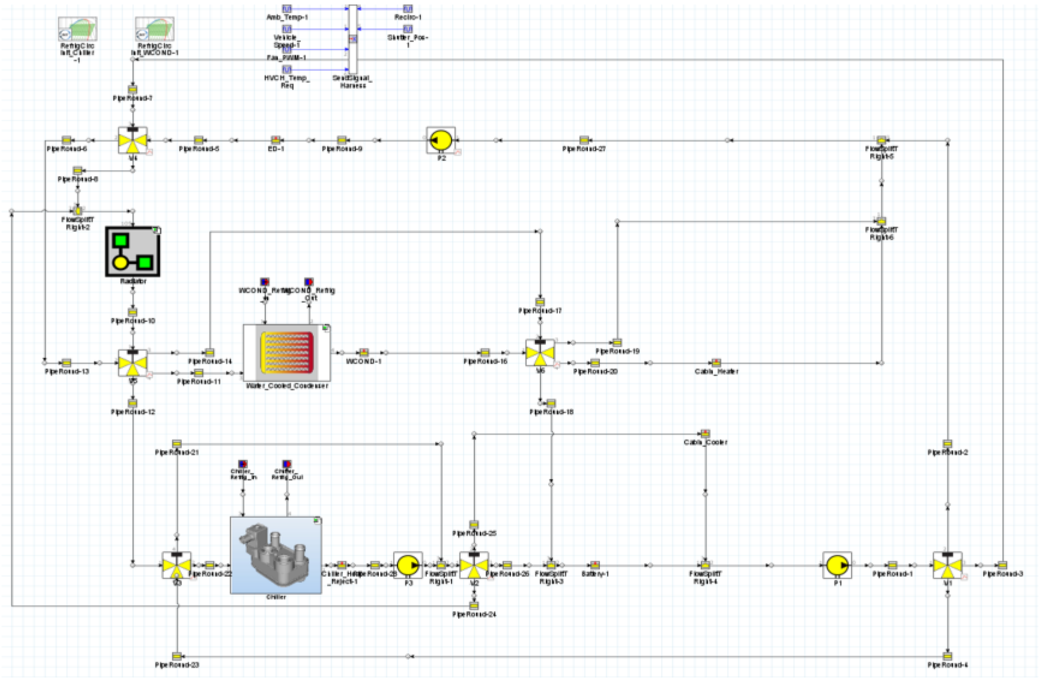


**Figure 3.4:** GT model: Propane

### 3.6.3 Parameters - Simulations

The parameters are the specific factors that will define and control our simulations. These will set initial values to various temperatures through out the circuit. These also scope the boundaries of the simulation and specify the cases that would be simulated.

The following parameters were used in our simulations:

- Soaked car at ambient temperature: All the components, fluids and other assemblies of the car were kept at ambient temperature in the beginning. For our specific consideration, fluids like coolant and refrigerant were soaked too.
- Status of Vehicle was Fast Charging: The vehicle was assumed to be stationary and battery was being supplied by DC.
- No loads implied: As the simulation was a flow pressure survey, no heat loads were implied on any components.
- Simulation boundaries defined as:
  - Adiabatic Walls of coolant hoses and valves.
  - Normalised pressure drop across major components.
  - Adiabatic Pumps.
  - Steady State conditions.
- Cases Simulated:
  - Coolant Temperatures (in °C): -10, 25, 40, 65
  - Pump Speeds (As a % to full capacity): 100%, 75%, 50%, 25%

# 4

# Results

## 4.1 CO2 Layout

### 4.1.1 Mode 1 : Passive Cooling of Battery and Heat to Cabin

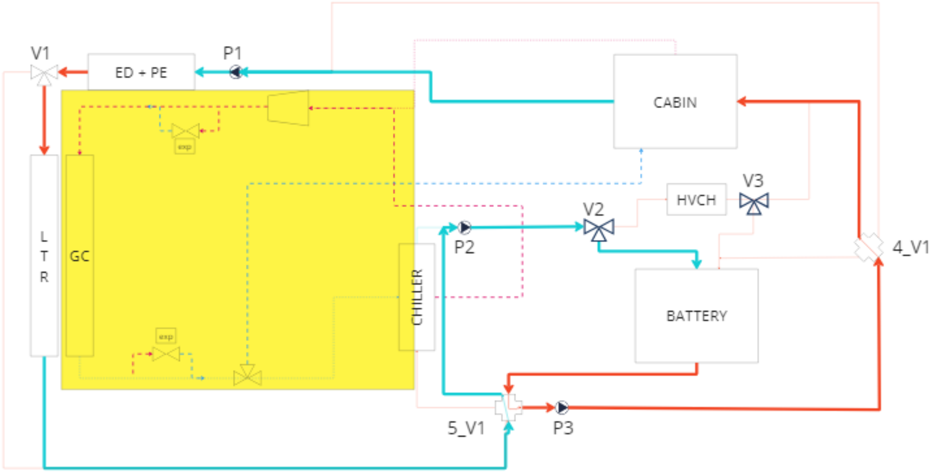


**Figure 4.1:** Passive Cooling of Battery and Heat to Cabin

In mode 1 the battery is cooled using ambient conditions and the heat from the battery is rejected to the cabin as useful heat.
To achieve cooling in first the ED circuit, pump P1 drives the coolant through the ED section which arrives at radiator bypass valve V1. From this point V1 directs the flow towards the radiator (LTR) to reject waste heat to ambient. The cooled coolant from the LTR flows to a 5 way valve 5_V1 where the position of the valve orifice move the coolant towards the suction side of pump P2 that pushes the flow towards valve V2 from where the coolant flows to the battery cooling plate and picks up heat rejected from the battery. After the battery, the heated coolant is redirected to pump P3 through 5_V1 which pumps the hot coolant to a 4 way valve 4_V1. Since the cabin requires heat, the hot coolant can reject its heat to conserve energy of the battery put towards active heating of the cabin, thus valve 4_V1 is positioned such that the coolant is re-routed towards the cabin where it looses it's heat and the goes back to pump P1 to complete the circuit.

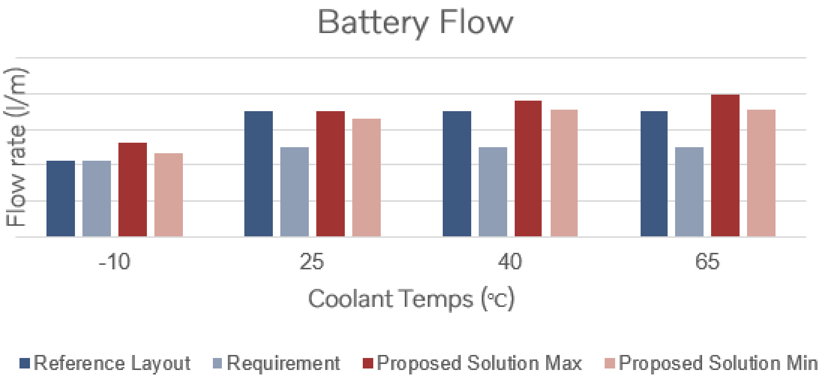


**Figure 4.2:** Mode 1 : Battery Flow

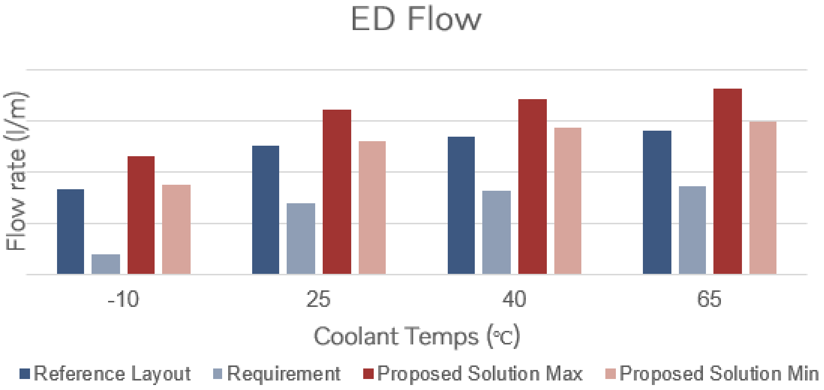


**Figure 4.3:** Mode 1 : ED Flow

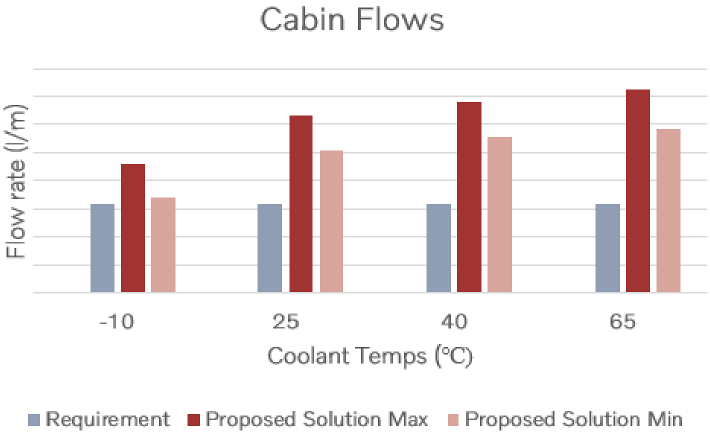


**Figure 4.4:** Mode 1 : Cabin Flow

The comparison of flow rate from proposed CO2 layout for mode 1 can be viewed above. The comparisons of flow is done such that, the maximum flow and the optimized flow that can be achieved from the proposed CO2 layout is compared to the flow requirement set by VCC and the flows that VCC's current layout can achieve. Mode 1 would be most significant at subzero ambient conditions where the vehicle

is charging with passengers in the cabin. For this reason, the most relevant results would be at the temperature of -10°C.
In the Figure 4.2 battery flow results, the reference layout (**dark blue bar**) is on par with the requirements (**grey bar**) at -10°C. Looking at the maximum achievable flow from the proposed solution (**red**), it is sufficiently high to cover the requirement and thus can be optimized for lesser energy consumption by the pumps. The resulting flow from this optimization can be seen on the **pink bar**, which is lower than the maximum flow (**red bar**) yet higher than the requirement (**grey bar**).
Figure 4.3 represents the flows in the ED circuit. The flow from reference layout (**dark blue**) is higher than the requirement (**grey**), and the proposed layout can reach flows (**red**) that are higher than reference layout, thereby opening an opportunity to optimize. After optimization the flow obtained (**pink**) is on par with the reference layout, thus proving to the sufficiently higher than the requirement (**grey**).
Figure 4.4 shows the flow rate of coolant that can be achieved in the cabin. Notice here there is no reference layout (**dark blue**) as the reference layout from VCC doesn't have a coolant flow in the cabin. At -10°C, the maximum flow (**red**) is sufficiently higher than requirement (**grey**) and after optimization we can get the flow down (**pink**) to a minimum level that would meet the requirement.

### 4.1.2 Mode 2 : Passive Cooling of Battery

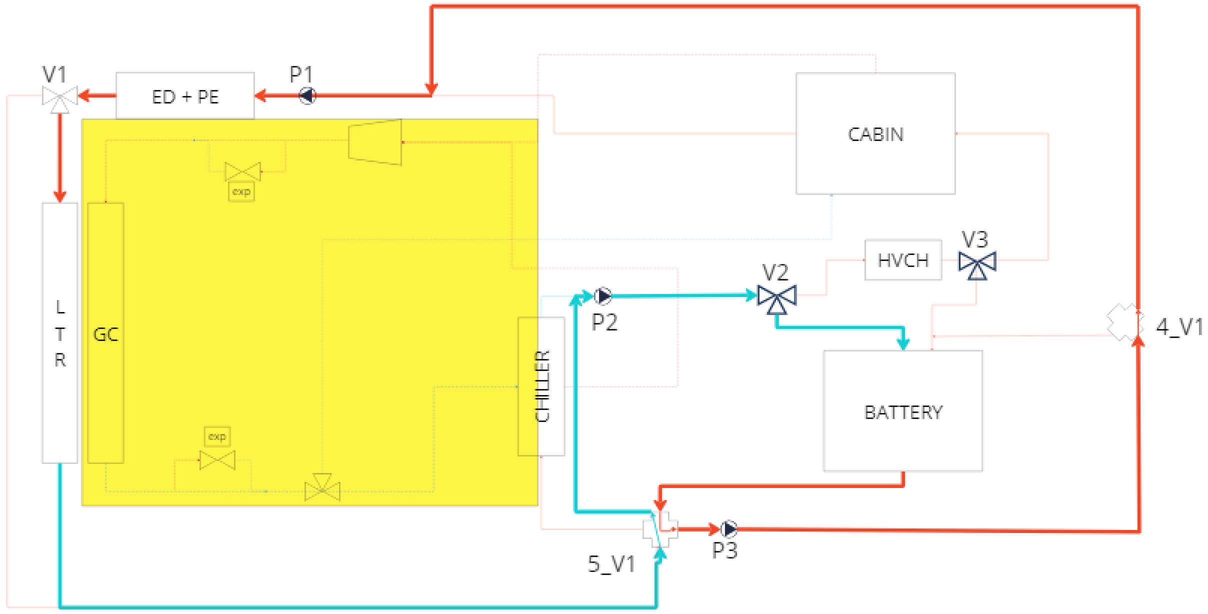


**Figure 4.5:** Passive Cooling of Battery

In mode 2, only the battery apart from the ED and power electronics requests thermal management. The flow from pump P1 is driven towards the ED circuit to provide cooling, where it has picked up heat that is rejected through the radiator (LTR) as the coolant is routed through V1. After the heat is rejected to ambient through the radiator, the coolant flows to the 5 way valve 5_V1 where it bypasses the chiller and is pulled into the suction side of pump P2, that further forces the coolant towards the battery for cooling through valve V2. The cold coolant now picks up heat generated by the battery and flows from the 5 way valve 5_V1 towards the 4 way valve 4_V1 through pump P3. At the 4_V1, it is directly routed towards pump P1 as no other requirement has to be full filled.

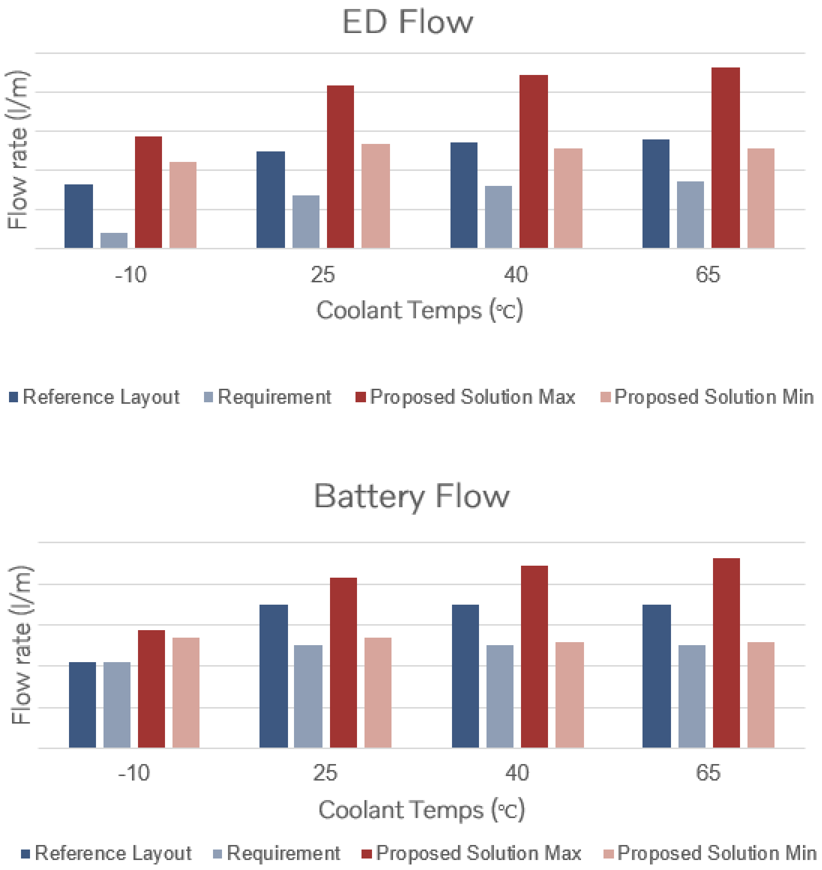


**Figure 4.6:** Mode 2 : ED and Battery Flow

The configuration of mode 2 is ideal for cooling the battery at temperatures like 25°C, where the ambient conditions are enough to provide cooling for battery. Reviewing Fig. M a) we can observe at 25°C in the ED circuit the maximum flow of proposed layout (**red**) is very high when compared to the reference layout (**dark blue**) and the requirement (**grey**), therefore optimizing it would be highly benefical for the energy consumption. Upon optimization of the proposed layout, the flow (**pink**) is on par with the flow from reference layout (**dark blue**).
Analysing Fig. M b) for the battery flow at 25°C, it is noticeable how the flow from reference layout (**dark blue**) is sufficiently higher than the requirement (**grey**) and the flow before optimizing from the proposed layout (**red**) is higher than reference layout of VCC (**dark blue**). Upon optimizing this very high flow, it is possible to achieve a minimum flow (**pink**) that is much closer to the requirement (**grey**), thus saving on energy utilised from the battery.

### 4.1.3 Mode 3 : Active Cooling of Battery

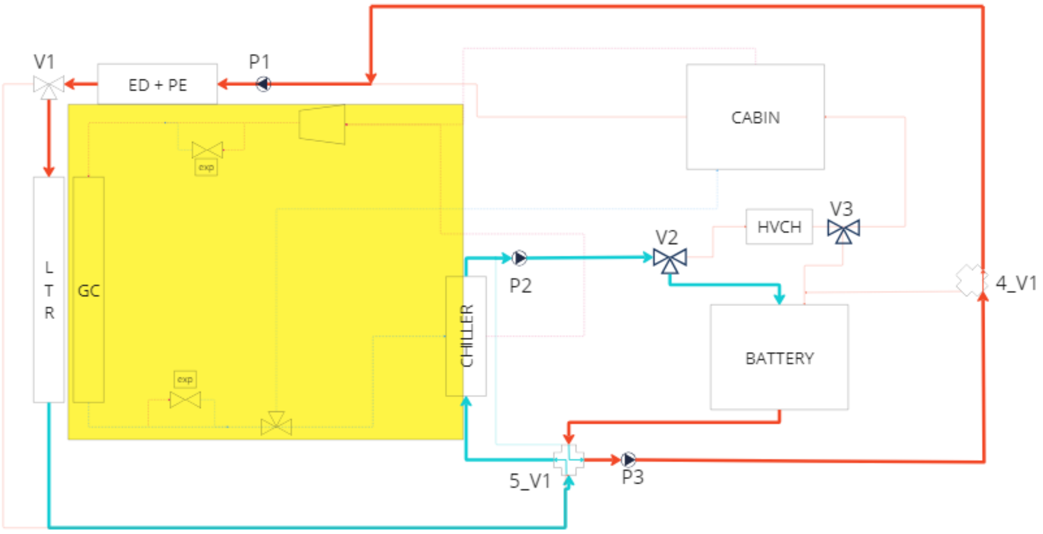


**Figure 4.7:** Active Cooling of Battery

At higher ambient temperatures, mode 3 becomes relevant, where the battery is cooled actively using the chiller. Starting from pump P1, the flow travels through the ED circuit picking up heat and cooling that section down. Next the coolant rejects the heat to the ambient through the radiator (LTR) as it passes via V1. Post ambient cooling, the coolant temperature is still high, thus through the 5 way valve 5_V1, it passes to the chiller that cools it down to required temperature. This flow in the chiller is further driven by pump P2 to the battery through valve V2 for active cooling of battery. After passing through the battery, it is directed to pump P1 again via the combination of 5 way valve 5_V1, pump P3 and the 4 way valve 4_V1.
Mode 3 is the configuration the layout would assume at higher ambient temperatures (35°C +). Thus focusing on the system flow deliverables at 40°C and 65°C in Figure 4.7 for ED Flow, we observe that the maximum flow (**red bar**) at 100% pump speeds is excessively higher than the requirement (**grey**). This allows us to run the pumps at lesser speeds to find a more energy conversing configuration that would still satisfy the requirement. The flow through this optimized configuration is shown as the **pink bar** which is marginally lower than the maximum flow from reference circuit (**dark blue**) and satisfies the requirement (**grey**). In Figure 4.7 Battery flow requirements (**grey**) is now higher due to the increases temperature, however the maximum flow in the layout (red bar) is sufficient enough to satisfy this, rather it is higher thus giving us a chance to optimize the energy consumption of pumps by varying their running speeds. Upon finding an ideal configuration of pump running speeds, the resultant flow can be observed in the **pink bar** which is nearly on par with the requirement, satisfying it.

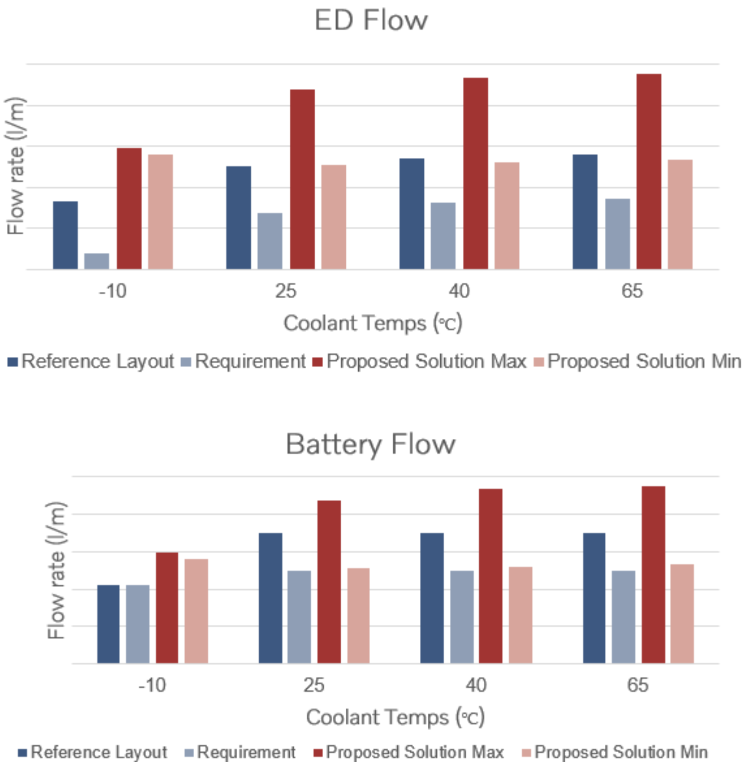


**Figure 4.8:** Mode 3 : ED and Battery Flow

### 4.1.4 Summary

It is important to check the flow through the different components in order to make sure that sufficient flow is provided for cooling of the components. This provides us basis for flow comparison of the conceptual layout with the requirement as well as Volvo Cars' layout. From the results of CO2 layout, it was evident that the requirements were being fulfilled by a large margin when all the three pumps were being operated at their full capacity. This meant optimization of the pump running speeds was a viable option to cut the energy penalty of running the system. When optimized the flow requirements were being met with a good margin thus proving that the layout was satisfactory through the flow point of view. In mode 1, when a flow to cabin was required, the flow to the other components could not be optimized to the lowest required flow, this proved to be a bottleneck in the system causing higher energy penalty.

## 4.2 Propane Layout

### 4.2.1 Mode 1 : Passive Cooling of Battery

In this function, the battery is cooled passively, meaning it relies on the ambient temperature for cooling via the radiator. The process begins with the coolant circulating through the radiator, where it dispenses the accumulated heat to the

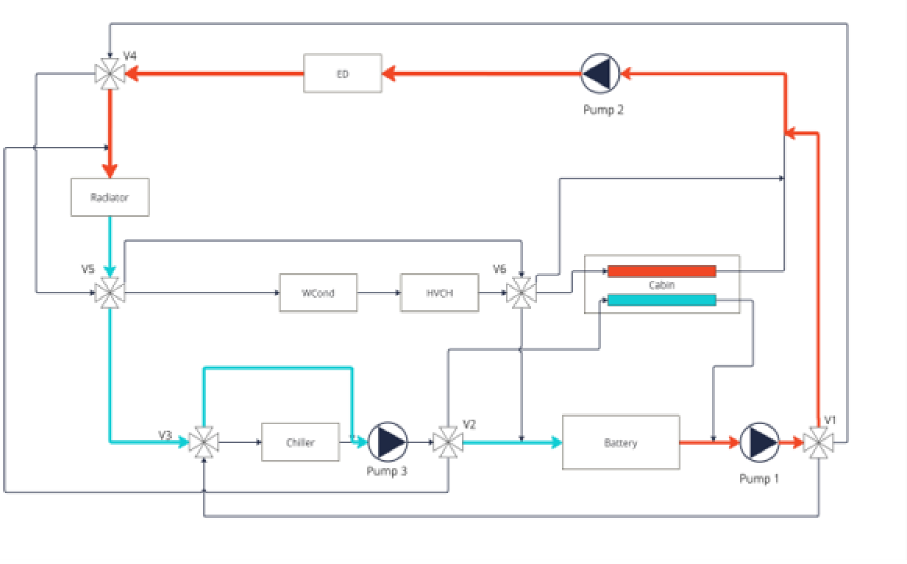


**Figure 4.9:** Mode 1 : Passive Cooling of Battery

surrounding environment. As a result, the coolant's temperature decreases, making it cooler when it exits the radiator.

This cooled coolant then flows to the battery, absorbing the heat generated by the battery during operation. As the coolant absorbs this heat, the battery is effectively cooled down, which in turn causes the coolant's temperature to rise. After the coolant has absorbed the heat from the battery, it continues its journey through the system.

Next, the heated coolant passes through the ED unit, where it undergoes further heat exchange processes to reduce the temperature of the ED components before returning to the radiator. Once it reaches the radiator again, the cycle repeats. This continuous loop ensures that the battery remains at an optimal temperature, preventing overheating and maintaining its performance and longevity.

The efficiency of this passive cooling system hinges on the effective heat exchange at the radiator, ensuring the coolant consistently removes excess heat from the battery ans ED components. This method of using ambient temperature for cooling is advantageous as it does not require additional energy input for active cooling mechanisms, thus enhancing the overall energy efficiency of the system.

In Figure 4.10, it is evident that the volumetric flow of the reference layout (represented by the dark blue line) consistently exceeds the minimum required flow (indicated by the grey line) across all coolant temperatures in the ED components. This indicates that the reference layout is effective in maintaining an adequate flow rate to meet the baseline requirements under various temperature conditions.

In contrast, the suggested layout demonstrates a significant improvement when all pumps are operated at full capacity. The volumetric flow in the ED components

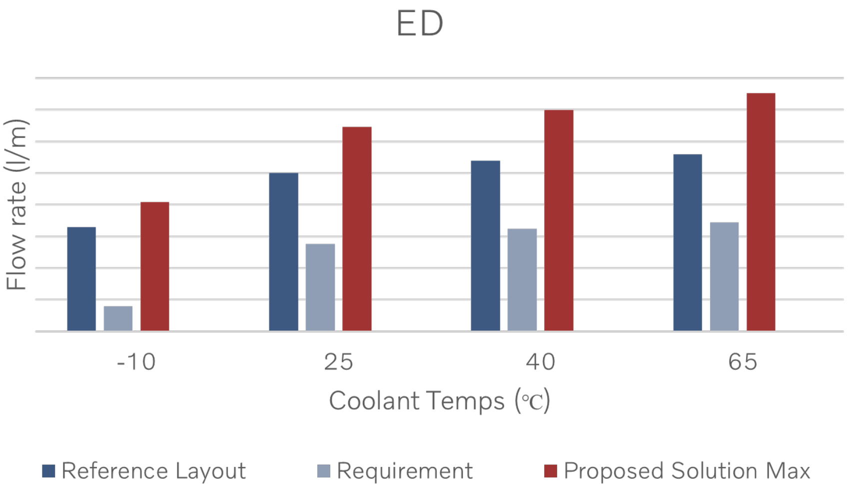


**Figure 4.10:** Mode 1 : ED flow

(represented by the red line) not only meets the minimum flow requirement (grey line) but also surpasses the flow observed in the reference layout (dark blue line). This suggests that the proposed configuration is more efficient in managing and directing the coolant flow, thereby enhancing the performance of the ED components.

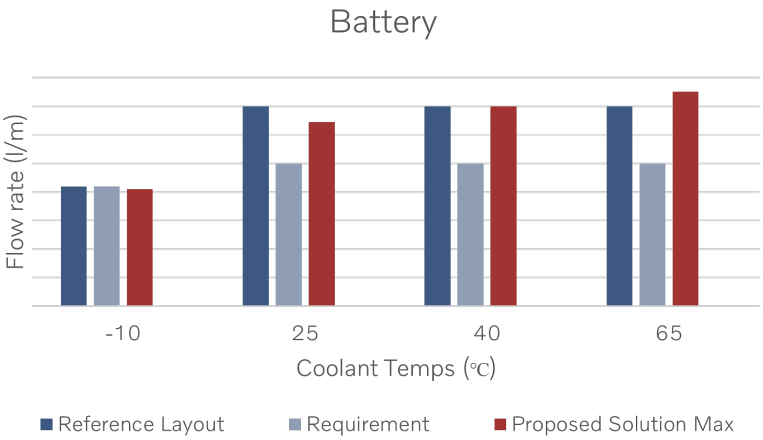


**Figure 4.11:** Mode 1 : Battery flow

In Figure 4.11, the volumetric flow of the coolant across the battery component is analyzed, with bar graphs illustrating the trends based on varying ambient temperatures.

At -10 degrees Celsius, the volumetric flow of coolant in the reference layout (depicted by dark blue bars) is equivalent to the minimum flow required (indicated by grey bars) for the battery to function properly. This suggests that at this low temperature, the reference layout just meets the essential cooling requirements.

At other temperatures, the reference layout consistently surpasses the minimum flow requirement, indicating that it provides adequate cooling across a range of conditions. This is evident as the dark blue bars are always above the grey bars, ensuring efficient battery performance.

In the proposed layout, different patterns emerge:

- At -10 degrees Celsius, even with all pumps running at full capacity (represented by red bars), the volumetric flow does not meet the minimum requirement (grey bars). This indicates a deficiency in the proposed layout's cooling capability under extreme cold conditions.
- At 25 degrees Celsius, the flow in the battery for the proposed layout (red) meets the minimum flow requirement (grey). However, it still underperforms compared to the reference layout (dark blue), which provides a higher volumetric flow and thus better cooling efficiency.
- At 40 degrees Celsius, the proposed layout's flow (red) matches the flow in the reference layout (dark blue) and surpasses the minimum requirement (grey). This shows an improvement in the proposed layout's performance, aligning it with the reference layout at this moderate temperature.
- At 65 degrees Celsius, the flow in the proposed layout (red) not only surpasses the flow in the reference layout (dark blue) but also exceeds the minimum requirement (grey). This indicates that the proposed layout becomes more effective at higher temperatures, providing superior cooling performance compared to the reference layout.

### 4.2.2 Mode 2 : Active Cooling of Battery

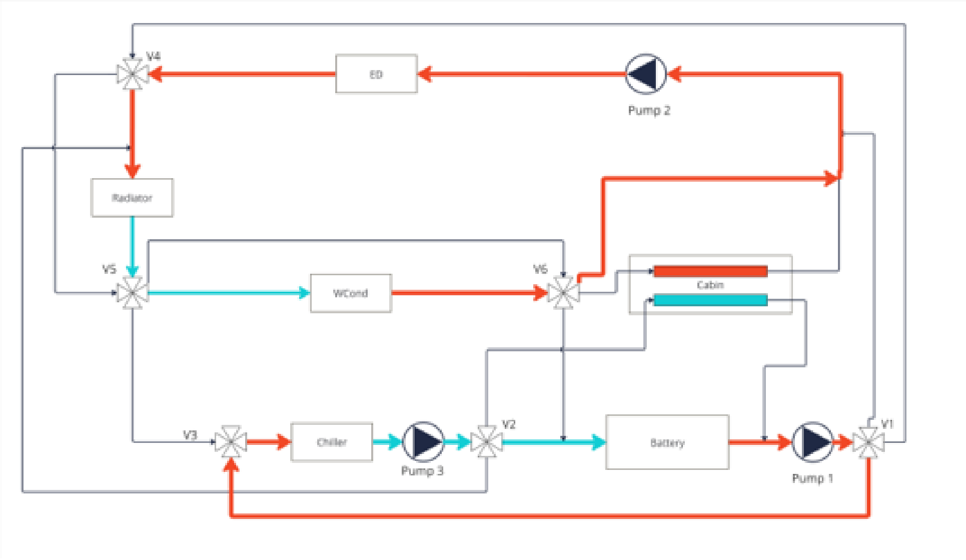


**Figure 4.12:** Mode 2 : Active Cooling of Battery

In this function, we actively cool the battery using a compressor-based system, ensuring efficient thermal management. This setup involves two separate circuits designed to maintain optimal temperatures within the battery and other components.

The first circuit, referred to as the ED circuit, begins with the coolant flowing through the ED components. After passing through the ED components, the coolant then moves through the radiator. The primary purpose of the radiator in this circuit is to dissipate the accumulated heat from the coolant into the ambient environment, thereby reducing its temperature. Following this, the coolant enters the wet condenser, where it is further heated up, completing its journey through this circuit. The coolant, now at a higher temperature, returns to the ED pump to start the cycle anew.

The second circuit is dedicated to managing the heat generated by the battery. In this circuit, the coolant absorbs heat from the battery, effectively cooling it down. The heated coolant is then directed to a chiller, where it releases the absorbed heat. The coolant, now cooled down, is recirculated back to the battery to absorb more heat, ensuring the battery remains at an optimal temperature.

A refrigerant circuit interconnects the chiller and the wet condenser, playing a crucial role in the heat exchange process. In this circuit, the refrigerant absorbs the heat released by the coolant in the chiller. The heated refrigerant is then transported to the wet condenser, where it releases the heat it has absorbed. This exchange allows the refrigerant to cool down before it is cycled back to the chiller to repeat the process.

This integrated system of active cooling ensures that the heat picked up from the battery by the coolant is efficiently transferred to the wet condenser via the refrigerant circuit. By continuously cycling through these stages, the system maintains the battery and other components at their desired operating temperatures. The compressor-driven approach allows for precise control over the cooling process, enhancing the overall performance and longevity of the battery and associated components.

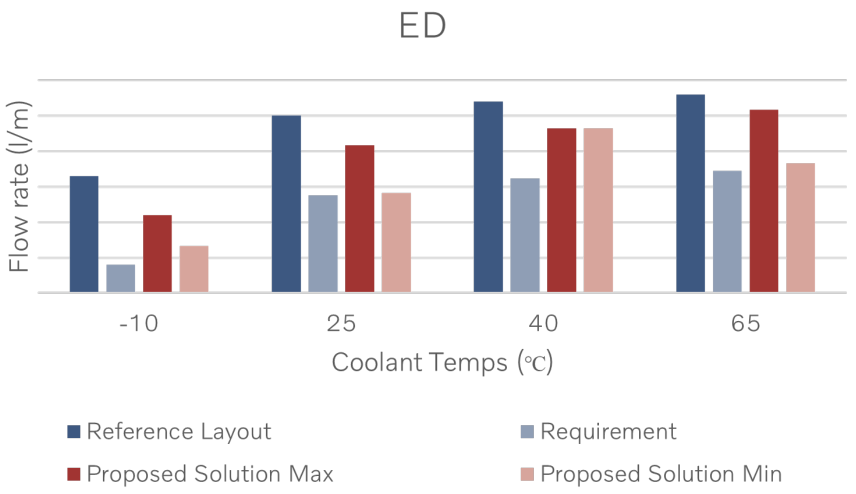


**Figure 4.13:** Mode 2 : ED flow

n Figure 4.13, we can observe that the volumetric flow in the Electric Drivelines (ED) components of the reference layout (dark blue) significantly exceeds the minimum flow required (grey) across all temperature conditions. This demonstrates that the reference layout consistently provides more than enough cooling capacity for the ED components, ensuring their optimal performance.

When all pumps are operated at full capacity in the proposed layout, the volumetric flow in the ED components (red) also surpasses the minimum requirement (grey). However, this flow is still less than that observed in the reference layout (dark blue), indicating that the reference layout is more efficient in delivering higher flow rates under full pump operation.

Interestingly, the proposed system does not necessitate running the pumps at full capacity to meet the minimum flow requirements for the ED components at all temperatures. The data shows that the pumps can operate at optimized speeds (pink) to fulfill the minimum flow requirements, ensuring adequate cooling while potentially reducing energy consumption and wear on the pumps.

These optimized pump speeds present a valuable consideration for system design. By calibrating the pumps to operate efficiently at these lower, yet sufficient speeds, the system can achieve a balance between performance and energy efficiency. This optimization not only ensures that the ED components receive the necessary cooling across various temperatures but also contributes to the overall sustainability and longevity of the cooling system.

In summary, Figure 4.13 illustrates that while the reference layout delivers the highest volumetric flow rates for the ED components, the proposed layout with pumps running at full capacity still meets the necessary cooling requirements, albeit at slightly lower flow rates. More importantly, the possibility of operating the pumps at optimized speeds to meet the minimum requirements provides a promising approach to enhance system efficiency and reliability without compromising performance.

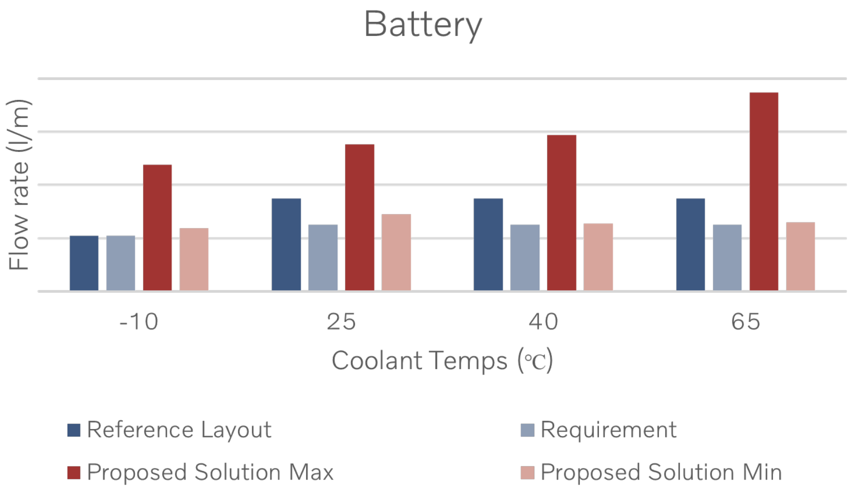


**Figure 4.14:** Mode 2 : Battery flow

In Figure 4.14, we can observe several important trends in the volumetric flow of coolant across the battery for different layouts and temperatures.

At -10 degrees Celsius, the volumetric flow in the battery for the reference layout (dark blue) matches the minimum requirement (grey). This indicates that at this very low temperature, the reference layout just meets the necessary flow needed to maintain battery performance.

However, for temperatures above -10 degrees Celsius, the reference layout performs considerably better, providing a volumetric flow that exceeds the minimum requirement. This increased flow ensures more efficient cooling and better thermal management of the battery, contributing to its optimal operation.

In contrast, the proposed layout shows a markedly different performance. The volumetric flow in the proposed layout (red) is significantly higher than that in the reference layout (dark blue) across all temperatures. This indicates that the proposed layout delivers a substantially greater cooling capacity, which is beneficial for maintaining lower battery temperatures and enhancing overall performance.

Due to the higher flow rates achieved by the proposed layout, there is an opportunity to optimize the system by running the pumps at lower capacities. The data suggest that even when the pumps are operated at reduced speeds (pink), the volumetric flow still meets the minimum requirement for the battery. This optimization allows for substantial energy savings while still fulfilling the necessary cooling needs.

By adjusting the pump speeds to these optimized levels, the system can achieve significant energy efficiency gains without compromising the cooling performance. This approach not only reduces energy consumption but also minimizes wear and tear on the pumps, potentially extending their lifespan and lowering maintenance costs.

In summary, Figure 4.14 highlights the superior performance of the proposed layout in terms of volumetric flow rates across the battery, especially at higher temperatures. The data support the possibility of running the pumps at lower capacities to save energy while still meeting the minimum cooling requirements. This optimization strategy enhances the overall efficiency and sustainability of the battery cooling system.

### 4.2.3 Mode 3 : Heat Pumping from Battery to Cabin

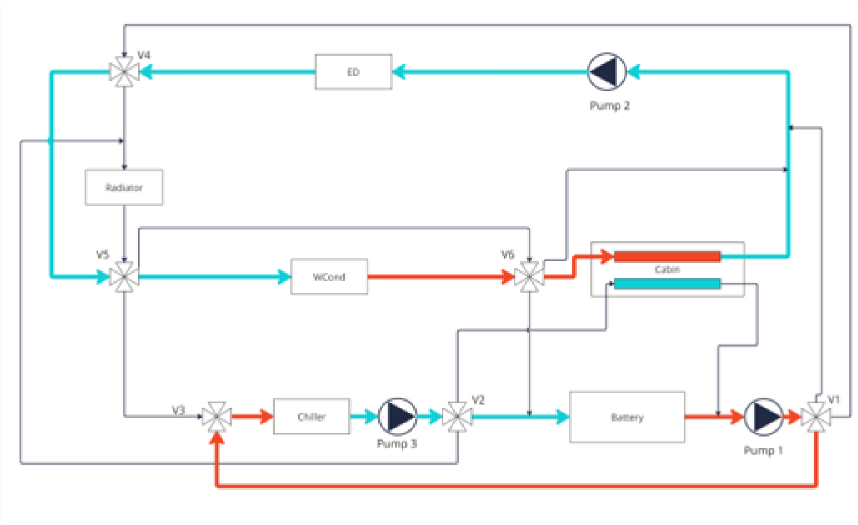


**Figure 4.15:** Mode 3 : Heat Pumping from Battery to Cabin

In this function, the system utilizes a compressor to transfer heat from the battery to the cabin, thereby achieving a dual purpose of cooling the battery and heating the cabin. The layout is divided into two distinct circuits, similar to the previous function, ensuring efficient thermal management and energy utilization.

The first circuit focuses on the battery. In this circuit, the coolant absorbs heat from the battery, effectively cooling it down. This process is critical as it maintains the battery within its optimal operating temperature range, preventing overheating and ensuring longevity and performance. The heated coolant, now carrying the thermal energy from the battery, is directed to a chiller.

At the chiller, a refrigerant circuit comes into play. The refrigerant absorbs the heat from the coolant, thereby chilling it. This chilled coolant is then recirculated back to the battery to absorb more heat, continuing the cooling process. The refrigerant, now carrying the absorbed heat, moves to the second circuit.

The second circuit is responsible for transferring the absorbed heat to the cabin. The refrigerant, warmed by the heat picked up from the battery coolant in the chiller, is directed to a heat exchanger or condenser located within the cabin's HVAC system. Here, the refrigerant releases the stored heat, effectively heating the cabin. This process continues until the cabin reaches its desired temperature, as set by the occupants.

As the refrigerant releases heat into the cabin, it cools down and is cycled back to the chiller to absorb more heat from the battery coolant, thus maintaining a continuous loop. This cycle ensures that the battery remains cool while the cabin is heated efficiently.

By using this dual-circuit system, the heat extracted from the battery, which would otherwise be wasted, is utilized to warm the cabin, enhancing overall energy efficiency. The use of a compressor in this system allows for precise control over the heat transfer process, ensuring that both the battery and the cabin are maintained at their optimal temperatures.

The continuous cycling of heat between the battery and the cabin via the refrigerant circuit maximizes the efficiency of the thermal management system. The compressor-driven approach not only provides effective cooling for the battery but also utilizes the otherwise wasted heat to create a comfortable cabin environment. This integration of cooling and heating functions into a single system represents a sophisticated and efficient use of thermal energy, contributing to the overall performance and energy efficiency of the vehicle.

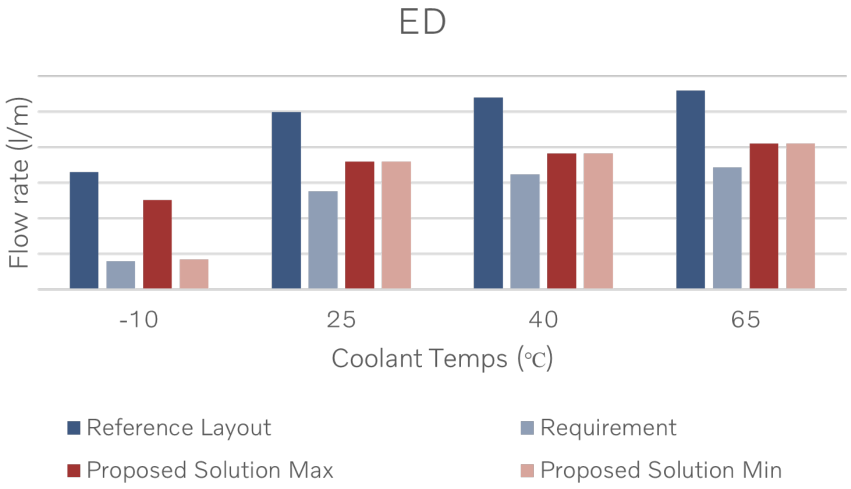


**Figure 4.16:** Mode 3 : ED flow

In Figure 4.16, the volumetric flow across the Electric Drivelines (ED) components is depicted for various temperatures, highlighting the performance of both the reference and proposed layouts.

For the reference layout (dark blue), it is observed that the flow rate is consistently much higher than the minimum required flow (grey) for all temperatures. This indicates that the reference layout provides ample cooling capacity, ensuring that the ED components are well within their optimal operating conditions across a range of temperatures.

In the proposed layout (red), the flow rate at -10 degrees Celsius is significantly higher than the minimum requirements (grey). This demonstrates that the proposed layout can effectively cool the ED components at extremely low temperatures. However, at other temperatures, the flow rate in the proposed layout is not as high. Although it remains above the minimum requirement (grey), it is always lower than the flow rate provided by the reference layout (dark blue). This suggests that while the proposed layout is adequate for maintaining minimum cooling needs, it does not offer the same level of excess capacity as the reference layout.

Interestingly, the data shows that at -10 degrees Celsius, it is possible to run the pumps at a lower capacity (pink) to meet the minimum flow requirement (grey). The optimized pump speeds (pink) at this temperature provide the same flow rate as when the pumps are running at full capacity (red). This indicates an opportunity for energy savings by reducing pump operation without compromising the cooling performance for the ED components at -10 degrees Celsius.

Overall, the analysis in Figure 4.16 suggests that while the proposed layout can maintain adequate cooling across all temperatures, the reference layout consistently provides greater cooling capacity. Additionally, the opportunity to optimize pump operation at -10 degrees Celsius in the proposed layout offers a practical solution for enhancing energy efficiency without compromising on performance.

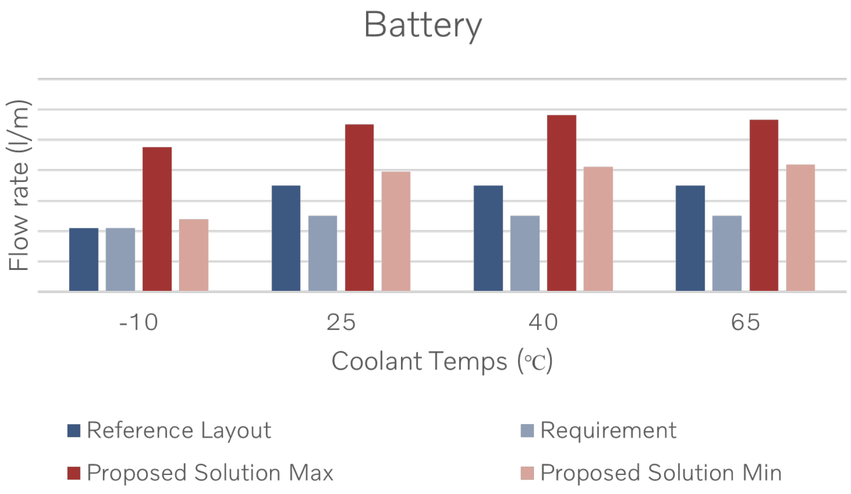


**Figure 4.17:** Mode 3 : Battery flow

In Figure 4.17, the volumetric flow rates for the battery component are depicted across different temperatures, comparing the performance of the reference layout and the proposed layout.

For the reference layout (dark blue), the flow rate at -10 degrees Celsius is exactly the same as the minimum requirement (grey). This means that at this low temperature, the reference layout just meets the necessary cooling demand for the battery. However, at higher temperatures of 25, 40, and 65 degrees Celsius, the flow rate in the reference layout exceeds the minimum requirement (grey). This indicates that the reference layout provides sufficient cooling capacity to ensure the battery operates efficiently under these conditions.

In contrast, the proposed layout (red) shows a different performance trend. When the pumps are run at full capacity, the flow rate not only exceeds the minimum requirement (grey) but is also significantly higher than the flow rate of the reference layout (dark blue) across all temperatures. This suggests that the proposed layout delivers a much greater cooling capacity, which can be advantageous for maintaining optimal battery temperatures, especially under higher thermal loads.

Moreover, the data indicates a potential for optimizing the system by running the pumps at lower speeds (pink). This optimized solution suggests that it is possible to achieve the necessary cooling requirements (grey) for the battery without operating the pumps at full capacity, thus saving energy and reducing operational costs. The pink bars represent these optimized pump speeds, which still meet the minimum cooling requirements while likely consuming less power compared to running the pumps at full capacity (red).

Overall, the analysis in Figure 4.17 suggests that the proposed layout, when running pumps at full capacity, offers significantly better cooling performance compared to the reference layout. Additionally, the possibility of optimizing pump speeds presents a practical approach to enhance energy efficiency while maintaining necessary cooling for the battery component across various temperatures.

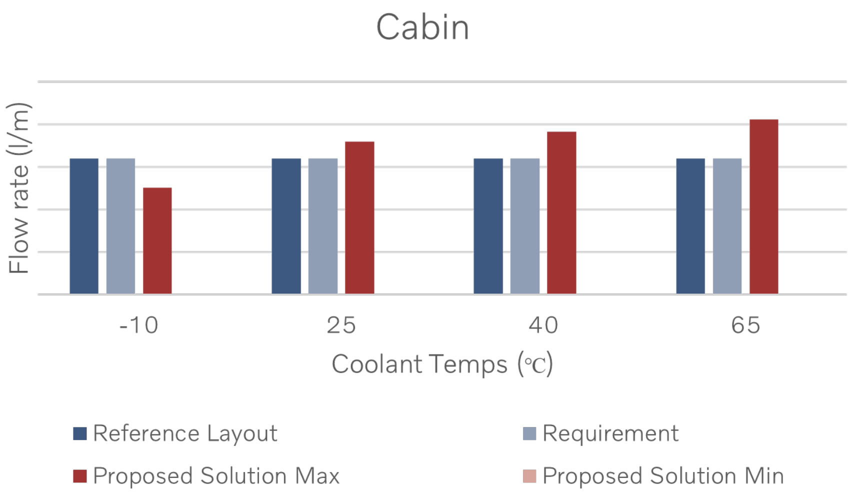


**Figure 4.18:** Mode 3 : Cabin flow

In Figure 4.18, we can observe the volumetric flow rates for the cabin component, comparing the performance of the reference layout and the proposed layout across different temperatures.

For the reference layout (dark blue), the flow rate exactly meets the minimum required flow (grey) for all temperatures. This indicates that the reference layout is precisely designed to fulfill the cooling or heating needs of the cabin without providing any excess capacity. It ensures that the cabin environment remains within the required thermal comfort range under all conditions.

In contrast, the proposed layout (red) shows a varied performance. At -10 degrees Celsius, the flow rate does not meet the minimum requirement (grey). This suggests that the proposed layout, when operating at full capacity, is insufficient to maintain the desired thermal conditions in the cabin at extremely low temperatures. This shortfall highlights a potential limitation of the proposed system under severe cold conditions.

However, at higher temperatures (25, 40, and 65 degrees Celsius), the proposed layout successfully meets the minimum flow requirements (grey). This indicates that the system is capable of providing adequate thermal management for the cabin under these conditions. The ability to fulfill the flow requirements at these temperatures suggests that the proposed layout can maintain a comfortable cabin environment in a range of moderate to high-temperature scenarios.

Overall, the analysis in Figure 4.18 suggests that while the reference layout is precisely calibrated to meet the cabin's thermal needs across all temperatures, the proposed layout requires optimization to address the shortfall at -10 degrees Celsius. Nonetheless, it performs satisfactorily at higher temperatures, ensuring the cabin remains comfortable under these conditions.

### 4.2.4 Summary

#### 4.2.4.1 Mode 1: Passive Cooling of Battery

- This mode uses ambient temperature to cool the battery passively through a radiator.
- Coolant circulates from the radiator to the battery, absorbing heat and then passing through the ED (Electric Drivelines) unit and back to the radiator.
- The system enhances energy efficiency by eliminating the need for active cooling mechanisms.

**Performance Analysis (Figures 4.10 and 4.11):**

- ED Components: Reference layout exceeds minimum flow requirements at all temperatures. Proposed layout meets or exceeds these requirements, suggesting improved efficiency.
- Battery: Reference layout is adequate across all temperatures except -10°C. Proposed layout struggles at -10°C but performs better at higher temperatures.

#### 4.2.4.2 Mode 2: Active Cooling of Battery

- Involves a compressor-based system with two circuits: one for the ED components and one for the battery.
- The ED circuit dissipates heat through a radiator, while the battery circuit uses a chiller for cooling.
- A refrigerant circuit facilitates heat exchange between the battery coolant and the cabin.

**Performance Analysis (Figures 4.13 and 4.14):**

- ED Components: Both layouts meet cooling needs, but the reference layout provides higher flow rates.
- Battery: Proposed layout offers greater cooling capacity across all temperatures and can optimize pump speeds to save energy.

#### 4.2.4.3 Mode 3: Heat Pumping from Battery to Cabin

- Uses a compressor to transfer heat from the battery to the cabin, cooling the battery and heating the cabin.
- The system employs two circuits: one for cooling the battery and another for heating the cabin using the heat absorbed from the battery.

**Performance Analysis (Figures 4.16 and 4.18):**

- ED Components: Reference layout provides ample cooling capacity. Proposed layout meets minimum requirements and offers opportunities for energy savings through optimized pump speeds.
- Battery: Proposed layout delivers higher cooling capacity across all temperatures, with potential for energy efficiency improvements.
- Cabin: Reference layout meets minimum flow requirements precisely, while the proposed layout falls short at -10°C but performs adequately at higher temperatures.

# 5

# Discussion

## 5.1 Conclusion

In conclusion, this thesis has outlined the conceptualization and modeling of a new thermal management system designed for alternative refrigerants, specifically targeting the needs of battery electric vehicles (BEVs) while ensuring compliance with sustainability standards. Through a thorough investigation of various refrigerants and their thermodynamic properties, the research highlights the critical importance of transitioning to PFAS-free alternatives that minimize environmental impact. The modelled layouts set the foundation for future development to build on their robustness for different environments and situations such that they could be successfully implemented in automotive industry in an expansive manner. The layouts being a preliminary working concept with existing components, also provide the basis for optimization at both system and specific component level to provide for ease of manufacturing at lower costs. It also brings out the importance of efficiency specially in BEVs where a limited source is responsible for providing energy to various equipment.

## 5.2 Future Scope

1. Integration of refrigerant circuits
2. Different thermal loads on the components
3. Heat Rejection Study
4. Driving cases with WLTP cycle
5. Complete flow pressure sweep for all functionalities
6. Power Consumption of Overall Layout

# References

[1] I. Tools", “"why is co2 the most promising refrigerant in cooling industry?.” `https://instrumentationtools.com/co2-refrigerant/#summary`, 2022.

[2] K. Li, J. Wang, S. Luo, Z. Wang, X. Zhou, J. Fang, L. Su, and R. Tu, “Experimental investigation on combustion characteristics of flammable refrigerant r290/r1234yf leakage from heat pump system for electric vehicles,” *Royal Society Open Science*, vol. 7, p. 191478, 04 2020.

[3] A. Wawzyniak, Wiebelt, “Thermal management for electrified vehicles..” `https://doi.org/10.1007/s38313-016-0026-1`, 2016.

[4] X. Zhang, Z. Li, L. Luo, Y. Fan, and Z. Du, “A review on thermal management of lithium-ion batteries for electric vehicles,” *Energy*, vol. 238, p. 121652, 2022.

[5] U. Secretariat", “"information on global warming potentials.".” `"https://unfccc.int/documents/3631"`, June 2004.

[6] A. Gbènagnon, A. C. Houngan, V. Chegnimonhan, C. Awanto, M. Anjorin, and A. Vianou, “Study of the performances of a residential air conditioner converted respectively to propane and isobutane in tropical conditions,” *IRA-International Journal of Applied Sciences (ISSN 2455-4499)*, vol. 14, p. 1, 09 2019.

[7] “"propane as a refrigerant for the hvac industry".” `https://www.acrjournal.uk/news/propane-as-a-refrigerant-for-the-hvac-industry/`, "October" 2022.

[8] O. Caliskan and H. K. Ersoy, “Energy analysis and performance comparison of transcritical co2 supermarket refrigeration cycles,” *The Journal of Supercritical Fluids*, vol. 189, p. 105698, 2022.

[9] B. A. D. J. L. C. N. C. S. J. R. S. "Fenton SE, Ducatman A, “"per- and polyfluoroalkyl substance toxicity and human health review: Current state of knowledge and strategies for informing future research.",” "March" 2021.

[10] “Review of thermal management technology for electric vehicles.” `https://www.mdpi.com/1996-1073/16/12/4693`, 2023.

[11] M. Held, M. Tuchschmid, M. Zennegg, R. Figi, C. Schreiner, L. D. Mellert, U. Welte, M. Kompatscher, M. Hermann, and L. Nachef, “Thermal runaway and fire of electric vehicle lithium-ion battery and contamination of infrastructure facility,” *Renewable and Sustainable Energy Reviews*, vol. 165, p. 112474, 2022.

[12] P. Fu, L. Zhao, X. Wang, J. Sun, and Z. Xin, “A review of cooling technologies in lithium-ion power battery thermal management systems for new energy vehicles,” *Processes*, vol. 11, no. 12, 2023.

[13] . Koki Ogura, Mohan Lal Kolhe, “Battery technologies for electric vehicles.” `https://doi.org/10.1016/B978-0-12-803021-9.00004-5.`, 2017. Pages 139-167.

[14] B. Bilgin and A. Emadi, “Electric motors in electrified transportation: A step toward achieving a sustainable and highly efficient transportation system,” *IEEE Power Electronics Magazine*, vol. 1, no. 2, pp. 10–17, 2014.

[15] E. Laloya,  Lucía, H. Sarnago, and J. M. Burdío, “Heat management in power converters: From state of the art to future ultrahigh efficiency systems,” *IEEE Transactions on Power Electronics*, vol. 31, no. 11, pp. 7896–7908, 2016.

[16] P. C. . D. P. Bires, M., “Smart approach for the thermal management of electric vehicles. atz worldw 123, 40–43 (2021)..”

[17] W. Ferraris, F. Bettoja, M. Casella, M. Rostagno, and A. Tancredi, “Heat pump for bevs: Architectures and performance analysis,” *SAE Technical Paper*, June 2020.

[18] T. Blatchley, “"secondary loop residential heat pump design, performance, and cost analysis utilizing r290" (2017). open access theses. 1254..” `https://docs.lib.purdue.edu/open_access_theses/1254`.

[19] GT, “Gt-suite - gamma technologies.” `https://www.gtisoft.com/gt-suite/`.

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