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Engine Electrified Cooling System: System and Control Design in Simulation Environment

Methodology and tool development in Simulink to model and simulate the engine cooling system and its controls with electric pump, electric fan and three-way valve

Master's thesis in Automotive Engineering

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Department of Mechanics and Maritime Sciences
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Abstract

A cooling system is a vital part of any combustion engine. The cooling system helps maintain the temperature of the engine without allowing it to reach extreme values. A part of the power produced by the engine is used for the cooling system operations. Any savings in the energy consumption of the cooling system is used to improve the fuel efficiency of the vehicle.

This master thesis deals with the development of an electric cooling system. This is done by replacing conventional parts of the cooling system with electric variants. Electrifying the cooling system creates additional degrees of freedom like control of pump speed and fan speed which are addressed by developing a control system and generating strategies to operate the components of the cooling system in the most energy efficient manner.

The product of this thesis is a methodology to simulate the electric cooling system and its control system using PID controllers in Simulink. While tuning the controllers to perform as required was a challenging task, a lot of time and effort was invested in improving the robustness of the existing system model to yield good results.

The developed methodology can be used to optimise the cooling system in a conventional vehicle, as well as, be adapted to the development of cooling systems in hybrid or electric vehicles. The recuperated energy while braking can be utilised to power the cooling system hence improving the performance and range of the vehicle.

Keywords: Electric cooling system, Control system, PID controllers, Electric pump, Electric fan, Thermostat, Three-way valve

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Abhishek Makam, Gothenburg, September 2019

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1
Introduction

Improving the fuel efficiency of any automotive vehicle has been an engineering goal for the automotive industry. This is to ensure that the products of the automotive companies are not harmful to the environment. Automotive emissions have been one of the major contributions of global warming. Stringent laws are being enforced to reduce the emissions caused by vehicle pushing the vehicle manufactures to come up with innovative ideas to make their products more efficient.

It is a fundamental phenomenon, anything that burns produces heat. Since heat is a form of energy, it can be used in numerous ways to do work. In case of a conventional combustion engine, when fuel is ignited, it burns rapidly and generates heat. Approximately one third of the heat generated is used to propel the vehicle. One third of the heat released is carried away by exhaust gases. The last third of the heat remains in the engine block and needs to be extracted to avoid any damage due to excessive heat. A part of this unused heat is rejected to the environment/ambient through the walls of the engine. In small engines where the ratio of exposed surface area to heat generated is high, the extraction of heat relies on the circulation of air directly over the engine. In large engines, where the ratio of exposed surface area to heat generated is low, and the heat produced is higher, relying only on air circulation over the engine to extract the excess heat is not sufficient and requires additional aid. This job is done by the engine cooling system.

Engines that are attached with a cooling system have a passage for the coolant to flow through the engine cylinder block and the head. As the coolant flows through these passages, it interacts with the hot metal and absorbs the heat away from the metal parts. Cooling system is designed so that the flow rate of the coolant is matched to maintain the engine at a temperature at which the combustion process is most efficient and also protect the engine block materials from damage due to very high temperatures.

Coolant is generally a mixture of water and ethylene glycol in varying proportions. Ethylene glycol or other anti-freeze chemicals are added to water to decrease the freezing temperature of the coolant to be able to do its job when the ambient temperature is low. Since the mixture has a limited heat carrying capacity, the heat absorbed from the engine needs to be rejected to the environment so it can continue the cycle efficiently. A radiator is used to reject the heat from the coolant to the environment. The radiator is placed at the front of the vehicle, behind the grill. When the vehicle is in motion, the ram air flows through the grill over the radiator. Ram air is the flow of air on and over the vehicle body caused due to the relative motion between the vehicle and air around the vehicle. A mechanical fan is attached to the radiator to improve the air flow when the ram air is not sufficient, for example, at a traffic signal, where the engine is running but the vehicle is stationary. When the coolant is flowing through the radiator and the air is flowing over it, the heat is transferred from the coolant to the walls of the radiator and in turn to the air. Hence, the heat carried by the coolant from the engine is transferred to the environment at the radiator.

To keep the coolant flowing, a pump is used, generally a centrifugal type. As the pump starts to run, the coolant is forced to flow through the engine to extract heat, then it flows through the radiator to cool down by rejecting heat to the environment and returns to the pump to continue the cycle again.

Conventionally, the pump and the fan are driven mechanically by the engine. A part of the power from the engine is utilised by the cooling system to meet the engine cooling requirement. In addition to this, since the pump and the fan are physically connected to the engine through a belt, the engine speed dictates the speed of the pump and fan. With advancement in technology and increasing need to improve the fuel efficiency of the vehicle, the physical connection between the engine and the cooling system components is seen as a disadvantage as there is no control over the operation of the components, specially at high engine loads and efforts are being put to make the cooling system independent of the state of the engine. One of the solutions to this problem is to attach the fan and the pump with their own drivers e.g, electric motor. With an electric motor driving the pump and the fan, the components can now work independently without the engine speed dictating the component speed. With this additional degree of freedom, there is a possibility to improve the efficiency of the cooling system by optimising the operating points of the components to suite the requirement which can lead to reduction in energy consumption and in turn improving the efficiency of the entire vehicle.

The findings of this study are not limited to vehicles with combustion engines alone. The methodology developed can be adapted to hybrid and all electric vehicles with different cooling requirements and various components that are a source of heat, e.g, electric wheel motors, batteries or DC inverters.

1.1 Thesis Goal

This master thesis is an attempt to develop an electric cooling system through mathematical modelling and to demonstrate the benefits of using electrified components by the development of a control system to operate them. The aim is to investigate the potential areas of energy savings of an electric cooling system compared to the conventional system.

1.2 Mechanical Cooling System

This section will explain the working principle of a conventional cooling system. A typical cooling system consists of a heat exchanger to reject the heat from the coolant to the atmosphere. The coolant flows through the heat source, in this case the combustion engine, and extracts the heat. The heat from the engine walls is transferred to the coolant when the two come in contact. The mode of heat transfer is mainly through convection. A mechanical pump which is driven by the engine (engine output shaft is connected to the pump through a belt or in some cases gears) keeps the coolant flowing. In the case of the study,the pump assembly consists of a hydraulic pump and an electromagnetic clutch which switches between high flow mode and low flow mode. When the cooling requirement is high, a signal from the engine ECU switches the pump to high flow mode while other times, the pump is running in low flow mode at a speed proportional to the engine. A mechanical fan is attached to the radiator to improve the air flow to aid in the heat rejection from the radiator to the atmosphere. The fan is also driven by the engine through a belt drive system. To get a better control of the fan operation, it is attached with a viscous clutch which can be proportionally engaged or disengaged based on requirement. The ECU actuates the viscous clutch when required. Figure 1.1 demonstrates a typical cooling system setup.

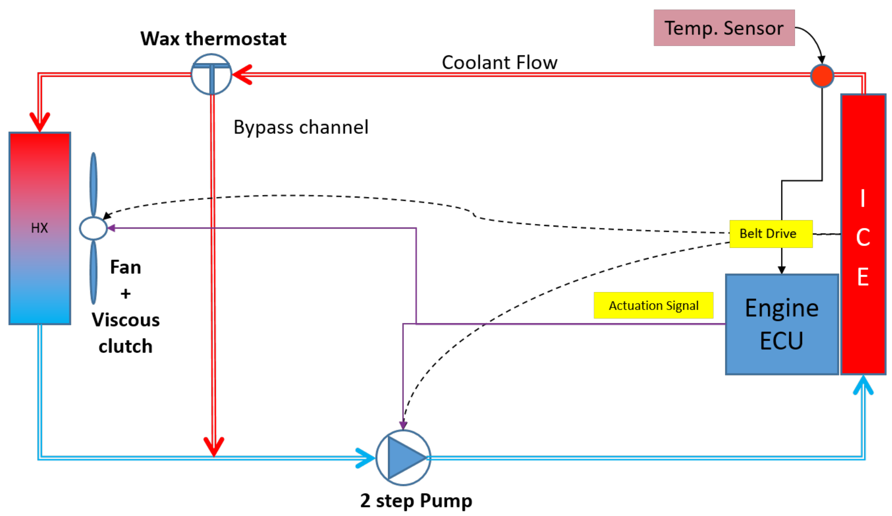

Figure 1.1: Schematic of a Mechanical Cooling System

A wax thermostat is placed before the radiator to control the flow of coolant through the radiator when the coolant is not hot enough. It is important to retain the temperature of the coolant to ensure that the engine is warm enough to operate efficiently. When the temperature of the coolant flowing through the thermostat is high, the wax melts allowing the coolant to flow through the radiator, in other cases, the coolant flows though the bypass channel. With the increase in the coolant temperature, the wax thermostat gradually opens a path for the coolant to the radiator and it becomes completely open above a certain calibrated value of the coolant temperature. A temperature sensor at the outlet of the engine continuously communicates the temperature detail of the coolant to the ECU so that appropriate actions for the fan and pump can be taken.

2
Theory

A typical engine cooling system consists of a pump, a heat exchanger - commonly called as a radiator, pipes and hoses. In most cases, the heat exchanger is assisted by a fan to improve the heat exchange efficiency. A valve is also included in the flow circuit to control the amount of coolant flowing through the heat exchanger. Working principles and physical governing equations of each of these components are discussed in the following sections.

2.1 Pump

A pump is a device that converts one form of mechanical energy (rotating or reciprocating) to hydrodynamic energy and imparts it to the fluid. In case of a coolant pump, the fluid is the coolant and the most common type of cooling pump is the centrifugal type. Figure 2.1 shows a schematic of a simple centrifugal pump.

The coolant pump is coupled to the engines crankshaft by a belt (in some cases by gears). The inlet of the pump is located at the centre of the pump and the outlet is located radially outwards. As the pump spins, coolant is forced out through the outlet port and is continuously drawn through the inlet.

Typical pump performance data from the manufacturer would look similar to the figure 2.2 which describes the characteristics of the pump. With the red curve as a reference and using the affinity laws, information like the flow rate, pressure head, hydraulic power and efficiency at different operational speeds (N_1,N_2 or any other value) can be gathered.

All centrifugal devices (pumps and fans) follow the Affinity Laws. These laws describe the relationship between various performance parameters and changing operating conditions. The law has three parts,

- Flow rate (Q) is proportional to the shaft speed(N)

$$\frac{\mathbf{Q_1}}{\mathbf{Q_2}} = \frac{\mathbf{N_1}}{\mathbf{N_2}} \tag{2.1}$$

- Pressure head(H) is proportional to the square of shaft speed(N)

$$\frac{\mathbf{H_1}}{\mathbf{H_2}} = \frac{\mathbf{N_1^2}}{\mathbf{N_2^2}} \tag{2.2}$$

- Power(P) is proportional to the cube of shaft speed

$$\frac{\mathbf{P_1}}{\mathbf{P_2}} = \frac{\mathbf{N_1^3}}{\mathbf{N_2^3}} \tag{2.3}$$

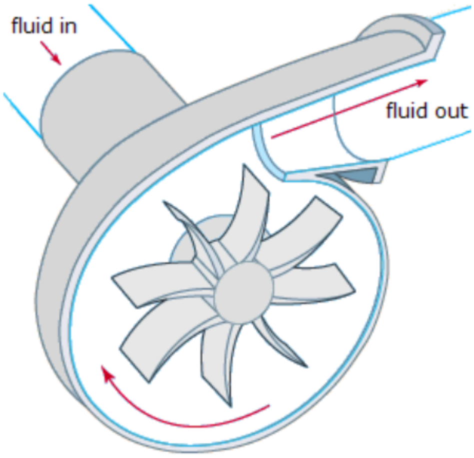

Figure 2.1: Schematic of a centrifugal pump [1]

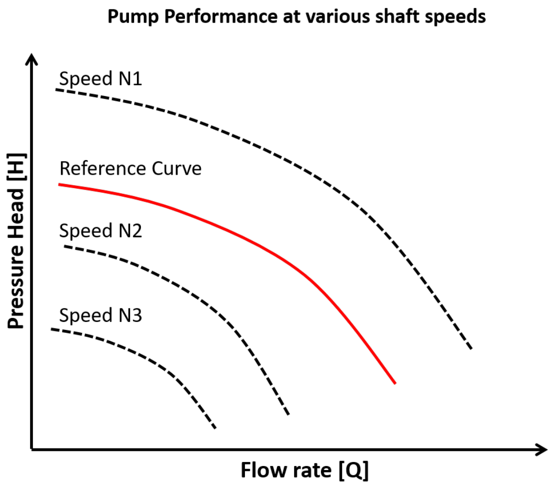

Figure 2.2: Coolant pump performance

Equation 2.1, 2.2 and 2.3 can be used to find the flow rate, pressure head and power consumption at a different pump speed from a given data point.

The affinity law can be extended to determine the flow properties for a variation in impeller diameter (D).

$$\frac{Q_1}{Q_2} = \frac{D_1}{D_2}; \quad \frac{H_1}{H_2} = \frac{D_1^2}{D_2^2}; \quad \frac{P_1}{P_2} = \frac{D_1^3}{D_2^3} \tag{2.4}$$

Equations 2.4 are used to study the effects of varying the impeller diameter or the pump size on the flow properties. These equations hold good for a constant shaft speed N.

2.2 Heat Exchanger or Radiator

Heat Exchanger or the Radiator is a device that transfers heat from one medium to another. In automotive applications, it is used to reject the heat from the coolant carried from the engine (and other parts) to the atmosphere. The mode of heat exchange is mostly by convection. A schematic of a typical automotive radiator is shown in figure 2.3.

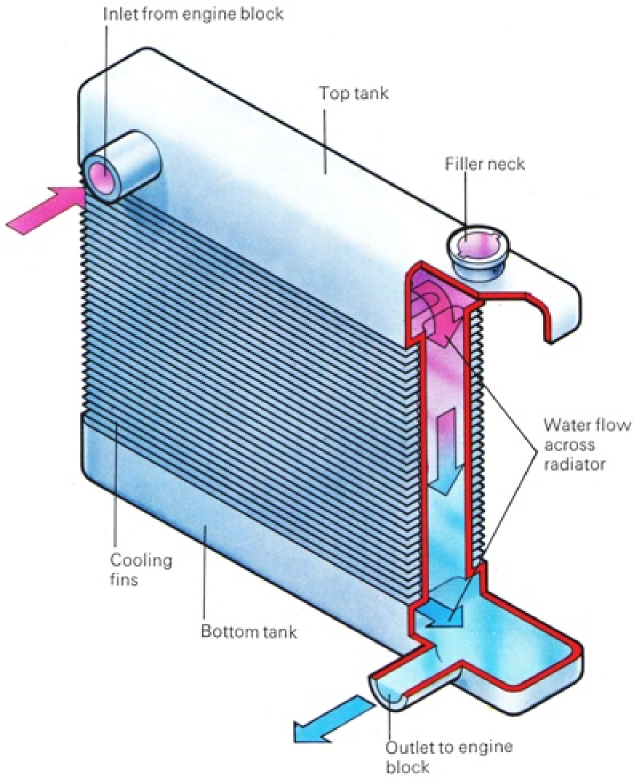

Figure 2.3: Schematic of automotive Radiator [2]

Since air is not a good conductor of heat, the size of the radiator is made as large as possible to increase the effective area of interaction between air and the radiator tubes. The efficiency of heat exchange sometimes called effectiveness depends on the mass flow rate of the coolant, mass flow rate of air and the absolute difference in the temperatures between them. Typically, the supplier provides effectiveness data along with the radiator. Effectiveness of a radiator is measured and calculated in a bench test performed in a controlled environment.

As we do not have control over the atmospheric temperature or over the coolant temperature, manipulating the flow rates of the two fluids will change the heat exchange efficiency. Performance data from the radiator supplier generally contains correlation between the coolant and air flow rate, coolant and air inlet temperature and the heat rejected. Sometimes, coolant outlet temperature is provided instead of heat rejected. In both cases, efficiency of heat exchange can be determined using the governing equations presented in 2.5 [3].

$$\text{Efficiency}(\epsilon) = \frac{\text{Actual Heat Transfer}}{\text{Maximum Possible Heat Transfer}} \quad (2.5)$$

Actual heat transfer is either supplied with the data or can be calculated using equation 2.6.

$$\text{Actual Heat Transfer} = \dot{m}_{coolant} * C_{pcoolant} * \Delta T_{coolant} \quad (2.6)$$

$\Delta T_{coolant}$ is the difference in temperature of coolant flowing in and flowing out of the radiator, $C_{pcoolant}$ and $\dot{m}_{coolant}$ are the specific heat and mass flow rate of the coolant respectively.

Equation 2.7 is the maximum possible heat transfer. For a given combination of flow rate of the two fluids, the maximum heat transfer increases with increase in the temperature difference between the two mediums.

$$\text{Maximum possible heat transfer} = min(\dot{m}_{coolant} * \dot{C}_{p_{coolant}}; \dot{m}_{air} * \dot{C}_{p_{air}}) * (T_{coolant_{in}} - T_{air_{in}}) \quad (2.7)$$

Using interpolation techniques and inverting the efficiency table, for a given operating condition, the coolant temperature at the radiator outlet can be determined. Equation 2.8 calculates the coolant temperature at the radiator outlet for a given flow-rate of air and coolant.

$$T_{coolant_{out}} = \frac{\epsilon * min(\dot{m}_{coolant} * \dot{C}_{p_{coolant}}; \dot{m}_{air} * \dot{C}_{p_{air}}) * (T_{coolant_{in}} - T_{air_{in}})}{\dot{m}_{coolant} * \dot{C}_{p_{coolant}}} \quad (2.8)$$

where $\dot{m}_{air}$ is the mass flow rate of air flowing over the radiator, $\dot{C}_{p_{air}}$ is the heat capacity of air and T_air_{in} is the temperature of air that flows over the radiator.

2.3 Radiator Fan

Fan is also a centrifugal device that works just like the pump, but the difference is in the working fluid. While the pump works on the coolant liquid, the fan works on air.

When the fan is turned on, it forces the air over the radiator which improves the heat exchange process. Similar to the pump, the fan is also driven by the engine through a belt drive. Sometimes, the fan comes attached with an electric motor. In this case, the fan is not driven by the engine rather by the electric motor. If the width of the radiator is relatively larger than the height, sometimes, two small fans are attached instead of one. Figure 2.4 shows one such example of two fans attached on a radiator. However, in a Volvo FH truck, a single large fan over the radiator is driven by the engine. A viscous clutch enables the activation and deactivation of the fan.

Since the radiator fan also follows the Affinity laws like the pump, equations 2.1, 2.2 and 2.3 hold good to find the flow rate, pressure head and power consumption at various fan speeds from a known data point. The fan supplier provides the data sheets on its performance parameters.

Figure 2.4: Two fans attached on a radiator [4]

2.4 Thermostat Valve

Thermostat valve or simply a thermostat is a device that enables or disables the flow of fluid. Its main job is to allow the engine to heat up quickly to bring it to a temperature which makes combustion of fuel more efficient, and then to keep the engine at a constant temperature by enabling or disabling the flow of the coolant through the radiator.Its control is based on the temperature of the flowing fluid (in this case, the coolant). Figure 2.5 shows a typical automotive thermostat.

While the temperature of the coolant is above a certain calibrated value, a wax element in the thermostat melts which opens up a path for the coolant to flow through the radiator. In the other case, when the temperature is lower than the calibrated value, the path to the radiator is blocked and the coolant flows through the bypass channel allowing it to retain the coolant temperature.

Figure 2.5: Wax thermostat for automotive applications [5]

2.5 PID Controller

PID Controllers are the most commonly used control mechanism. PID stands for Proportional, Integral and Derivative. The controller includes elements of these three functions. They can regulate flow rate, temperature, speed or other physical variables of any system. Using PID controllers can eliminate the necessity for manual intervention. For the development of the electric cooling system, multiple PID controllers were used to control the coolant temperatures and to maintain the speeds of the electric machines that drive the pump and the fan.

Figure 2.6 shows a basic structure of a PID controller. Controlled Variable (CV) is the controller output that influences the plant/process to change the Process Variable (PV). An error (e(t)) is calculated by comparing PV to the Set Point (SP). The calculated error is the input to the PID controller.

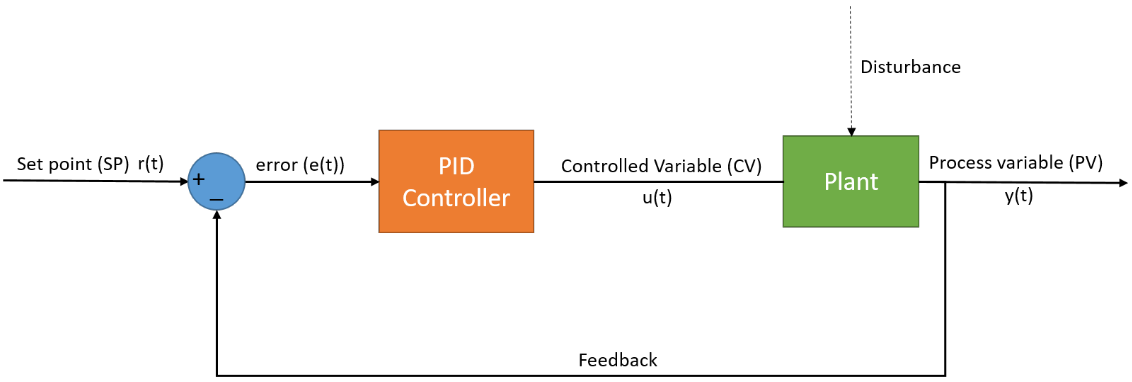

Figure 2.6: Basic structure of a PID controller

Generalised mathematical structure of a PID controller is

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{d}{dt} e(t). \tag{2.9}$$

Set point (SP) is the desired value of the process variable (PV). If there is a disparity in the PV compared to the SP, a corrective action needs to be applied. When there is an error e(t), the controller changes the CV according to the equation 2.9. As the CV changes, the plant brings the process variable equal to the SP. The corrective action by the PID controller depends on the terms K_p which is the coefficient of the proportional part, K_i which is the coefficient of the integral part and K_d which is the coefficient of the derivative part. It is not necessary to use all the three terms in the control algorithm. Using only the proportional part of the PID controller makes it a Proportional Controller or simply, P controller. When using the proportional and integral parts, it would be called a PI controller. Different processes require different elements of the PID controller, while some processes work well with only the proportional part, other processes require all the three components. However, using all the three elements produces a better controlling function but also demands higher computational requirements.

One of the common applications of PID controller in a car is for Cruise control. Cruise control is an application in modern cars that maintains the speed of the vehicle at a target value without any driver intervention. In this case, the car would be the plant, cruising set speed is the SP, and the controlled variable is the engine power. When the car is approaching an uphill, constant engine power would slow the car down. Since the error between SP and the actual speed of the vehicle(PV) increases, the PID controller restores the desired cruising speed by requesting additional power from the engine.

In-order to have good control over the process, the PID controllers have to be tuned such that, it is fast, robust and should avoid any overshoot in the PV. Overshoot is a term to describe the situation when the process variable moves further past the desired set point. The PID controller tuning procedure is described in the following section.

2.5.1 PID Tuning

While there are multiple ways of tuning the controller and finding the coefficients of the controller parameters, Lambda (λ) tuning is one of the commonly used methods because of it ability to generate a smooth non-oscillatory control effort when responding to changing set point [6]. It is a model-based tuning method, where the response of the process is recorded when the plant is subjected to a step change in its input. λ tuning method permits to easily determine the initial values of proportional and integral coefficients of any function. From the initial values, the P and I coefficients can be fine tuned to get the required response from the controller. The idea of tuning the controller is to find a compromise between the responsiveness and to minimise the overshoot in the system.

Steps involved in tuning a PID controller using Lambda tuning method or Bump test [6]. Refer to figure 2.7 :

1. When the process variable y(t) is stable, increase u(t) by a step, upwards by B% such that there is a significant change in y(t). Record the change in y(t).

2. Draw an ascending line tangent to the steepest part of the process variable's trend line

3. Draw horizontal lines through the process variable's initial and final values.

4. Mark where the two horizontal lines intersect the ascending line at points 2 and 3.

5. Measure the dead-time, D, from point 1 to point 2 and the process time constant, T_p, from point 2 to point 4.

6. Record the change in the process variable from point 3 to point 4 then divide that by B to get the process gain, K_p.

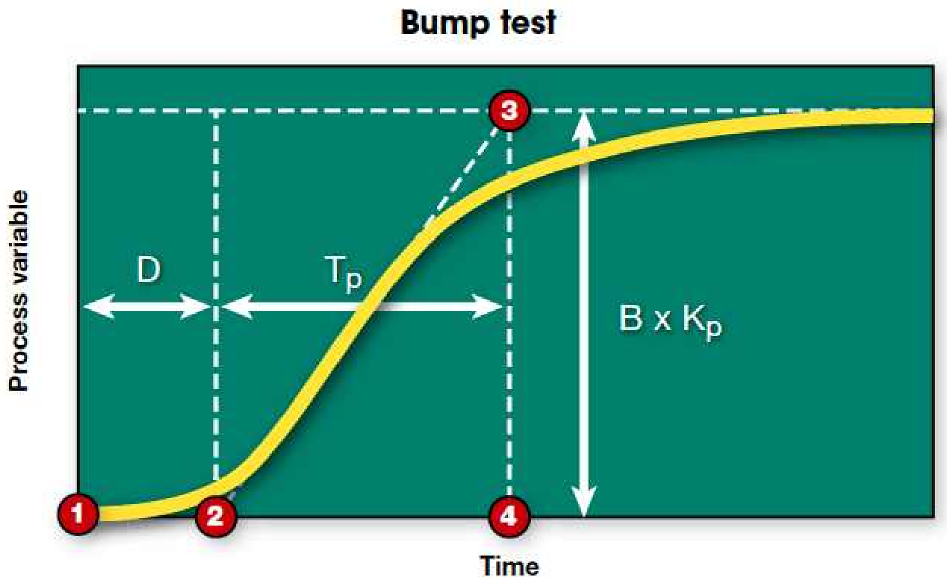

Figure 2.7: Change in process variable y(t) due to a step change in u(t) [6]

The lambda tuning method is useful for tuning a PI controller. The controller equation 2.9 can be written as

$$u(t) = K_c[e(t) + \frac{1}{T_i}\int e(t)dt] \tag{2.10}$$

Once the necessary parameters including process gain K_p, time constant T_p and the dead time D are calculated, the controller gain K_c is calculated using the following equations

$$K_c = \frac{T_p}{K_p(\lambda + D)} \tag{2.11}$$

$$T_i = T_p \tag{2.12}$$

where λ is the only parameter to be varied to change the responsiveness of the controller.

3
Methods

Volvo's most selling product, the Volvo FH series truck was used as a test object to modify and re-design the existing mechanical cooling system to an electric kind. Volvo FH series trucks are generally used for either long haul or regional distribution. An already existing Simulink model was used as a reference and the electric cooling system was developed by modifying the existing mechanical cooling system model.

This master thesis was carried out on computer simulation environment in Simulink in which a mathematical model of the vehicle was previously developed. The existing vehicle model was used to integrate the new electric cooling system and study its performance.

Figure 3.1: Volvo FH series truck

3.1 Vehicle Model

A detailed vehicle model was previously developed in Global Simulation Platform (GSP) which is a tool developed by Volvo GTT within Simulink. Mathematical models of all components in the vehicle were modelled independently and later integrated together. GSP is a commonly used tool to perform and understand most of the driveline simulations. The vehicle model also came with a Thermal Fluid Management System- TFMS. TFMS consists of the conventional mechanical cooling system and oil cooling system. For this thesis, the cooling system was the main area of focus. The components of existing cooling system were to be electrified. The following changes were made to the existing mechanical cooling system:

- The wax thermostat was replaced with a 3-way valve. An electrified valve allows the user to control the flow of coolant manually irrespective of the temperature of the coolant, like in a wax thermostat.

- The engine driven coolant pump which was attached with a 2-speed clutch was replaced with an electric cooling pump. An electric motor was added to drive the cooling pump now allowing the pump to run at a speed defined by the user and not by the engine

- The radiator fan which was driven by the engine through a viscous clutch was replaced by an electric fan. Similar to the coolant pump, an electric motor was added to the fan eliminating the need for a clutch.

The cooling system extracts the heat not only from the engine, but also from other accessories that are in the vehicle. For example, the coolant flows though the oil cooler to extract the heat from the engine oil. The coolant also flows through the EGR(Exhaust Gas Re-circulation) cooler, the transmission retarder, transmission oil cooler and the heat from the coolant is also used to heat up the cabin when needed.

3.2 Modelling of a 3-way Valve

A wax thermostat was replaced by a three-way valve to have control over the coolant flow rates through the radiator and the bypass channel. To model a valve, it is important to understand how the flow through parallel branches is solved in the simulation.

Figure 3.2 shows a schematic of a three-way valve. If $\dot{m}$ is the mass flow rate of the coolant flowing into the main channel and $\dot{m}_1$ and $\dot{m}_2$ are the coolant flow rates flowing out of branch 1 and branch 2 respectively, the flow is split in such a way that the pressures loss across both the branches Δp_1 and Δp_2 (or all the branches, if multiple) is same.

$$\Delta p_1 = \Delta p_2 \tag{3.1}$$

From laws of conservation of mass, the sum of coolant flow exiting the two branches is equal to the flow of coolant entering the main branch, considering there is no loss in matter for example due to leakage.

$$\dot{m}_1 + \dot{m}_2 = \dot{m} \tag{3.2}$$

From laws of conservation of energy, flow rate through a pipe is proportional to the cross section of the pipe A, A_1 and A_2, and the velocity with which the coolant is flowing, v, v_1 and v_2. The constant of proportionality is the friction factor that can be determined by the Darcy-Weisbach Equation. The proportionality constant

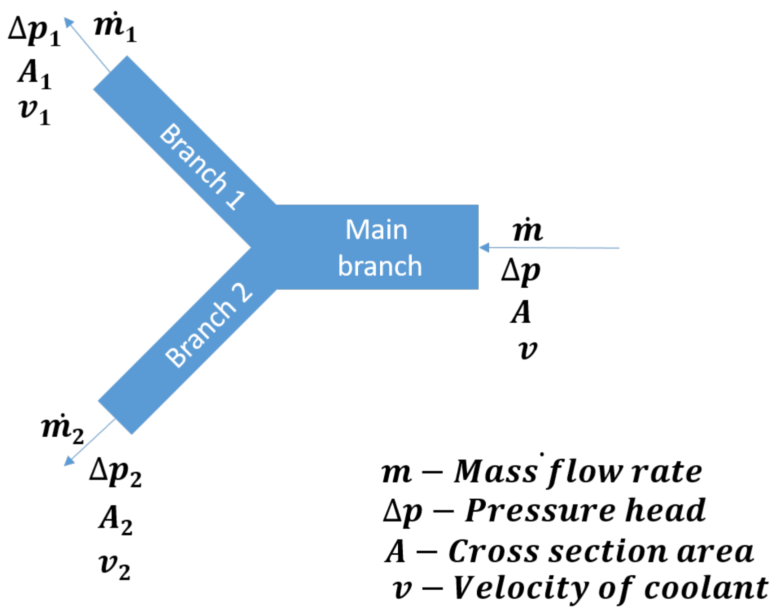

Figure 3.2: Representation of coolant flow through branches

is dependent on the friction of the material the coolant (or any fluid) is flowing through. If all the paths of the fluid are made up of the same material, the friction constant is the same value and can be omitted from the calculations

$$\dot{m} \propto v * A; \quad \dot{m}_1 \propto v_1 * A_1; \quad \dot{m}_1 \propto v_2 * A_2 \tag{3.3}$$

If the split in the pipes is fixed, the diameter and the cross-section area of each branch is fixed. It is simple to calculate the ratio of split in flow between branch 1 and 2. Since a three-way valve is a device that modifies the cross-section area of the two branches by varying the diameters at the beginning of the split, a PI controller is used to modify the flow rate $\dot{m}_1$, $\dot{m}_2$ between the two branches such that the condition in equation 3.1 is satisfied. The set point to the controller is the condition that,

$$|\Delta p_1 - \Delta p_2| = 0 \tag{3.4}$$

This condition is satisfied by modifying $\dot{m}_1$ and $\dot{m}_2$. The speed and accuracy with which the controller is performing is one of the factors for the accuracy and the robustness of the model.

3.3 Modelling of Electrified Components

In practice, an electric pump and an electric fan come as single physical units where the pump or the fan is attached to the electric motor and each of these components have their specific performance data. To avoid spending time on the electric component technologies and obtaining their performance data, a generic model of an electric machine was developed. Since the performance data of mechanical components was already available, adding an electric machine model to the already existing pump and fan models would work as electric variants of the mechanical components.

Figure 3.3 shows a schematic of the electric machine model developed in Simulink. The **Torque_limitation** block contains a map of electric machines performance. The map describes the motor's torque availability for the entire speed range. EM torque can be limited by either the maximum torque (rated torque) or by the maximum power and speed. Based on the torque request from **inport1** block and the actual speed of the machine, limited torque is calculated, this is the output of the **Torque_limitation** block. Since the EM performance data and the torque maps are generated at steady state conditions, the motor's own inertia has to be compensated. This is done in the **inertia_Compensation** using the equation 3.5. A first order filter is used to model the response time of the motor in the **EM response time**' block.

$$EM\ Torque_{output} = Limited\,Torque - (Inertia_{EM} * \frac{\Delta Speed}{\Delta time}) \tag{3.5}$$

EM_efficiency block contains the motors overall efficiency data, including the power electronics the motor comes with. The electric machine efficiency is a function of the motor speed and torque. Figure 3.4 is an example of how the efficiency varies with speed and torque. However, to keep the model simple, a standard efficiency of 80% was used for all the simulations.

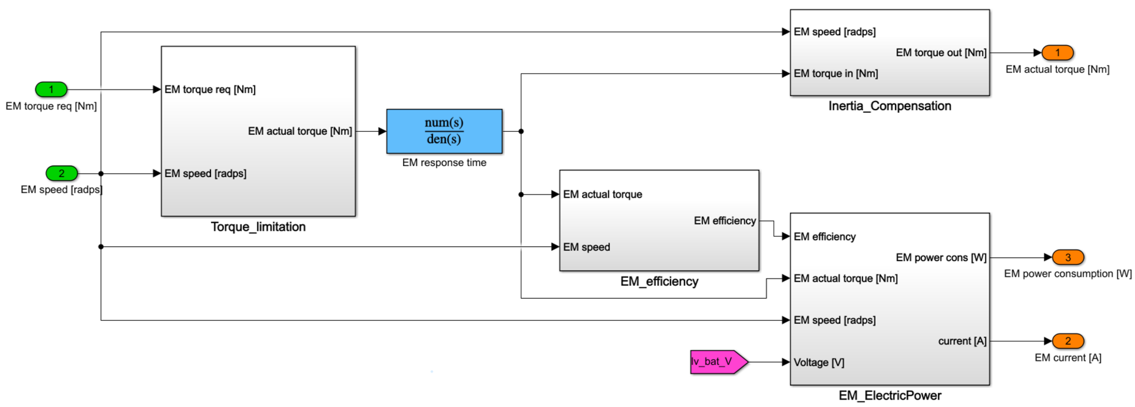

Figure 3.3: Simulink model of an Electric Machine

The generic electric machine model was attached to the existing hydraulic pump and fan to convert them to electric variants. Contrary to the mechanical power consumed by the pump and fan, the electrical power consumed by the electric machine to drive the pump and the fan would account to the total energy consumed by each

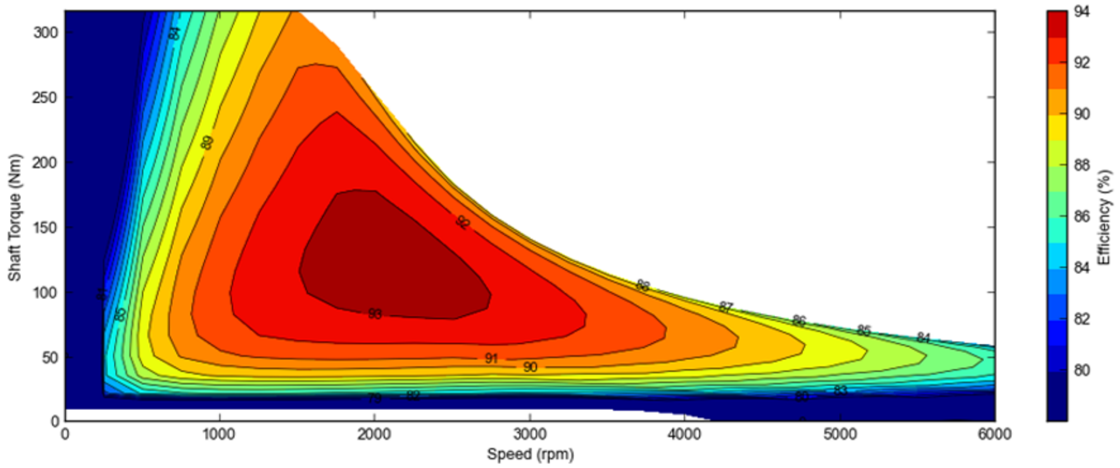

Figure 3.4: Example of efficiency map of Electric Machine in motor mode [7]

component. The electric machine would run only in the motor mode and the electrical power consumed by the motor accounts to the energy consumption of which ever component the electric machine is attached to. The **EM_ElectricPower** block calculates the power consumption of the electric machine.

The electric power is calculated using the equation 3.6. From the calculated power consumption, the current draw by the electric machine can be derived using equation 3.7. The current drawn is important in designing the wiring harness between the motor and the batteries (or other sources of energy). The current drawn might also be the limiting factor of the size and type of battery. For the purpose of the simulation, the energy required to drive the motor is supplied by the on-board battery present in the vehicle model. The batteries are charged by the alternator which is driven by the engine. The load of the alternator is added to the engine load thereby increasing the engines fuel consumption. Since this study will focus on the energy consumption of the cooling system and not on fuel efficiency of the vehicle or engine, drawing energy from the battery to power the eclectic cooling system will not affect the results. However, when calculating the fuel efficiency, it becomes important to take into account how is the energy produced to power the components of the electric cooling system.Integrating EM_Power over time would result in Electric machines total energy consumption in Joules [J]

$$EM\_Power[W] = \frac{EM\_Torque[Nm] * EM\_Speed[rad/s]}{EM\_Efficiency} \tag{3.6}$$

$$EM\_current[A] = \frac{EM\_Power[W]}{BatteryVoltage[V]} \tag{3.7}$$

3.3.1 ePump

An electric variant of the hydraulic pump was created by adding the electric machine model along with a pump speed controller to the existing mechanical pump model. Figure 3.5 shows the implementation of the electrification of the mechanical pump in Simulink.

The EM + PumpSpeedController block in figure 3.5 contains a calibrated PID controller to maintain the pump speed at a value decided by the temperature controller. The set speed or target speed calculated by the temperature controller (temperature controller not shown in figure) is carried by the inport block as seen in the left of the figure 3.5. An error is calculated by comparing the actual or current speed with the target speed. If any difference in the speed exists, it is used to request higher or lower torque from the electric machine. The change in torque of the electric machine changes the speed of the pump, setting it to the speed indicated by the temperature controller. The energy consumed by the ePump is the cumulative electrical power consumed by the electric machine that is driving the ePump.

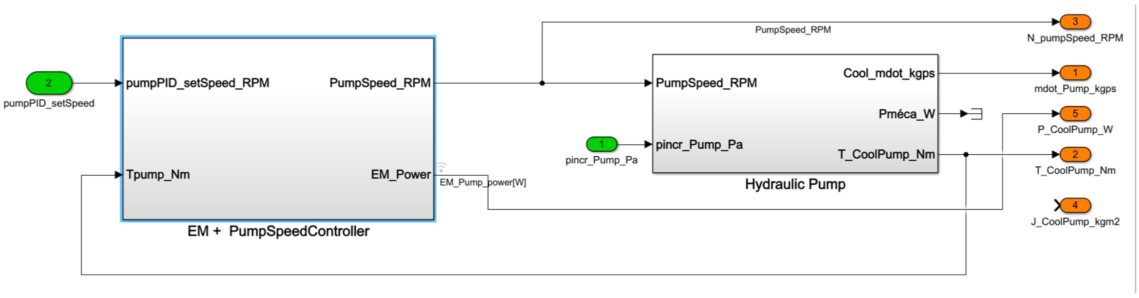

Figure 3.5: Electrification of mechanical pump in Simulink

3.3.2 eFan

Similar to the pump model, mechanical fan model was electrified by adding an electric pump to it. A PI(D) controller was developed to control the speed of the fan. The electric machine and the controller are modelled in the EM + FanSpeed-Controller block. The inport2 block carries the speed target signal calculated by the fan temperature controller. An error is calculated based on the new set target speed and the current speed in order for the fan speed controller to take appropriate action. The fan speed controller requests additional torque from the motor if the actual speed is less than the set speed and vice verse. The energy consumed by the fan is the cumulative electrical power consumed by the electric machine driving the fan.

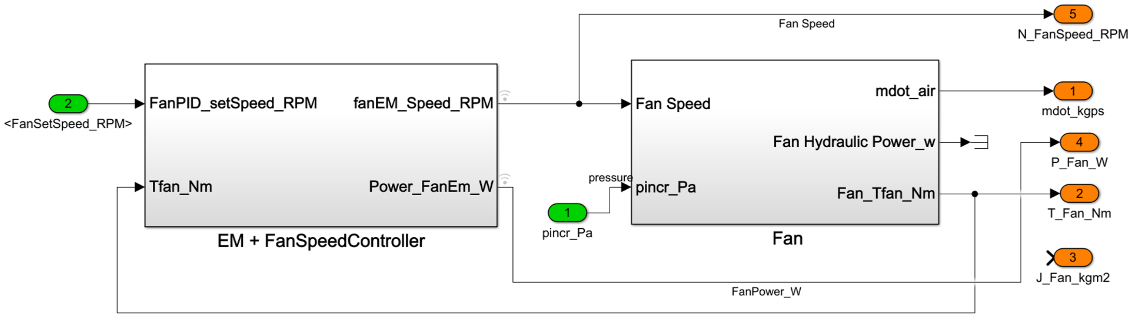

Figure 3.6: Electrification of mechanical fan in Simulink

3.4 Requirements of an electric cooling system

1. The engine block (and head) shall not become too hot. This is the basic requirement and the function of the engine cooling system. The cooling system is responsible to remove the extra heat from the engine and maintain it at an optimal temperature value.

2. The cooling system should fulfil a minimum coolant flow rate. A constant coolant flow rate is required to flow through the engine in order to make sure that any hot spots in the engine block and other components are quenched before they can cause any damage.

3. The difference in the coolant temperature entering the engine and exiting the engine should be kept within a certain range in order to extend the durability of the engine. Excessive gradation in the temperature across the engine block induces unwanted thermal stress and uneven expansion of metal. This will eventually deteriorate the performance and life span of the engine.

4. The system should consume as low power as possible. Lower energy consumption by the cooling system will improve the fuel efficiency of the vehicle.

3.5 Strategies for electric cooling system

The development of four strategies will be discussed in this section. The strategy 1 is a simple one inspired from the control strategy of a conventional cooling system. In strategy 2, 3 and 4, an additional temperature sensor was added at the coolant inlet of the engine. This would allow a feedback of the temperature entering the engine. It can be used to control the coolant flow rate to maintain the temperature at a desired value.

3.5.1 Strategy 1: Control of engine outlet temperature

The first strategy for the electric cooling system was inspired by the mechanical system. The valve, pump and the fan control the coolant temperature at the engine outlet, similar to how the mechanical system works. The temperature sensor at the coolant outlet of the engine reads the temperature of the coolant and sends this information to the ECU. The ECU has the three temperature controllers, one for the valve, one for the pump and one for the fan. These controllers calculate the error based on the actual coolant temperature and the target temperature so the components can take appropriate action.

Figure 3.7 shows a schematic of how strategy 1 works. The valve, the pump and the fan controllers have a set target temperature that each component is trying to control. With an assumption that the actuation of the valve consumes the least amount of energy to operate compared to the pump and the fan, it was a logical solution to actuate the valve first. As the coolant temperature starts to rise, the valve starts to open a path for the coolant to flow though the radiator. At the stage where the valve is partially open, some of the hot coolant flows though the radiator and the rest flows through the bypass channel. If the temperature of the coolant rises above its target temperature value, the valve completely opens and all the coolant flows through the radiator. If the temperature of the coolant continues to increase even after the valve is completely open, an actuation signal from the ECU instructs the coolant pump to increase its speed in order to pump more coolant through the engine to extract more heat from it. In case the engine is generating a lot of heat and the pump is already running at full speed, the radiator fan starts to work and increases the air flow over the radiator there by increasing the heat exchange process.

Figure 3.8 shows an illustration of how this strategy works. The horizontal lines in the first graph are the target temperatures that the valve, the pump and the fan are trying to control at the outlet of the engine respectively.

As the engine outlet temperature, T_{Eng_out}, starts to increase,

- The valve starts to open the path to the radiator.The curve in the second graph shows this change in valve position from 0 to 1. 0 refers to fully closed position(path closed for the coolant to flow through the radiator, instead coolant flows through the bypass) and 1 represents fully open (path open for the coolant to flow through the radiator).

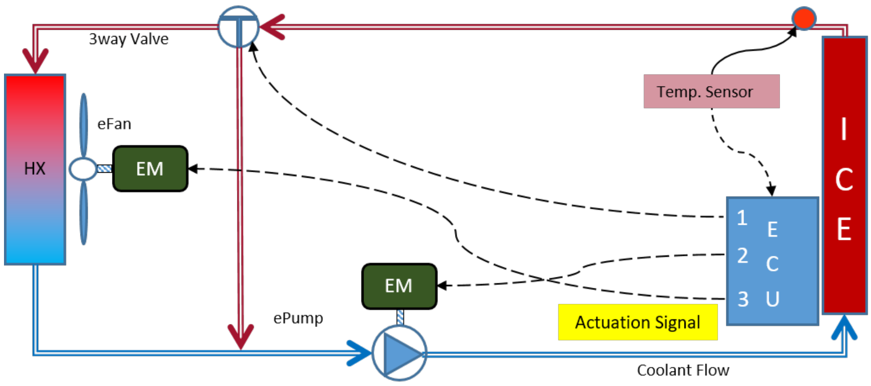

Figure 3.7: Demonstration of Strategy 1 of Electric Cooling System

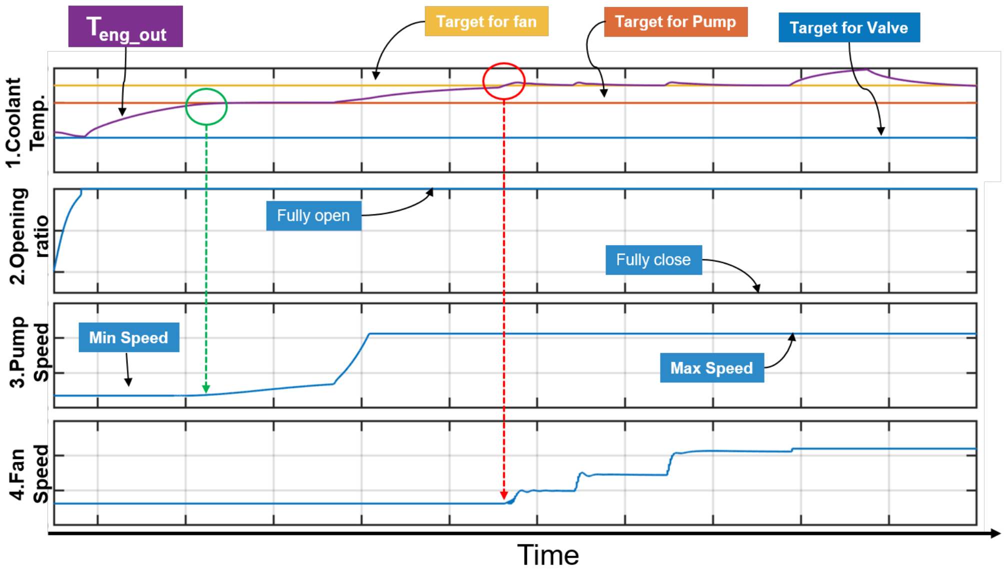

Figure 3.8: Demonstration of Strategy 1 of Electric Cooling System

- Once the valve is completely open, with further increase in T_{Eng_out}, the pump starts to work by gradually increasing its speed as seen in the third graph. The green arrow indicates the beginning of the actuation of the pump as the temperature begins to increase beyond the pump target temperature. It can be observed that, as the pump begins to increase its speed, the temperature is somewhat maintained at the target valve. With further increase in T_{Eng_out}, the pump speed becomes saturated.

- After the pump is running at its full speed and T_{Eng_out} continues to increase beyond the pumps target temperature, the fan starts to work to improve the heat exchange at the radiator. This can be observed by the red arrow pointing the rise in temperature beyond the target value and the increase in fan speed in the last graph of figure 3.8

3.5.2 Strategy 2: Control of engine inlet and outlet temperature

The second strategy of electric cooling system consists of an additional temperature sensor at the inlet of the engine. An additional sensor enables to have better control over the difference in temperature of the coolant at the engine inlet and at the outlet. It is important to maintain a low and consistent difference. This will ensure to extend the life of the engine and reduce the thermal stress on the engine block.

With information from two temperature sensors, the ECU can now try and control the inlet and the outlet temperatures. The three actuators are controlling temperatures at two locations. In this strategy, the valve and the fan shall control the coolant temperature at engine inlet while the pump controls the coolant temperature at engine outlet.

The figure 3.9 shows a schematic of how the temperature sensors communicate with the ECU and in turn, the ECU sends actuation signals to the valve, pump and the fan.

- As the engine generates heat, the coolant temperature at engine outlet,T_{Eng_out}, starts to increase. To maintain the temperature, the pump receives instructions from the ECU to take appropriate action.

- The hot coolant now flows through the radiator to reject the heat from the coolant to the environment. Since the valve is controlling the coolant temperature at the inlet of the engine, the actuation signal from the ECU instructs the valve to position itself to ensure that the coolant flow is distributed between the radiator and the bypass channel hence controlling the temperature at the engine inlet.

- If the inlet temperature continues to increase after the valve is completely open, the ECU actuates the fan to increase the airflow over the radiator. The additional air flow improves the heat exchange between the coolant, radiator and the ambient air hence controlling the temperature of coolant at the inlet.

The figure 3.10 shows a graph demonstrating the working of strategy 2. Graph A shows the coolant temperature at engine inlet T_{Eng_in} and the target temperature for the valve and the fan. The actuation of the valve can be seen in graph C. The curve moves from 0 to 1 indicating that the path to the radiator is open. The red arrows point to the actuation of valve because of the increase in T_{Eng_in}.

Graph B shows the pump target temperature and the temperature of coolant at engine outlet T_{Eng_out}. The actuation of pump can be seen in graph D. As T_{Eng_out} increases beyond pumps target, the pump increases its speed to compensate for the extra heat from the engine. With further increase in T_{Eng_out}, the pump speed increases upto its maximum.

In graph E, target fan speed is the fan actuation signal from the ECU. While the target speed is 0 initial actual speed is higher because of the ram air effect. Eventually, as the target speed increases, the actual fan speed follows. The green arrow points to the actuation of fan because of increase of T_{Eng_out} beyond the fan target temperature.

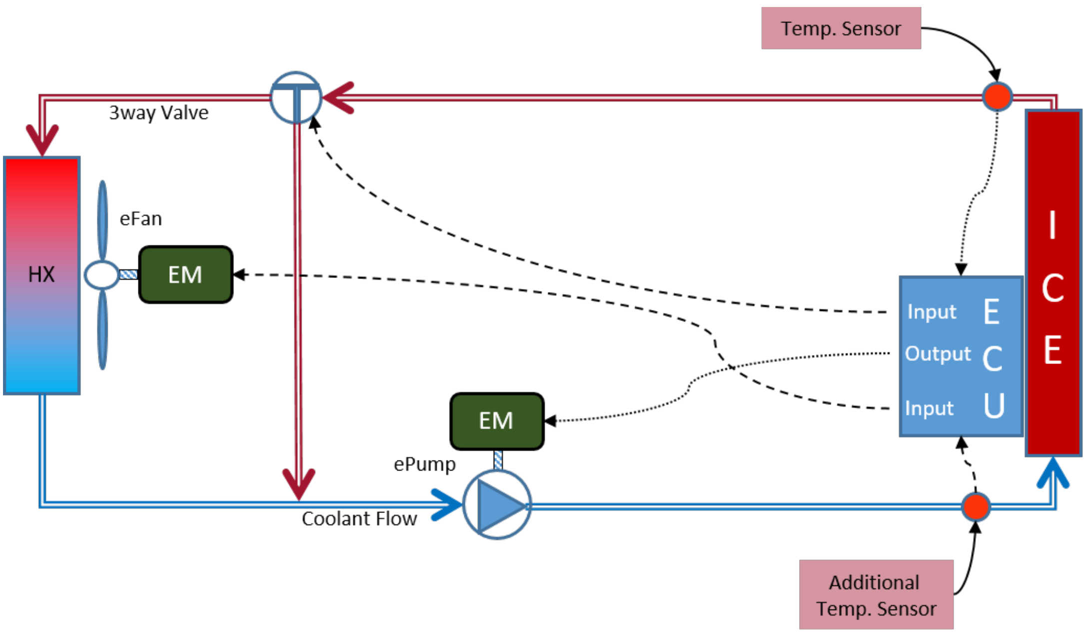

Figure 3.9: Demonstration of Strategy 2 of Electric Cooling System

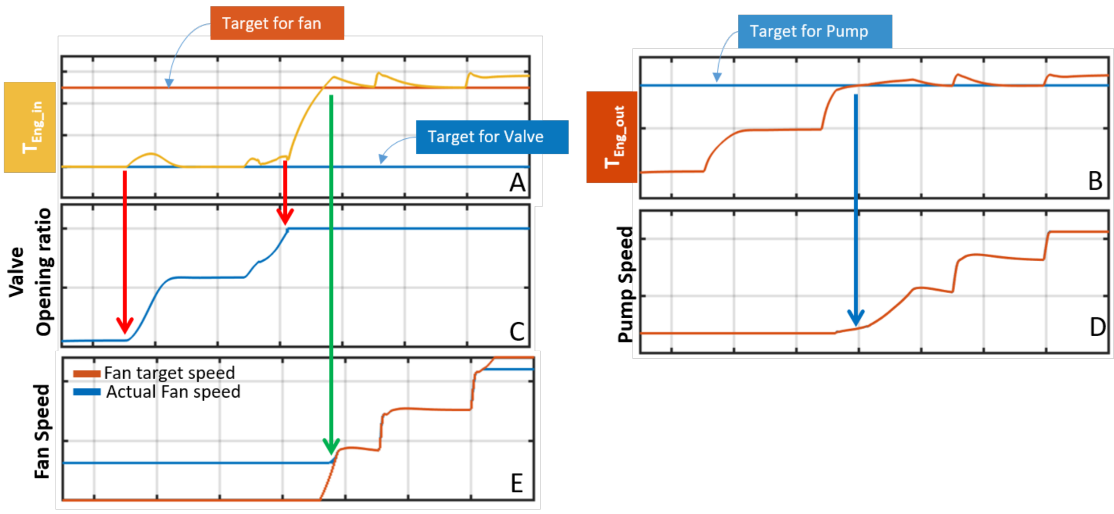

Figure 3.10: Demonstration of Strategy 2 of Electric Cooling System

3.5.3 Strategy 3: Control of engine inlet and outlet temperature with advanced pump control

This strategy is a combination of control of coolant temperature at engine inlet and outlet similar to strategy 2. The coolant inlet temperature is controlled by the valve and the fan, while the temperature at the outlet is controlled by the pump. In addition, while the fan is in operating condition, the pump is operated at a speed which maintains the coolant flow rate that produces the maximum heat exchange efficiency at the radiator. This strategy exhibits a possibility of improvement in power consumption of the pump without affecting the cooling performance. The following actions are taken by the cooling system when the temperature of the coolant increases

- The valve temperature controller in the ECU maintains the coolant temperature at engine inlet by actuating the valve. By varying the valve position, the amount of coolant passing through the radiator is controlled which in turn controls the temperature of coolant flowing through the engine.

- A fan temperature controller, regulates the the fan speed. When the inlet coolant temperature is higher than the fan temperature target, the fan starts to run at a a higher speed. Increase in fan speed increases the air flow over the radiator aiding in heat exchange. The fan target temperature value is set higher than the valve temperature target. At the time when the fan starts to operate, the valve is always completely open.

- The pump controller regulates the pump speed to maintain the temperature of the coolant flowing out of the engine. Varying the pump speed changes the mass flow rate of the coolant and hence the heat extracted from the engine is adapted. As the temperature of the coolant flowing out of the engine increases, the pump starts to increase its speed to increase the coolant flow rate through the engine. In addition to this, the controller also monitors the speed of the fan to calculates the heat exchange efficiency of the radiator according to the equation 2.5. If there is a possibility to lower the pump speed and not deteriorate the heat exchange efficiency, the controller reduces the pump speed to reduce the power consumption.

Figure 3.11 shows the Simulink model of the three temperature controllers and how the fan set speed data is the input to the pump temperature controller. The fan speed data is used to calculate the optimal pump speed. The fan speed data is continuously input to the pump temperature controller. As the fan starts to function, its speed information is used to calculate the pump speed corresponding to maximum heat exchange efficiency of the radiator.

Figure 3.12 shows the implementation of calculation of pump speed for maximum heat exchange efficiency. The calculation is done using pre-defined maps. The output of the first block in the figure 3.12 is the the mass flow rate of air over the radiator. The airflow rate is a combination of fan speed and vehicle velocity. The amount of air flowing over the radiator increases with increase in vehicle velocity due to ram air effect. The look up table contains data of influence of vehicle

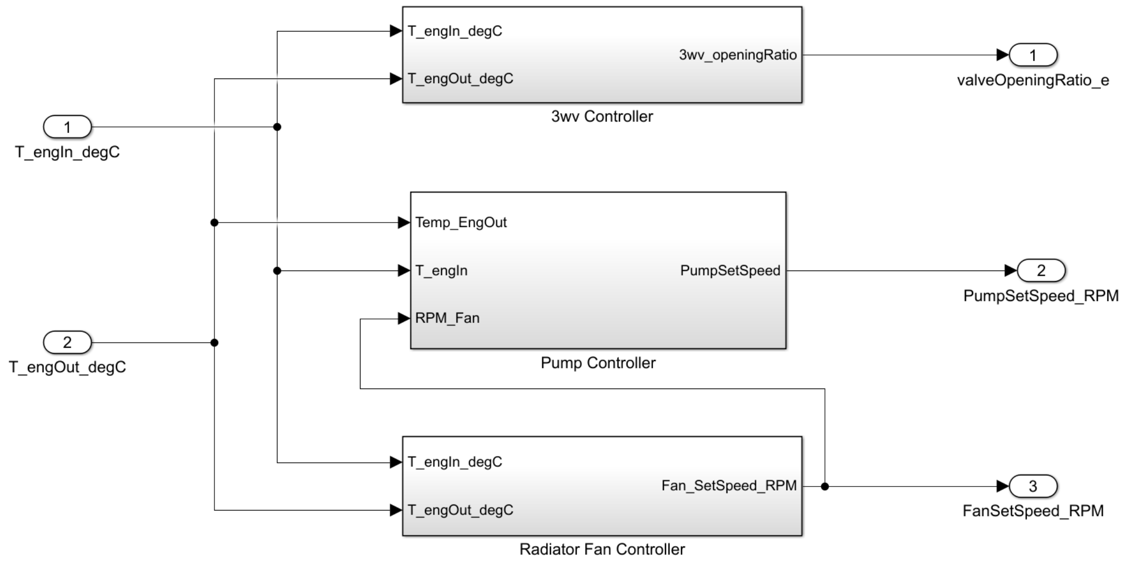

Figure 3.11: Simulink block showing three temperature controller blocks and communication between fan temp. controller and pump temp. controller.

velocity and fan speed for various distinct combinations. The block uses linear interpolation technique to compute the air flow rate for any combination of fan speed and vehicle velocity. The calculated air flow rate is the input to the second block $m\_coolFromM\_airFor\_max\_HX\_eff$ where the coolant flow rate is computed for a combination of air flow rate and maximum heat exchanger efficiency. The output of the second block is the coolant mass flow rate. The calculated coolant flow rate is used to calculate the pump speed in the third block. The third block $pumpRPM\_from\_m\_cool$ contains the relationship between pump speed and coolant flow rate. To keep the calculation simple, the position of valve is not accounted for the system back pressure, instead an average value (for valve fully closed and valve completely open) of pump speed is calculated.

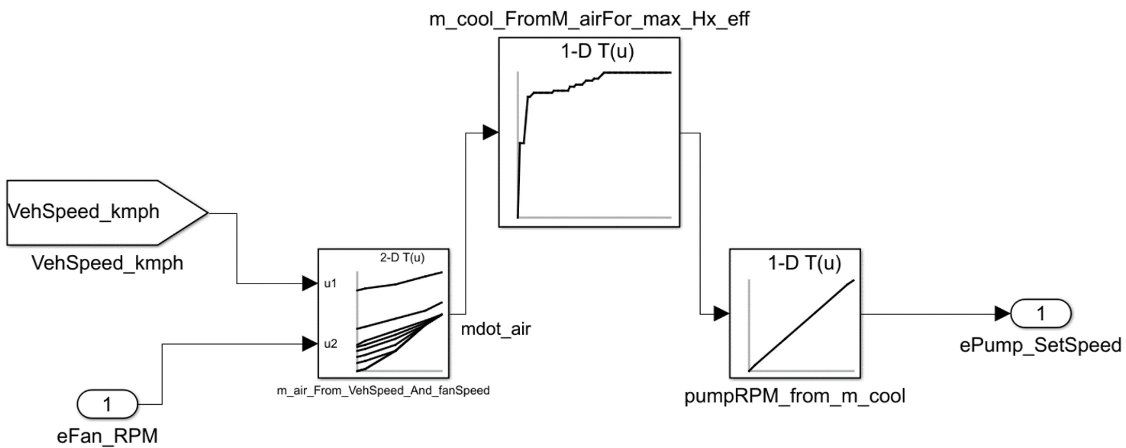

Figure 3.12: Simulink model for calculating pump speed corresponding to max. heat exchanger efficiency

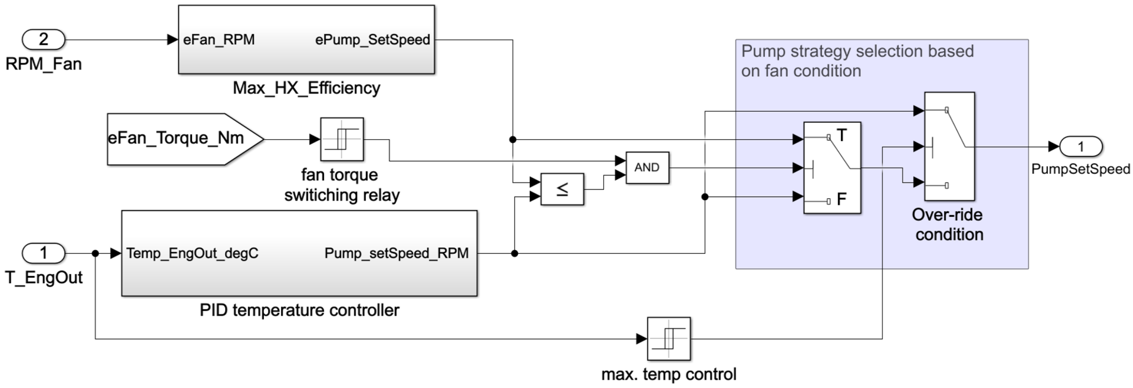

Figure 3.13: Simulink model of pump temperature controller. The PID controller block and Max_HX_efficiency block calculate the pump speed

At this stage, the pump temperature controller receives two sets of target speeds, one from the temperature PID controller and the other by calculating the maximum heat exchange efficiency corresponding to fan speed. If the calculated pump speed (taking fan speed as a reference and maximising heat exchange efficiency) is lower than the temperature controller speed, the pump will run at the speed corresponding to maximum heat exchange efficiency. In general, at any point, if the fan is working, the pump temperature controller will set the pump speed which is lower of the two values. In Simulink, this is implemented by taking the fan torque request as an enabling criteria and other conditional blocks. Figure 3.13 shows the implementation of this strategy in Simulink.

Maximising the heat exchange efficiency does not mean the actual heat exchange is also maximum. In very demanding conditions when the engine is producing tremendous heat, lowering the pump speed when the fan is working might not be an option. Pump speed switching override condition was developed for such cases. When the temperature of coolant flowing out of the engine exceeds a certain value, the pump will continue to follow the speed set by the PID controller even when the fan is working.

3.5.4 Strategy 4: Control of engine inlet and outlet temperature with pump speed based advanced fan controller

The fourth strategy was an inspiration and a development of the third strategy. Similar to the third strategy, the pump and the fan communicate with each other and run at a speed which produces maximum heat exchange efficiency. Unlike how the fan speed dictates the pump speed in the third strategy, the pump speed dictates the fan speed in this strategy.

The valve controls the temperature of the coolant at the inlet of the engine while the pump controls the temperature of coolant flowing out of the engine. The fan speed is set by the operating condition of the pump such that the heat exchange efficiency of the radiator is maximised. Irrespective of the pump speed, the inlet coolant temperature can be controlled as the valve can regulate the amount of coolant flowing thought the radiator by varying its position.

For instance, when the pump is running at the minimum speed and the coolant mass flow rate is low, if the coolant inlet temperature is higher than the target, the valve might positions itself at 50% open to satisfy the temperature target. In the other case when the the pump speed high and the coolant mass flow rate is high, for the same error in temperature as before, the valve would be completely open allowing all the coolant to flow through the radiator to maintain the temperature target. In this way, the valve and the pump can control the temperatures of coolant at the engine inlet and outlet.

Figure 3.14 shows the interaction between the pump temperature controller and the fan temperature controller. The fan temperature controller continuously receives the pump speed information. Based on the pump speed, the fan temperature controller calculates the optimal speed that the fan should operate in order to maximise the heat exchange efficiency.

Since the pump maintains a minimum speed to supply a continuous minimum coolant flow, with this strategy, the fan would also work at all times, even when the cooling demand is low. To avoid any unnecessary activation of the fan, a check on pump speed is continuously done to make sure that fan works only when the cooling demand is high. One way to assess the high cooling demand is when the pump is running at a speed higher than the minimum set speed. For example, figure 3.14 shows a block that compares the pump speed to a constant value. The speed check block's output becomes true when the condition is satisfied and vice verse, when the condition is not satisfied, the blocks output is false. The true condition activates the fan controller while the false condition from the speed check block instructs fan to stop working. In fact, one can come up with different conditions instructing the fan to operate. One such example could be the temperature of the coolant. If the temperature of coolant is higher than a specific set valve, the fan temperature controller can then start working and aid in cooling off the hot coolant.

Like previously stated, the fan temperature controller calculates the speed the radiator fan should follow based on the the pump speed. The coolant flow rate is one of the inputs to the fan controller. It is intuitive that, the heat exchange efficiency is maximum for a particular value of coolant flow rate and air flow rate. In other words, for a combination of specific coolant flow rate, the heat exchange

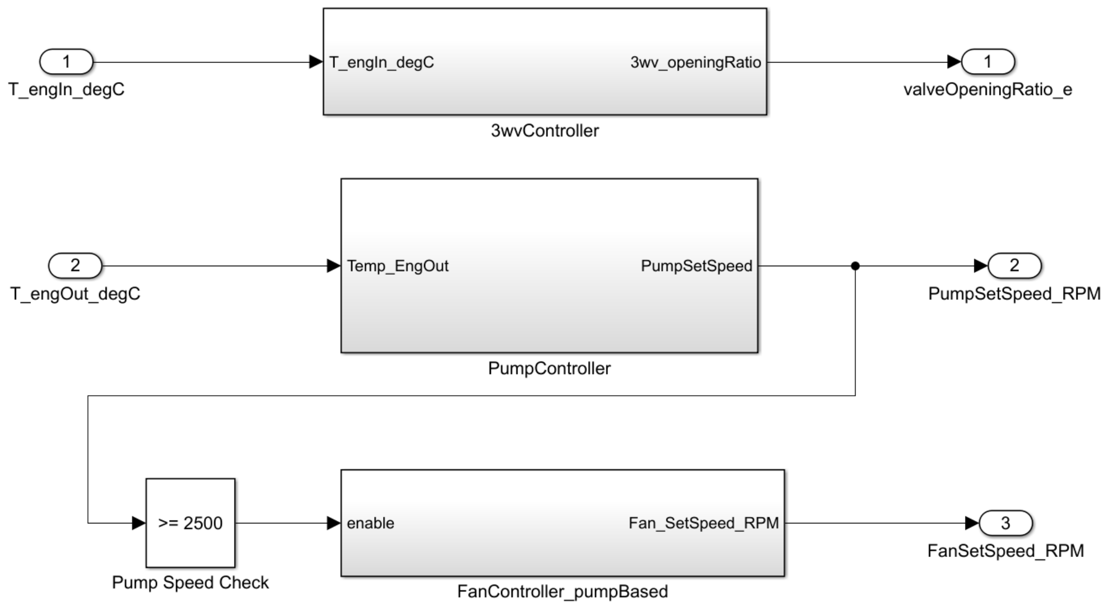

Figure 3.14: Simulink model demonstrating the interaction of pump and fan temperature controllers

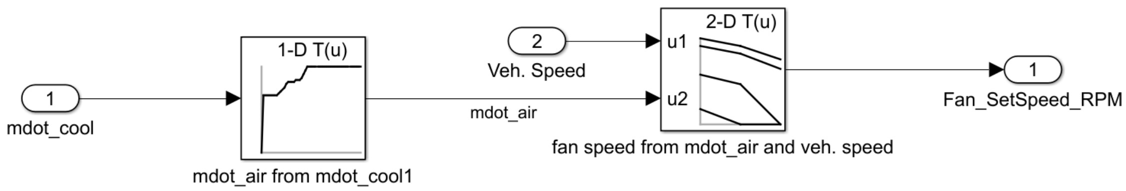

Figure 3.15: Schematic of fan temperature controllers

efficiency is maximum at a specific air flow rate. A matrix of data was generated with the optimal air flow as a result from a combination of coolant flow rate and the maximum heat exchange efficiency of the radiator. In figure 3.15, the block 'mdot_air from mdot_cool' contains a look up table which outputs the optimal air flow required to maximise the heat exchange efficiency for a specific coolant flow rate. The airflow over the radiator could be by any means, either the fan or by ram air. With vehicle in motion, specially at higher speed, the effect of ram air can be sufficient to provide the calculated optimal airflow. A second lookup table is used to set the fan speed. The vehicle speed is one of the inputs to this lookup table and the previously calculated optimal air flow is the other input. Based on the two inputs, the block calculates the fan speed. For instance, if the optimal airflow rate required is higher than what ram air can produce when the vehicle is running at a certain speed, the fan speed is set such that the additional requirement in air flow is provided by the fan. Conversely, when the ram air itself produces enough to maintain a good heat exchange efficiency, the fan speed would be set to zero.

4

Results

The performance of the electric cooling system will be discussed in this chapter. The aim of the thesis was to develop a methodology to implement an electric cooling system and/or convert a mechanical cooling system to an electric version in the simulation environment. Hence, the results presented are not absolute and need a lot of validation before we can rely on the simulation results. The results presented are only for a intuitive idea for the potential for the energy saving of the cooling system and an illustration of what can be done with the tool developed in this thesis.

Simulation were performed for multiple driving cycles. Results of some simulations and how the tool developed could be used is presented in the following sections. Results from the simulations can be used to understand the performance of the electric cooling system operating with different strategies. Though all the strategies showed good results in terms of coolant temperature regulation, some strategies were more energy efficient compared to others.

4.1 Simulation of electric cooling system running with strategy 1

The working principle of strategy 1 of electric cooling system is described in section 3.5.1. Since all the components work in response to the variations in the coolant temperature at engine outlet, at any time, only one of the three components is handling the regulation. The order of response is first the valve actuates, with further increase in the temperature of coolant, the pump increases its speed and eventually when the valve is completely open and the pump is running at full speed, the fan starts to work.

Figure 4.1 shows the results from simulation of electric cooling system running on strategy 1 . The three horizontal lines in the top graph are the target temperatures of valve, pump and fan. The second graph shows the instantaneous position of valve over simulation time. When the valve position is 1, it is completely open and when the valve position is 0, it is completely closed. The third graph contains two lines overlapping each other. The blue line represents the actual speed of the pump while the orange line represents the target speed for the pump set by the pump temperature controller. The two lines overlapping each other is a good indication that the pump speed controller is performing well to keep up with the changes in the target speed.The fourth graph shows the fan speed. The blue line represents the actual speed of the fan while the orange line represents the target set by the fan temperature controller. Though the fan temperature controller set the speed to zero, the actual speed of the fan in not zero as the ram air flowing over the fan though the front grill keeps the fan in motion. This rotation of the fan does not produce any work nor does it consume any energy. The dip in the actual fan speed at the end of the simulation is due to the reduction of vehicle speed which causes the reduction of ram air velocity and consequently, the fan speed reduces.

Since only the outlet temperature is controlled in this strategy, the three components react to the changes in the coolant temperature at the engine outlet,T_{Eng_out}. It is evident from the figure, as T_{Eng_out} increases, the valve initially tries to position itself in order to maintain T_{Eng_out} at the target value. With increase in temperature beyond the target value, the valve completely opens and stays open until T_{Eng_out} is reduced to the set target.

As the actuation of the valve is able to maintain T_{Eng_out} at or below the target temperature, the pump and fan are hardly active. However, the pump is always running at a minimum speed to be able to maintain a minimum coolant flow rate. Towards the end of the simulation, when T_{Eng_out} increases beyond the pumps target value, the pump speeds up to bring down the temperature below the target value.

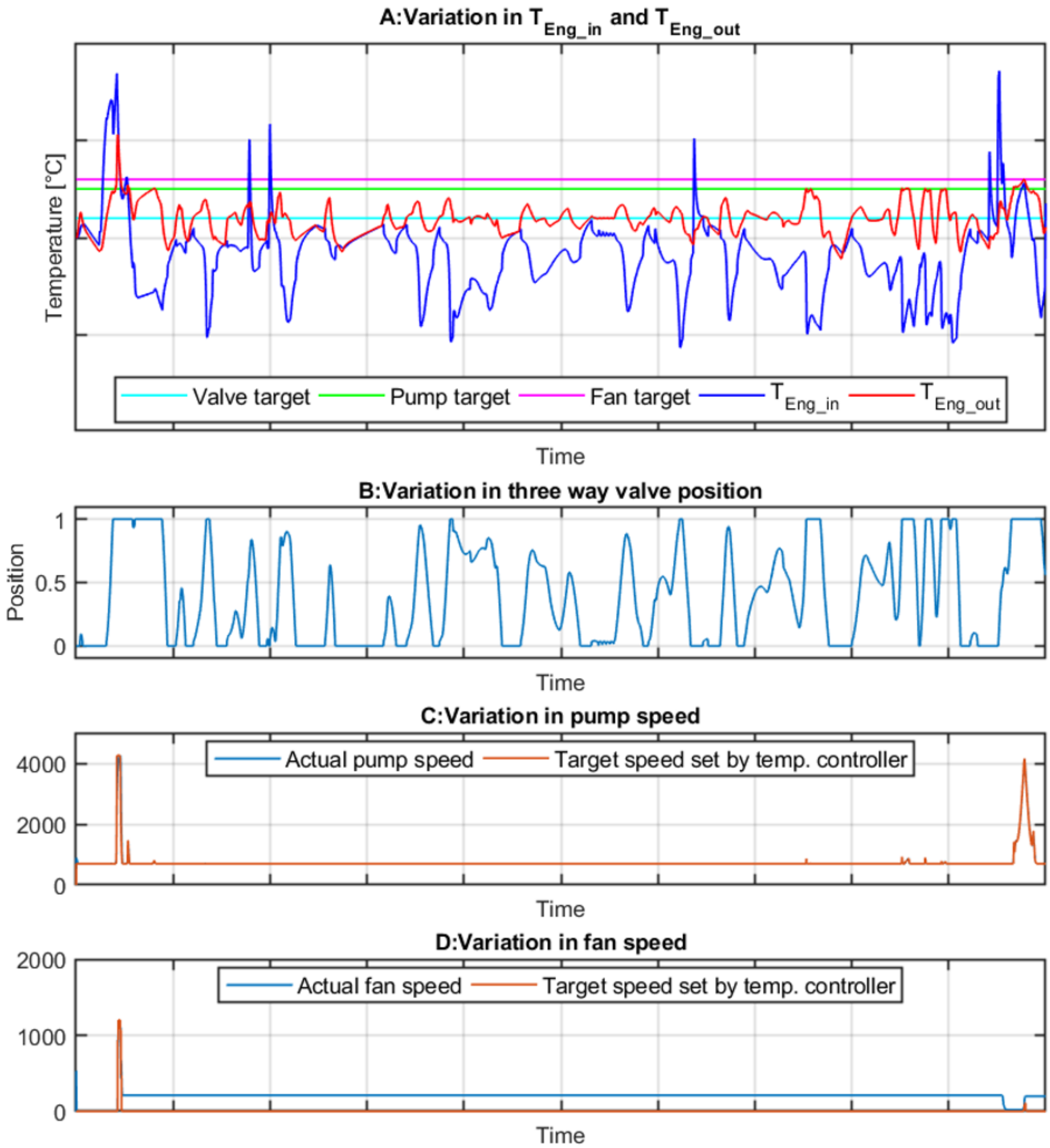

Figure 4.1: Simulation results of electric cooling system running on strategy 1

4.2 Simulation of electric cooling system running with strategy 2

In the second strategy, the inlet and outlet temperatures are controlled. While the valve and fan control the T_{Eng_in}, the pump controls the T_{Eng_out}. As the inlet temperature increases, the valve actuates first and with further increase in the inlet temperature, the fan starts increasing speed. Similarly, the pump increases its speed in T_{Eng_out} increases.

Figure 4.2 shows the variation in the T_{Eng_in} and T_{Eng_out} along with the target temperatures of the valve, pump and fan temperature controllers. To interpret the simulation results, the graph is reorganised.

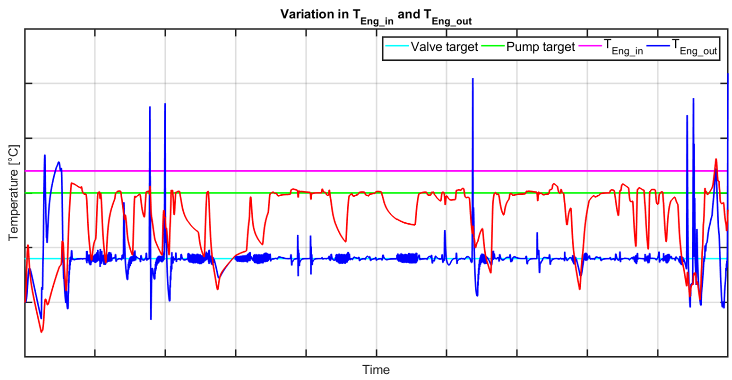

Figure 4.2: Variation in coolant inlet and outlet temperature; electric cooling system strategy 2

The graphs in the figure 4.3 are the results from simulations of electric cooling system running on strategy 2. The horizontal lines in Graph A are the target temperature values of the valve and fan while the horizontal line in graph D is the target temperature values of the pump. Graph A shows T_{Eng_in}. Graph B which shows the position of valve over time, it is clear that as T_{Eng_in} increases, the valve moves from 0 to 1. This indicates that T_{Eng_in} is increasing. In order to maintain T_{Eng_in}, the valve starts to open a path for a part of the coolant to flow through the radiator for it to cool off. If T_{Eng_in} continues to increase, the valve completely opens and all the coolant flows though the radiator. If T_{Eng_in} continues to increase after the valve is completely open, the fan starts to operate to increase the air flow over the radiator to increase the heat exchange capacity. It is clear from the graph B and C, that the fan only operates when the valve is completely open. This allows to maximise the effort of the fan to cool off as much coolant as possible. This way, the inlet temperature is controlled.

Similar to valve and fan, the pump also responds to the variation in coolant temperature. Unlike the valve and fan, the pumps response depends on the coolant temperature flowing out of the engine, T_{Eng_out}. With increase in outlet temperature, the pump increases its speed to increase the coolant flow into the engine. Towards the end of the simulation, the pump increases its speed drastically to compensate for the increase in T_{Eng_out} beyond the target temperature.

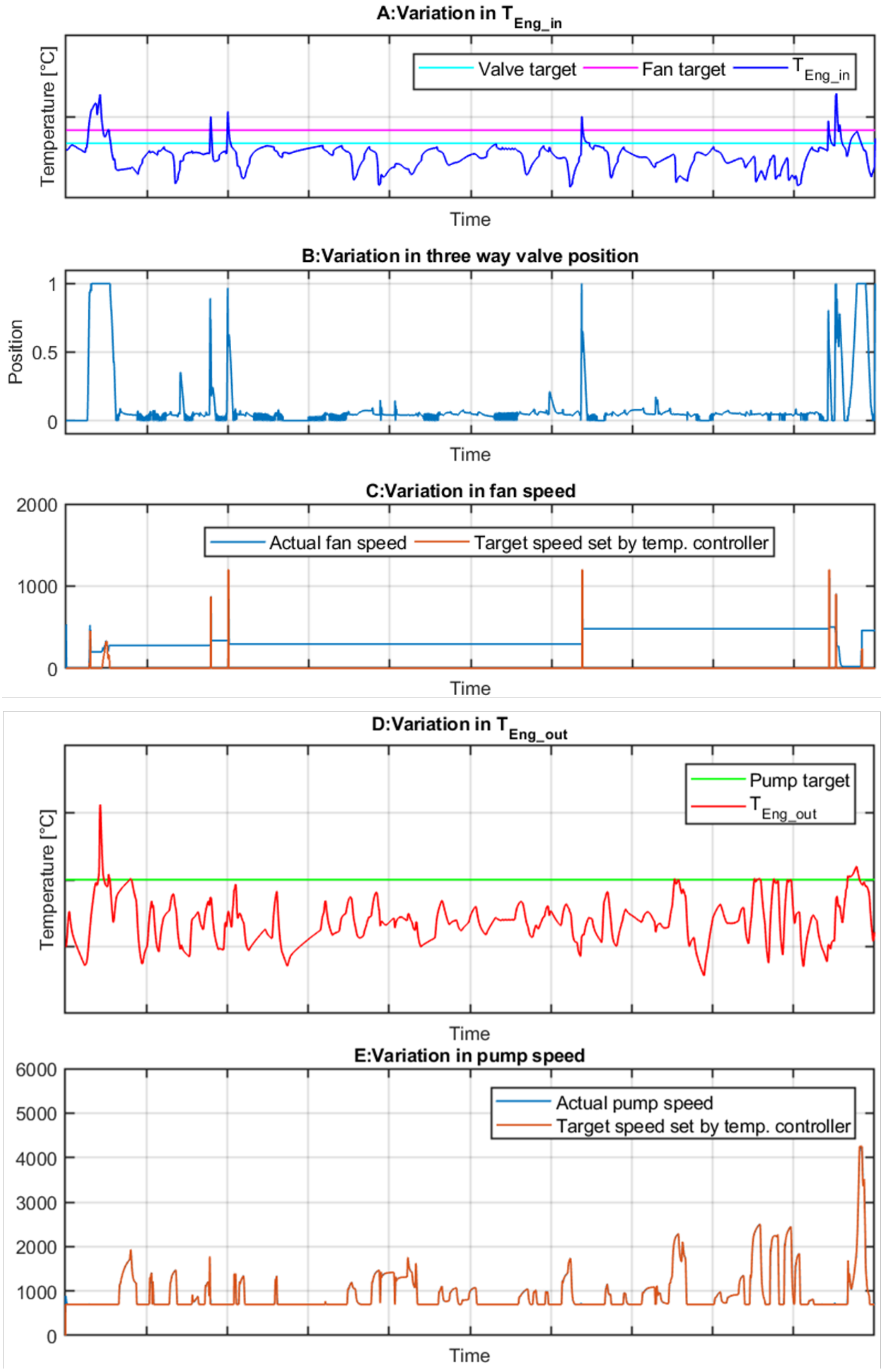

Figure 4.3: Simulation results of electric cooling system running on strategy 2

4.3 Simulation of electric cooling system running with strategy 3

Strategy 3 is very similar to strategy 2, where the valve and fan control T_{Eng_in} while pump controls T_{Eng_out}. As discussed in section 3.5.3, the pump temperature controller communicates with the fan controller to decide the pump speed in order to improve the heat exchange efficiency. The effect of the communication between the two controllers will be demonstrated in this section.

Figure 4.4 are snippets of pump speed and fan speed comparison when the electric cooling system is running on strategy 2 and 3. Graph A shows the reduction in pump speed as the fan starts to work. Discussed in section 3.5.3, as the fan starts to increase its speed, the temperature controller gets two values of the pump speed to be set

- Speed calculated by the PID controller based on the difference between set target temperature and actual temperature T_{Eng_out}
- Speed calculated based on the fan speed to maximum heat exchange efficiency

In a particular case shown in the figure 4.4, when the pump speed set by the fan is lower than the speed set by PID controller, the pump speed is set to the lower value.

However, maximum efficiency of heat exchange does not always correspond to maximum heat exchange. Improving the heat exchange efficiency was an attempt to improve the heat exchange process in the radiator by lowering the pump speed to conserve energy. If the lowered pump speed and maximising the heat exchange efficiency does not maintain the coolant temperature, an override command switches the pump speed back to the value set by the PID controller.

Figure 4.5 shows the cumulative energy consumption of the pump and the fan when running on strategy 2 and strategy 3.

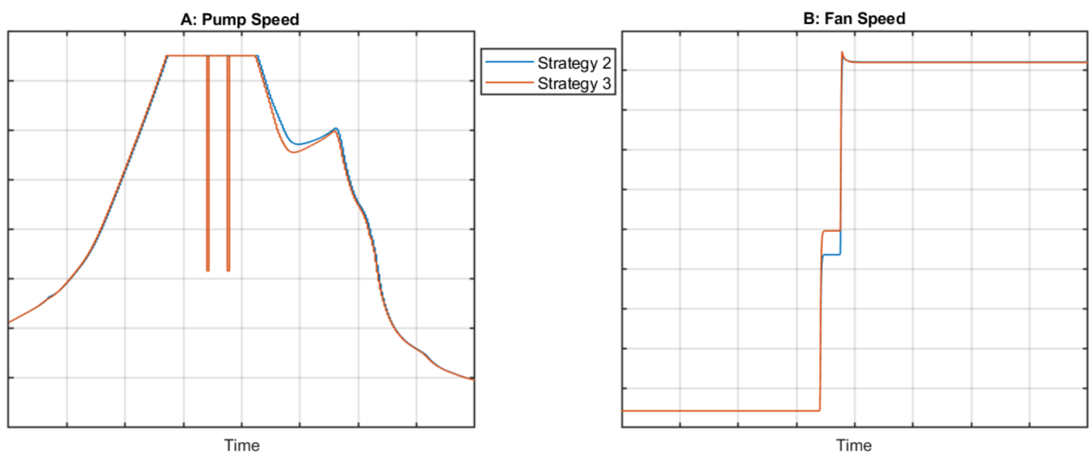

Figure 4.4: Influence of fan speed on pump speed:Electric cooling system on Strategy 3

When comparing the pump energy and fan energy consumption, it was observed that in strategy 3, when the pump speed reduces, a slight increase in fan energy consumption is observed. However, when comparing the total energy consumption approximately 3% reduction in total energy consumption is observed in electric cooling system running on strategy 3 compared to strategy 2.

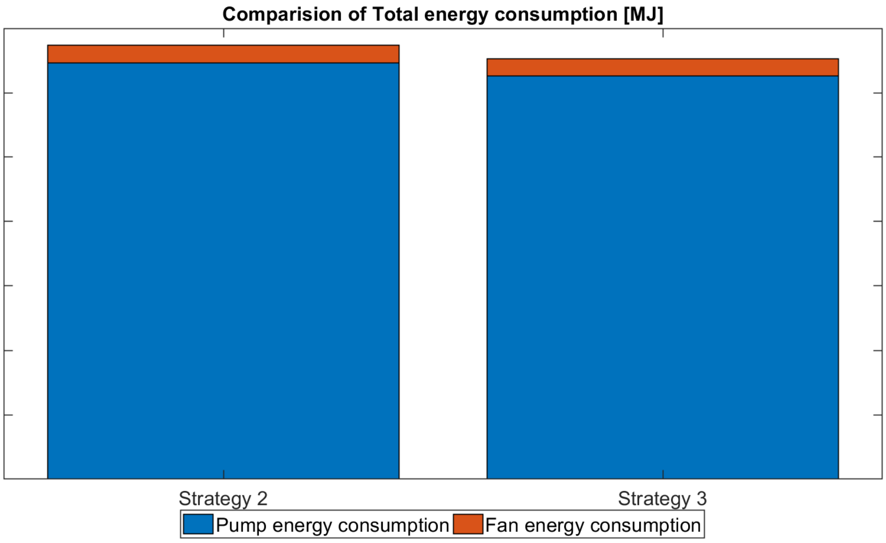

Figure 4.5: Comparison of energy consumption

4.4 Simulation of electric cooling system running with strategy 4

In strategy 4, the fan temperature controller is removed since the fan is always controlled by the pump. The fan would become active when the pump speed increases beyond 2000RPM. The valve controls T_{Eng_in} while the pump controls T_{Eng_out}. Figure 4.6 are the results from simulation of strategy 4. Graph A shows the target temperatures of the valve and pump and also the instantaneous T_{Eng_in} and T_{Eng_out}. In graph B, the valve position is shown. Valve position 0 refers to fully closed and valve position 1 refers to fully open. As the T_{Eng_in} increases, the valve opens a path for coolant to the radiator. However, the valve remains mostly always closed since the T_{Eng_in} is well maintained at the valve target temperature.

Graph C in figure 4.6 shows the pump speed while graph D shows the fan speed. It can be observed that, as the pump speed reached 2000RPM, the fan also increases its speed.

With this strategy, the inlet and the outlet temperatures are well regulated. However, in situations when the load on the engine is high but the vehicle is moving at low speeds, the heat exchange at the radiator might deteriorate due to lack of airflow. At these instances, the fan should be able to function to aid the airflow requirements. This strategy might be an issue since there is no control of the fan with respect to the coolant temperature. In high load and low speed situations, for example when the vehicle is travelling up hill at a very slow speed, for the fan to operate, first the pump need to increase its speed and then the fan begins to operate. An override function needs to be implemented so that the fan can operate when required without following the pump speed.

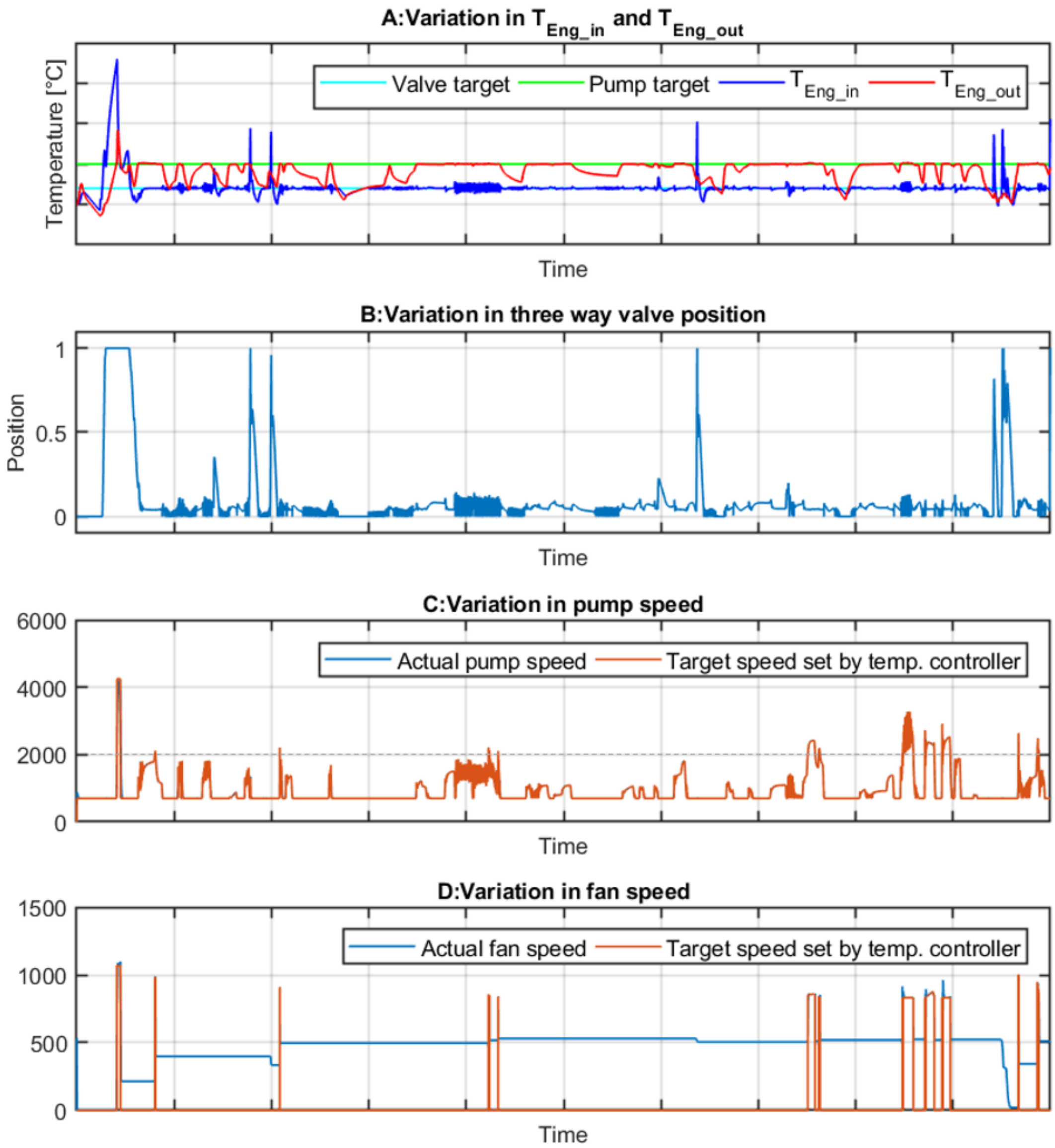

Figure 4.6: Simulation results of electric cooling system running on strategy 4

5
Discussion

The results presented in the previous section will be discussed here. With a new tool to simulate the electric cooling system, various strategies along with multiple conditions for the operation of the components can be implemented and tested. As seen from the results of strategy 3, with an addition of a condition to lower the pump speed, we can have a potential to save the energy consumed by the electric cooling system. To implement the electric cooling system, it is also important to determine the source of electricity. If the alternator which is run by the engine is used to charge the batteries, it is important to take into account the additional load on the engine to generate the energy required by the cooling system. It is a trade-off between the temperature performance requirement and the energy consumption. A strict temperature regulation will tend to consume more energy compared to when the temperature regulation requirements are a little flexible.

Comparing strategy 1 to strategy 2, the energy consumption of the electric cooling system is lower in strategy 1. This however comes with a drawback of not being able to maintain the difference between T_{Eng_in} and T_{Eng_out}. In complex engines where it is important to maintain a small temperature gradient, implementing strategy 2 or 3 would yield a good result compared to running the electric cooling system on strategy 1.

Figure 5.1 shows a plot of distribution of coolant temperature difference. The x-axis is the temperature difference ($T_{Eng\_out} - T_{Eng\_in}$) and y-axis shows the number of times the temperature difference occurred in the simulation at a particular value.

T_{Eng_in} and T_{Eng_out} were set 8°C apart in the simulations. It is clear from the image that strategy 2 and 3 perform well in terms of temperature regulation. The average temperature difference is around 8°C with not much deviation with the maximum difference being 10°C. While similar results are observed in results from strategy 4, when the electric cooling system was running on strategy 1, the coolant temperature difference ranges from about −20°C to 30°C. These larger values in coolant temperature difference might not be acceptable. Temperature of coolant is proportional to the temperature of the engine block and a large difference in T_{Eng_in} and T_{Eng_out} suggests that the two ends of the engine block are at varying temperatures. The gradient in block temperature might cause uneven expansion of metallic parts and may be a cause for potential damage of engine parts.

However, strategy 1 consumes the least energy compared to the other strategies. Figure 5.2 shows the energy consumption of pump and fan running on all four strategies. Since strategy 2 and 3 are very similar, the difference in the energy consumption becomes larger with longer driving cycles. The probability of the number of times the pump switches its speed to increase the heat exchange efficiency

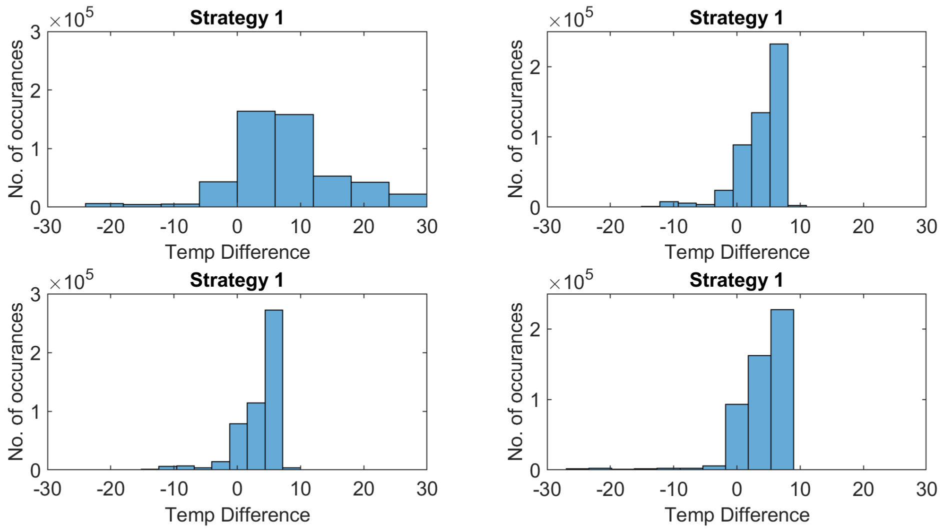

Figure 5.1: Distribution of temperature difference

in strategy 3 increases with increase in simulation distance. This will eventually lead to reduced energy cost compared to strategy 2.

The fan energy consumption in strategy 4 is relatively higher because every time the pump speed exceeds a set value, the fan becomes active irrespective of its necessity. A better switching condition for the fan to turn on or off will improve the energy efficiency of cooling system.

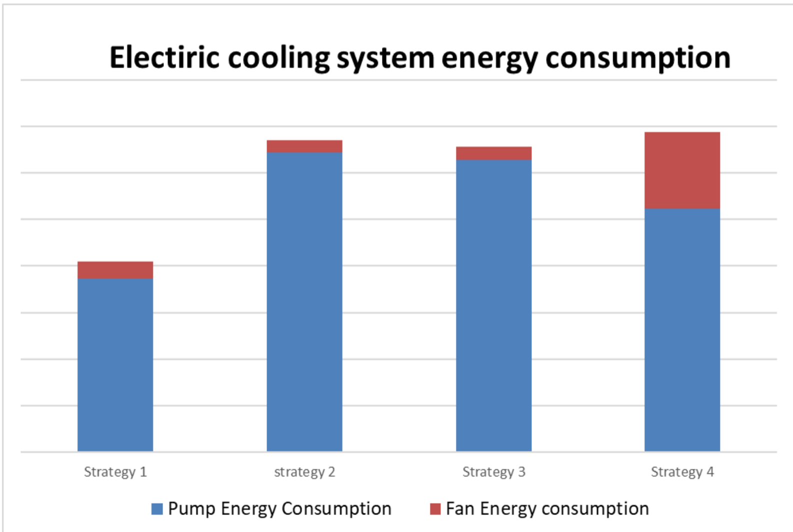

Figure 5.2: Comparison of energy consumption of pump and fan of electric cooling system running different strategies

To compare the mechanical cooling system to that of the electric is a difficult task since the mechanical cooling system does not work on feedback control but rather on certain conditions based on the data from the coolant temperature sensor at the outlet of the engine. The aim of the mechanical cooling system is to avoid peak temperatures in the engine and the coolant, while the electric cooling system aims to maintain the temperature of the engine and the coolant at a particular value.

Figure 5.3 shows the variation in coolant temperature at the engine inlet and outlet. It can be clearly observed that the electric cooling system running on strategy 2, 3 and 4 have good control over the temperature. The T_{Eng_in} and T_{Eng_out} are regulated at certain values which were the chosen targets of the temperature controller. In strategy 1, T_{Eng_out} is regulated quite well, while T_{Eng_in} doesn't exhibit any obvious peak value and also has a wide range of values, both less than and more than the target value. The temperature distribution in strategy 1 is somewhat similar to that of mechanical cooling system with improvements in the control of outlet temperature. While, the temperature range is wide for both T_{Eng_in} and T_{Eng_out} when running on the mechanical cooling system,T_{Eng_out} is well regulated when running on electric cooling system with strategy 1.

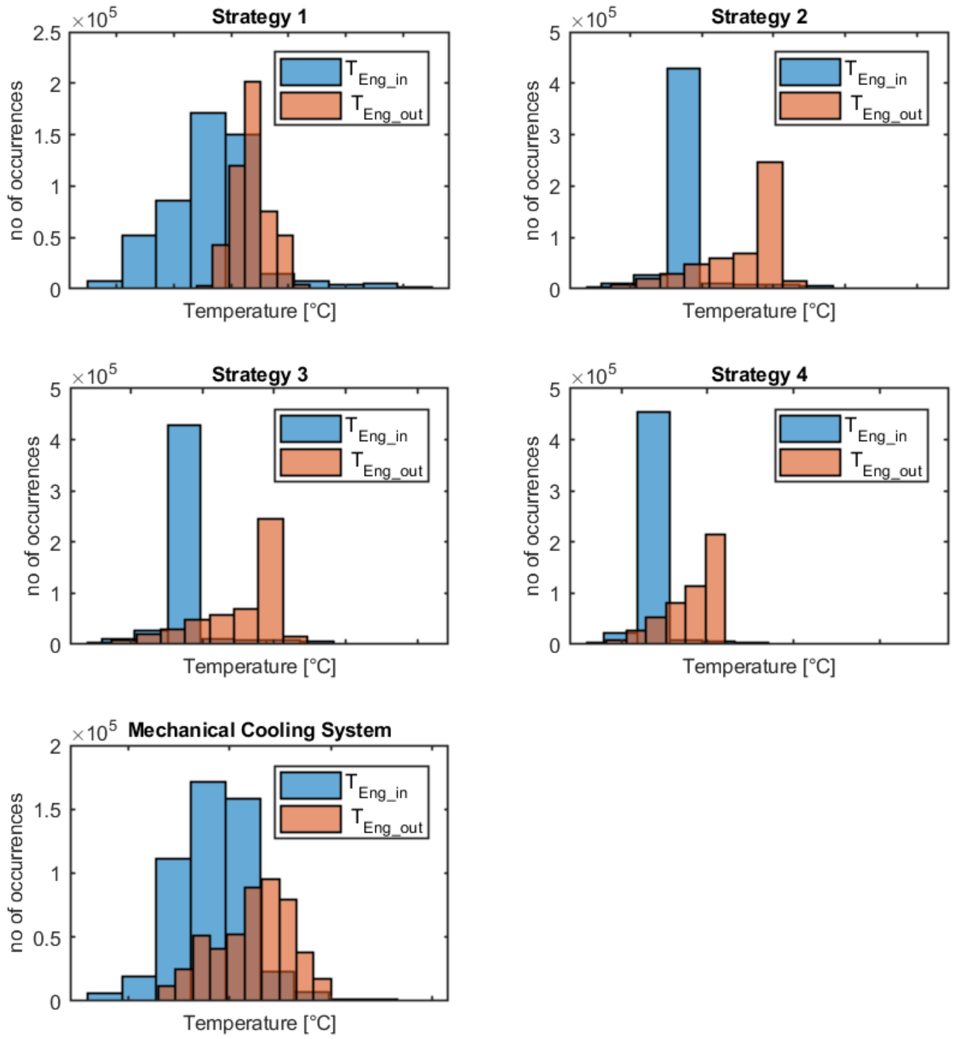

Figure 5.3: Comparison of inlet and outlet temperature distribution between mechanical and electric cooling system with different strategies

The electric cooling system can easily be deployed in a wide range of vehicles. Commercial vehicles can be broadly classified based on their application. Some vehicles are used within the city limits to deliver goods. These vehicles generally run at low speeds with multiple start and stops, sometimes even long idle time. Some vehicles are mostly used for long haul applications for transporting good from one city to another, and maintaining highway speed. Sometimes, these vehicles need to navigate extreme terrains and even different weather conditions based on its location. Implementing a cooling system for vehicles with different cooling needs and optimising energy consumption becomes a tedious task working with mechanical system. The ratio between the engine speed and pump speed needs to be optimised, the valve need to be calibrated for a particular vehicle are some of the tasks among other modifications. Moreover, an OEM would need to maintain a catalogue of same components that fit in different vehicles. With electrification of the cooling system, many of the components can be commonised and with changes in the software, they can be controlled as desired. Figure 5.4 shows the variation in coolant temperatures and coolant temperature difference for 3 cases with different minimum pump speeds. Base speed refers to the min pump speed that would maintain a min coolant flow that was one of the requirements. If we could challenge the minimum coolant flow requirement, there is a chance that the minimum pump speed could be reduced and in other case when the minimum flow requirement is increased, the minimum pump speed also need to be increased. To make these changes, a modification in the software would be enough and no changes in the hardware is required. From the figure 5.4, it can be observed that, even with different minimum pump speed values, temperature regulation can be achieved as required. Reducing the minimum pump speed would also reduce the pump energy consumption further adding to the savings. On the other hand, increasing the minimum pump speed increases the energy consumption. Challenging the requirements allows to improve the energy efficiency of the system without hampering the cooling performance.

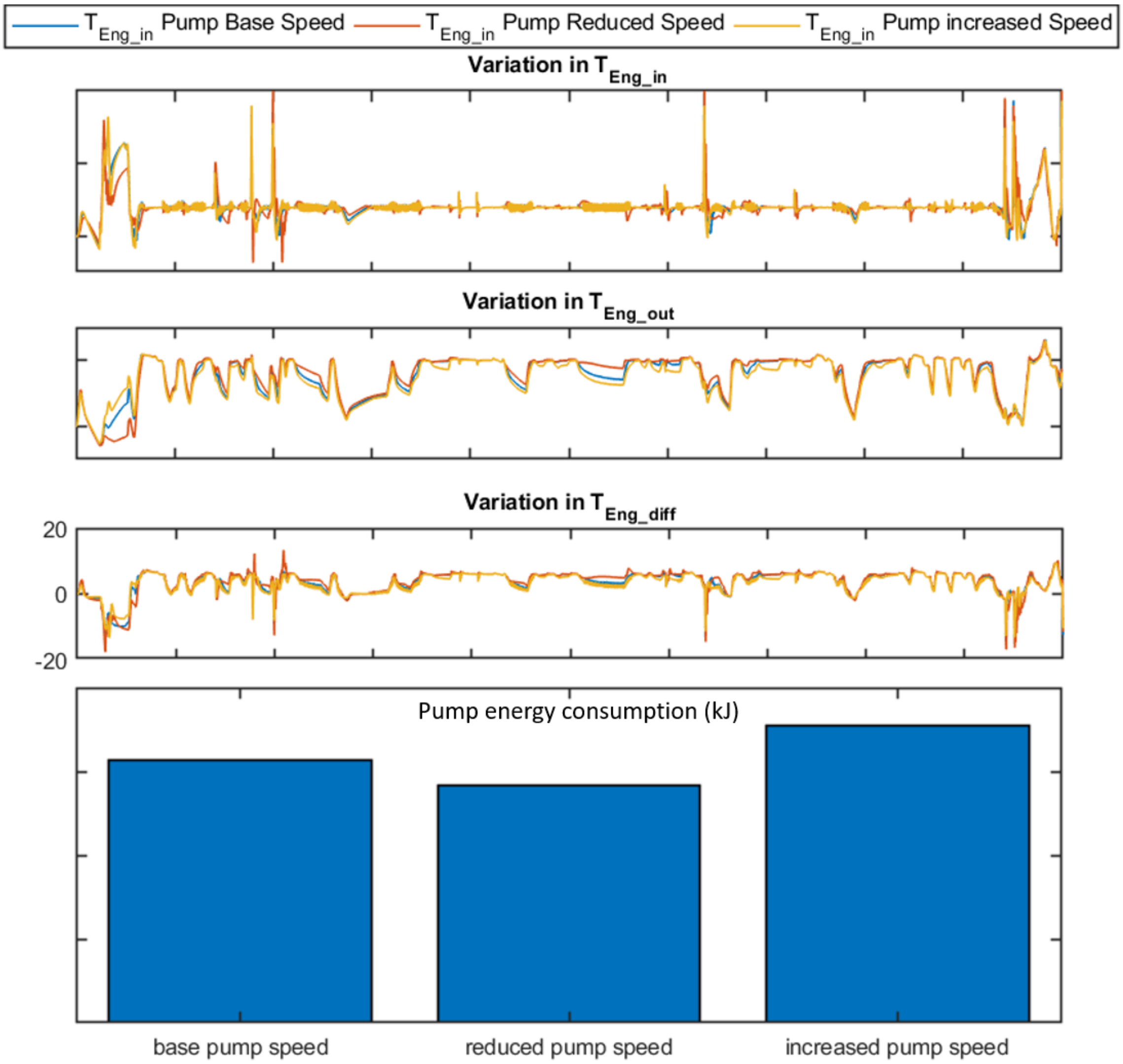

Figure 5.4: Coolant temperature variation and pump energy consumption for differnt values of minimum pump speeds

6
Conclusion and future work

While this report demonstrated satisfactory results of electric cooling system in the chapter4, it was only to showcase the idea of how electrifying the cooling system could benefit in terms of thermal management of the engine. Electrifying the cooling system allows the vehicle manufactures to optimise the cooling strategy and also the component size. Like seen in the results, with certain strategies, the pump hardly runs at full speed. This could be an indication to explore the possibility to downsize the pump. Similarly, the fan can also be downsized to meet the requirement. With downsized components, they can be run at much more efficient operating points and smaller components also reduce the vehicle weight. Reducing the weight of each component can cumulatively impact the the weight of the vehicle and improve the fuel efficiency of the vehicle. In trucks, weight reduction is specially important as this allows to carry a larger payload on the road.

With electric cooling system, the temperature of the engine can be precisely controlled which paves way to improvement in fuel combustion efficiency. Warmer engines also reduce the heat losses leading to improved fuel efficiency. In addition, with fewer and less extreme thermal stress on the engine block, the durability of the engine can also be extended.

While discussing the implementation of electric cooling system on a conventional truck with an IC engine, it is important to consider the availability and production of electricity to operate the electric motors that run the pump and the fan. On a conventional truck, the batteries supply the required energy to the engine accessories, including the cooling system. The batteries are charged by an alternator which is driven by the engine. In other words, though the electric cooling system can seem to be more efficient, the energy required by the electric cooling system is in turn generated by the engine. This might become counterproductive. The product of this master thesis can be used to assess the benefits of electrifying the cooling system on a conventional truck using simulation tools and mathematical models of the entire vehicle. From the early stage of development of a new vehicle, the tool can be exploited to test various cooling strategies and select the most appropriate one for the vehicle application.

Electric cooling system can be seen as a big possibility to be adapted in the hybrid trucks where, the energy lost in braking is used to charge the batteries. The energy from the batteries can be used to power the electric cooling system and other accessories.

Future work

With the developed tool, more strategies can be developed to run the electric cooling system. Rule based conditions can be imposed to attain a specific requirement. A few recommendations to continue the research on the cooling system are listed below

1. With more focus on mathematical modelling of the cooling system, many approximations can be eliminated leading to much realistic results. For example, while while the valve changes its position specially when it moves from fully open to closing position, the back pressure in the system decreases which causes the pump to increase it speed abruptly. Investigation on this and updating the model to eliminate this overshoots in the pump speed will lead to better simulation results

2. Using actual data instead of some assumptions will also add to the improvement of the results. The efficiency data of the electric machine can be gathered and updating the model with the actual efficiency instead of using standard value will also tend to better and reliable results.

3. Exploring more pump and fan technologies to attain better control over the dynamics of the process might also add to the improvement in the efficiency of the cooling system. For example, investigating the effect of replacing a big fan with array of smaller fan on the radiator might be interesting. With smaller fans, there might be a possibility to use only some of the fans close to the coolant inlet (inlet of radiator) where there temperature of the coolant is high. Improving the air flow over warmer coolant will improve the heat exchange efficiency without spending large amounts of energy.

4. Exploring feed forward and predictive control to reduce the overshoots in the coolant temperature. When there is information about the high power demand(from pedal position or from GPS data), the pump and fan can already start to work faster even before the coolant becomes too hot. This will enable to re-calibrate the target temperature of the components and making them work lesser than usual hence adding to the energy savings.

5. With active control over the cooling system components, there is a possibility to down sizing the pump and fan. The components can be selected such that they are operated at the most efficient conditions to improve the energy consumption. The cooling system can be designed to suit vehicles with specific driving patterns. This can include the strategy selection and the selection of the components.

Bibliography

[1] *Introduction to Centrifugal Pumps*. URL: http://www.wermac.org/equipment/pumps_centrifugal.html.

[2] *How it Works:The Radiator*. URL: https://www.uniquecarsandparts.com.au/how_it_works_radiator.

[3] T. Kuppan. *Heat Exchanger Design Handbook*. CRC Press, 2000.

[4] *Radiator Fan*. URL: https://www.google.com/imgres?imgurl=https://i.ytimg.com/vi/4U419tXwnRg/maxresdefault.jpg&imgrefurl=https://www.youtube.com/watch?v%3D4U419tXwnRg&docid=mtrth2-vVeJMEM&tbnid=9nVHapkFAroroM:&vet=1&w=1280&h=720&source=sh/x/im.

[5] *Thermostat*. URL: https://www.mein-autolexikon.de/fileadmin/user_upload/Inhalt/Produkte/Thermostat/thermostat-2.jpg.

[6] Vance Vandoren. *Fundamentals of Lambda Tuning*. URL: https://www.controleng.com/articles/fundamentals-of-lambda-tuning/.

[7] *Efficiency mapping and performance across a duty cycle*. URL: https://www.motor-design.com/motor-cad-software/lab/.