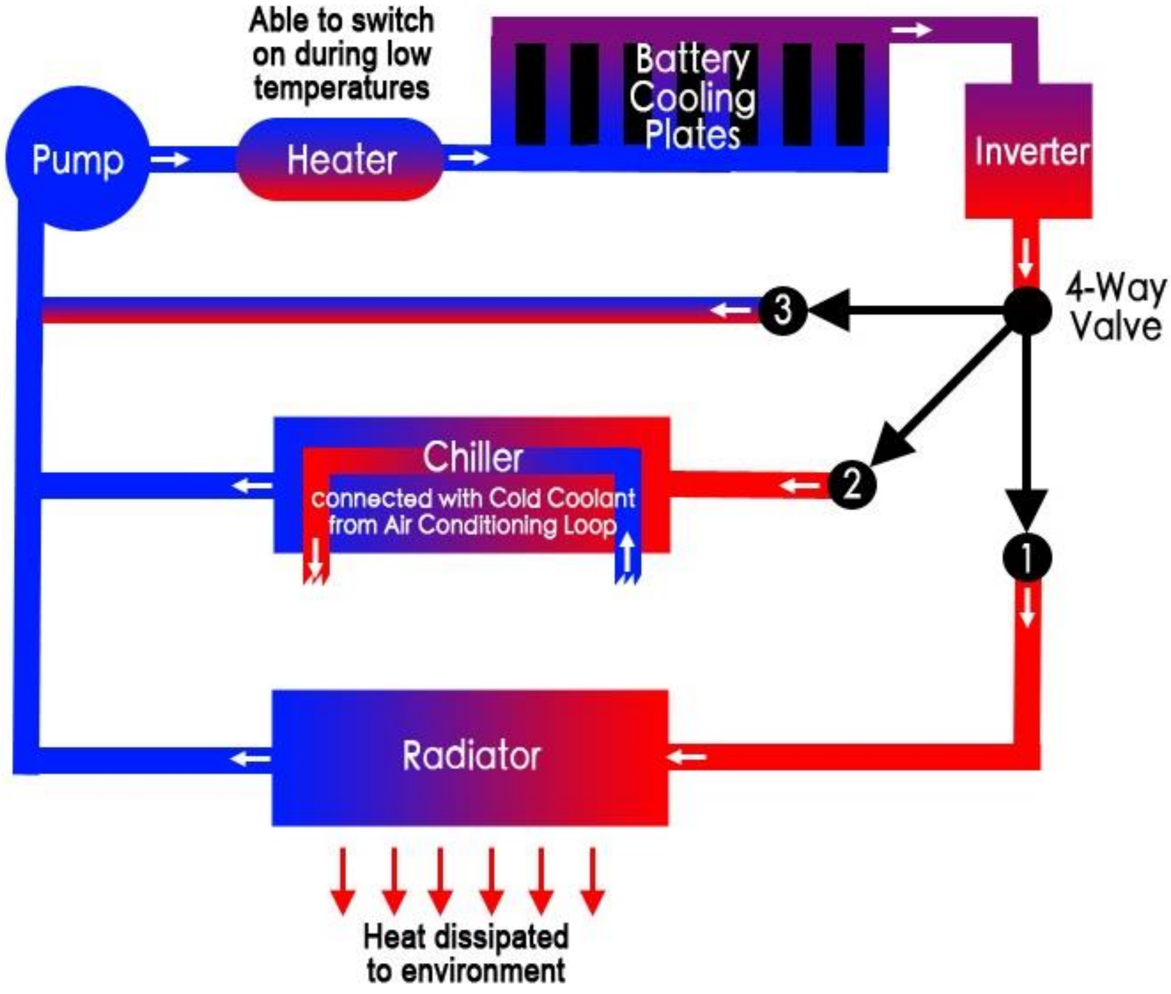

Modelling and Simulation of Cooling Systems for BEV High Voltage Battery

Master’s thesis in Automotive Engineering Master’s Programme

Pradeep Dinakar and Gautham Rajeeve

Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

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Abstract

The depletion of oil around the world due to extensive consumption has led to drastic increase in fuel prices. Also, there is a need to reduce emissions to move towards a sustainable future. The emission laws are becoming stricter to counter this and instigate vehicle manufacturers to produce low or zero emission vehicles. The answer to this are Hybrid vehicles and Battery Electric vehicles. Battery powered electric vehicles have zero emissions, if it is considered that the electricity is generated from renewable sources.

The biggest challenges associated with these vehicles are maintaining the range and performance as that of conventional vehicles. The problem associated with these vehicles is frequent charging/discharging of the Battery which reduces the Battery performance and longevity. Relatively high levels of heat generated by the cells during these cycles, may lead to very high temperatures. If this is not monitored, it can be very harmful to the Battery. Thus, thermal management of the Battery system is critical, so that necessary cooling is provided to reduce the temperature rise in Battery during its operation, which will increase the longevity of the Battery. This will in turn improve the overall efficiency of the vehicle, affecting the performance and the range of the vehicle. Hence, it is important to ensure that the Battery cell temperatures do not exceed permissible levels, thus preventing component degradation.

This thesis work aims at modelling and simulation of cooling circuits for the High Voltage Battery in future Battery electric vehicles via a 1D CFD approach using the commercial software GT-SUITE. The motive behind setting up simulations in a virtual environment is to replicate the physical representation of systems and to predict their behaviour. The advantage of using these models at concept stages of vehicle development helps to apprehend the system better.

The study helps in understanding the importance of regulating Battery temperature for various drive case scenarios. A basic control strategy is suggested based on using the cooling system in an energy efficient manner, which could result in decreasing the power consumed and thereby possibly maximising the range of the electric vehicle. Complex control strategies could be determined from analysis much more detailed and comprehensive than the example exhibited in this thesis work.

Key words: 1D CFD, GT-SUITE, Simulation, Battery Cooling

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Pradeep Dinakar and Gautham Rajeeve

Notations

$1D$	One dimensional	
$3D$	Three dimensional	
CFD	Computational fluid dynamics	
CAE	Computer aided engineering	
Hx	Heat exchanger	
DOE	Design of experiments	
BEV	Battery electric vehicle	
$\dot{Q}_{Cond}$	Thermal conduction heat transfer rate	[W]
$\dot{Q}_{Conv}$	Thermal convection heat transfer rate	[W]
$\dot{Q}_{Max}$	Thermal radiation heat transfer rate	[W]
k	Thermal conductivity	
A_S	Surface Area	[m^2]
T_{Fluid}	Fluid temperature	[°C]
T_{Wall}	Wall temperature	[°C]
C_P	Pressure loss coefficient	
e	Total internal energy	[J/kg]
$\dot{m}$	Mass flow rate	[kg/s]
h	Heat transfer coefficient	[W/m^2K]
T_S	Surface Temperature	[°C]
σ	Stefan-Boltzmann constant	[W/m^2K^4]
ε	Emissivity	
ρ	Density	[Kg/m^3]
ν	Viscosity	
c	Velocity	[m/s]
D_h	Hydraulic diameter	[m]
P	Pressure	[bar]
T	Temperature	[°C]
L	Length	[m]
d	Diameter	[m]
Re	Reynolds number	
Pr	Prandtl number	
Nu	Nusselt number	

1 Introduction

1.1 Background

The depletion of non-renewable sources of energy i.e. fossil fuels with the increasing demand towards a sustainable future has led to most of the automotive manufacturers to look beyond conventional fuel powered vehicles. The concern of saving the planet began to grow at national and international levels as 188 countries signed the Kyoto protocol. EU transport emission of CO_2 contribute to 3.5% of total global CO_2 emissions. Out of this, cars are responsible for 12% of total EU emission of CO_2, one of the primary greenhouse gases. These have been contributing majorly to the climatic changes around the world in recent times. As the EU legislation is coming up with mandatory emission reduction targets, manufacturers are also striving to meet the needs set by the government. The current law requires passenger vehicles registered under EU not emitting more than 130g of CO_2 per km. But by 2021, the target is to bring this down to 95g of CO_2 per km. [1]

The use of alternative energy sources and fuels that could reduce emissions is being encouraged and investigated deeply. These are the prime reasons behind the manufacturers moving towards hybrid vehicles and completely electric vehicles. These vehicles have the potential for nearly or totally zero emissions considering the electricity is produced from renewable energy sources. In order to increase customer demand for these vehicles, it is necessary to develop electric vehicles in such a way that they meet the requirements that the rival conventional vehicles that run on fuel have to offer. One of the primary issues faced by the industry during 1990s while first contemplating adoption of Electric Vehicles (EV) was and continues to be the fight between cost and performance. EVs did not initially prove to be reasonably priced alternatives to their Internal Combustion engine counterparts and as a result EVs mostly appeared in market for low speed vehicles or prototypes for research. [2]

Hence, the main aim of these vehicles to compete in current market would be to replicate the performance (top speed, acceleration) and range of these petrol/diesel engine vehicles while maintaining zero emissions and be affordable. The challenge lies in using energy efficient methods of operating the Battery and maintaining it throughout. Battery life and performance strongly depends on temperature which is the reason why there is a need for optimum thermal management of the system. Since the Battery packs always work at high discharging and charging rates, there is high heat generation rates associated with this, resulting in uneven temperature distribution. Another crucial case would be during sub-zero ambient conditions, due to which there is a significant loss in the driving range. [3] In general, extending life of Battery using an effective Battery thermal management system depends on the design of the thermal management system along with specific Battery chemistry, cell and pack design, vehicle system characteristics and operating conditions.

1.2 Objective

There are always pros and cons associated with moving from conventional petrol or diesel engines to hybrid or completely electric. In the case of Battery electric vehicles, the major challenge as mentioned above, is the trade-off between vehicle cost and performance factors like top speed and driving range. To match the customer and market demand, it is necessary to use a Battery with high power and energy capacities to produce high performance vehicles. Being the major component of electric vehicles, Battery performance and Battery temperature are related to each other. Ageing of the Battery is accelerated if the temperatures go 40 - 50 °C above the critical temperature and even higher temperatures (120 – 150 °C above) will result in Battery thermal runaway. [4] The high temperatures in Battery lead to extensive chemical reactions in Battery degrading the cells and thus reducing the Battery longevity. As mentioned above, the degradation is further accelerated when the Battery is exposed to higher temperature during which the cell to cell performance tend to decrease which in turn reduces the Battery performance. Therefore, main challenges include regulating and controlling heating of the Battery and other electrical components below their critical temperature.

Thermal management of these Battery electric vehicles is very critical in determining the overall performance of the vehicle. So the main part of the thesis work consists of cooling associated with the Battery and other electrical components. The primary work of this thesis constitutes of modelling and simulating the cooling circuit under different test cases. It also includes analysing and evaluating different configurations and strategies on how to regulate the Battery thermal management system in an energy efficient way. These models form a base for the complete vehicle model that will be used by Volvo Car Corporation. The modelling is done in a way so as to form an interface to couple the models of climate and electric propulsion systems using 1D CFD system modelling approach in the software tool GT-SUITE.

The conventional method employed by auto manufacturers have been to use Radiators which reduces the temperature of the circulating Coolant. Similarly, in cooling systems for EVs, Radiators are used to reduce the temperature of the Coolant in two separate cooling circuits i.e. one for the Battery alone and another to regulate the temperature of the electrical components. Air conditioning (AC) in vehicles is known to have a significant impact on the performance and fuel economy of any vehicle. In EVs, the systems in the AC unit consume power from the Battery and their operation affects the charge drawn from the Battery, which in turn affects the vehicle performance. But, the refrigeration system is a potential heat sink and can be used to provide cooling power to the Battery [5]. These possibilities for cooling the Battery are explored in this study.

The thesis work includes investigation and quantification of energy from AC systems and Radiator at various points in different driving cycles for accurate prediction of cooling provided by each of the systems respectively. From this study, inferences in terms of strategy for cooling the Battery in an efficient way can be made. It also includes a simulation case which will examine the function of the cooling system in sub-zero ambient conditions. In such a scenario, there might a requirement to pre-condition the Battery by providing it heat via heating the Coolant and thereby increasing the Battery temperature and maintaining it within its operating temperature range. The thesis work also includes component level validation for some of the components with the supplier data available and evaluating the accuracy of modelling in GT-SUITE.

1.3 Thesis Goal

The goal of this thesis work is

- To produce model of cooling systems for high voltage Battery system in electric vehicles using CAE (1D-CFD) methods and predict the Battery temperature under different test conditions.
- To make sure the Battery temperature is always below the critical temperature irrespective of the demand from the road and external conditions that are given by the driving cycles.
- To acquire knowledge about using the available energy efficiently in regulating the temperature and provide sufficient cooling to the Battery.

1.4 Methodology

In order to carry out the thesis work, a 1D CFD modelling tool was used to model the cooling system for Battery. The software used to accomplish this thesis work was GT-SUITE, a commercial software very widely used in automotive industry for vehicle development.

The cooling circuits were modelled on the basis of cooling system models for a Plug-in Hybrid Electric Vehicle (PHEV) model that was previously built. Two separate cooling system circuits were made for Battery and Electrical Components respectively. At the first level, individual components was modelled based on supplier data and component properties and collecting these (data) was an essential part in the study. These components, modelled in GT-SUITE, were then calibrated against test data that was available from the supplier to validate the model and to maintain good reliability of the component.

The individual components were combined to form the main cooling circuit. From a system perspective, there were many concepts of the cooling circuit configurations, all of which were modelled. A master model was built for both cooling system circuits, modelled in a way so as to form an interface for other models to work mutually with it. Some of the models were provided by other departments and a common procedure was followed while developing these models. This was done to ensure that all the models merge without conflicts in the master model.

After this was done, the entire system was simulated, first for steady state conditions and then for different load cases and scenarios to observe the response of the cooling system to the varying state of the Battery. Since this study was carried out during the concept stage of vehicle development, validation of these models with real data was not possible. The results from the study formed as a foundation for future work and detailed study of the whole system.

1.5 Assumptions and Limitations

- The scope of thesis work limits itself to the study and evaluation of thermal management of Battery electric vehicles. The primary assumption made during this study is that all the pipes that were used to model the Battery cooling system was adiabatic pipe but this is generally not true in real case scenarios. This was essentially done to in order to prevent complexity in simulations performed on the Battery cooling system model.

- The thesis work is mainly focuses on 1D CFD for flow across the components and pressure drop across it. 3D CFD is not of high importance in this thesis work because usually 3D CFD techniques are used for complex systems to obtained detailed information of fluid flow and fluid properties [6]And typically working with cooling systems that incorporate several components like valve, Pumps, expansion tanks.1D CFD simulation tool is a common choice mainly because it relies on the accuracy of data received for thermal analysis and secondly the computational time and cost is relatively less. [7]

- The thesis work was carried out when the project was in its initial concept phase, so there was no data available at Volvo against which the cooling system could be validated.

- Since the use of the entire AC circuit would be complicated and consumes more simulation time, simple end conditions were imposed for the Chiller, which meant that the cabin heating or air conditioning was overlooked. The effect of this on the entire system is not considered in the final results.

- In this study, the drive cycles that are used as an input, are results of another simulation. This data consisted of the time, velocity, power consumed by the Battery and current usage for every time step. This is an approximation in itself as these results were not validated.

- The thesis is limited by the information of cell configuration, arrangements and flow through the Battery which is already available from the electric propulsion systems. These factors are also one of the major contributors to the heat generated and are the parameters that plays a pivotal role in Battery thermal management.

- The fan in the Radiator assembly was not modelled in GT-SUITE but the map of the fan was derived and this was used to impose as mass flow for air on the Radiator.

2 Theory

2.1 Computational Fluid Dynamics

Computational fluid dynamics or CFD is a numerical method of analysis for fluid flows, heat transfer and chemical reactions by means of computer based simulations. This technique is very powerful and used for industrial and non-industrial applications. [8]

The most common method in solving CFD related problems are by using a finite volume method. The entire volume is discretised into smaller volumes, which are usually referred to as cells and governing equations are applied to these cells. The governing equation used are the Navier-Stokes equations on the flow of fluids. The equations represent the conservation laws of mass momentum and energy.

In this thesis work the commercial software GT-SUITE was used as 1D CFD tool which is a widely used tool across most of the leading automotive manufacturers. The software is developed by Gamma Technologies. The model in GT-SUITE solves the conservation equations of continuity, energy and momentum in one dimension (1D) which eventually gives the quantities that are averaged across the flow. There are 2 types of time integration methods, implicit and explicit. The explicit solver is generally used when the wave dynamics are important for example in engine, acoustics, and fuel injection and the other is the implicit solver which is used when high frequency wave dynamics are not important and Mach number is less than 0.3, for instance cooling, air conditioning, and map based lubrication. [9]

1D conservation equations solved by GT-SUITE are as follows

Continuity:

$$\frac{dm}{dt} = \sum \dot{m} \tag{2.1}$$

Energy:

$$\frac{d(me)}{dt} = -p\frac{dV}{dt} + \sum (\dot{m}H) - hA_s(T_{fluid} - T_{Wall}) \tag{2.2}$$

Momentum:

$$\frac{d\dot{m}}{dt} = \frac{dpA + \sum(\dot{m}u) - 4C_f\frac{\rho u|u|}{2}\frac{dxA}{D} - C_p(\frac{\rho u|u|}{2})A}{dx} \tag{2.3}$$

GT-SUITE divides the entire system into sub volumes called computational cells. The discretization length is the length into which the pipe is discretised for computational purpose. The larger discretization will result in smaller computational time but the results accuracy is affected in case of smaller discretization length, consequently the finer discretization results in better accuracy but the computational time increases exponentially.

The Governing equations are applied to the system and the solver calculates the scalar quantities such as temperature, pressure and enthalpy and vector quantities such as velocity and mass flux. As seen in Figure 2-1, the vector quantities are solved for at the boundaries and the scalar quantities are solved for in the cells. [10]

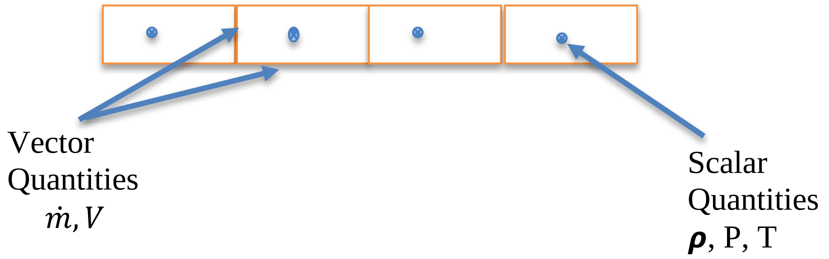

Figure 2-1 An example where scalar quantities are solved in the computational cells and the vector quantities are solved at the boundary [12].

2.2 Orifice Connection

An orifice is defined as a hole in which the diameter is fixed or controllable. The orifice is the link between different components. By specifying the diameter to be smaller than the component connected flow restrictions can be specified.

The momentum Equation (2-3) is solved to calculate the flow rate through the orifice. The orifice accounts for pressure loss due to contraction and expansion. [10]

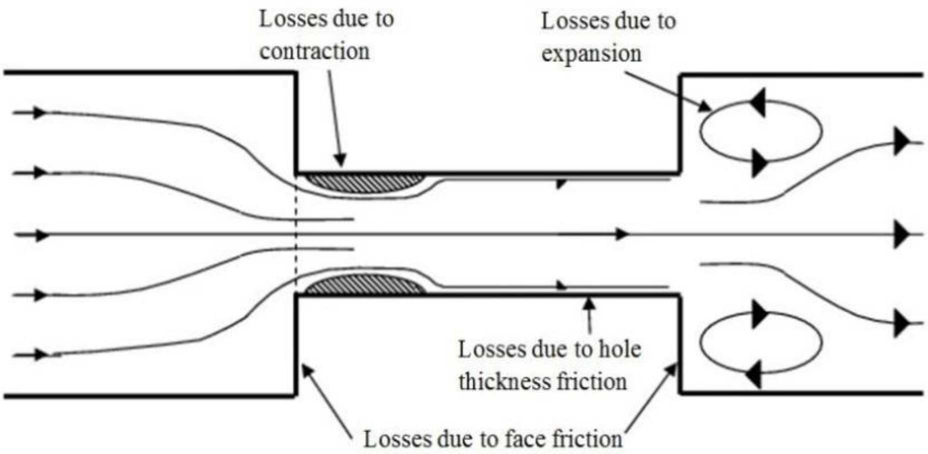

Figure 2-2 Various reasons for pressure losses in an orifice [10]

2.3 Pressure loss connection

In components where it is challenging to solve the pressure drop, it is easier to just impose the pressure loss as a function of volumetric flow rate or mass flow rate. The orifice can be replaced with the pressure loss connection, which can be used for this purpose. The momentum equation is not solved which implies the pressure loss connection uses steady flow data and has a limitation on transient situations. The pressure loss connection thus has a reduced effect when the flow is unsteady. [10]

2.4 Flowsplits

When there are more than one or more openings in the flow, the interactions cannot be captured by 1D methods. In order to take this into account for conservation of momentum in these objects flowsplits are used. The geometry of the volume is considered by taking into account the relative angles between the flows in and out of the volume. There is also options for considering the length a pressure wave must travel through the volume and the geometry of the flow entering the chamber.

The solution of flow split is similar to that of pipe where the scalar quantities are of the pipe are calculated at the centre of the volume. However the momentum equation is solved for each of the volume opening separately. [10]

2.5 Heat Transfer

Heat transfer is the transfer of thermal energy in the form of heat between physical systems. The rate at which this heat transfer takes place depends on temperature difference between the systems and the medium through which heat is transferred. Heat transfer can occur only from a system of higher temperature to a system of lower temperature. Heat Transfer is classified into 3 fundamental modes: Conduction, Convection and Radiation.

2.5.1 Conduction

Conduction is the transfer of energy from more energetic particles to the adjacent less energetic ones as a result of interaction between the particles due to temperature gradient. The transfer of heat takes place when one or more substance are in contact with each other. The conduction process can take place can happen in solid, liquids, gases and plasmas. The energy transferred through conduction process is described in the form of equation shown below. [11]

$$\dot{Q}_{cond} = -kA\frac{dT}{dx} \tag{2.4}$$

The above mentioned equation is the one dimensional form of Fourier’s law of heat conduction. The proportional constant k is known as thermal conductivity expressed in W/m-K. Good conductors such as copper have a high thermal conductivity and insulators have a low conductivity.

2.5.2 Convection

Convection is the mode of heat transfer where the transfer of energy is between a solid surface and liquid or gas. It includes both the effects of conduction and fluid motion. The faster the fluid motion the greater the convective heat transfer. [11]

There are two types of convection namely forced and natural, when the fluid is forced to flow over surfaces by external means such as a Pump, fan or wind it is called forced convection and on the other hand when the fluid motion is caused by density difference due to variation in temperature which in turn creates buoyancy forces is called natural convection. [11]

The rate of convective heat transfer is proportional to temperature difference and expressed by Newton's Law of Cooling.

$$\dot{Q}_{Conv} = hA_s(T_s - T_\infty) \tag{2.5}$$

Where h is convective heat transfer coefficient in W/m^2 and A_s is the surface area through which convective heat transfer takes place.

2.5.3 Radiation

Radiation is the energy emitted by electromagnetic waves as a result of the changes in the electronic configuration of the atoms. The transfer of energy doesn't require any medium when compared to conduction and convection. The maximum rate of radiation that can be emitted from a surface at absolute temperature is given by Stefan-Boltzmann law.

$$\dot{Q}_{max} = \sigma A_s T_s^4 \tag{2.6}$$

Where $\boldsymbol{\sigma}$ = 5.67*10^{-8} W/m^2.K^4 is Stefan-Boltzmann constant. The ideal surface that emits radiation at this maximum rate is blackbody and the radiation emitted by a blackbody is blackbody radiation. The radiation emitted by real surfaces is given by

$$\dot{Q}_{max} = \varepsilon\sigma A_s T_s^4 \tag{2.7}$$

Where $\boldsymbol{\varepsilon}$ is the emissivity of the surface. [11]

2.5.4 Forced flow Heat Transfer

In cooling systems the heat transfer through the pipes and heat exchangers is a common phenomenon. It is necessary to calculate the heat transfer coefficient which is usually calculated using the non-dimensional numbers namely Prandlt(Pr), Nusselts (Nu) and Reynolds(Re).

Prandlt number is the ratio between viscous diffusion rate and thermal diffusion rate. It usually provides the information regarding the fluid. It also provides information about the hydrodynamic and thermal boundary layer thickness.

$$Pr = \frac{v\rho C_p}{k} \tag{2.8}$$

Nusselts number is the ratio of convective heat transfer to conductive heat transfer.

$$Nu = \frac{hD_h}{k} \tag{2.9}$$

Reynolds number gives an idea about the fluid being laminar or turbulent. It is defined as ratio of internal forces to the viscous forces.

$$Re = \frac{cD_h}{v} \tag{2.10}$$

The Nusselt number expression helps to compute heat transfer from the characteristics of the flow with the help of Re and Pr, hence helping in determining the heat transfer.

$$Nu = \frac{hD_h}{k} \xrightarrow{yields} h = \frac{Nuk}{D_h} \tag{2.11}$$

The Nusselt number is expressed as a product of Re and Pr. The Dittus-Boelter equation gives the heat transfer coefficient from Reynolds and Prandtl number along with experimentally obtained coefficients, which gives equations for cooling and heating applications. The correlation is considered less accurate when the temperature difference is large across the fluid and expressed as follows. [9]

$$Nu = 0.023. Re^{0.8} Pr^{0.4} \text{ (Heating)} \tag{2.12}$$

$$Nu = 0.023. Re^{0.8} Pr^{0.3} \text{ (Cooling)} \tag{2.13}$$

2.6 Pressure drop

The difference in pressure between two points in a fluid flow is the pressure drop. It occurs when there is resistance offered in the flow. As mentioned above in the GT-SUITE software the scalar quantities are solved at the centre and the vector quantities at the boundaries between them. To counter the effects of geometry some of the attributes are adjusted i.e. Friction multiplier, heat transfer multiplier and pressure loss coefficients. In the thesis work all the pipes are modelled as adiabatic pipes hence the heat transfer multiplier is of no significant importance in this work. The other two multipliers are explained below.

2.6.1 Friction multiplier

GT-SUITE calculate the flow losses due to friction between the fluid and the interiors of the wall. This is done by a friction multiplier C_f as a function of Reynolds number R_e based on the diameter of the pipe and the surface wall roughness. There are three methods to calculate the friction losses in the pipe in GT-SUITE namely simple, improved friction and improved friction bend. These methods are compromise between computational time and accuracy of the result. The automatic option picks one of them for all nodes and it automatically choose the best method.

2.6.2 Pressure loss coefficient

The pressure loss in pipes that are caused due to bends, tapers or irregular cross section are calculated with pressure loss coefficient C_p

$$C_p = \frac{p_1 - p_2}{\frac{1}{2}\rho V_1^2} \tag{2.14}$$

where $p_2$total pressure at inlet and the total pressure at outlet is p_1, $\boldsymbol{\rho}$ is the density of the fluid at inlet and $V_1$is the inlet velocity. [12]

2.7 Cooling System

The concept of cooling system originated with a lot of importance being shown in the area of thermal management for combustion engines in vehicles. There have been a lot of research and development in this area. Similarly, for electric vehicles, the most important and crucial component is the Battery. Since there is a lot investment and complication regarding the Battery, it is always important to maintain the condition of the Battery. To get the best performance out of the Battery, it is vital to maintain the temperature of Battery within a certain optimal range. A lot of studies have shown the significance of a Battery thermal management system. This requires a cooling system specifically for the Battery, so as to regulate the temperature and maintain it within its operating range for temperatures.

There are two types of cooling systems currently available in the market for electric vehicles, air cooling and liquid cooling systems. There are advantages and disadvantages to using both these types of cooling systems. While air cooling systems can be cheaper and less complicated, liquid cooling systems take lesser space and provides more cooling, enabling the Battery to handle a larger "pulse" of power. There are many drawbacks in using liquid cooling system, including the possibility of Coolant leakage (which could cause short circuit) and the fact that maintenance and repair can be costly and complicated. But one of the main reasons to prefer liquid cooling is due to its effectiveness at maintaining a uniform temperature within and between the cells. This can be crucial for the Battery to have a longer life. Also, liquid cooling carries away more heat from the Battery and more quickly than air cooling. [13]

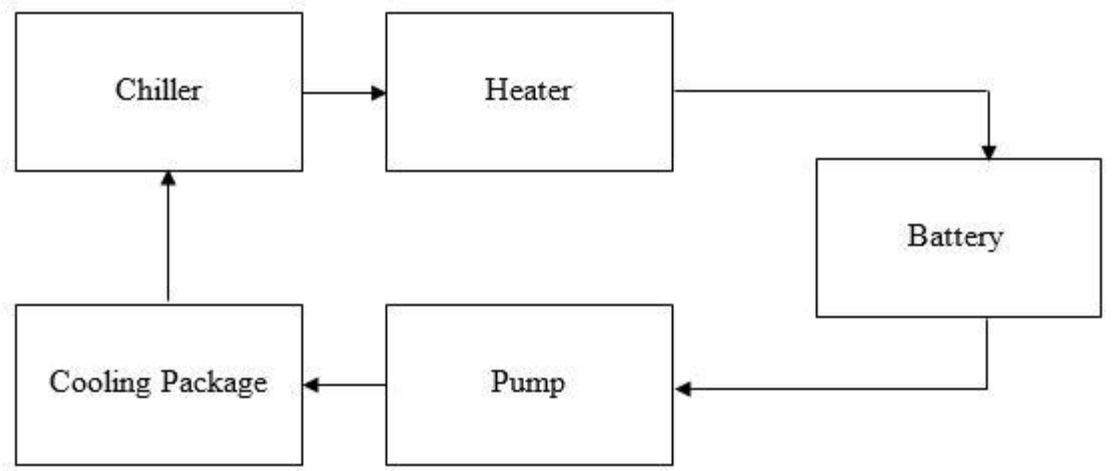

Figure 2-3 A simple schematic arrangement of a complete cooling system with Battery, Pump, Coolant Heater, Chiller and Cooling Package and the direction of the arrows indicating the direction of Coolant flow

Cooling system for Electric vehicles and Hybrid Electric vehicles usually consists of two separate cooling circuits, one specifically for the Battery and another for the electrical components. The cooling circuit for the Battery looks as shown in the Figure 2-3.The Coolant flow throughout the system is maintained by the Pump. The underhood cooling package essentially consists of two Radiators, one for each of the cooling circuits, a low temperature Radiator for the Battery and a high temperature Radiator for the electric circuit. This is where the hot Coolant from the Battery loses its heat and reduces temperature. Since, the bottleneck for electric vehicles is the Battery, it is very important to ensure its temperature does not go over the limits.

Thus, there is provision for the Coolant to exchange heat with the AC system through the Chiller, if there is a requirement for more cooling. There is another important component in the circuit which is the Heater, whose role is to heat the Coolant to warm the Battery during cold climate conditions. This is necessary since before the Battery will be used, it is required to ensure the temperature of the cells are within its operating range. There a few other components that are included to maintain the flow through all the systems which is discussed in section 2.8.

Liquid cooling systems are common in combustion engine vehicles, to ensure the engine does not overheat and also aid the engine in warming up. Although the purpose of the liquid cooling systems is the same in both combustion engine vehicles and electric vehicles, the functioning is slightly different. For example, the Coolant Pump is often mechanically driven in case of combustion engine vehicles. But in the case of electric vehicles, the Coolant Pump would be powered by an electric motor and there is more freedom for Pump control in this case, which allows efficient use of such components.

2.8 Components

As mentioned earlier, many components working together make up a cooling system. In this section, the different components used in the cooling system is explained.

2.8.1 Pump

The most common type of Pump used in these cases is the centrifugal Pump. The centrifugal Pump is powered by a device called impeller. When the impeller moves fast, centrifugal forces makes the water to move along the blades and in the process getting compressed. This causes the water to exit the impeller as a high-speed jet. In electric Pumps, the impeller is rotated by the means of a motor inside the Pump using a simple gear drive. As mentioned earlier, electric Pumps provide an extra dimension with respect to control.

Figure 2-4 50 W electric Pump used in Battery cooling system [17]

The speed and output of the Pump can be controlled on the basis of many control variables, allowing vehicle manufacturers to utilize the power efficiently. The Figure 2-4 is a 50 W Pump that is commonly used in Battery cooling systems. [14]

2.8.2 Cooling Package

The cooling package is one of the essential components in the cooling system. The cooling pack might typically consists of heat exchangers and fans. By using heat exchanger the Coolant loses the heat that it gains from the Battery before it is recirculated back to the circuit. For electric vehicles, the cooling package usually might consist of two Radiators, a Condenser and one or more fans. The purpose of using two separate Radiators is to accommodate the cooling needs for both the Battery and the electrical components separately. The high temperature Radiator handles the cooling for the electrical components and the low temperature Radiator is used to cool the Battery. The Condenser which is part of the AC system is present along with these Radiators to form the heat exchanger package. The cooling package is completed by fans, one or more depending on the requirement, used to provide more airflow at lower vehicle speeds and thereby increase the heat transfer.

Figure 2-5 Cooling Package located at the front of a vehicle, consisting of mainly of heat exchangers and fans [12]

The basic principle behind the working of the Radiator is that as hot Coolant passes through the pipes in the Radiator, there is a certain rate of air mass flow over the pipes simultaneously (either natural or forced air flow). This results in heat transfer between the liquid Coolant and air in the form of convection, causing the Coolant to lose its heat. The fans in the cooling package assist in providing more air flow through the Radiator, if there is necessity for more heat transfer.

2.8.3 Chiller

A Chiller is a heat exchanger that helps in absorbing heat from the hot Coolant from the Battery and additionally support the process of Battery cooling in high cooling requirement conditions. Fundamentally it is a plate heat exchanger with provisions for both the fluids to move across it the Coolant exchanges heat with the refrigerant in the AC circuit. With this component it is possible to use the AC system to cool the Battery when there is no need for the cabin to be cooled and there’s high load on the Battery. The use of Chiller could come in handy during conditions when the Radiator is not able to cool down the Battery on its own, i.e. during high load and ambient temperature conditions.

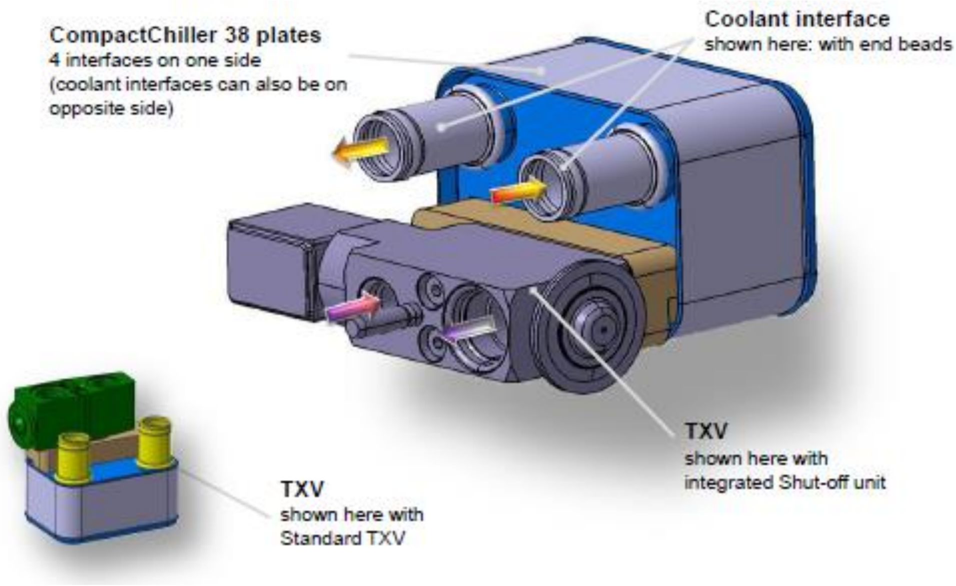

Figure 2-6 Representation of a Chiller used as a heat exchanger for heat transfer. The direction of the fluids is indicated by the arrows

2.8.4 High Voltage Heater

The High Voltage Heater is used in plug-in hybrids and Battery electric vehicles as a heating system for the Coolant. It converts electricity with DC voltages from 250 to 450 volts into heat without loss, while raising the temperature of the Coolant to warm up the Battery in low temperature conditions.

Figure 2-7 High Voltage Coolant Heater used to heat up the Coolant during lower ambient temperatures so as to warm up the battery during cold conditions

This is an important component in ensuring the temperature of the Battery to be above the critical limit below which the performance of the Battery is poor. Loading the Battery highly at low temperatures can affect the Battery performance as mentioned earlier.

2.8.5 3-way Valve

The 3-way valve is the component in the cooling that enables controlling the direction of Coolant flow. In the cooling system circuit for the Battery, a 3-way valve is used either to guide the Coolant to the inlet of the Radiator or bypass the Radiator. This function is done by thermostats quite commonly, which controls the direction of the Coolant flow based on the temperature of the Coolant. But the 3-way valve can use more control variables to switch the direction of the flow and is less complicated than the thermostat. The 3-way valve can also be used similarly with the Chiller to ensure efficient use of the entire cooling circuit system to cool the Battery, depending on various

Figure 2-8 Representation of a 3-way valve, responsible to controlling the direction of coolant depending on conditions

conditions.

2.8.6 Expansion Tank

The expansion tank is a container that is connected to the Radiator, providing extra storage space for the Coolant when it expands. As the Coolant temperatures increase, it tends to expand and the expansion tank acts as an outlet for this expansion. But once the system cools down, vacuum is created in the cooling system that causes the Coolant to be sucked back to the flow circuit. Another function of the expansion tank is to remove air bubbles from the Coolant circuit.

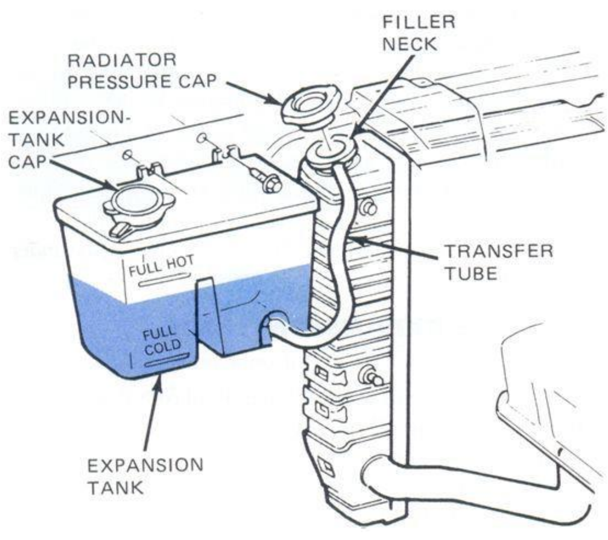

Figure 2-9 Expansion Tank adjacent to the Radiator that helps in maintaining the coolant pressure below limits [15]

2.8.7 High Voltage Battery

The High Voltage Battery is the most critical part in Battery electric vehicles as the name suggests. The source for electrical energy required by the vehicle is the Battery, the most important being the energy demand of the drive motors and associated components. It stores and provides energy when there is a demand made by the vehicle. The use of Battery, either while charging or discharging it is accompanied with heat generation. Battery performance and its life is dependent on the usage of the Battery and maintaining its temperature within safe limits. Hence thermal management of the Battery is quite essential especially in Battery electric vehicles because the Battery gets heated up quite fast during drive case scenarios and there is cooling required for the Battery. Since it is common for the batteries to get really cold during sub-zero temperatures, there is a need to warm up the Battery and this is part of the objective for the Battery thermal management.

The cooling in such batteries is provided by air or liquid cooling as discussed earlier in section 2.7. The heating up of the Battery is associated with energy provided for the vehicle from the point it starts functioning. Because the Battery is very heavy, its placement plays a very vital role. The problems associated with these batteries are large, one of the major issues being short circuit, any material that is used which is reactive and unstable could be harmful. Initially, batteries based on lead acid technology were used in cars. Then came the NiCad batteries which are widely used in laptops and mobile phones. Further developments within this field resulted in NiMH batteries. Electric or hybrid cars presently use the Li-ion Battery technology due to its superior energy capacity and life.

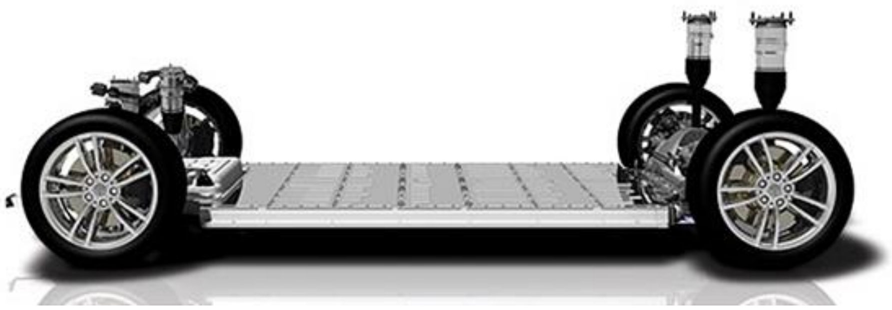

Figure 2-10 Battery Placement on the chassis with placement of cells in series/parallel

2.9 Modelling Interface in GT-SUITE

GT-SUITE is a 1D CFD tool developed by Gamma Technologies. It can be used for a wide range of applications involving system simulations and analysis. A comprehensive set of component libraries allows the possibility of simulating the physics of fluid flow, thermal, mechanical, controls, etc. with a user friendly interface.

The licensing under GT-SUITE enables using softwares like COOL3D, GEM3D, GT-SpaceClaim, etc. by using software (GEM3D) 3D models can be converted to a 1D platform and seamlessly integrated with the 1D model. The possibility of modelling components or systems individually and then coupling different system models is advantageous. In addition to this, other advanced features like DoE, optimization and possibility of distributed and parallel processing improves the effectiveness and user productivity.

As mentioned previously, GT-SUITE is a 1D system modelling and simulation tool and hence the modelling in GT-SUITE is object based. The library consists of many different templates (objects) used to describe parts of the system. Every model has a mini map which indicates the different objects/templates used in the model. Any new template is dragged from the component library and placed in the map. Each template is to be defined by filling the attributes using parameters or values. The graphical user interface is called GT-ISE.

2.9.1 GEM 3D Preprocessor

GEM 3D is a 3D pre-processor tool that is licensed under GT-SUITE and is used to build/import 3D models of components and convert them into 1D models for the GT-ISE platform. GEM 3D can be used to convert models of primitive parts in the model such as pipes, flow splits, shells, etc. for much more accurate modelling of the same in the 1D platform. It allows these components to be imported in a 3D format from other applications. It provides a much more accurate representation of components with complex structures and that cannot be defined as attributes in GT-SUITE 1D platform easily.

Not only can these 3D models be imported and characterized, but it is possible to add components in GEM 3D. It can be used for a wide range of applications varying from engine performance, acoustics, lubrication, cooling systems, cranktrains, etc. The Figure 2-11 shows the conversion of the 3D model of a pipe with complex geometries into a 1D object.

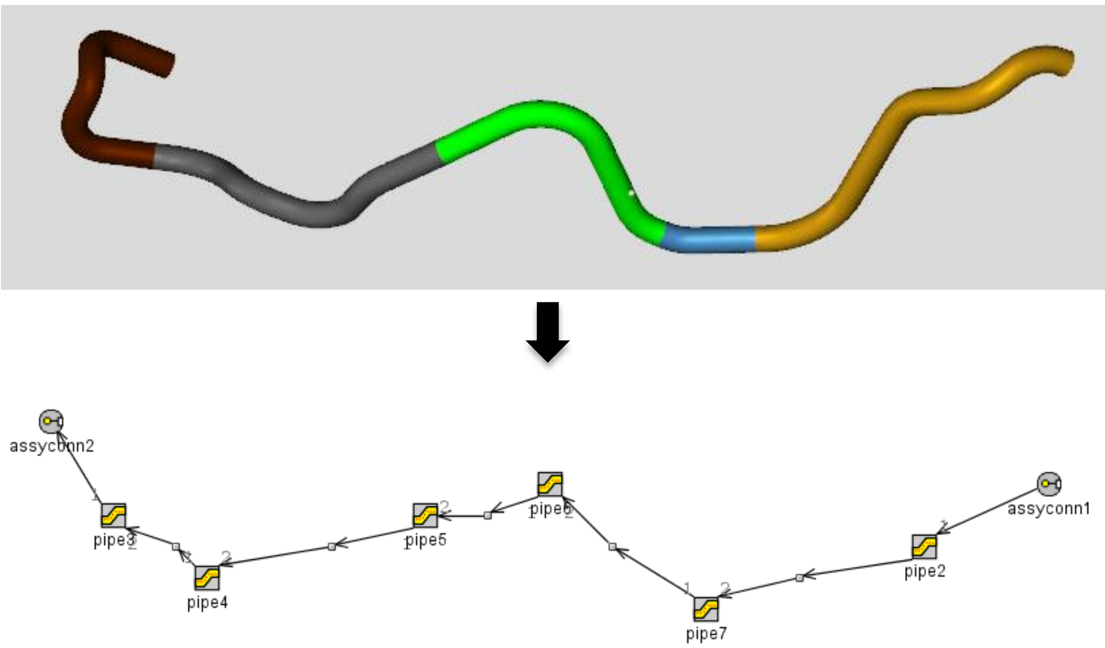

Figure 2-11: Represents the conversion of bent pipes from GEM 3D to 1D in GT-ISE. The below mentioned figure is the actual 1D representation of the 3D model of the pipe above

3 Methods

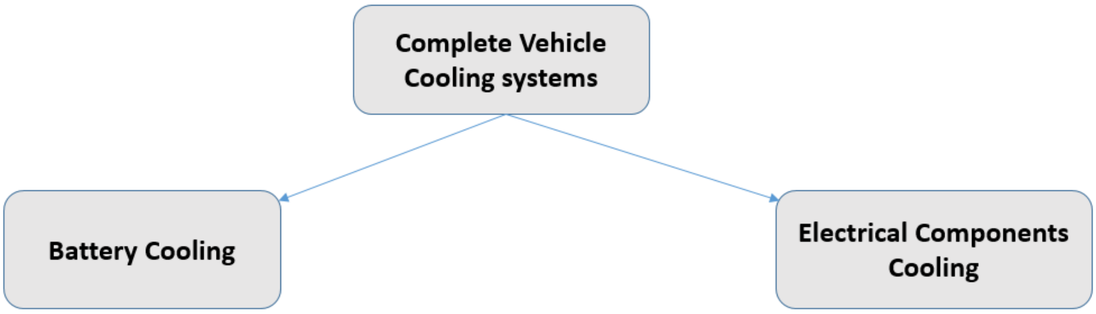

Figure 3-1 Classification of Cooling systems for components that are available in complete vehicle model

As seen in Figure 3-1, two of the cooling systems as a part of the complete vehicle cooling systems category are the Battery cooling system and the Electrical components cooling system. The Battery remains as one of the important components in an electric vehicle, because of the fact Battery is very expensive in comparison to other electrical components and due to its high maintenance requirements. These electrical components result in high rates of heat generation during critical scenarios which is harmful in terms of their functioning. Hence the main systems that need cooling are the Battery system and the Electrical components system. The emphasis of the thesis work mainly focuses on Cooling System for the High Voltage Battery. This chapter will consist of methods employed in modelling different systems in the entire Battery cooling system, the calibration of some of the components and discussing the boundary conditions for the whole system.

3.1 Cooling System Components

This chapter will consist of methods employed in modelling different systems in the entire Battery cooling system, the calibration of some of the components and discussing the boundary conditions for the whole system.

3.1.1 Pump

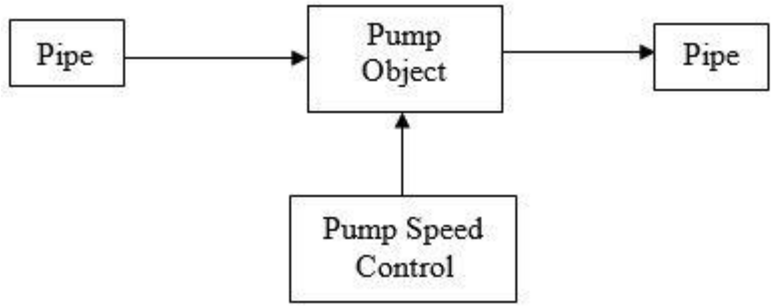

Figure 3-2 Representation of a Pump in GT-ISE platform. The geometrical and performance characteristics of the pump are defined using the templates as shown in the figure

The Coolant electric Pump is modelled in the GT-SUITE environment by a Pump object, which is based on performance data such as data points. Characteristic maps are provided by documentation available at corporate database which the Pump manufacturer provides. The task of the Pump is to constantly increase the pressure in order to maintain fluid motion. The power requirements of the Pump never exceed 50 [W].

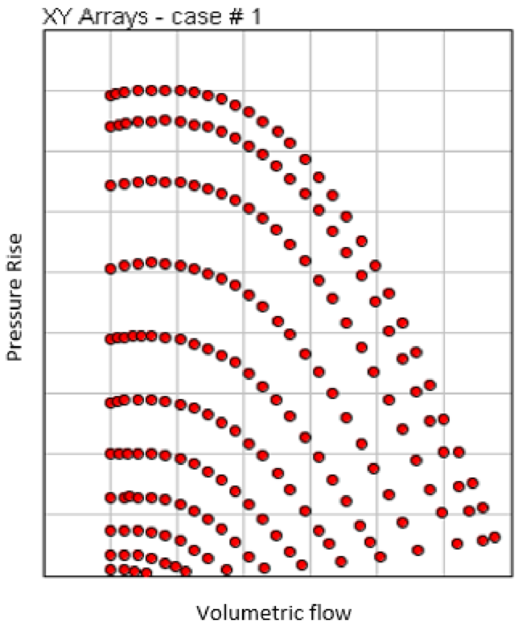

Figure 3-3 Representation of the Pump map which is used as a look up table in GT-SUITE model of the Pump

The Figure 3-2 represents a final model of the Pump with the Pump object represented in yellow and an arrow at the centreline. The Figure 3-3 represents the pressure rise on Y-axis against volumetric flow on X-axis corresponding to contour lines which represent varying rotational speed. The object of the Pump contains different Pump maps for different temperatures. According to the temperature of the Coolant, the Pump maps are selected. The power is found by pressure rise and volumetric flow at a given rotational speed and set to the Pump to satisfy the requirement. In the complete circuit model the Pump is always running at its maximum rotational speed to provide the maximum cooling to the Battery circuit. A basic control plan is enforced on the Pump which is discussed in section 3.10.

3.1.2 Separator Assembly

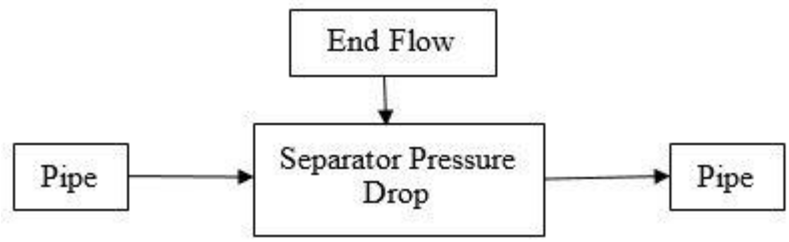

Figure 3-4 Illustration of a separator assembly used in the cooling system circuit as a block diagram

The modelling of the separator assembly is relatively straight forward, the Coolant enters the separator assembly after it exits from the Battery. The task of the separator assembly is to remove bubble from the flow. The pressure drop is provided by the documentation from the corporate database which is modelled using a “PressureLossConn” object. The object is placed between flow components to impose a pressure drop. The separator assembly, modelled in GT-SUITE consists of only pipes and a given pressure drop with an “EndFlowCap” object that represents a dead boundary condition. The separator assembly output is connected to the entry of the Pump.

3.1.3 Expansion Tank

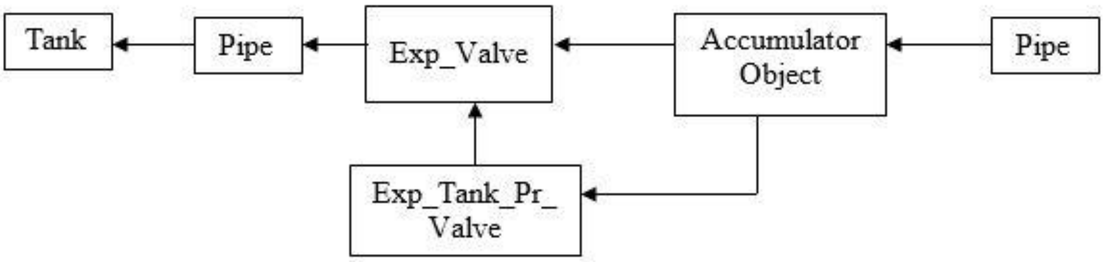

Figure 3-5 GT-SUITE representation of expansion tank

The expansion tank is modelled by using the accumulator object in the general flow components option available in GT-SUITE, the total volume in the accumulator is always conserved. The thermal behaviour of the accumulator is also taken into account. The distribution of volume between the two parts changes freely in order to maintain the pressure balance. There is an option to model two fluids in the tank, for our purpose they are air and the Coolant. The tank has a capacity of 1.5L of which is divided among both the fluids. There is an expansion tank pressure valve that is quite evident in the model which detects the pressure rise in the tank and if the pressure is above 2.45 bar the expansion tank, the valve is opened up. The pipes leading to the accumulator and after it have been modelled according to dimension. Modelling of correct pressure levels in the Coolant circuit is difficult and time consuming, but since Coolant is a liquid, its properties will not change significantly with pressure.

3.1.4 3-way valve

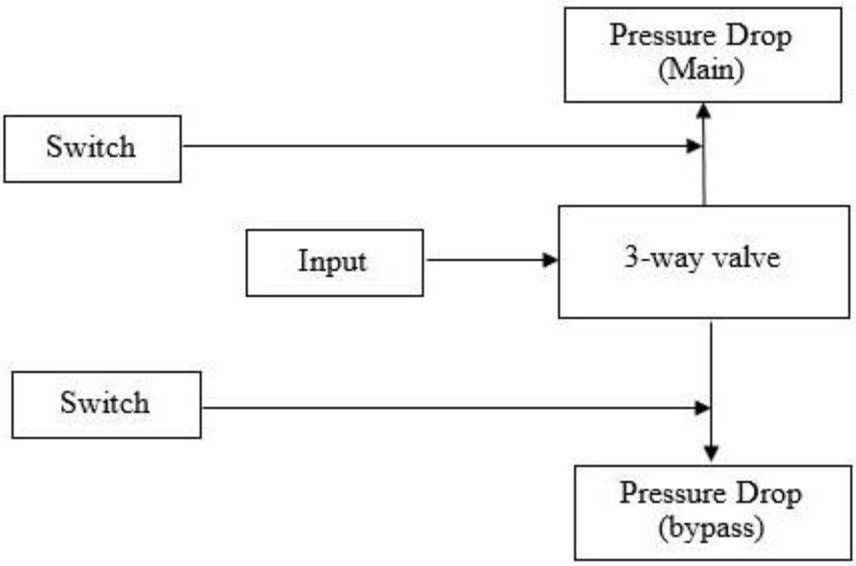

Figure 3-6 Representation a 3-way valve as a block diagram with pressure drop data imposed for the main flow and bypass flow. There is presence of toggle switch for direction of Coolant

The main purpose of 3-way valve is to allow the flow according to the cooling system requirements and regulate it. It is placed just before the flow in the cooling circuits joins the Radiator pack and before the Coolant enters the Chiller component. When there is cooling required from the Radiator, the bypass is closed and the flow passes through the main pipe. The other 3-way valve modelled is ahead of the Chiller. The flow through the Chiller is similar to the one explained for the Radiator. Both the main pipes are closed when there is no cooling required from either of the components.

The 3-way valve works on the basic logic of a switch as the toggle is between 1 and 0, where 1 signifies open and 0 for closed. The forward discharge coefficient and the backward discharge coefficient are defined and the values given to each of them is 1. Depending on the signal received (1 or 0), the switch controls the direction of the Coolant by opening one of the gateways and closing the other. The modelling of pressure drop is modelled with outlet pipes with calibrated diameter. The 3-way valve is crucial in determining the overall cooling performance of the system.

3.1.5 Heater

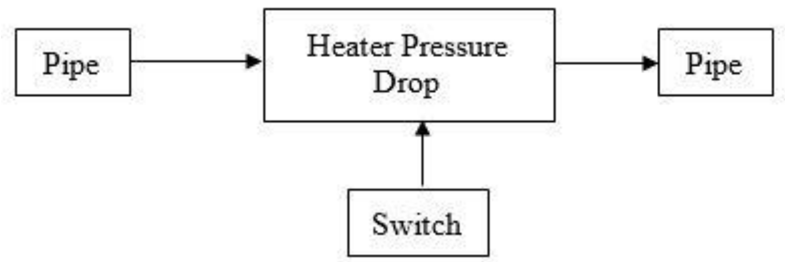

Figure 3-7 Illustration of heater component used in the cooling circuit as a block diagram

The Heater component is present just before the Battery in the complete circuit modelling as it has to perform its function of heating the Coolant before it is sent to the Battery in cold ambient conditions.

The modelling of the Heater component consists of a heat addition object which is used to impose the heat added to the Coolant to raise the temperature and consequently result in warming up the Battery. The pressure drop that the Coolant will experience, which has been acquired by documentation available from the corporate database is also defined. The heater is modelled by straight pipes which lead to the heat addition object described as heater in mentioned Figure 3-7.

3.2 Cooling Package

The cooling package of a vehicle essentially consists of a Radiator and a Condenser with fans attached to it to increase the air flow. In the cooling package of an electric vehicle, there consists two Radiators and a Condenser along with a fan. The two Radiators are part of two separate cooling circuits, one for the Battery and the other for the electrical components. The cooling package modelled for this study has the Battery Radiator (Low temperature Radiator) shown as LT Radiator present at first, followed by the Condenser and then the other Radiator (High Temperature Radiator) shown as HT Radiator followed by the fan. A schematic of the cooling package is as shown in the Figure 3-8.

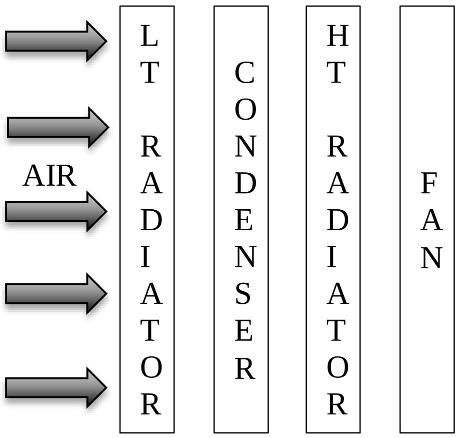

Figure 3-8: Schematic of the arrangement of components in the Cooling Package. It consists of two Radiators, with a Condenser between them and a fan.

In this thesis, the fan is not modelled due to unavailability of data and thus the airflow due to the fan is provided as a map while defining the boundary conditions for the cooling package. At a system level each of the heat exchangers were defined individually using “Master” and “Slave” objects as shown in the Figure 3-9.

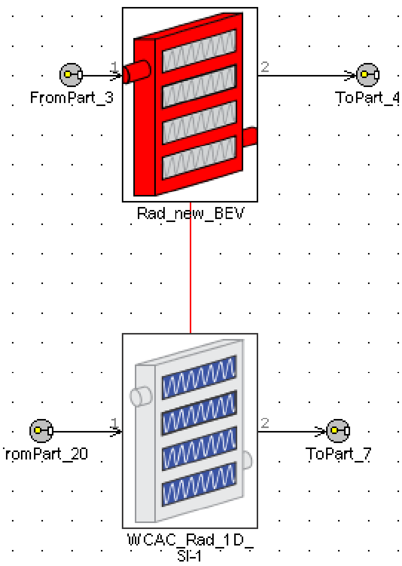

Figure 3-9: Representation of Heat Exchangers in GT-SUITE. Two objects are used to model the interaction between the two fluids as shown

The “Master” is defined with all the properties of the Radiator, including the geometrical dimensions of the heat exchanger, the heat transfer maps and the pressure drops for both the Coolant flow and air flow across the heat exchanger. The “Master” object captures the heat transfer between the Coolant and the walls of the pipe and the “Slave” object computes the heat transfer between air and the outer surface of the pipe. Both the objects are made distinct by assigning different initial state conditions depending upon the object. The Condenser is also modelled in a similar way but the “Master” object in this would be defined to describe the heat transfer between the refrigerant and the pipe walls. The method employed in calibrating one of the Radiators is explained in section 3.6.

Once these models are calibrated with supplier data, they are linked together in GT-ISE to form the complete system of the cooling package. To make things easier, each of these heat exchangers are converted in the form of a “sub-assembly”. The ends of these sub-assemblies or blocks are left open so that they can be connected with other blocks to complete the system structure. It is important to name the open ends of these blocks distinctly and assign them different ID numbers. The sub-assemblies can be then dragged onto the model map and are linked together as shown in the Figure 3-10. While combining different objects using links it is important to connect them correctly. For example, as shown in the figure below, the red links show the flow of the Coolant and they must be connected to the open links to the “Master” object in the Radiator “sub-assembly”. The blue links denote the air flow and they need to be connected to the open links in the “Slave” object in each of the sub-assemblies. There can be conflicts if these are not connected properly and sometimes might even be the cause of convergence issues.

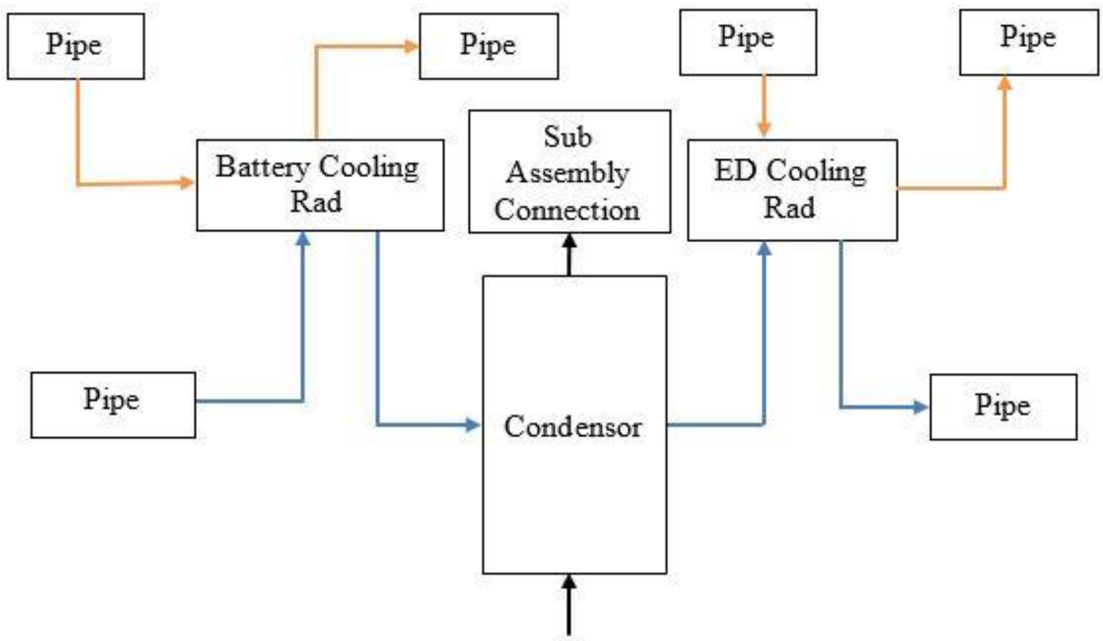

Figure 3-10 Illustration of cooling package as modelled in GT-SUITE with the presence of low temperature Radiator, high temperature Radiator and Condenser in-between these two Radiators.

This completes the modelling of the cooling package. The final step is to create the whole cooling package as a sub-assembly. This implies that there would be open links to each of the heat exchangers, separately for air flow, Coolant flow and refrigerant flow. The entire system is then combined to form an external sub-assembly which can be used as a whole block representing the cooling package in the final system model conveniently.

It is also possible to model the cooling package using Cool3D, licensed under GT-SUITE, which allows to build 3D models and exporting underhood cooling module models into the GT-ISE platform. A model for the cooling package was built using Cool3D and both the cooling packages were simulated for a time of 500 seconds for the same boundary conditions. It was observed that the results produced were the same but the computational time was almost 2.5 times more while using the Cool3D model. The use of the Cool3D model only increased the computational time while providing the same results and was thus discarded for this application.

3.3 Battery Model

The complete system model of the Battery was provided by the electric propulsion systems group at Volvo. The model was built using GT-SUITE as well and is a calibrated version, representing the Battery as an electro-thermal system with feedback. This means that it provides results e.g. with respect to heat generated by the Battery for varying inputs of the current and Battery state. It is modelled to have a feedback from electric and thermal points of view of the Battery and it responds to changes in different factors due to the influence of the cooling system.

The entire Battery pack is divided into many modules, with provision provided for Coolant flow and it is modelled based on this. Each of these modules are modelled to have an interaction with the Coolant flow, resulting in heat transfer. It is also developed to represent the heat transfer between the insulated Battery pack and the ambient. The model uses basic physics to calculate the heat generated resulting in increase in temperature of the Battery during its normal operation.

The inputs to the Battery model are in the form of parameters, one being the current input to it. Heat generated by the Battery and the changes in its temperature during the simulation plays a major role in the variation in Coolant temperatures which is the main output from the Battery model for operation of the cooling system. The system model is constructed to have an inlet and outlet for Coolant flow and this is important while coupling the cooling system model with the Battery model.

3.4 Chiller

The modelling of the Chiller is considered challenging when compared to the other models because it must accurately capture the interactions between the Coolant and refrigerant. The Chiller component is modelled as a heat exchanger with Coolant fluid on one side and refrigerant on the other. This calibrated and validated Chiller component was provided by the climate control group. The Chiller consists of three heat transfer objects, one for each of the passes the refrigerant makes in the Chiller. The idea behind making three passes is to capture the counter and co current flow. The model ably captures heat transfer, pressure drop and flow parameters using the “Master” and “Slave” quite similarly to how it performs the same for the Radiator model. The Coolant enters the three Coolant “Master” objects separately and exchanges heat with the refrigerant side and exits the Chiller. With this organization of the objects, the refrigerant will pass the Coolant with counter current flow in the first pass and co current in the second.

3.5 Cooling System Model

Once all the components in the cooling system are individually modelled and calibrated, these are linked together to make the cooling circuit. Since the cooling package, Chiller and Battery are modelled to be separate sub-assemblies, it is essential to create open links as an inlet and outlet, to and from these parts respectively. The cooling circuit mainly consists of two 3-way valves, a Coolant Heater unit, an electric Pump, a separator assembly and an expansion tank, all of which are modelled and validated separately and are in the form of sub-assemblies with open links on its ends.

The purpose of the 3-way valves is to direct the Coolant to either of the heat exchangers (Chiller or Radiator) or bypass them. The Coolant Heater is placed just before the Coolant enters into the Battery and is active under cold climate conditions, in order to raise the temperature of the Battery higher than critical limit below which the performance of the Battery very poor and back within the operating range. The arrangement of the cooling circuit is as shown in the schematic below.

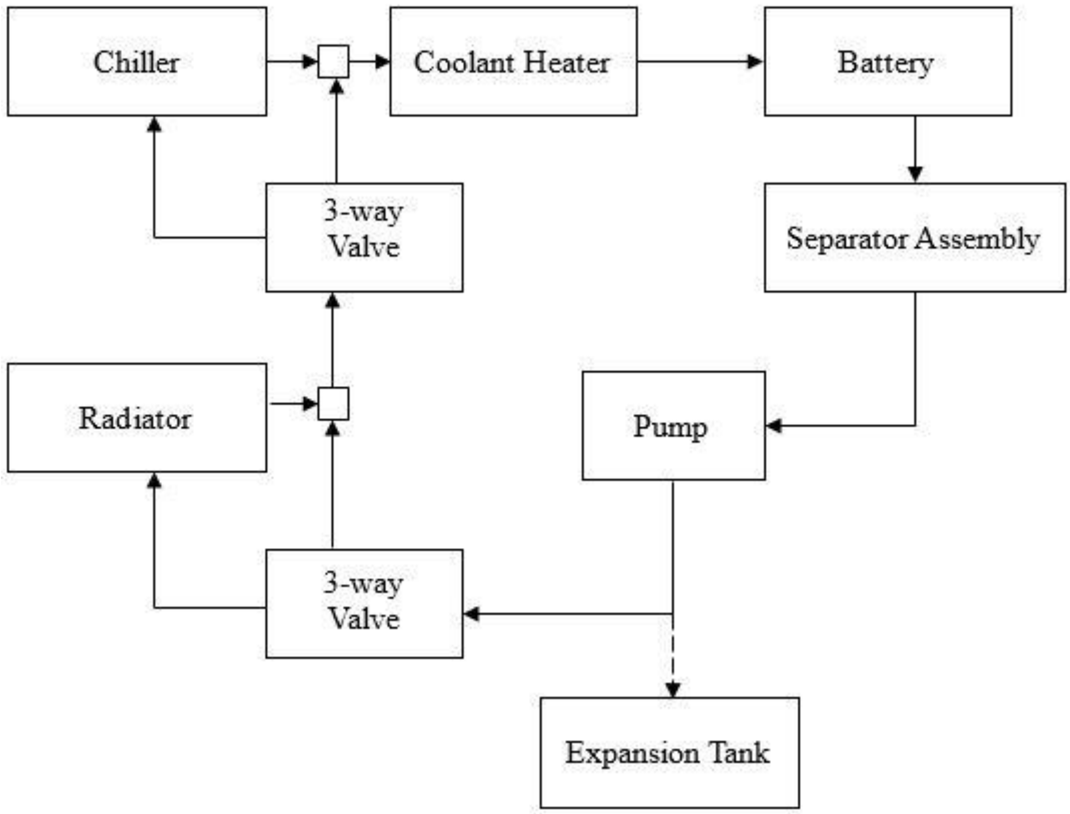

Figure 3-11 Schematic diagram of the arrangement of components in the cooling circuit. The direction of the arrows represent the direction of the coolant flow across the entire system

3.6 Calibration of Radiator

Calibration of components is very essential in order to maintain a good fit between the model that is developed in GT-Suite and the data available from the supplier so that computer simulations correlates to the available data. The calibration explained in this section is that of the Radiator i.e. heat exchanger. A harness model of the Radiator is made with end environment (boundary) conditions applied to the Coolant side and the air side. The input provided to the air side is ambient air and the Coolant on the other respectively, which is quite well known with the help of supplier data provided by the Radiator manufacturer. The input is in terms of mass flow rate (in kg/s) and temperature (in K). A map, in terms of look up table for heat transfer rate is also an input to the model.

The modelling of the Radiator pack is done as explained in the section 3.2. With relevant data like pressure data for air side and Coolant side, a heat exchanger model that represents a Radiator in real case is made by modelling it in a virtual environment to verify the behaviour of the Radiator for various critical conditions. The critical conditions were cold and hot ambient temperatures.

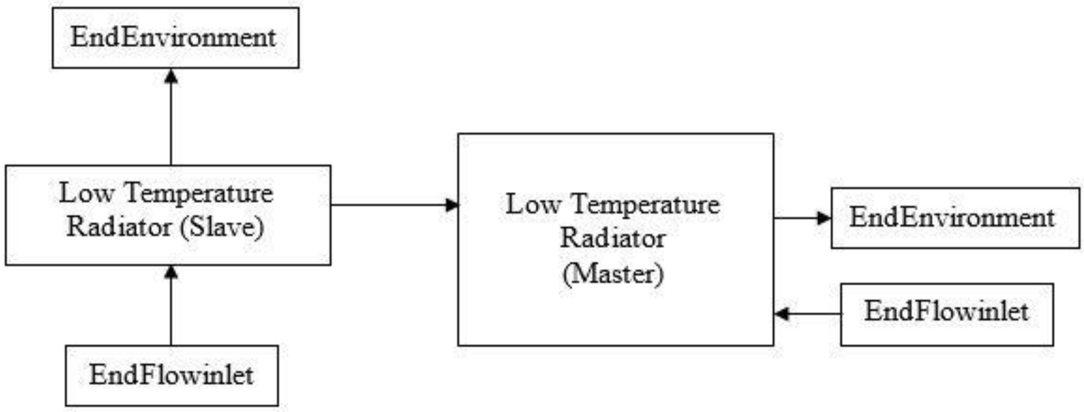

Figure 3-12 Verification model of the Low temperature Radiator modelled in GT-Suite with end flow conditions

System level representation of the Radiator which is modelled for calibration with end boundary conditions is shown in the Figure 3-12. The figure shows a Radiator being modelled as a heat exchanger with Coolant side on ‘’Master’’ side and ‘’Slave’’ represented by air on the other side. The steady state simulation cases were run to calibrate the model against supplier data which was available.

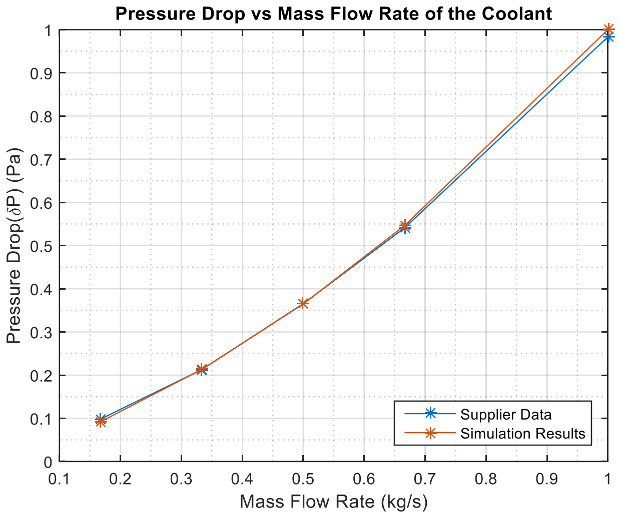

Figure 3-13 A normalized plot showing the comparison between the GT-SUITE model and the supplier data for pressure drop across Coolant side.

The Figure 3-13 is a comparison between the supplier data provided in the data sheet, for the difference in pressure between inlet and exit of the Radiator in the Coolant side. This is calculated by providing inlet conditions in terms of mass flow rate (kg/s), inlet temperatures (in K) and providing dummy pressure drop at the exit. The magnitudes of both Mass Flow Rate and Pressure Drop are normalized to 1.

The model calculates the pressure drop at the exit with the inputs given to the Radiator in terms of the map. The obtained pressure drop at the exit is noted and verified against the pressure drop provided by the supplier at the exit. This is represented in Figure 3-13. The GT-Suite model is a perfect fit for the data provided by the supplier data. The air side ΔP is calculated in a similar way as to the Coolant side pressure drop calculation, but the only difference being the outlet pressure is checked for the air side i.e. slave in the heat exchanger component. These validations are usually done at a component level because when the component behaves well with the supplier data, the model works absolutely fine while coupling these models with other models.

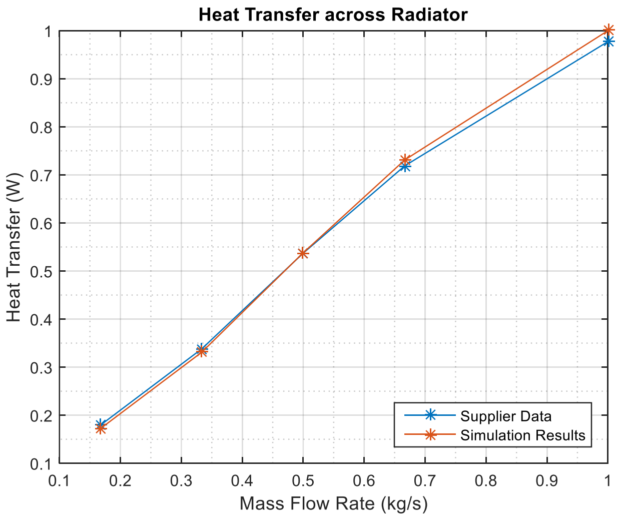

Figure 3-14 A normalized plot showing the comparison between the GT-SUITE model and supplier data for the heat transfer.

The Figure 3-14 shows a graph that displays the relative comparison between the GT-SUITE model and the supplier data for the heat transferred. The heat transfer rate is given as an input to the "Master" object for a particular temperature, mass flow rate and a pressure of the master and slave. The model interpolates the heat transfer rate for a particular set of input conditions which is the verified against the supplier data sheet. The comparison from the graph quite clearly illustrates that there is a good fit between these two graphs at lower mass flow rates.

3.7 Cooling Circuit

Once all the components in the cooling system are individually modelled and calibrated, these are linked together to make the cooling circuit. Since the cooling package, Chiller and Battery are modelled as separate sub-assemblies, it is essential to create open links as an inlet and outlet, to and from these parts respectively. The cooling circuit mainly consists of two 3-way valves, a Coolant Heater unit, an electric Pump, a separator assembly and an expansion tank, all of which are modelled and calibrated separately and are in the form of sub-assemblies with open links on its ends.

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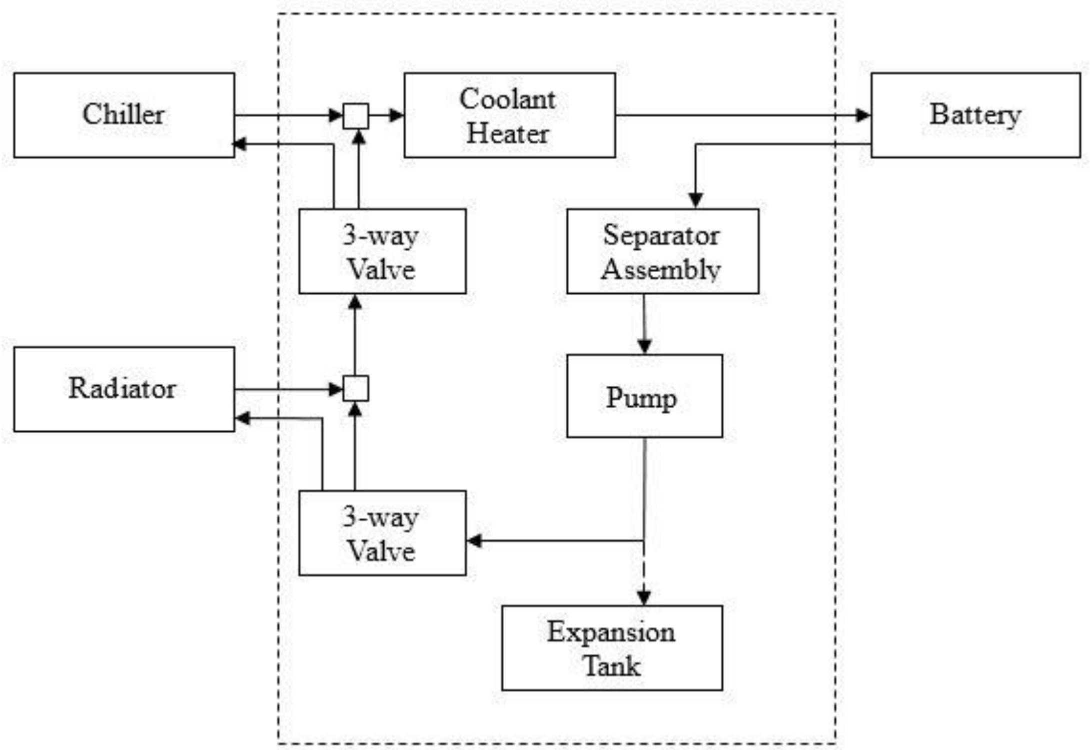

Figure 3-15 Schematic diagram of the arrangement of components in the cooling circuit. The components enclosed in the box make up the cooling system model. Different connections, represented by the arrows, are made from the other system models

The components are arranged as shown in the Figure 3-15 and the cooling system components are made into one sub-assembly. This gives the option of having different concepts of cooling circuits, different configuration setups and the possibility of testing and analysing them without much inconvenience. The enclosed box as shown in the figure forms the cooling system sub-assembly, with open links to the heat exchangers and the Battery model. Control parameters were assigned to activate the 3-way Valves, Coolant Heater and the Pump, which will be discussed in detail in section 3.10. Since the Chiller and Battery models were calibrated individually and provided, the construction of the system model had to be done carefully to make sure there were no conflicts while coupling all the models together.

3.8 System Model

The system model essentially consists of sub-assemblies that were individually constructed, as explained earlier in sections 3.1 to 3.4, linked together and a block that consisted of parameters defined for control. Since each of these sub-assemblies have many open links inside them, it is very important to correctly connect these blocks with each other. Each of these open links are distinctly named and numbered to avoid any confusion while linking the sub-assemblies together.

Since different sub-assembly models are joined together in the system model, it is also important to follow a standard procedure while naming parameters to not result in conflicts. One of the advantages of GT-SUITE is the possibility of using the same object in the same model more than once and also in different models/sub-assemblies. But in such cases it is crucial to name the objects discretely in order to avoid conflicts between sub-assemblies with regards to similarity in object name.

3.8.1 System Architecture

The architecture of the final system model is as shown in Figure 3-16. The blue arrows represent the Coolant flow throughout the system. Since the cooling package and Chillers are heat exchangers, there is a need for providing boundary conditions (represented by B.C. block) that provides the flow through the "Slave" objects in these blocks.

The red dashed arrow represents the refrigerant flow which is the secondary fluid object in the Chiller. The cooling package consists of two Radiators and a Condensers. The green dashed dot arrows represent the air flow through the cooling package. Since the Condenser is originally a part of the AC system which is not present in this model, the refrigerant side is also provided as a boundary condition, represented again with red arrows. The controls block essentially consists of different control parameters used in each of the system blocks.

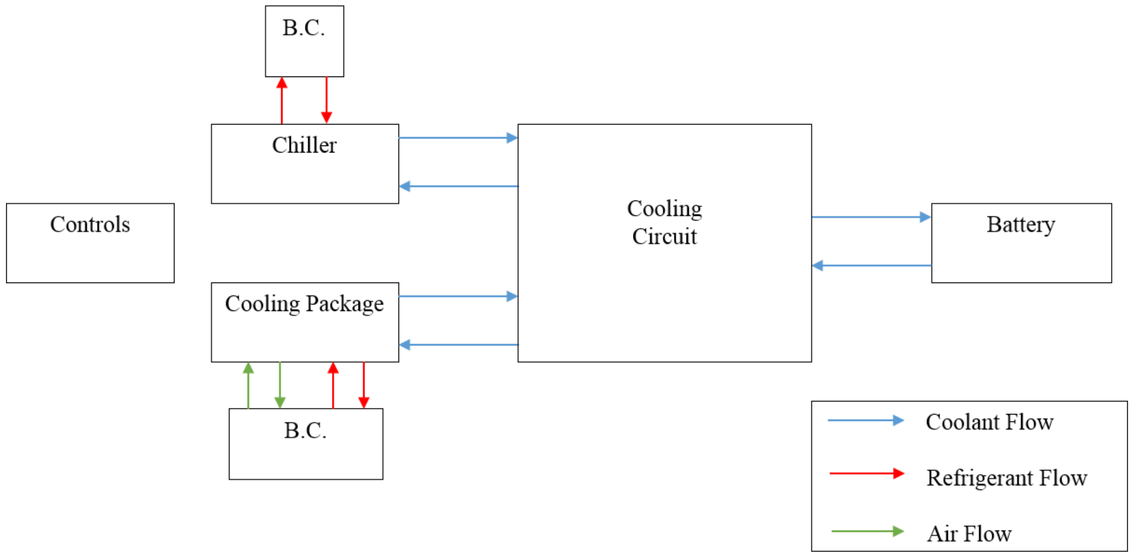

Figure 3-16: System model Architecture. Consists of the main system blocks with coolant flow interaction between them, a controls block and boundary conditions provided for the heat exchangers

The signals are transmitted from the controls block to the other blocks using "SendSignal" and "ReceiveSignal" objects, which are templates in the GT-SUITE library. These are mostly parameters used to control the action of components in the cooling circuit and also signals used for post-processing. One of the control parameters used is the one that the 3-way valve requires to switch the direction of Coolant flow, i.e. either into the heat exchanger or bypassing it. Another important parameter present is the one to control the speed of the Pump to regulate the Coolant massflow. But as mentioned earlier, to maximise the heat transfer, the Pump speed is always at a maximum in all simulations run in this thesis work.

The reason for having a block separately for controls is to follow a systematic procedure of modelling in order to avoid confusions while handing the responsibility of the model to another user. This is necessary when the model is required to be used as a part of the vehicle model and there is a need to couple this without causing any inconsistencies between the models. It also allows the user to model a control system using Simulink and integrate it with this model, which is one of the other advantages of GT-SUITE. The initial value of the parameters are defined in the case setup and depending upon the control strategy, the value is overridden.

3.8.2 Boundary Conditions

The two main parameters concerned with this study is the ambient temperature and the Battery temperature. To make a comprehensive study of the variation in Battery temperatures for different cases, the initial value of these parameters play a significant role in the results. The Battery Coolant temperature and the cooling package inlet air temperature are defined to be the same as the ambient temperature. As mentioned earlier, the control parameters are defined with an initial value in the case setup. Another important parameter is the initial value of the SoC (State of Charge) of the Battery, which is varied depending on the case. Battery current is used as an input for providing a transient case and is defined depending on the scenario. Data for this is collected from results of another simulation where different drive cycles are provided as an input and the operation of the Battery and the electrical systems (propulsion unit) is studied.

The result is a dataset, which consists of data regarding power consumption and current drawn for different timesteps throughout the simulation. A Negative value of this signifies the Battery being charged and a positive value means the Battery is discharging.

Boundary conditions were provided for the heat exchangers, for the secondary fluid. While considering the boundary conditions for the cooling package, i.e. at the air side, it is important to specify the inlet temperature of the air and the mass flow, the pressure being maintained at the atmospheric level.

The massflow of air through the cooling package is mainly due to the ram air that is associated with the vehicle movement and also the presence of a fan, which is used during low vehicle velocities. Since the fan is not modelled in this work, a 2D look-up table is created for simulating the airflow through the cooling package, based on a CFD study on the airflow through the grill and the cooling package as a function of vehicle speed.

The fan power is one of the inputs requested by the look-up table, in terms of percentage of its capability. The value ranges from 0 to 1, with 0 being fan switched off and 1 being the fan running at max power. The other input is the vehicle speed, which is defined in the case setup depending on the case. This is seen to be a function of the Battery current from the provided dataset. The look-up table is as shown by

Table 3-1: The 2D look-up table for massflow rate of air through the cooling package. Vehicle Speed and air mass flow rates are normalized to 1

Vehicle Speed (km/hr) / **Power Usage (%)**	**0**	**0.18**	**0.43**	**1**
0	0	0.07	0.26	0.70
20	0.07	0.14	0.32	0.76
40	0.15	0.21	0.37	0.82
60	0.22	0.28	0.44	0.88
80	0.29	0.35	0.5	0.94
100	0.37	0.41	0.55	1

The conditions set for the refrigerant side are different for both the Condenser and the Chiller. The boundary conditions for the refrigerant side on both these components are set using the results from running the AC system in isolation. The inlet conditions for the Condenser, on both fluid sides will not affect the results greatly and are not of much significance. It is important to provide the right conditions for the Chiller on the refrigerant side as it play a pivotal part in the analysis of the results. The key parameters are the massflow and the desired outlet pressure and these are maintained at levels that indicate normal operation point of the Chiller.

3.9 Test Scenarios

This section explains the different scenarios used for the investigation of the model. In section 3.8, it was mentioned that there are a few parameters that play an important role in defining different and unique cases. Fundamentally there are two test scenarios while considering cooling system for the Battery, the cool-down and the heat-up cases. Cool-down symbolises the phase where the Battery needs to be cooled in order to avoid overheating of the Battery. Heat-up characterises the need for the Battery to be heated during cold climate conditions, in order to raise its temperature over sub-zero levels.

The initial values of the ambient temperature and the Battery temperature form the base for any test scenario that is simulated. By varying these, the response of the Battery and consequently the cooling system is analysed throughout different drive cycles. While associating thermal management to Battery technology, the important aspects to look into are charging and discharging cycles of the Battery. And these cycles are defined in the form of the current drawn from the Battery during operation of the vehicle or the input current to the Battery that increases its state of charge (SoC).

The current is provided as an input and is a function of time and vehicle speed, as discussed earlier. These profiles of current form the basis for a transient analysis of the Battery. These drive cycles can be categorised based on the type of current input (charge/ discharge) and are explained as follows:

- ❖ Charging Cycles
    - Super-Fast Charging
    - Semi-Fast Charging
    - Normal Charging (Plug-in)
- ❖ Discharging Cycles
    - City Drive Cycle
    - Constant Speed with trailer (1900 kg) and uphill driving
    - Constant Speed with trailer (1900 kg) and highway driving
    - Constant Top speed

After an initial run, it was observed that the Super-Fast charging cycle is the highest thermal load case for the Battery and all the systems were designed and dimensioned according to the cooling needs for this cycle. Among the discharging cycles, the top speed drive cycle was observed to be the case where the Battery generated heat the most. The profiles of current for these two drive cycles are as shown below,

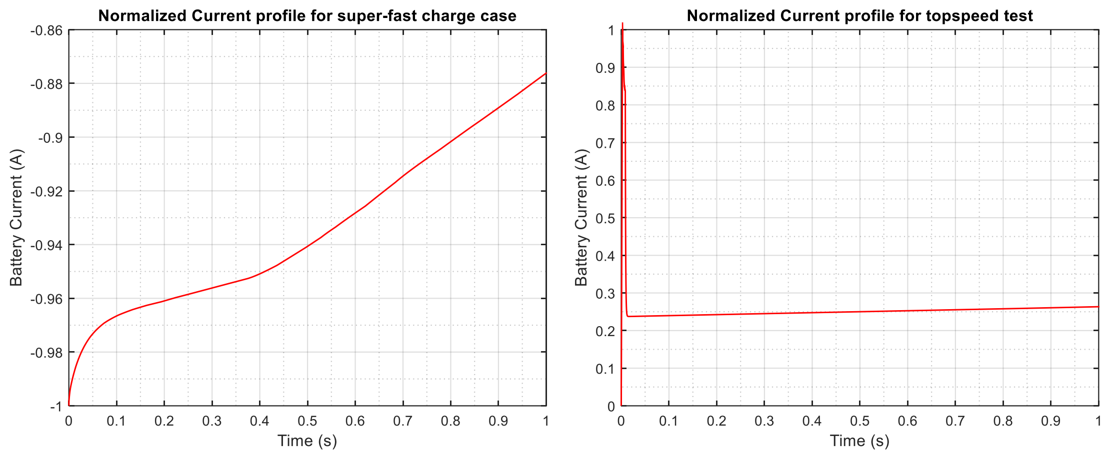

Figure 3-17: Profiles of Current for Super-Fast Charging (left) and Constant Top Speed Cases (Right), both representing the flow of current across the Battery during its operation, normalized to 1.

A few of the cycles were combined to form drive cycles in an effort to simulate a higher load case. They are as listed below:

- Combined Drive Cycles
  - Constant Speed with trailer uphill driving + Super-Fast Charging + Constant Top Speed
  - Constant Speed with trailer highway driving + Constant Speed with trailer uphill driving + Super-Fast Charging
  - Constant Top Speed followed by Super-Fast Charging

It can be noticed that the Super-Fast Charging cycle is included in all three drive cycles and this is an intention to subject the system model to a higher load overall. Since the vehicle is subjected to a wide range of ambient temperatures in a real world, it is also vital to investigate the behaviour of the Battery and cooling system in cold conditions. There is a need to heat the Battery during cold climate and maintain its temperature over sub-zero temperatures. Hence, this case is another essential scenario for inspecting the cooling system. The Super-Fast Charging cycle, Constant Top Speed cycle and one of the combined drive cycles is used to examine the system model during this scenario.

The system model is also subjected to two other scenarios. One of them represents a real world driving case from a customer point of view. This will represent a scenario that illustrates a day-to-day (one-day) use of the vehicle and will include two city drive cycles that sandwiches a resting phase, reflecting the phase where the vehicle is parked. This scenario is explored for different ambient temperatures as it is influential in resulting in a change in the Battery temperature during the resting phase.

Another study that is of great consequence from a customer point of view is the range test, which is used to roughly calculate the estimated range of the electric vehicle. The velocity vs time profile for this cycle is similar to the "one-day" cycle. A WLTC (World harmonized Light vehicles Test Cycle) is used for a certain time and that follows a constant vehicle speed cycle, followed by another WLTC. The system model is simulated for this drive cycle, which is represented by the vehicle speed profile as shown in Figure 3-18.

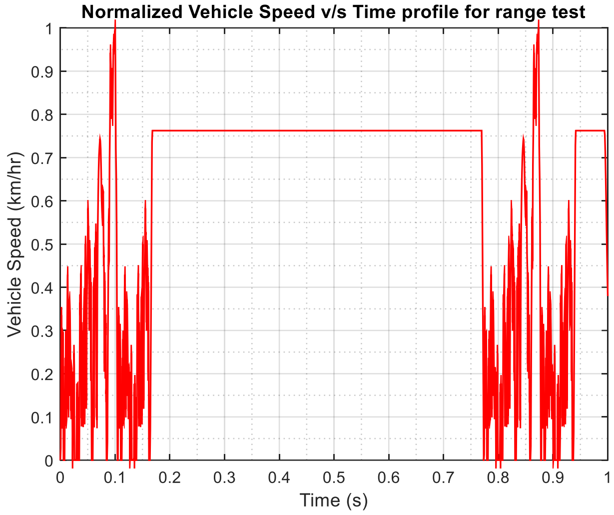

Figure 3-18: Velocity vs Time profile for range test, performed on the vehicle to estimate the range of the electric vehicle. A fully charged Battery is used at the beginning of the cycle and is fully discharged at the end. The velocity and time are normalized to 1.

Since the Super-Fast charging case was observed to be the most demanding case from the thermal perspective of the Battery, the model was simulated for this charging cycle for a wide range of ambient temperatures between 0 °C and 1 °C (normalized as a factor of the maximum safety limit of temperature for the Battery) and initial Battery temperatures between 0 °C and 0.875 °C (normalized as a factor of the maximum safety limit of temperature for the Battery). This was done using the DOE setup option in GT-SUITE which allows the user to run a DOE (Design of Experiments) such as this. The other drive cycles were analysed for ambient temperatures of 0 °C, 0.5 °C and 1 °C, while maintaining an initial Battery temperature of 1 °C (normalized as a factor of the maximum allowable temperature of the battery).

For the heat-up cases, i.e. the scenario during cold climate when the Battery needs to be heated, was evaluated for ambient temperatures of -0.5 °C, -0.325 °C and -0.25 °C (normalized as a factor of the maximum allowable temperature of the battery) for different initial Battery temperatures. During these cases, it is also important to study the effect of heating the Coolant to warm up the battery and self-heating of the Battery separately. The following table lists the different cases and scenarios investigated and the range of initial temperatures specified.

Table 3-2: Test scenarios that constitute the different cases that are simulated. The values of temperatures are normalized to 1 as a factor of the maximum safety limit of temperature for the Battery.

Drive Cycles	Scenario	Ambient Temperature (°C)	Initial Battery Temperature(°C)
Super-Fast Charging	Cool-Down	0 - 1 (14 levels)	0 - 0.875 (7 levels)
	Heat-Up	-0.5, -0.375, -0.25	-0.5, -0.25
Semi-Fast Charging	Cool-Down	0, 0.5, 1	1
Normal Charging (Plug-in)	Cool-Down	1	1
City Drive Cycle	Cool-Down	0, 0.5, 1	1
Constant Speed with trailer (1900 kg) and uphill driving	Cool-Down	0, 0.5, 1	1
Constant Speed with trailer (1900 kg) and highway driving	Cool-Down	0, 0.5, 1	1
Constant Top speed	Cool-Down	0, 0.5, 1	1
	Heat-Up	-0.5, -0.375, -0.25	-0.5, -0.25
Constant Speed with trailer (1900 kg) uphill driving + Super-Fast Charging + Constant Top Speed	Cool-Down	0, 0.5, 1	1
Constant Speed with trailer (1900 kg) highway driving + Constant Speed with trailer (1900 kg) uphill driving + Super-Fast Charging	Cool-Down	0, 0.5, 1	1
	Heat-Up	-0.5, -0.375, -0.25	-0.5, -0.25
Constant Top Speed followed by Super-Fast Charging	Cool-Down	0, 0.5, 1	1
Range Test	Cool-Down	1	1
One Day	Cool-Down	0 - 1 (4 levels)	0.625, 0.75, 0.875

3.10 Control Strategy

After all the drives cases were run during an initial simulation in the cool down scenario it was observed that the highest thermal load case for the Battery was the Super-Fast Charging case. For formulating a control strategy to operate the cooling system, it was necessary to analyse the system model for a wide range of ambient temperatures and initial Battery temperatures for this case. This was found to have an adverse effect on the results. Hence, as mentioned in section 3.9, a DOE for different ambient temperatures and initial Battery temperatures and this was done for different configurations of the cooling system. The configurations of cooling system were changed by using the control valves to direct the flow to either of the heat exchangers (Chiller or Radiator) or both. Hence, the three main strategies for the cooling system operation are:

- Cooling by only the Chiller (1)
- Cooling by using both the heat exchangers (2)
- Cooling by only the Radiator (3)

The results from the DOE are organised together and analysed. After inferring from the Battery temperatures at the end of cycles for the different configurations, the strategies were decided manually. This is discussed in detail in section 4. The Table 3-2 is formulated from analysing these results and is used to implement this strategy. This table is used as a look-up table using which the switches that control the 3-way valves are manipulated. This enables the use of a generic system that helps to switch between strategies of cooling system operation depending on the ambient and Battery temperatures.

Table 3-3: Strategy Selection table for the control system to manage cooling system configurations. The values of temperatures specified are normalized to 1 as a factor of the maximum safety limit of temperature for the Battery.

	Battery Temperature (°C)						
Ambient Temperature (°C)	**0**	**0.15**	**0.3**	**0.45**	**0.6**	**0.75**	**0.9**
0.00	0	0	3	3	3	3	3
0.08	0	0	3	3	3	3	3
0.16	0	0	3	3	3	3	3
0.24	0	0	3	3	3	3	3
0.32	0	0	3	3	3	3	2
0.40	0	0	3	3	3	2	2
0.48	0	0	3	3	3	2	2
0.57	0	0	3	3	2	2	4
0.65	0	0	3	2	2	4	4
0.73	0	0	3	2	2	4	4
0.81	0	0	2	2	1	4	4
0.89	0	0	2	2	1	4	4
0.97	0	0	1	1	1	4	4
1.05	0	0	1	1	1	4	4

This 2D look up table (read as “strategy selector”) uses the ambient temperature and the Battery temperature as inputs and depending upon the value of these parameters, the appropriate strategy is output as a number. This number denotes which heat exchanger to use during a particular case and that is as shown above adjacent to the strategies for cooling system operation. Using this as an input to another look-up table, the 3-way valve is commanded to either send the Coolant through the heat exchanger or bypass it. A simple switch operation accomplishes this task, with ‘1’ being letting through and ‘0’ being the command for bypassing. This then proceeds to a condition where it is checked if the Coolant temperature is lesser than the temperature of the fluid in the heat exchanger. It is important to check this since, if the temperature of the fluid is greater than the Coolant, the Coolant will absorb heat from the fluid and contradict the normal operation of a heat exchanger. If this condition is not satisfied, the command from the strategy selector is overridden and the Coolant is bypassed.

It can be seen in the table that the ‘0’ value denotes the cases in which the Battery temperature cannot be restricted to below the higher limit of temperature under normal operation. Using this control strategy there is a possibility of keeping the Battery temperature well within its higher limit by maximising the power output of the Chiller. This also done by referring to the look up table of control strategies and regulating the massflow of refrigerant and the outlet pressure that ensures increased cooling output from the Chiller.

It was also observed that the cooling system operation could be optimized to be used efficiently during most of the drive cycles since the heat generated was not very high. Hence it was also implemented in the model to control the operation of the Pump, basically an on/off operation depending on the demand. This ensured that the Battery temperature was maintained within a specified range of temperatures and the cooling system was not required to be used unnecessarily. The results are discussed in detail in section 4.

4 Results & Discussions

In this particular section the control strategy results have been discussed with respect to an energy efficient standpoint of cooling the Battery.

4.1 Case: Super-Fast charging

4.1.1 Strategy Selection

Super-Fast charging cycle requires a higher amperage of current to be input to the Battery to satisfy the power requirements to charge it from zero to full capacity for a lesser time. This consequently means more heat generated as heat is directly proportional to the square of the current. Hence, this was observed to be most demanding case for the Battery in terms of heat generated.

The results from DOE were analysed using the post processing utility GT-POST, licensed under GT-SUITE. As mentioned in section 3.10, values (1, 2, 3 or 4 and 0 indicating "no cooling") that point to the cooling system configuration to be used for a particular condition (a case with one particular ambient temperature and initial Battery temperature) are specified. The selection of which cooling system configuration to be used was done after analysing the final Battery temperatures using the three different configurations for each of these conditions. Figure 4-1 was constructed on the basis of this and using Table 3-3. All the temperature values are normalized as a factor of the maximum safety limit of temperature for the Battery.

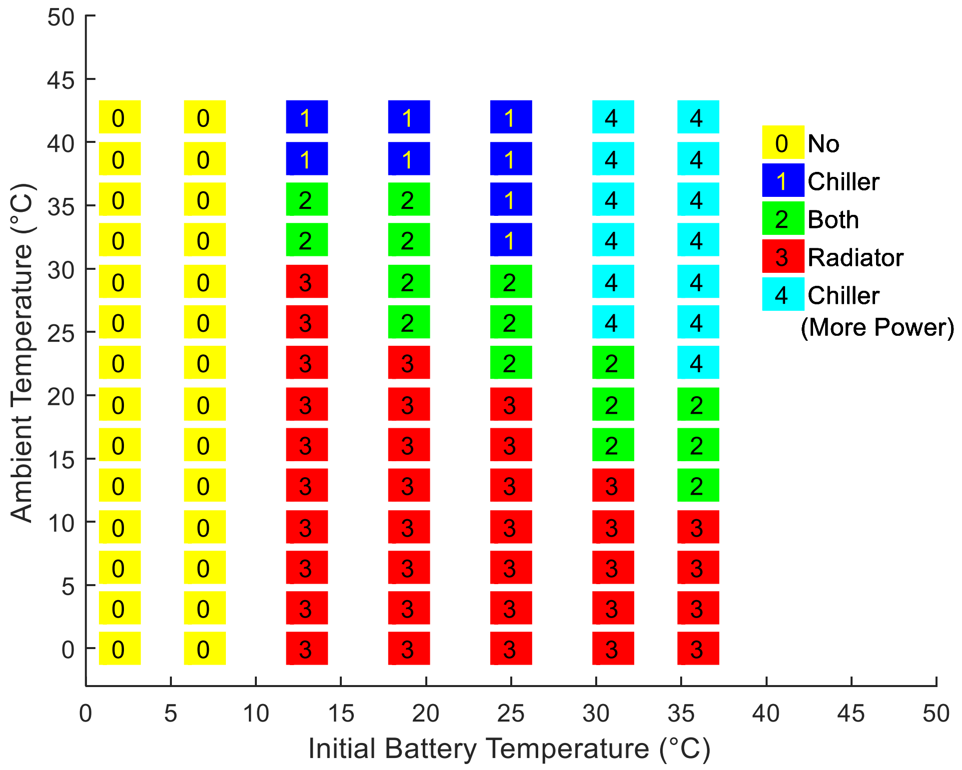

Figure 4-1 The Battery initial temperature on x-axis and ambient temperature on the y axis. Each Initial Battery temperature corresponds to varying ambient temperatures and each of the box represents the cooling provided by particular component. The temperature values are normalized to 1 as a factor of the maximum safety limit of temperature for the Battery.

It can be seen that for low Battery temperatures and low ambient temperatures, there is no need to operate the cooling system and the Battery can be allowed to heat without the necessity to cool. This condition holds well for all ambient temperatures, even though the condition where the ambient is very hot and the Battery temperature is very low is unlikely.

For low ambient temperatures, it is observed that the Radiator can be used to cool the Battery, regardless of the initial Battery temperature. The cold air aids in very high heat exchange rates and the Battery heats up at a slower rate. There are cases in the mid-region, when the ambient is hot and the Battery initial temperature is lower than this. It is usually recommended to not use the Radiator since this will heat up the Coolant as the ambient is at a higher temperature. But once the temperature of the Coolant rises above the ambient temperature during the charging cycle, the Radiator provides enough cooling to keep the final Battery temperature well within limits.

When the ambient and the Battery initial temperature is moderately high, cooling using just the Radiator is not possible and the cooling system in this case uses the assistance of the AC system, via the Chiller to provide cooling for the Battery. These cases are indicated by the green boxes. It needs to be noted that, operating the Chiller alone in these cases will result in lower final temperatures of the Battery but this will consume more power. While using both the heat exchangers for cooling, the load on the Chiller is lesser.

Then there are the higher thermal load cases which require operating only the Chiller. There is no possibility to use the Radiator in these conditions as it is really hot and will be ineffective. Operating the Chiller alone will result in the final temperature of the Battery being lesser than the maximum limit. Extreme conditions might force using the Chiller at a much higher load than normal operation and this means more power will be consumed from the Battery for cooling it down. Hence it is recommended to maintain the Battery temperatures below 0.75 °C, especially at very hot ambient conditions before supercharging the Battery.

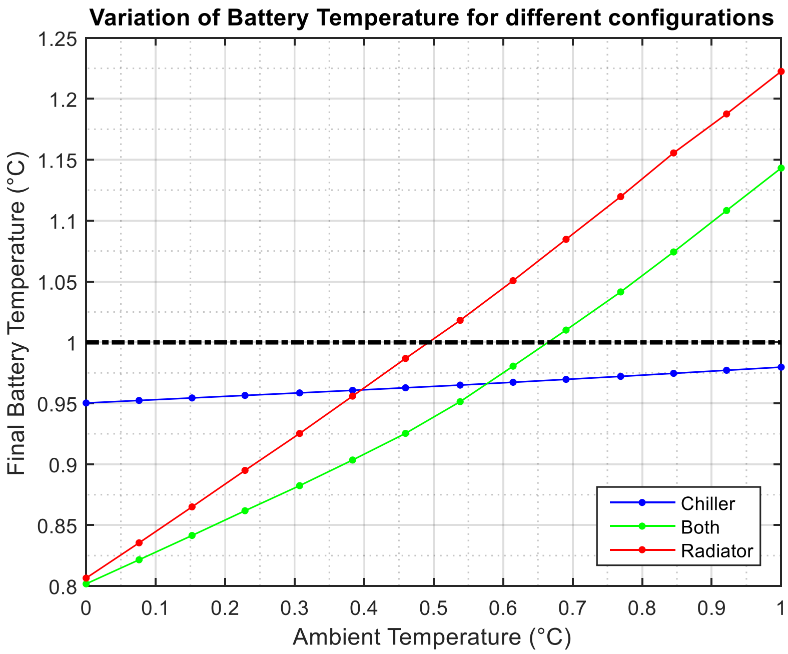

Figure 4-2: Evaluation of cooling system for different configurations during the Super-Fast charging cycle. The initial temperature of the Battery is 0.6 °C. For the first few cases, the Radiator can be used until final temperature is higher than the limit of 1 °C. Both Chiller and Radiator are used for a couple of cases when only radiator cannot be used and the rest of cases use only Chiller. The magnitude of temperatures is normalized to 1 as a factor of the maximum safety limit of temperature for the Battery.

The process of how each case was analysed and how the solution to use a particular configuration of the cooling system was arrived at can be explained by referring to Figure 4-2. Consider a case when the Battery initial temperature is 0.6 °C. As shown in the Figure 4-2, the green line represents cooling by both the Radiator and Chiller. The blue line represents the cooling provided by the Chiller system and the green line represents the cooling provided by the Radiator. For various ambient temperatures, when the Battery initial temperature is at 0.6 °C, final Battery temperature is as shown in the Figure 4-2. The black dotted lines represent Battery critical temperature above which operating it would cause damage to the Battery.

Even though the graph represents that the cooling provided by both the Radiator and Chiller is more efficient at lower ambient temperatures, it is recommended to use the Radiator and not consume power to operate the AC system. Also, as the ambient temperatures go higher, operating just the Chiller is the best option for cooling the Battery. There is always a trade-off between power consumption and cooling provided. It is necessary to maintain the balance and try to minimise power consumed by the cooling system.

4.1.2 Results of Super-Fast Charge Cycle

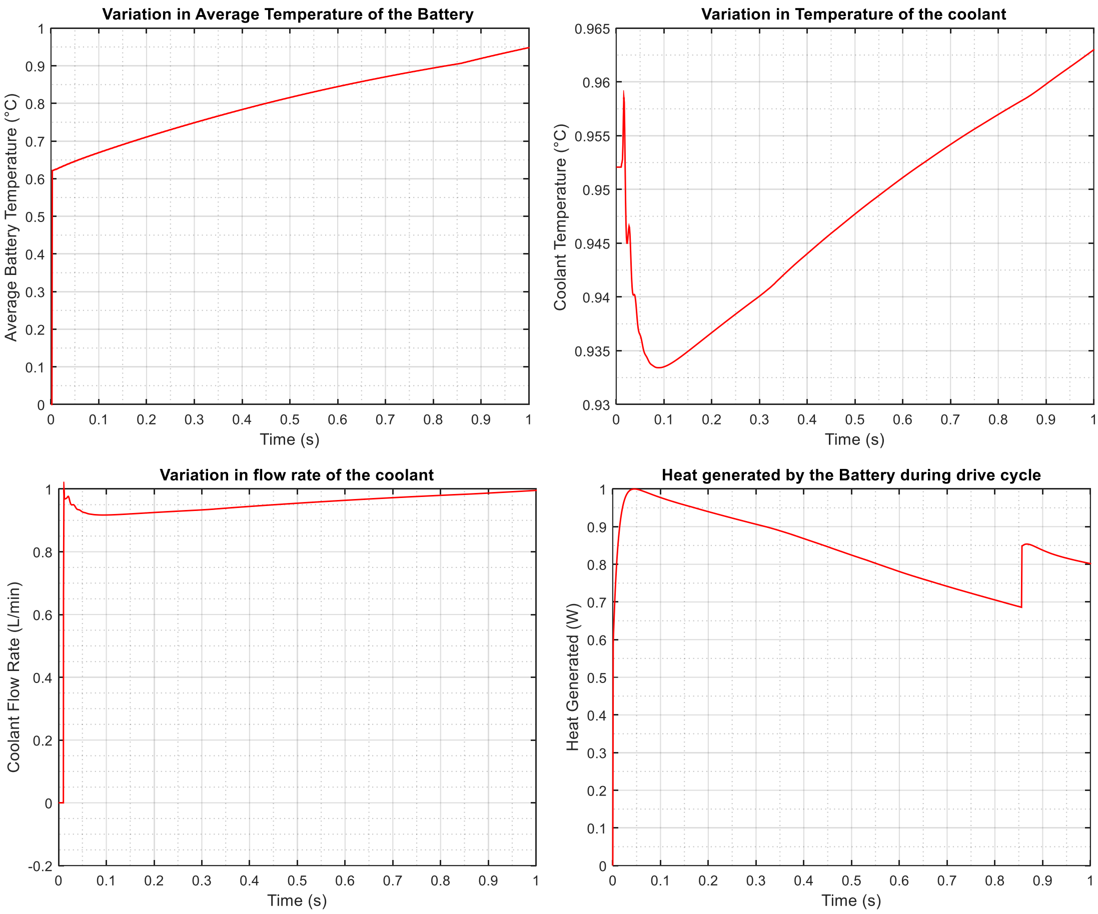

Figure 4-3: Results of variation in Battery temperature, Coolant temperature, Coolant flow rate and heat generated during the cycle. The temperature of the Battery increases despite cooling provided to it and hence is the highest thermal load case. Coolant flow rate needs to be maximum during this case. The magnitude of temperatures is normalized to 1 as a factor of the maximum safety limit of temperature for the Battery.

The Super-Fast charging cycle is simulated for an ambient temperature of 1 °C and an initial Battery temperature of 0.675 °C. It can be seen that during the cycle, there is a steep increase in the Battery temperature despite the cooling system functioning fully. This illustrates the high magnitude of thermal load on the cooling system during this charging cycle. This is reflected in the heat generation plot of the Battery as shown in Figure 4-3 which is of the order of almost 5 times the heat generated during a Semi-Fast charging cycle (section 4.6.2). The rise in the generated heat at the end of the cycle is due to the definition of the input current cycle, which repeats itself for a short amount time until the SoC is full. The initial dip is due to the operation of the cooling system and this gradual increase indicates that during normal operation of the Chiller, it is not possible to reduce the temperature of the Coolant during the Super-Fast charging cycle. In this case it is only possible to reduce the rate at which the temperature increases and it can be seen that the Battery temperature does not go above the maximum specified limit.

4.2 Case: Range test

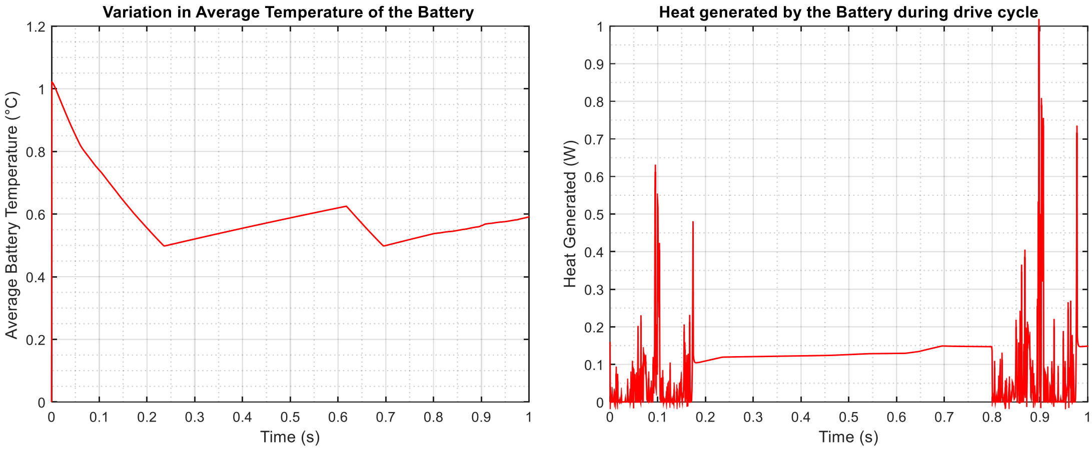

Figure 4-4 Battery temperature and Heat Generated by the Battery during the Range test simulation. The temperature of the Battery reduces and is maintained between 0.5 °C and 0.625 °C by the cooling system. This helps to maintain the temperature of the Battery within its optimal operating temperature limits. The magnitude of temperatures is normalized to 1 as a factor of the maximum safety limit of temperature for the Battery. Heat generated values are normalized to 1.

The results obtained for the range test were for an ambient temperature of 1 °C and the Battery initial temperature at the same temperature. The graphs in Figure 4-4 represents the behaviour of the Battery during the range test, which is a drive cycle used to estimate the expected the range of the electric vehicle. It can be seen that the circulation of Coolant through the Battery during this drive cycle decreases its temperature and maintains it between 0.5° C and 0.625° C, which studies have suggested is the optimum working range of temperatures for the Battery. This is done by switching the Pump on/off and maintaining it within the range depending on the instantaneous Battery temperature as it can be seen in the temperature plot. It is interesting to see that when the WLTC cycle is repeated again the heat generated has higher peaks. This is because there is no Coolant flow during this time as it can be seen in Figure 4-5.

This plot seen in Figure 4-5 shows the operation of the Coolant Pump as a function of the Battery temperature. When the temperature of the Battery is 0.5 °C, the Pump is turned off which can be seen in the plot as zero Coolant flow rate. And when it rises back up to 0.625 °C the Pump provides flow until the temperature of the Battery reduces to 0.5 °C again. The outcome from this range test was an approximate value of the expected range of the vehicle for a full discharge of the Battery.

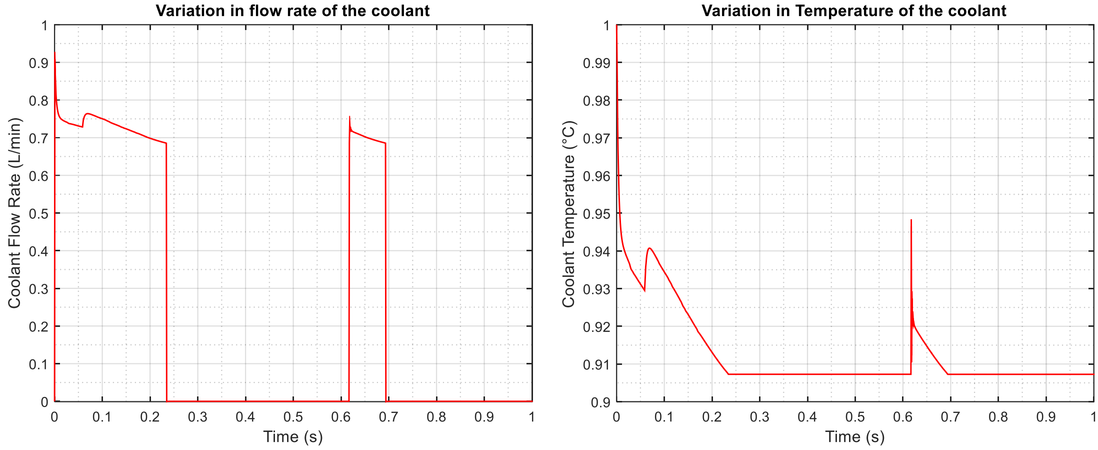

Figure 4-5 Coolant flow and Coolant Temperature as a function of time. The zero Coolant rate corresponds to the period when the cooling system is turned off when the Battery temperature falls below 0.5 °C. The magnitude of temperatures is normalized to 1 as a factor of to the maximum safety limit of temperature for the Battery.

4.3 One day cycle

Figure 4-6 represents results from the one day cycle as described in the section 3.9. This drive cycle was simulated and analysed using the system model for ambient temperature of 0.625 °C and Battery initial temperature of 0.875 °C. It can be seen that during the city drive cycle, when the cooling system is operating fully, the temperature of the Battery is reduced by almost 0.2 °C, over a small period of time. During the "parked car" phase, the Battery temperature increases due to the influence of the hot ambient conditions and there is quite a significant change. Further discharge in the Battery results in more decrease in the Battery temperature.

The heat generated as seen is very minimal, with some peaks that span for a very short time and is not very significant in heating up the Battery. The plots with respect to Coolant signify the period when the vehicle is not operating during the "parked" phase. This is represented by zero Coolant flow rate. These results play a crucial role in developing more complete control strategies. This is because, during hot ambient conditions there is a need for using the AC system to cool the cabin. During this phase, if the Battery also is required to be cooled by the Chiller, this implicates that more power needs to be consumed by the AC system alone. But since the heat generated is not that high during normal driving cycles, the Battery can be cooled quite easily without needing to use the Chiller throughout and hence minimise the power consumption.

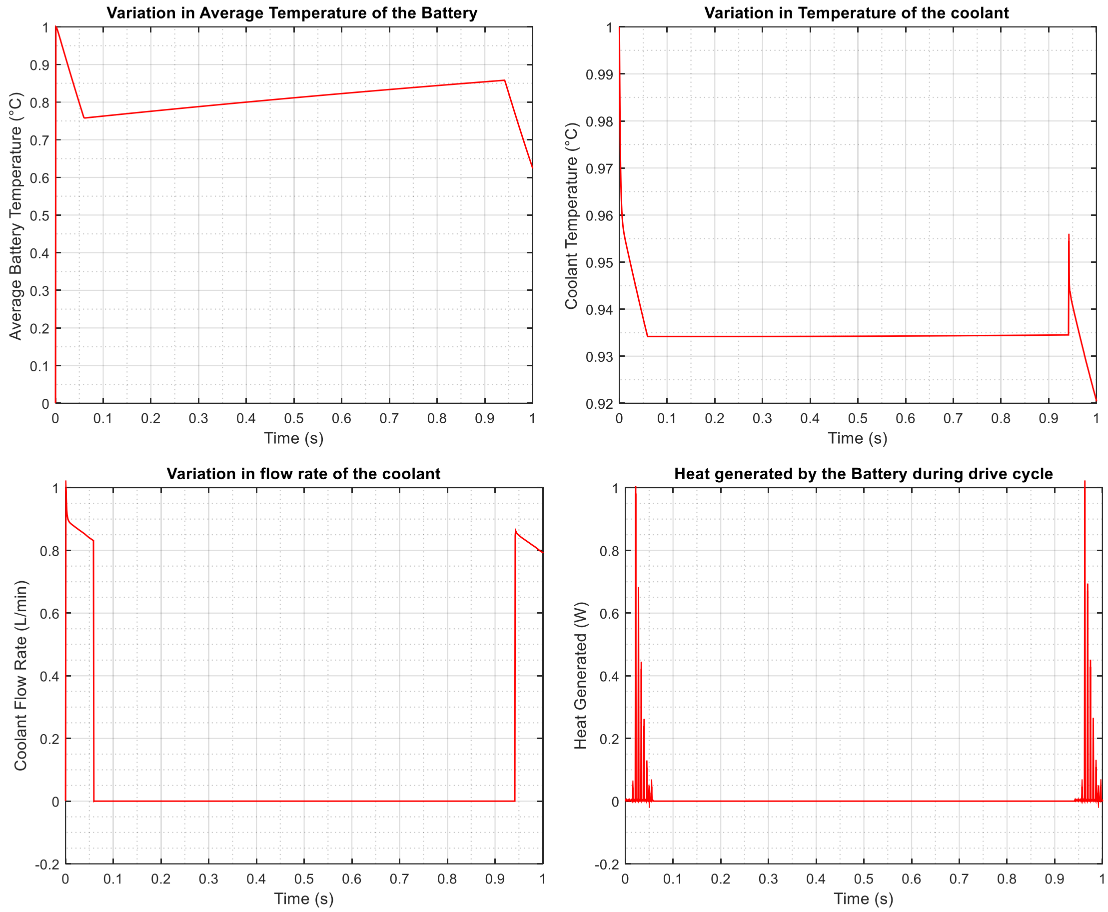

Figure 4-6 Battery Temperature, Heat generated, Coolant Flow rate and Coolant Temperature with respect to time during the one day drive cycle. The peaks of high heat generation signify the driving phase and the zero heat generation represents the parked phase. The Battery temperature rises during the parked phase due to the high ambient temperatures. The magnitude of temperatures is normalized to 1 as a factor of to the maximum safety limit of temperature for the Battery.

4.4 Case: Extreme Drive cases

This section highlights the thermal performance of the Battery during extreme drive cases. These drive cases are used to dimension the cooling system and it was important to study the results. Among the few such drive cases, the results from the "Uphill driving with trailer" case is shown below and discussed. These drive cases are very unlikely during normal operation of the vehicle, which is discussed in section 4.3.

It is important to note that the temperature of the Battery reduces quite significantly during the entire drive case. The two phases in the drive cycle can be observed quite easily, the initial phase being a straight road drive of the car, which as seen is very less heat generated by the Battery. The second phase, which is the uphill driving with heavy trailer results in higher heat generated. It can be also noticed that the SoC decreases quite severely during this phase. It is important to see that the full operation of the Coolant Pump will result in a significant decrease in the Battery temperature even in such extreme drive cases as these.

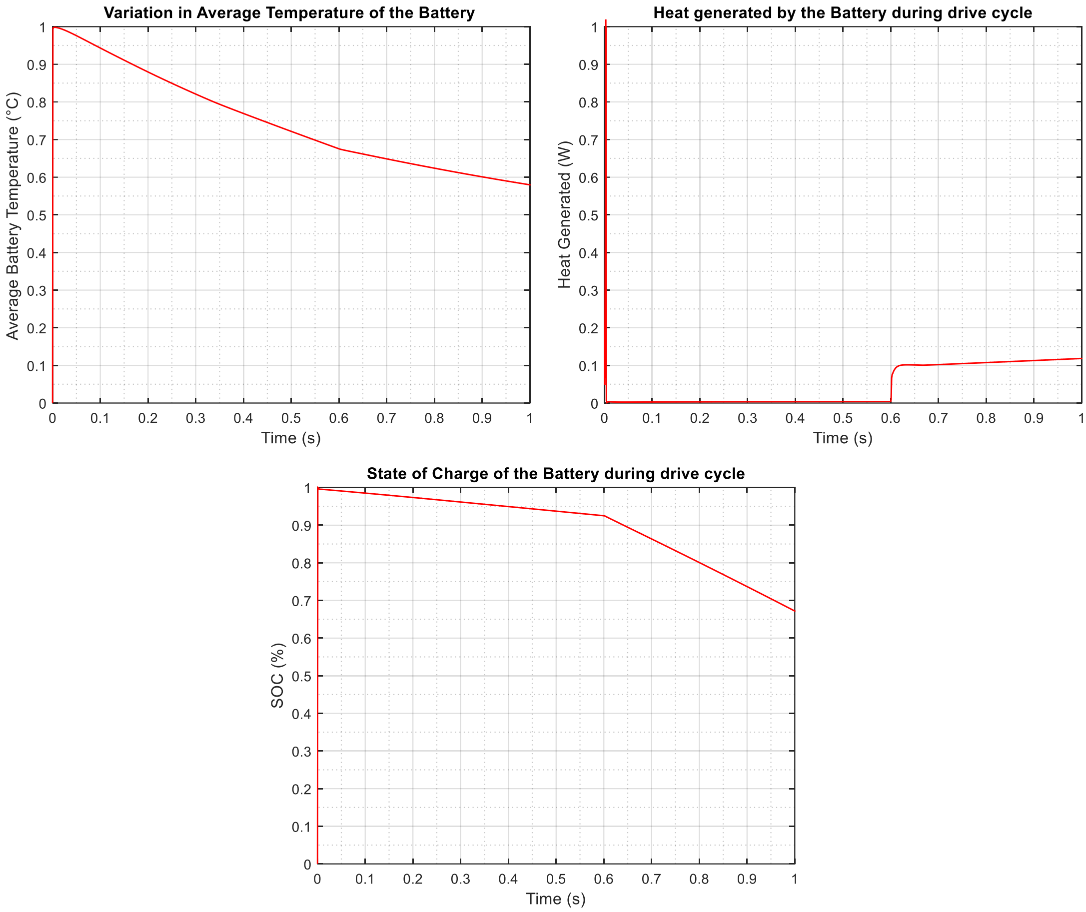

Figure 4-7: Variation in temperature of the Battery, heat generated by the Battery and its SoC during the drive cycle. Lower heat generation represents the normal driving with trailer and the uphill driving results in higher heat generated. This corresponds to a lower rate of temperature decrease. The magnitude of temperatures is normalized to 1 as a factor of to the maximum safety limit of temperature for the Battery.

4.5 Case: Combined Drive cases

The combined drive cycle cases included some of the extreme drive cycles combined with the Super-Fast charging cycle to form a high thermal load case. The plots shown in Figure 4-8 are results for the drive cycle, where the vehicle with a trailer drives at highway speed and maintains a lower constant speed while climbing a hill. At the end of the drive cycle, the vehicle is Super-Fast charged to almost full capacity. The highway drive does not result in a lot of heat from the Battery. This is reflected in the temperature of the Battery, which reduces during this cycle with full operation of the cooling system.

The SoC plot illustrates that the capacity of the Battery reduces to as much as the lower limit due the drive cycle and as there is a need to charge the Battery, the vehicle is Super-Fast charged, portrayed by the steep increase in the SoC. This is again replicated in the heat generation plot and the temperature of the Battery. There is an increase in the temperature during the Super-Fast charging phase. The rate at which this temperature increases is reduced due to the influence of the cooling system which results in the heat generated by the Battery reducing as seen in the plot. The ambient temperature in this case was at 1 °C and the Battery initial temperature is 1.05 °C representing a very high thermal load on the cooling system. It is significant to observe that it is possible to reduce the temperature of the Battery during this test cycle and keep it within limits.

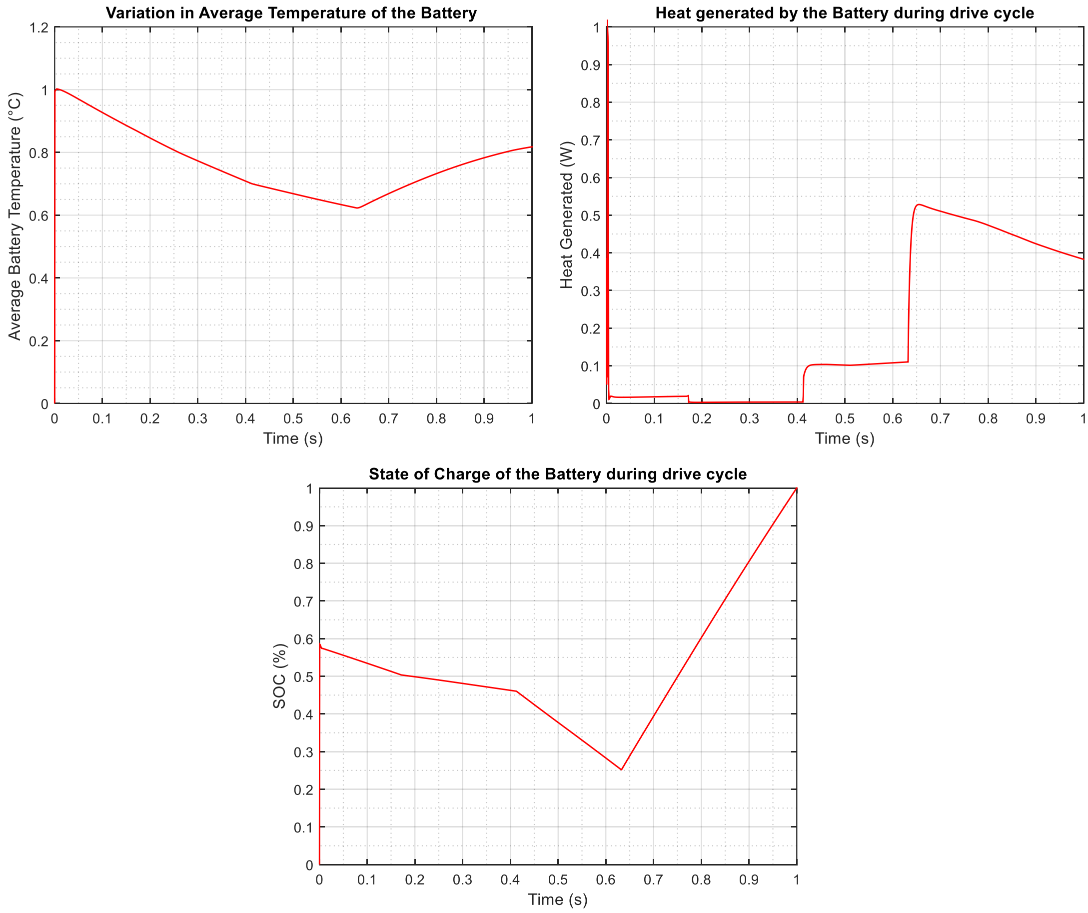

Figure 4-8: Average Temperature of the Battery, Heat generated and SoC as a function of time during the combined drive cycle. The maximum heat generated in this drive cycle is during the Super-Fast charging phase, almost 5 times more than the driving phase. The temperature of the Battery before this phase starts is required to be low to prevent it from rising above 1 °C. The magnitude of temperatures is normalized to 1 as a factor of to the maximum safety limit of temperature for the Battery.

4.6 Case: Normal and Semi-Fast Charging Cycles

This section below discusses the results from the charging cycles that represent the normal rate of charging. Apart from Super-Fast charging, the Battery in the vehicle can be recharged by supplying current at the rate of a normal household supply and by supplying higher magnitude of current to fasten the process. The response of the cooling system during these cycles are discussed below.

4.6.1 Normal Charging Cycle

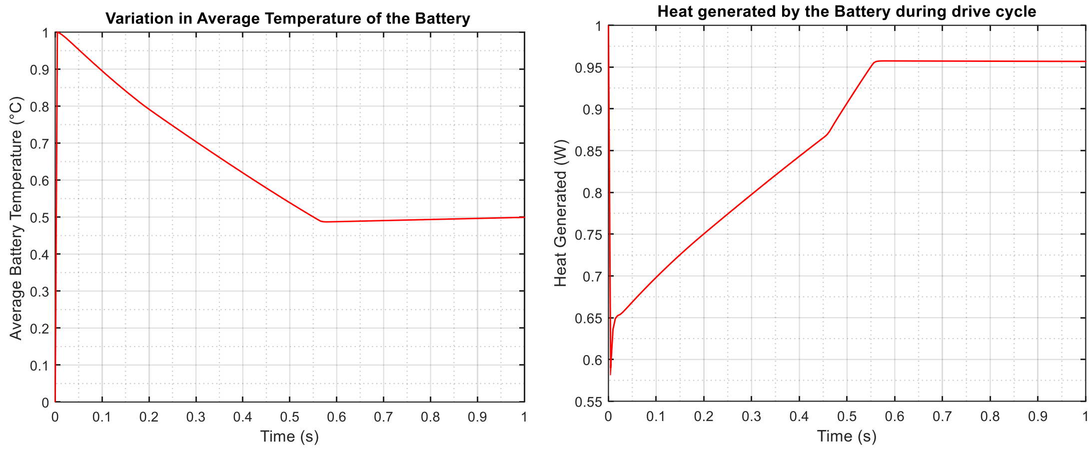

Figure 4-9: The average Battery temperature and heat generated by the Battery as a function of time during the normal charging cycle. The heat generated is almost negligible and the temperature can be reduced to 0.5 °C soon and cooling system is switched off. The magnitude of temperatures is normalized to 1 as a factor of to the maximum safety limit of temperature for the Battery.

The Figure 4-9 shown represents the variation in Battery temperature during normal charging cycle at home when the Battery initial temperature is at 1 °C and the outside temperature is 1 °C as well. During this cycle, the state of charge of the Battery increases by about 22%. The Battery temperature seems to reduce at a drastic rate since the Pump runs at full speed. The reason for this as it can be seen, the heat generated during this cycle is a very small amount for a thermal mass of this size. Hence the Coolant Pump at its maximum flow condition, provides more than sufficient cooling.

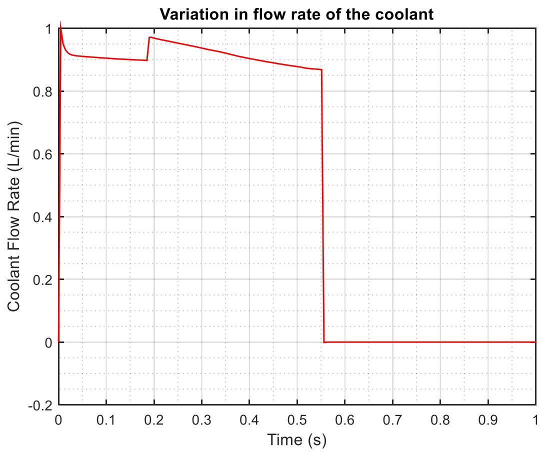

Figure 4-10: Flow rate of the Coolant during the normal household charging cycle. The Coolant Pump is switched off as soon as the temperature of the Battery is less than 0.5 °C and there is no need to switch it on again as the temperature of the Battery does not rise to more than 0.625 °C.

The Pump is switched off when the Battery temperature reduces below 0.5 °C as seen in the Coolant flow rate plot in Figure 4-10. This corresponds to an increase in the temperature of the Battery. The temperature of the Battery increases slightly during this phase, since there is a small amount of heat generated by the Battery during this charging cycle, which is sufficient to increase its temperature over a period of time without it being cooled.

It can be seen that the heat generated increases with a decrease in Battery temperature and vice versa. Heat generated by the Battery is a function of the internal resistance and is directly proportional to it. But the internal resistance increases with decrease in Battery temperature, which causes the increase in the heat generated for a constant value of current input. Hence the Battery temperature and the heat generated will have opposite trends.

From this the benefit of plug-in and its influence on the Battery temperature can be seen. This can be used to the vehicle's advantage, to condition the Battery before using it. Plugging in the vehicle, therefore helps to reduce the temperature of the Battery to within its optimum range in a very short time period. Since this is a low power consumption method, the vehicle can be plugged in during which the cooling system uses lower electrical load from the Battery and then Super-Fast charged until full SoC. This will be beneficial when the ambient and initial Battery temperatures are really high. First the vehicle can be plugged in and be "conditioned" and then Super-Fast charged. This method could be employed to ensure that the life can be maximised and by consuming less power for running the cooling system, the range of the vehicle can be extended.

4.6.2 Semi-Fast Charging Cycle

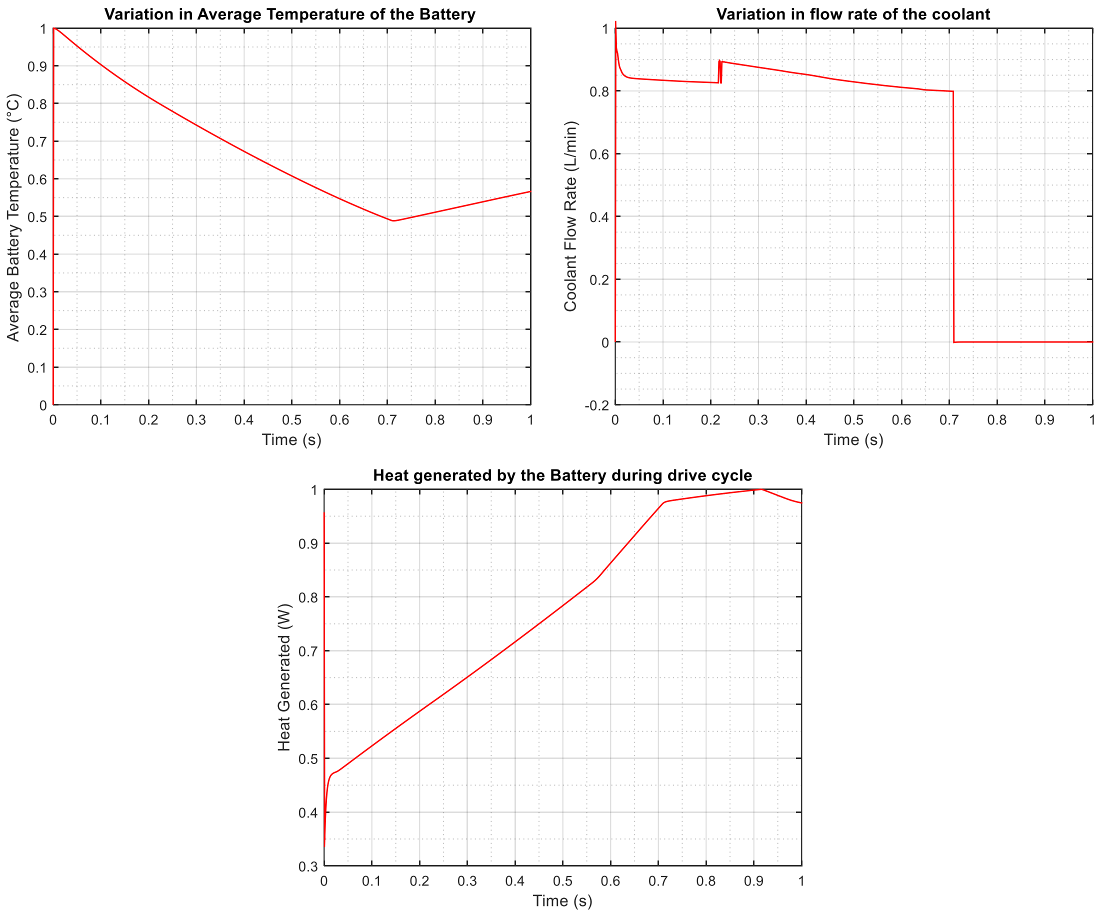

Figure 4-11: Average Battery temperature, Coolant Flow rate, Heat Generated and SoC during the Semi-Fast charging cycle. The heat generated increases with increase in current during the cycle and the rate of increase is lower as soon as the Coolant flow rate is zero. Coolant Pump is turned off as the Battery temperature reaches 0.5 °C. The magnitude of temperatures is normalized to 1 as a factor of to the maximum safety limit of temperature for the Battery.

Semi-Fast charging cycle is the middle ground between Super-Fast charging and plug-in. The current input during this cycle is almost 15 times that during household plug-in and hence the heat generated is a lot more and it is necessary to cool down the Battery during this phase. As it can be seen in the plots from Figure 4-11, the Battery temperature reduces at a much slower rate than compared to the plug-in cycle because the heat generated during this cycle is a lot more. These results are from the simulation where the ambient temperature is 0.5 °C and the initial Battery temperature is 1 °C.

It can be seen that the Battery is charged from zero to full capacity at a rate which is 3 times slower than Super-Fast charging. But it is important to note that the thermal load on the cooling system by the Battery in this case is much lower. This can be seen from the heat generation plot in Figure 4-11, the increasing trend in the heat generated by the Battery throughout the circuit. The heat generated by the Battery is a function of the internal resistance and the square of the current. The charging cycle is defined in a way that the current increases over a period of time and then stays constant. This does not represent the real world definition of this charging cycle.

This is the reason for the increase in the heat generated by the Battery, until it reduces when the current becomes constant. As it can be seen, the Pump is turned off during this phase, since the Battery temperature goes below 0.5 °C and due to this, there is an increase in the Battery temperature. Increase in the temperature of the cells implies that the internal resistances reduces, and due to the current being constant, this reduction indicates a reduction in heat generated.

Another interesting point that can be observed is the small rise in the Coolant flow rate during the initial phase of this cycle. This is due to the change in cooling system configuration as a result of the strategy. During this point, the cooling system configuration changes from using both the heat exchangers to just the Radiator. Since the Pump speed is the same throughout the cycle, the Coolant flow increases slightly causing the small rise and then decreases with temperature linearly until the Pump is turned off.

4.7 Case: Heat up

4.7.1 Heating up by electric Heater

The “heat-up” case is an analysis of the behaviour of the system model when it is subjected to cold ambient temperature conditions. There is a need to heat the Battery during such conditions to raise its temperature to be within sufficient limits and this is investigated in this case. Mainly two different studies were made on this, self-heating of the Battery and warming it up using an Electric Coolant Heater and the results of these are discussed below.

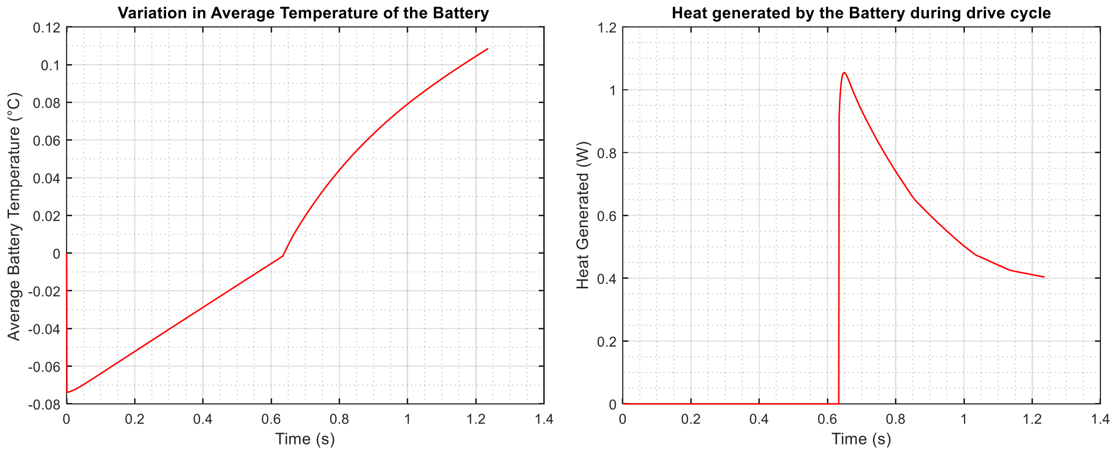

Figure 4-12: Representation of the heat up case where the Battery temperature is increased using the means of an Electric Coolant Heater. It is switched off as soon as the temperature of the Battery is above 0 °C. The magnitude of temperatures is normalized to 1 as a factor of to the maximum safety limit of temperature for the Battery.

These are results from running the cooling system to provide warm Coolant to the Battery with an initial temperature of -0.5 °C. The Coolant is heated by the electric Coolant Heater as seen in the rise in the Coolant temperature. This leads to the rise in the Battery temperature as seen in the temperature plot in Figure 4-12. It can be seen that it follows the same linear trend of rising temperature as seen in the Coolant temperature plot in Figure 4-13. During this phase, it is recommended not to operate the Battery too much, especially not charging it since at sub-zero temperatures, the rate of charging is affected quite heavily and can ultimately affect the life of the Battery.

Hence, during this phase, without operating the Battery, a significant time period is required to warm up the Battery from -0.5 °C to bring it above 0 °C. At this point the Coolant Heater is switched off and the Battery is Super-Fast charged. This can be seen from the heat generation plot, which indicates no heat generated during the "warming-up" phase and shoots up when the Battery is charged.

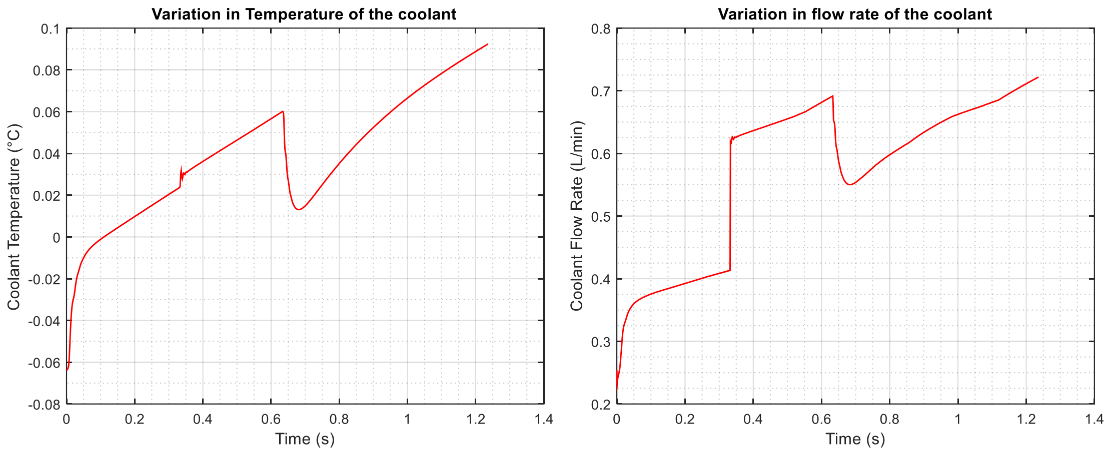

Figure 4-13: Coolant temperature and Coolant flow rate as a function of time. The Coolant flow rate is a function of the temperature and the high variations in Coolant flow is due to this. The Coolant temperature and flow rate have similar trends due to this. The magnitude of temperatures is normalized to 1 as a factor of to the maximum safety limit of temperature for the Battery.

It is interesting to see the variation in the Coolant temperature and the Coolant flow rate. The increase in Coolant temperature as a result of the heat provided by the Heater is seen. Coolant flow rate increases drastically once the temperature of the Battery is over 0 °C due to the definition of the Pump control because of which the Pump now runs at maximum rpm. The dip in Coolant temperature can be explained to be due to the Coolant Heater being switched off, although this is momentary. This trend is replicated with the Coolant flow rate as well. Once the Super-Fast charging cycle begins, the Coolant temperature increases as seen in the temperature plot.

4.7.2 Battery Self Heat up

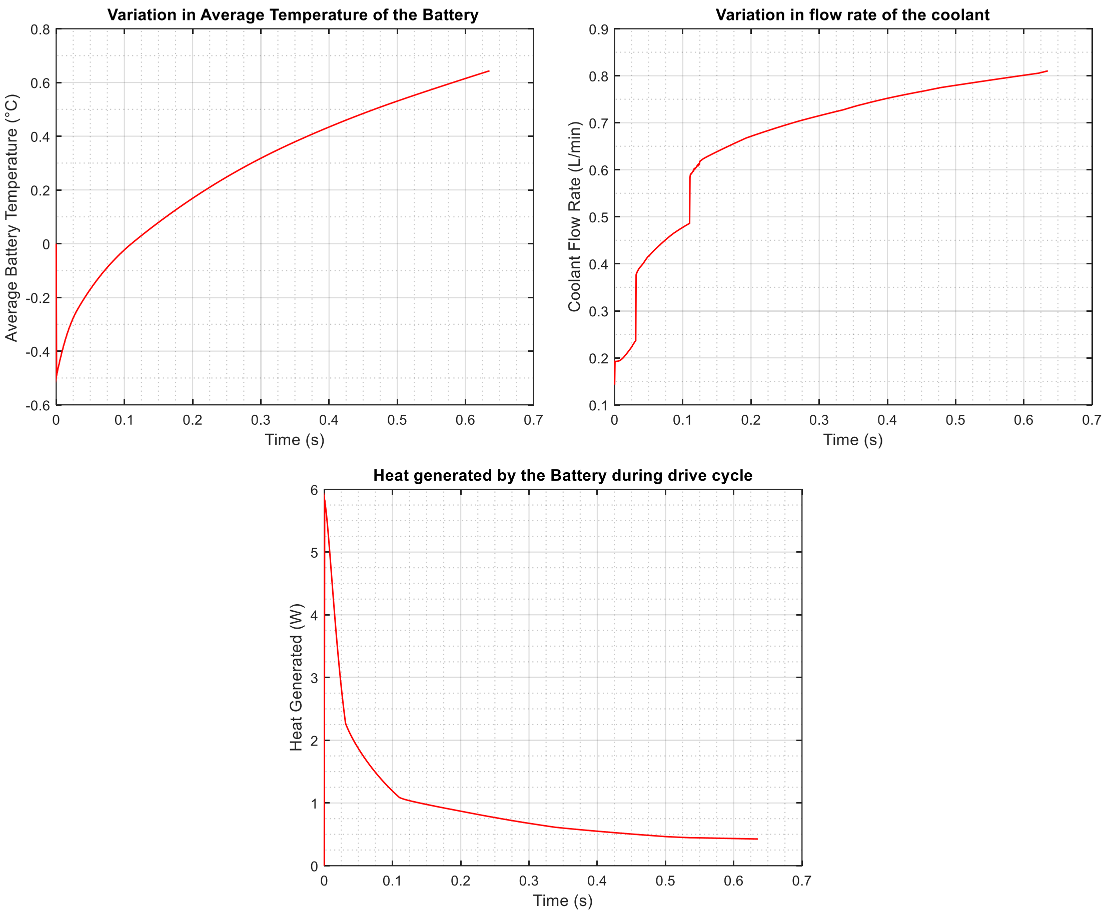

Figure 4-14: Results of the Heat up case without the aid of the Electric Heater during Super-Fast charge case. This represents an unrealistic case of the Battery Super-Fast charged when its temperature is -0.5 °C. The Battery temperature rises to 0 °C within a very short period of time. The magnitude of temperatures is normalized to 1 as a factor of to the maximum safety limit of temperature for the Battery.

These plots are an indication of how the Battery will heat up during a Super-Fast charge case when the temperature of the Battery starts at -0.5 °C. These results may not be entirely trusted since the rate of electrolysis is very low in such cold conditions, which is not captured by the model but is a good foundation for further analysis.

It can be seen that, the Battery heats up very quickly to get to a temperature higher than 0 °C. This is mainly due to the high heat generated during this phase which can be observed from the heat generated plot in Figure 4-14. The reason for such high heat generations is due to the high value of the internal resistances as a reason of such low cell temperatures. The other reason is the value of the current during Super-Fast charge in reality during this condition would be less and that is not accounted for in this simulation.

It is important to note the variation in the Coolant flow rate during this cycle. During low temperatures, the Pump is controlled to run at lower rpms. Low temperatures also mean higher pressure drop across components which results in lower Coolant flow rates initially. But as the temperature of the Coolant increases, due to rising Battery temperatures, the Coolant flow rate increases.

5 Conclusions

Need for reduced consumption of fossil fuel in order to reduce emissions and counter degradation in climate has resulted in many solutions to powertrain systems for the future. Battery technology being one of them, it is important to analyse the feasibility of this in modern day vehicles and reproduce the same performance as that of combustion engine vehicles. The performance and life of the Battery is dependent on its temperature and it is very important to maintain this within an optimum range to maximise its potential.

Such an analysis requires a detailed study of the Battery under different operating conditions. This can be carried out by many methods, one of them being 1D CFD modelling and simulation. One of the outcomes of this study is the possibility of representing a system model of the Battery which can predict the behaviour of the Battery under different test scenarios. Although 1D CFD modelling is based on assumptions and empirical relations, it is useful in concept stages of vehicle development for investigations from the perspective of a complete system and this is evident from this work.

The procedure followed while modelling is very systematic, the result of which is a reliable model of the cooling system, interacting with a part of the AC system and the full Battery model. This is used for a thorough study of the Battery during different drive cycles from a thermal point of view and suggest cooling system operations for effective thermal management of the Battery. The selected strategy was developed while keeping in mind to reduce the power consumed by the cooling system and thereby decrease the electrical load on the Battery for the purpose of cooling itself. The complete system model is further used to implement the suggested strategy for cooling system operation so as to observe the response of the Battery during these drive cycles under the influence of the cooling system. This suggested that by employing 1D CFD modelling methods it can be possible to optimise the thermal management of the Battery efficiently.

While the results from this study form a foundation for further in depth analysis into the same, a more extensive investigation would require many more factors to be considered. The control system used in the model for selecting the appropriate cooling system configuration depending on the condition would require to consider instantaneous parameters which will yield in better results and more efficient operation of the cooling system. The performance of the cooling system can be analysed more accurately using this as a part of the complete vehicle model as it will have an adverse effect on reduced power consumption which can benefit in increase in range of the electric vehicle. This study provides a good base for such in-depth analysis.

6 Future work

There is always room for improvements in any project. The following section briefly describes recommendations made to Volvo cars and future work that could be carried out.

The first suggestion to improve on the present model would be the modelling of fan. Due to lack of available data for the fan, the possibility of modelling the fan was ruled out. The present model has input in the form of a look up table for airflow due to the fan as a function vehicle speed, which is quite empirical. Hence modelling a fan could be the next step in order to the increase the accuracy of the results.

Secondly, a basic control strategy depending on the final temperature of the Battery was employed. Regulating Battery temperature using different components i.e. Chiller or Radiator, during different drive case scenarios involves calculations based of many parameters. Hence, a more comprehensive and sophisticated control strategy based on parameters such as power consumed by the cooling components, rate of heat generated by the Battery, etc. could be developed to produce energy efficient methods of cooling system operation.

The cooling for electrical components was modelled in GT-SUITE during the initial phase of thesis work. As there was lack of data available on electrical components, the cooling system for electrical components was neglected. Modelling of the cooling system for electrical components was done to investigate flow rates and pressure drops in the system. Furthermore, the electrical cooling system and the Battery cooling systems could be integrated in the complete vehicle thermal model for more extensive analysis. Integration would help in studying possible interactions between the two cooling system and behaviour of the connected systems.

The current cooling package configuration consists of a Condenser sandwiched between 2 Radiators, one each for Battery cooling system and electrical cooling system separately. Different combination of arrangements between the Radiators and the Condenser to look at the effect of air flow which affects the Coolant temperatures can be worth looking into. A 3D CFD study of this would be fruitful and will help provide better results.

Validating the complete circuit, modelled in GT-SUITE, with the findings from actual testing of the setup was not possible. This helps in getting an idea of the accuracy between modelling in GT-SUITE and test data.

It would be interesting to combine the cooling system model along with the complete Air Conditioning circuit. The present model uses the Chiller which is provided with boundary conditions on the refrigerant side. A more detailed analysis of the effect the AC system has on the cooling system operation during drive cases, especially during high temperatures can be carried out.

7 Appendix – Plots

7.1 Extreme Drive Cycle

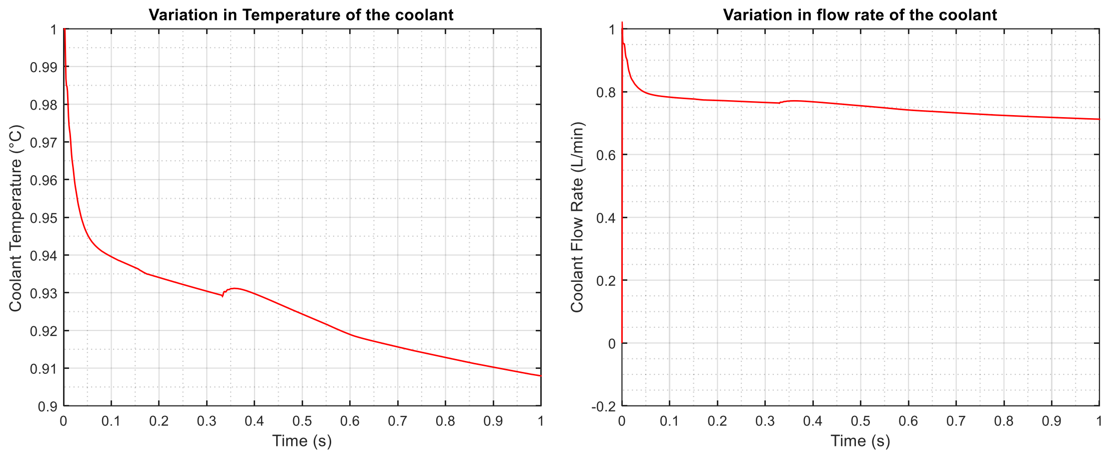

Figure 7-1: Representation of Variation in Temperature of the coolant and the Flow Rate of the coolant for the extreme drive cycle.

7.2 Combined Drive Cycle

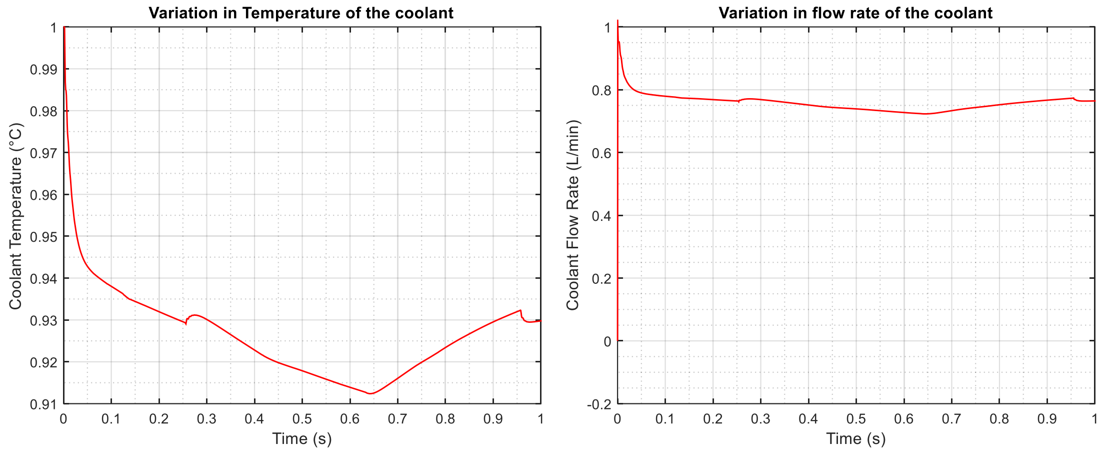

Figure 7-2: Representation of Variation in Temperature of the coolant and the Flow Rate of the coolant for the combined drive cycle.

7.3 Normal Charging Cycle

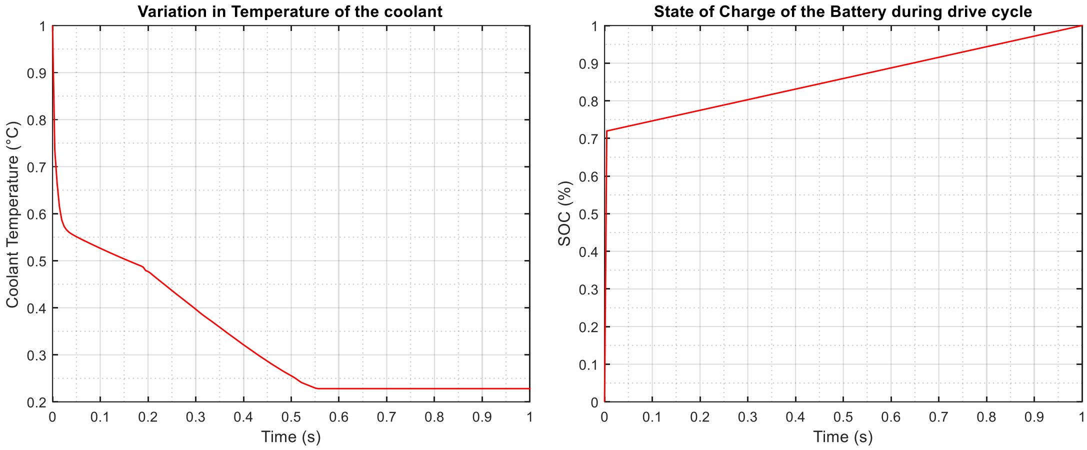

Figure 7-3: Representation of Variation in Temperature of the coolant and the State of Charge of the battery for the normal charging cycle.

7.4 Semi-Fast Charging Cycle

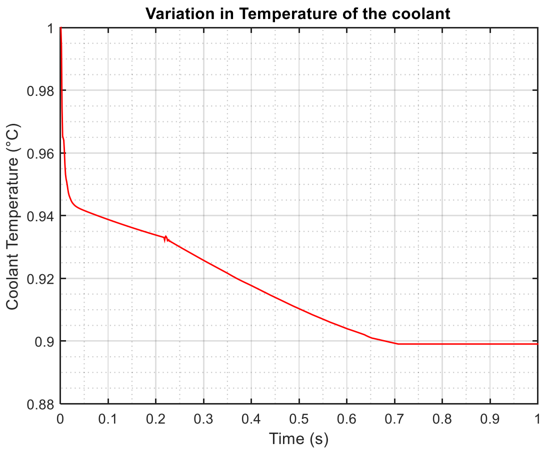

Figure 7-4: Representation of Variation in Temperature of the coolant for the semi-fast charging cycle.

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