POLITECNICO DI TORINO

**MASTER OF SCIENCE IN AUTOMOTIVE ENGINEERING**

**Master Degree Thesis**

**March 2021**

# GT-POWER SIMULATION OF LIGHT-DUTY TURBO DIESEL ENGINE (1.9L) WITH ELECTRIFIED WATER PUMP TO EXPLORE EFFICIENCY IMPROVEMENTS

Prepared by:

**MUHAMMAD YOUSUF TABREZ**

| | | |
|---|---|---|
| SUPERVISORS: | **Prof. Dr. Andre Boehman** | **University of Michigan** |
| | **Dr. Robert Middleton** | **University of Michigan** |
| INTERNAL SUPERVISORS: | **Prof. Dr. Stefano D'Ambrosio** | **Politecnico Di Torino** |
| | **Prof. Dr. Roberto Finesso** | **Politecnico Di Torino** |

## ABSTRACT:

The intend of this Master's thesis work is to explore the possibility of implementing electric water pump or an electrified cooling system that provides the means of controlling the circulation rate of coolant through the engine, which helps the engine to get hot faster and reducing the cold start time/period. The assessment is performed using the simulation software GT-Power on a Transient Warm up Drive Cycle Split Cooling.

The work starts with a bibliography review about researches with an electrified cooling system, to increase the vehicle performance and fuel efficiency.

In this thesis work, the electrified cooling system has been developed starting from the given model (1.9L Light-Duty Turbo Diesel Engine) which has been built for previous year project in University of Michigan, USA. Using the model in GT-Power i.e. Transient Warm-Up Drive Cycle with split cooling, the electrified cooling system is modified and made it consistent with the 1.9L given engine model.

Simulating four different cases using the entire New European Driving Cycle (NEDC) and Worldwide harmonized Light-duty vehicles Test Cycle (WLTC), it has been found that, electrified water pump running at 3000 RPM or above this speed, the fuel consumption increases and oil temperature tends to increase slowly. On the contrary, when electrified water pump running at 1000 RPM or lower than this, it requested less electric power, increased oil temperature and provide benefit of fuel consumption and at the same time it shortens the engine warm-up time (cold phase).

It resulted that Electrified Water Pump system requires electric motor and battery, but still installing these, we have benefit of fuel consumption of 1.3% approx. and shortens warm-up time with respect to baseline engine model.

# Contents

# LIST OF FIGURES

# LIST OF TABLES

# ACKNOWLEDGEMENTS

This thesis work comes at the end of my Master's degree journey, during which many people accompanied me, who have always been there or that they have come into my life, they have been close to me in a thousand different ways. I would like to express my deepest gratitude to my supervisors, Professor Andre Boehman, Robert Middleton, Professor Stefano D'Ambrosio, and Professor Roberto Finesso who supervised and directed me in the right direction while carrying out my Thesis work. I am thankful to my supervisors for their continued support.

Now, I want to thank all those who have not helped me materially to the preparation of this thesis work, but spiritually. Thanks to my parents, my number one inspiration who have always believed in me, and they always guided me to the right path and supported me throughout this entire journey. Thanks to my better half, with whom I shared everything, that manages to bring out the best in me. Thank you for your sincere advice and for the support. Thanks for always being there.

Thanks to all my friends and colleagues of Politecnico, the affection that you people continuously demonstrate throughout this entire journey.

# CHAPTER 1: INTRODUCTION

## 1.1. VEHICLE ELECTRIFICATION & ADVANCED THERMAL MANAGEMENT SYSTEM:

Vehicle electrification has been identified as one of the innovative technology driven trends in the automotive sector. On one end, electrification is being pushed by stricter environmental regulations about emissions. On the other hand, it is pulled by an increasing widespread customer acceptance.

In response to demands for improved fuel economy and current trends of rising heat rejection, increasing fan power, and reduced engine compartment package space, an electric cooling system which features electric water pump. The combination of these components improve the cooling system efficiency and are marked by a decrease in cooling system parasitic losses (fan and pump power). **[1]**

## 1.2. ELECTRIFIED COOLING SYSTEM:

The thesis work starts with an initial model i.e. 1.9L Light-Duty Turbo Diesel Engine that was made by General Motors (GM) and validated by a Project team of University of Michigan, USA in 2019. The engine model has been adopted as a starting model of my thesis work.

For this thesis work, transient Warm-up drive cycle split cooling is used for the development of electrified cooling system model, and is taken from the example model i.e. Cooling Engine "Transient_Warmup_Drive_Cycle_Split_Cooling.gtm" provided in GT-SUITE v2018 & v2020. Transient warm-up drive cycle model is feasible for the study of the engine warm up behavior and the effects of different cooling strategies on the engine performance and fuel consumption.

In this thesis work, the aim is to operate the initial model, with introducing an electric coolant pump, which helps the engine to get hot faster than with a conventional water pump. In addition, provides the enhancement of coolant circulation rate, which in turn decreases fuel consumption and increases oil temperature.

The electrified water pump system has been developed starting from the initial model. Modifications are made in the Transient Warm-Up Drive Cycle split cooling model and made it consistent with the 1.9L engine model.

The transient drive cycle model demonstrates a fuel economy drive cycle i.e. New European Drive Cycle (NEDC) and Worldwide harmonized Light-duty vehicles Test Procedure/Cycle (WLTC).

## 1.3. FAST RUNNING ENGINE MODEL (FRM):

For transient investigations like studies of the engine warm up behavior and the effects of different cooling strategies on the engine performance and fuel consumption, a predictive engine model can be connected to the thermal model to run a transient study.

The solution is a fast-running engine model (FRM), which simplifies the engine flow circuit to enable significantly reduced run times, but still delivers the accuracy needed for thermal simulations. Fast Running Engine is from the engine sub-system model of Transient Warm-up Drive Cycle Split Cooling Model, GT-SUITE v2018. **[2]**

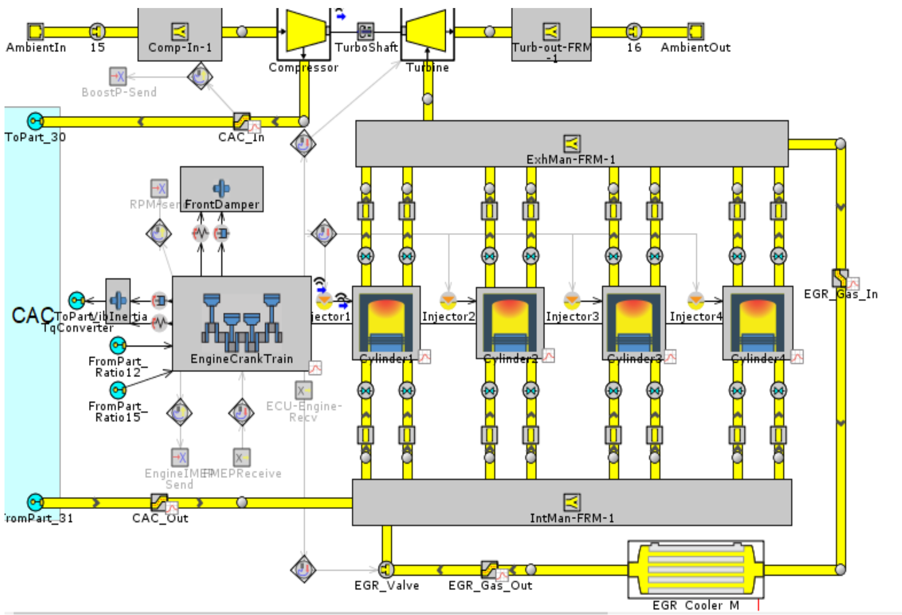



Figure 1. 1: Fast Running Engine Model (FRM) - Transient_Warmup_Drive_Cycle_Split_Cooling.gtm

As said before, this thesis intends to evaluate the possibility to power the electrified cooling system by incorporating the electric water pump, and to understand what amount of electric energy is required to run the water pump. Electrifying the coolant pump, we aim to increase the system efficiency and in turn reduce fuel consumption and shorten cold start period.

## 1.4. SIMULATION SOFTWARE: GT-SUITE v2018 & v2020:

This feasibility study has been completed using the simulation software GT-SUITE v2018 & v2020 (Gamma Technologies, LLC., Westmont, IL, USA). **[3]**

GT-Power is the industry standard engine performance simulation used by all major engine manufacturers and vehicle OEMs.

GT-Power is used to predict engine performance quantities such as power, torque, volumetric efficiency, fuel consumption etc. Beyond basic performance predictions, GT-Power includes physical models for extending the predictions to include cylinder and tail pipe out emissions and in-cylinder structure temperature. Standard GT-Power engine models are easily converted to real-time capable models (known as Fast Running Engine Models - FRMs). This provides accurate and physically based engine boundary conditions to the rest of the vehicle.

GT-SUITE is the ideal modeling platform for vehicle cooling analysis. GT-Suite models can be used to analyze flow distribution and thermal performance of liquid circuits. **[4]**

# CHAPTER 2: LITERATURE REVIEW

This section intends to provide a bibliography review of about the researches on electrified cooling system and mainly electric water pump having the similar concept and configuration considered here (i.e. electrified cooling system is independent of the engine speed with no mechanical gear connection with engine).

## 2.1. RELATED RESEARCH:

Gubbiotti studied engine cooling system, and found that using the electric water pump, there is a continuous circulation of the cooling fluid under pressure. **[5]** However, by an intelligent way, since the fluid will be controlled electrically providing gains to the whole system. He also found another significant factor that the beginning of the catalytic conversion (igniting) in a catalyst occurs due to the high temperature of the exhaust gases. The shorter the time for the "warm-up" of the catalyst, fewer will be the pollutants thrown in the atmosphere meeting the environmental legislations. Experimental tests show an improvement in the emissions indexes of 30% CO; 8% HC and 5% $NO_X$, due to the reduction of engine cold phase. In this way, the electric water pump perfectly meets this requirement since they leave the water pump inoperative during a period in the beginning of the engine operation, obtaining the quick engine heating.
Oil temperature of the engine also had a gain in the warm up time of 3 to 5 minutes, heating more quickly, evidencing that the entire engine is heated simultaneously. **[5]**

Wang and Wagner examined "Smart Engine Cooling System", their study investigated an advanced cooling system for ground vehicles which features three computer controlled actuators - a three way smart valve, a variable speed pump, and a variable speed electric radiator fan matrix. **[6]** Six experimental tests were performed to study the engine temperature transient response to a sequence of actuator step input profiles. From the experimental results, the valve operation causes the most engine temperature change (4.0%) followed by the radiator fan(s) (1.6%). Only controlling the pump speed hardly changes the engine temperature. The experimental results provide insight to fabricate a framework for advanced engine cooling system control strategy. This smart cooling system can be applied in the automotive industries by replacing the existing mechanical actuator(s) with a computer controlled electrical actuators and updating the electronic control unit (ECU) with a corresponding control strategy. The fuel economy is improved 3%-5% after applying this approach. **[6]**

Bartolomeo experimentally studied an engine coolant system. **[7]** A dynamic test bench for the experimental assessment of engine coolant pump was engineered. The test bench allows evaluation of pump efficiency, simulating real drive cycles and, in particular, the homologation cycles. This new design concept demonstrated its effectiveness in terms of mechanical energy consumption during a homologation WLTC cycle with respect to a conventionally designed pump having its Best Efficiency Point (BEP) when the engine requires the maximum coolant flow (maximum engine power). The new design concept saves 10% of mechanical energy of the pump. The energy reduction resulting was about 10-12% of the reference case, considering hydraulic or electrical energy. This result tends to increase for a more conventional pump which operates with lower efficiency at BEP and with a greater sensitivity of the efficiency to flow rate delivered and pump speed. **[7]**

Based on these studies, it is clear that it is quite difficult to find the right trade-off among engine performance, fuel economy and a convenient configuration of the cooling system; however, electrified cooling system could serve as the solution to reduce fuel consumption, reduce cold start emission, and, at the same time to increase the vehicle performance.

## 2.2. ADVANTAGES OF ELECTRIFIED WATER PUMP:

Some of the advantages of electrified cooling system are as follows:

- [5] In an electrified cooling system, the system has the possibility of quick heating of the engine in the warm-up phase as well as after the engine shut-off, with the fluid continuing to circulate until the complete homogenization of temperature. [5]

- The oil temperature of engine also has a gain in the cold phase (warm-up), heating more quickly, which shows that the entire engine is heated simultaneously.

- When we stop the vehicle after being used for some time, there occurs a phenomenon known as "after boil", which is the temperature increase and occurs by the heat conduction process. [5] This phenomenon can cause the fluid cooling, boiling, provoking air bubbles in the cooling system. This phenomenon can also provoke damage to the engine components, as head block warping by high temperature reached after engine shut-off. With the use of electric water pump we can have a strategy of continuing to pump the fluid until the entire engine is at an adequate temperature. [5]

- Higher temperatures in the engine could be admitted without concerns regarding the "after-boil" since with the electric water pump monitoring, engine temperature will be reduced. [5]

# CHAPTER 3: GT-POWER MODEL OF THE ENGINE AND MODEL MODIFICATIONS

This section presents the GT-Power model used as a starting point and the changes or modifications performed on the Transient Warmup drive cycle model to develop the electrified cooling system model.

## 3.1. STARTING MODEL:

The modelled engine is Diesel-4 cylinder, direct injection, 1.9L. Combustion is modelled by Multi Wiebe, a predictive combustion model using the detailed injection profiles. In-cylinder heat transfer is modelled using the Woschni Model.

The model also include VGT (Variable Geometry Turbine), Boost Control, intercooler, EGR circuit with cooler and EGR rate controller, injection limiting for smoke control, and exhaust after treatment device.

Initial model made by GM and validated by a Project team of University of Michigan, USA in 2019. That version was derived from the GT-Power provided "Diesel_4cyl_DIPulse_InjRateMap.gtm" example model for predictive Diesel combustion. The engine model has been adapted as a starting model for this thesis work, and it is shown in Figure 3.1.

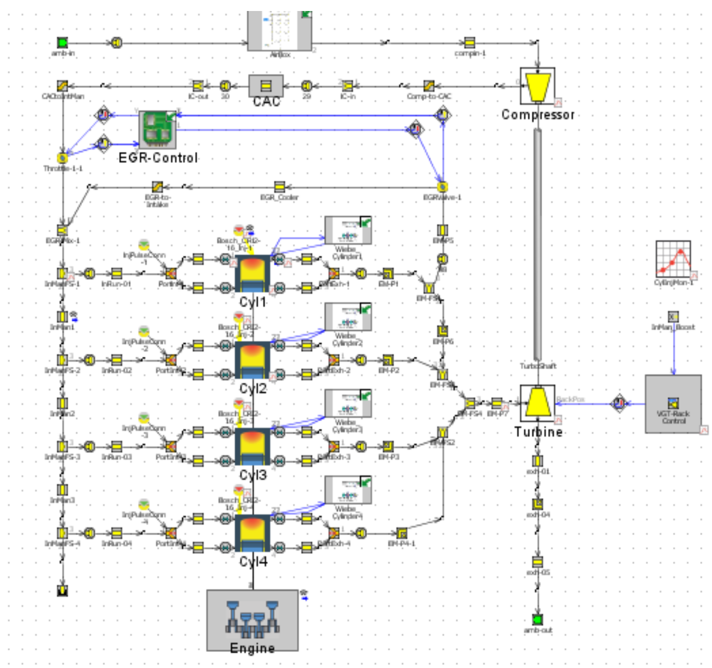



Figure 3. 1: Starting model (University of Michigan, USA)

### 3.1.2. INTAKE SYSTEM

The intake system consists of the air piping upstream of the compressor inlet, and contains a simple model of an air box. The air box is modeled as a group of interconnected flowsplits that represent the total volume of the air box. At the inlet and outlet of the air box, "bellmouth" orifice connections are used to model smooth transitions.

### 3.1.3. INTERCOOLER

The intercooler is found downstream of the compressor outlet. This intercooler is an air-to-air intercooler that is modeled using a "semi-predictive" method based on heat exchanger effectiveness. The intercooler is modeled using a pipe part. The pressure drop across the intercooler is calibrated using the Friction Multiplier in the pipe. Flowsplits are required to model the inlet and outlet of the intercooler since pipes cannot connect to pipes with the Number of Identical Pipes attribute greater than one. The desired intercooler outlet temperature is calculated by a simple control system and is imposed by actuating the wall temperature of the intercooler pipe. The Heat Transfer Multiplier in the pipe is increased to a large enough value so that the outlet temperature matches the wall temperature.

## 3.2. MODIFIED MODEL - TRANSIENT WARMUP DRIVE CYCLE SPLIT COOLING:

The transient drive cycle model demonstrates a fuel economy drive cycle. The model includes vehicle drivetrain, engine, cooling system, oil system, under-hood air, the engine cylinder and block/head structural mass.

Transient Warm-up drive cycle model is used for enhancement of results. This model employs an additional valve to stop flow in the engine block during warmup to improve fuel consumption. In this, we have Fast Running Engine Model (FRM). It is shown in the figure below, figure 3.2.

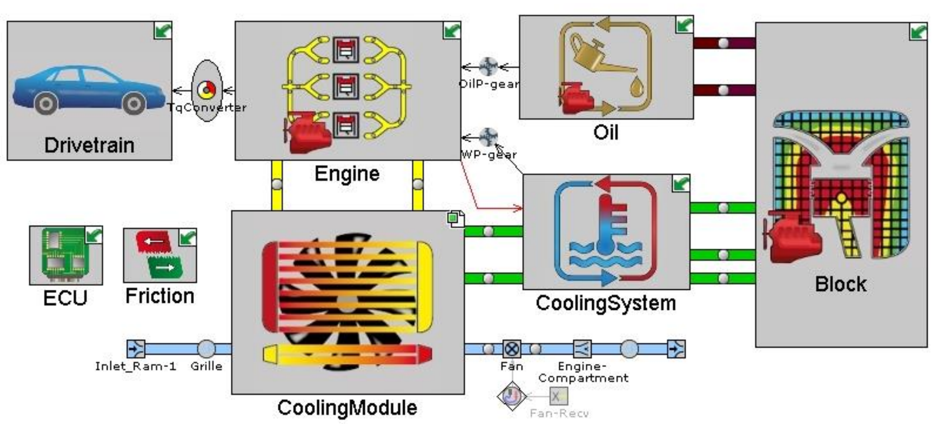



Figure 3. 2: Transient Warm-up Drive Cycle Split Cooling

The cooling and thermal system portion may run in approximately real time, but the detailed engine models may run hundreds of times slower than real time. The solution is a fast-running engine model (FRM), which simplifies the engine flow circuit to enable significantly reduced run times, but still delivers the accuracy needed for thermal simulations.

### 3.2.1. FAST RUNNING ENGINE MODEL:

The engine is modeled as a "fast running" engine model (FRM Engine). This means that the cylinders and valves are modelled in detail in the same way that a typical engine performance model would be built, but the intake and exhaust systems are simplified to reduce the number of volumes and increase the size (and resulting timestep). The EGR Cooler is discretized using only two divisions along its length. The acceptable level of discretization of this HX must be determined by investigating the trade-offs between accuracy and resulting runtime (the exhaust side volumes will typically be the restricting volumes for the engine.

The modelled engine is Diesel-4 cylinder, direct injection, 1.9L. Combustion is modelled by CombDIWiebe method. In-cylinder heat transfer is modelled using the Cylinder Heat Transfer (CylHeatTR).

**SPECIFICATIONS:**

- Cylinder Bore = 82 mm
- Stroke = 90.4 mm
- Compression Ratio = 18.6 : 1
- Firing order = 1-3-4-2
- Initial Engine Block Temperature = 308 K ± 1K
- Initial Coolant Temperature = 308 K ± 1K
- Initial Oil Temperature = 308 K ± 1K

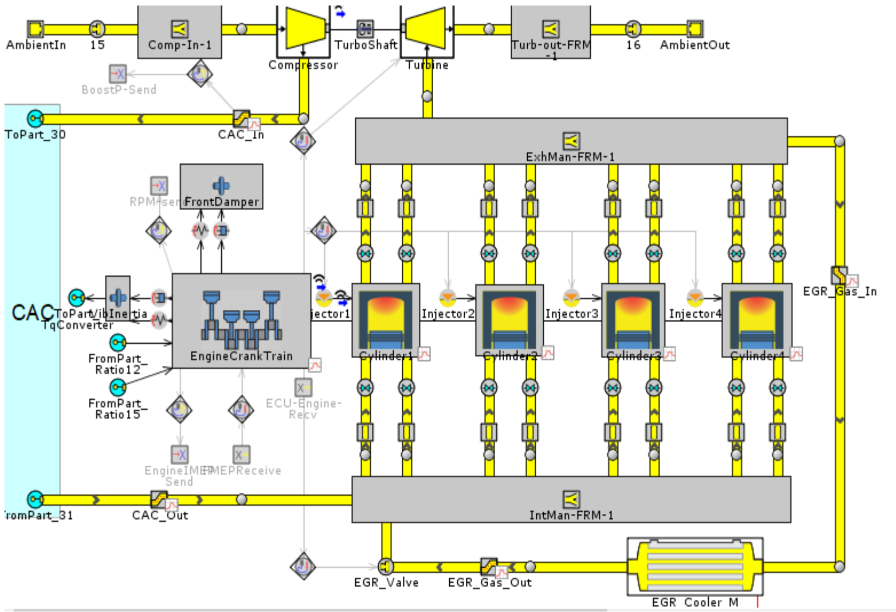



Figure 3. 3: Fast Running Engine Model (FRM) - Engine subassembly, Transient Warm-up Drive Cycle

### 3.2.2. COOLING SYSTEM CIRCUIT:

Diesel engines generating heat and therefore must be cooled. The engine is cooled by circulating a water-based coolant through a water jacket, which is part of the engine. The coolant is circulated through pipes to the radiator to remove the heat added to the coolant by the engine and then returned back to the engine.

The main components of the cooling system can be seen in the figure 3.4 and are as follows:

1. Water pump
2. Heat removing device (radiator)
3. Coolant expansion tanks (surge tanks)
4. Temperature control valves
5. Temperature and pressure switches and indicators
6. EGR Cooler

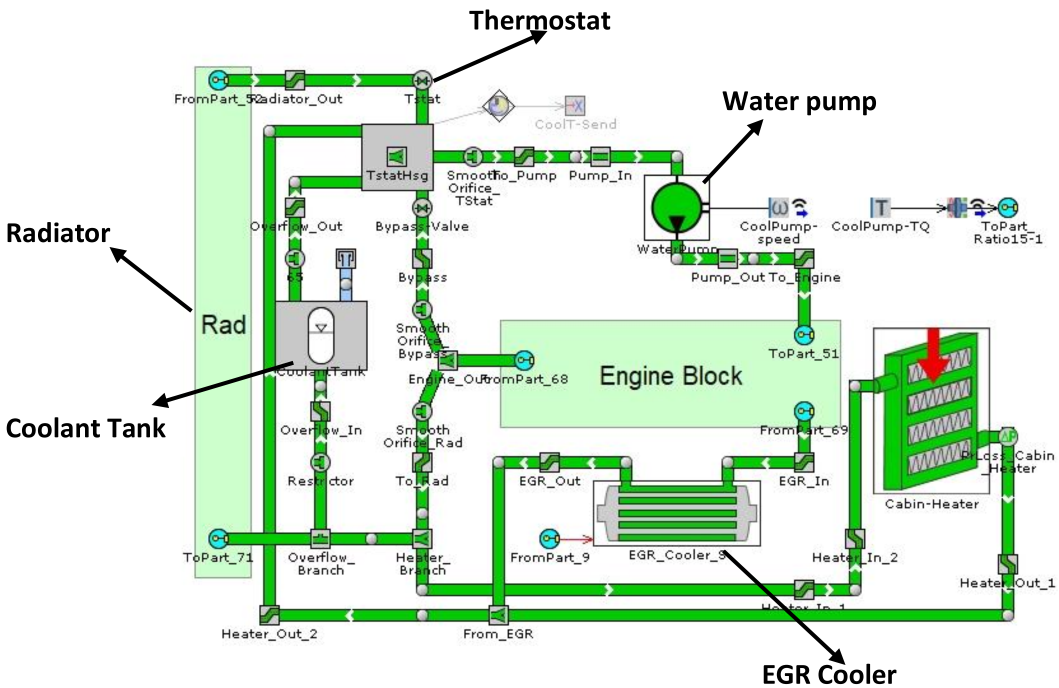



Figure 3. 4: Cooling System Circuit

In the above cooling system, we have a centrifugal type water pump. This water pump uses centrifugal force to send fluid to the outside while it spins, causing fluid to be drawn from the center continuously. The inlet to the pump is located near the center so that fluid returning from the radiator hits the pump vanes. The pump vanes fling the fluid to the outside of the pump, where it can enter the engine. The fluid leaving the pump flows first through the engine block and cylinder head, then into the radiator and finally back to the pump.

In this cooling circuit, we have splitting or split cooling because part of hot water circulating to the cabin heater, and the water from the heat exchanger going out, joins with coolant water in EGR cooler outgoing/outlet and it goes back to the pump. The remaining part of the hot coolant from engine block, for this we have bypass valve and thermostat.

If coolant at outgoing is not hot then water will not goes to radiator and it will be recirculated. However, if temperature becomes hot then the thermostat regulates the coolant temperature. The higher the temperature of coolant at the outlet of engine block, the higher should be the flow rate of water to go to the radiator to be cooled down. The hotter the temperature the higher/longer will be the opening of thermostat.

### 3.2.3. LUBRICATION/OIL SYSTEM CIRCUIT:

The lube oil system of the diesel engine lubricates the rotating and moving parts and gears of the engine to minimize the effects of metal-to-metal contact that causes both sliding and rolling types of friction, and to absorb a great amount generated heat to achieve smooth performance and lengthening the life of the internal parts of the engine.

In the oil system (figure 3.5), we have a positive displacement gear pump, driven from the crankshaft, which draws lubricating oil from the engine oil pan and circulates it through the system. It pulls oil from the lube oil pan (sump) and supplies it to the engine when the engine is running.

The oil passes through a suction strainer before entering the pump, then through filters and oil cooler before delivery to the engine parts. It is worth noting that the oil pump rotates at the same speed as the engine and that the absorbed power depends only on the engine speed.

The main parts of the lubrication/oil system are listed below:

1. Oil Pump
2. Oil Cooler
3. Oil Filter
4. Oil Pan

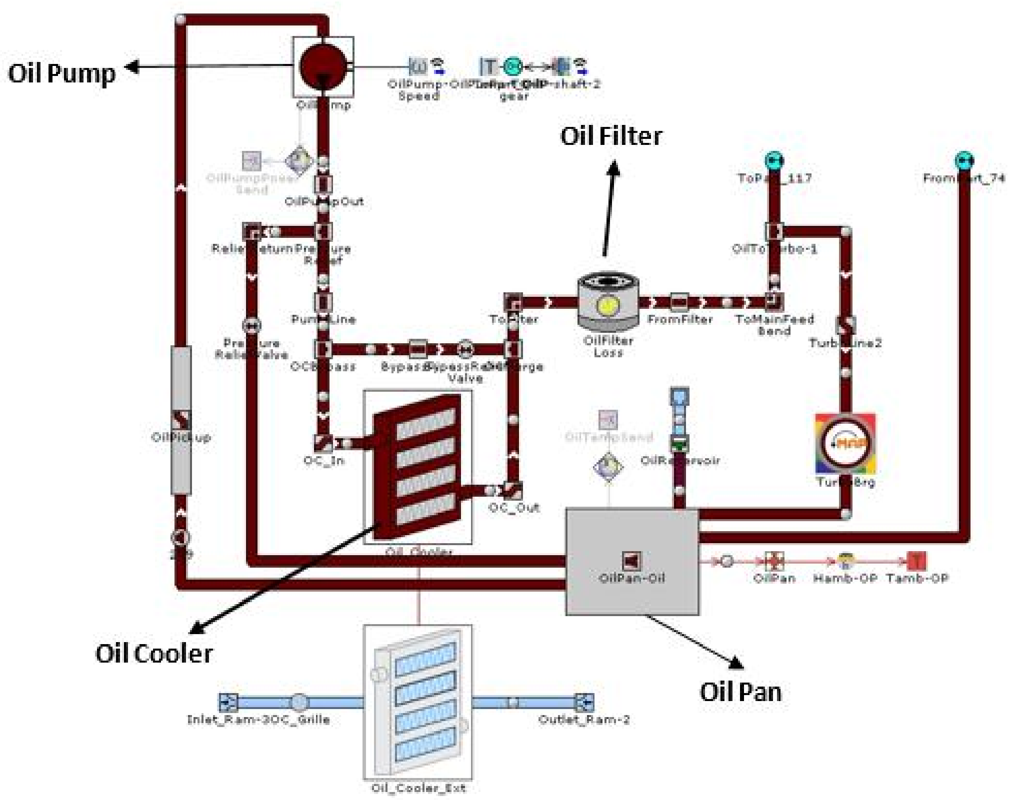



Figure 3. 5: Oil System Circuit

## 3.3. MODEL MODIFICATIONS:

The electrified water pump system has been developed starting from the initial model (1.9L Diesel Engine). Modifications are made on the Engine subsystem of Transient Warm-Up Drive Cycle split cooling and made it consistent with the initial 1.9L engine model.

### 3.3.1. CONSISTENCY OF FAST RUNNING ENGINE MODEL WITH STARTING MODEL (1.9L ENGINE)

The following steps have been performed:

- Changed the engine geometry of Fast Running Engine Model to be consistent with the initial engine model (1.9L Diesel Engine).
- Replaced the valve specifications in the Engine Subassembly of Transient warm-up Model.
- Changed the diameter and the position of the valves in the Engine sub-model "EngCylStruct" of Transient Warm-up Drive Cycle Split Cooling.

### 3.3.2. TRANSIENT WARM-UP DRIVE CYCLE SPLIT COOLING: INTRODUCING & MANAGING HYPOTHETICAL ELECTRIC MOTOR

Removing the mechanical connection between engine and cooling system, and introducing a function for water pump speed. In this way, the water pump works like an electrified water pump and it is called as "Hypothetical Electric Motor"

For introducing and managing hypothetical electric motor, following assumptions are made:

➢ Removing the gear connection of cooling system to the engine just to make speed of the pump independent of engine speed. In the figure 3.6 and 3.7, orange circles are referring, that mechanical connection of engine and cooling system is removed.

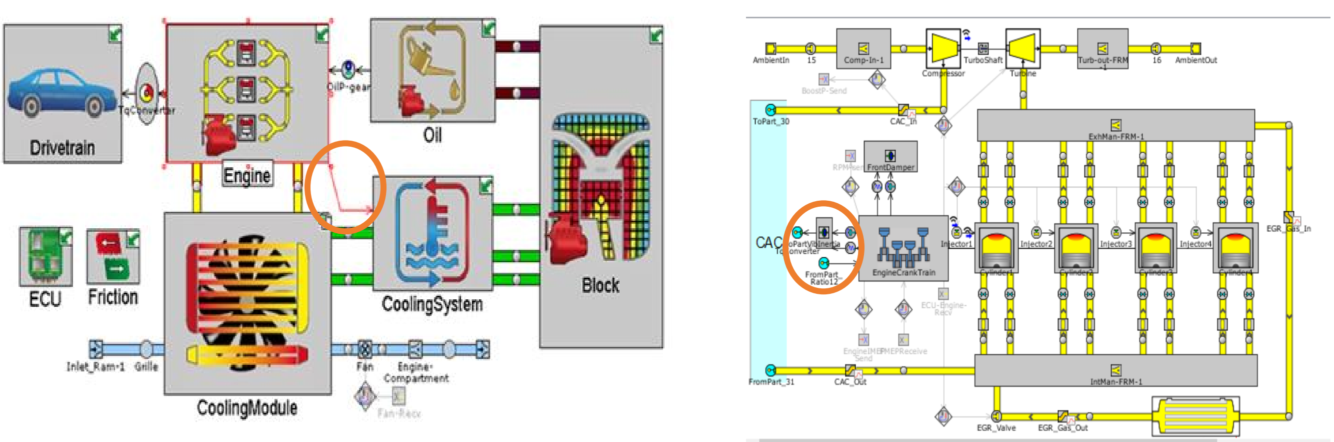
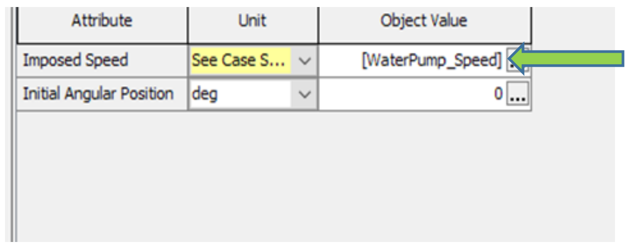



Figure 3. 6: Modifications in Transient warm-up Drive Cycle

➢ Introduced a function called "Wpump_speed" which is alternative to Electric machine/motor. In this way, the speed of the water pump becomes independent of engine speed, and it works like an electrified pump. If one can introduce an Electric motor for simulation so it is necessary to provide appropriate parameters to run the simulation/process. Instead, using the function, which provides us the same phenomena of electrified pump (i.e. pump speed independent of engine speed) for hypothetical Electric water pump.



| Attribute | Unit | Object Value |
|---|---|---|
| Imposed Speed | See Case S... | [WaterPump_Speed] |
| Initial Angular Position | deg | 0 |

➢ To clarify or manage the configuration of hypothetical electric motor "Speed Boundary Rot." is considered as a source of speed and it works like an electric motor. The speed of the water pump remains constant throughout.

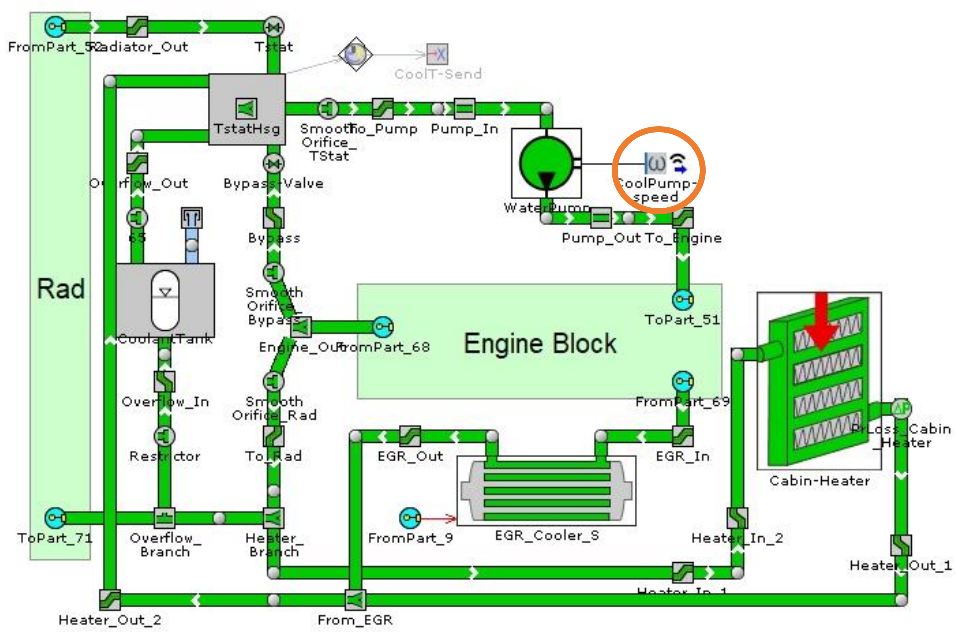



Figure 3. 7: Modified Cooling System Circuit

# CHAPTER 4: SIMULATIONS ON THE MODIFIED MODEL

The intent of this chapter is to analyze the simulation results obtained by the transient warm-up drive cycle using electrified water pump / hypothetical electric pump model and to compare them with baseline engine model results. First of all, simulations have been performed using NEDC (New European Driving Cycle and then performed using WLTC or WLTP (Worldwide Harmonized Light Vehicle Test Procedure).

## 4.1. SIMULATION CASES / WATER PUMP STRATEGIES:

The simulation has been performed for four different cases/strategies in order to analyze the behavior of the Transient Warm-up drive cycle split cooling model.

| CASE | WATER PUMP STARTEGY |
|---|---|
| A | Baseline Engine (Mechanical/Belted Configuration) |
| B | Hypothetical Electric Water Pump @1000 RPM |
| C | Hypothetical Electric Water Pump @3000 RPM |
| D | Hypothetical Electric Water Pump – Profile Transient |

First of all, the model is simulated with a normal mechanical water pump connection. Then we use two different constant RPM cases or hypothetical electric water pump cases (i.e. @1000 & 3000 RPM). Finally, we introduce another case, which is also a case of electrified water pump, wherein its speed is not constant throughout the NEDC and WLTC cycle. Starting with the low RPM (i.e. 1 RPM), it is like OFF state and remains the same up to half of the cycle, then from second half of the cycle the speed is 1000 RPM and remains the same throughout the cycle. We use a function called “Profile Transient”.

## 4.2. NEW EUROPEAN DRIVING CYCLE (NEDC):

The New European Driving Cycle (NEDC) is a driving cycle designed to assess the emission levels of car engines and fuel economy in passenger cars. It consists of four repeated ECE-15 urban driving cycles (UDC) and one Extra-Urban driving cycle (EUDC). **[13]**

Simulating the Baseline Engine Model and Electrified Pump Model using entire NEDC cycle (i.e. 1180 seconds). Simulating the entire cycle, in order to absorb dynamics of temperature for the engine. In this, there is an extra urban cycle at the end, which is quite challenging for coolant/water pump.

### 4.2.1. SIMULATION RESULTS:

Figure 4.1 shows the behavior of water pump speeds in all the four cases. The red line (i.e. of Baseline Engine) shows the fluctuation of water pump speed as in this case, water pump is connected to the engine and is dependent on the engine speed. While, in case of electrified water pump running at 1000 & 3000 RPM, the water pump speed is constant throughout the entire cycle. By introducing the function "Wpump_speed", the speed of the water pump becomes independent of engine speed. The flat line at the bottom is of Profile transient. In profile transient case, water pump is in OFF –state for half of the cycle and then it is turned on for the remaining half cycle. The water pump runs at constant 1000 RPM.

Referring to Figure 4.2, as we can see the electrified water pump values, the average total power tends to reduce after some time, because isentropic efficiency increases, which resulting in a decrease of power and torque, and the pump speed is constant.

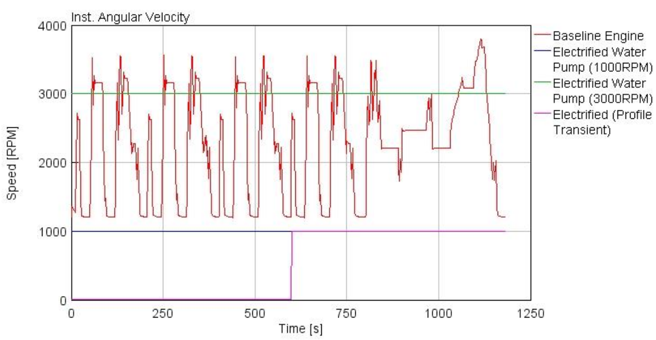



Figure 4. 1: Instant Angular Velocity - NEDC

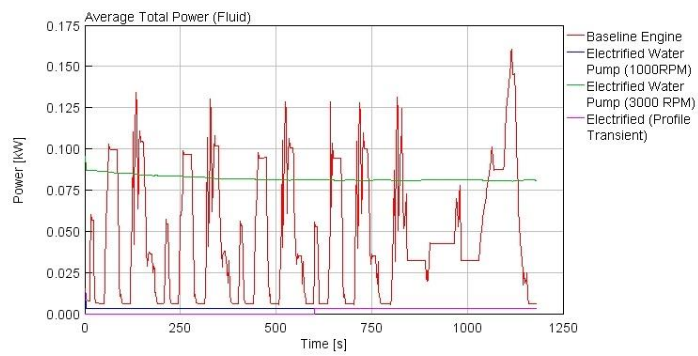



Figure 4. 2: Average Total Mechanical Power - NEDC

Referring to Figure 4.3 and 4.4, the oil temperatures are aligned to the expectation, which is related to warm-up phase. Oil temperature increases as the pump speed decreases. By looking at the graphs, it is clear that water pump running at 1000 RPM or in the case of Profile transient, we have an increasing trends of the oil temperature as compare to the other cases.

So, if we reduce mass flow rate of water it means we reduce heat flux from the engine to the water. Then engine is cooled less efficiently. Therefore, looking at the oil temperature it shows that it is more robust and reasonable variable that correlates to the engine thermal state.

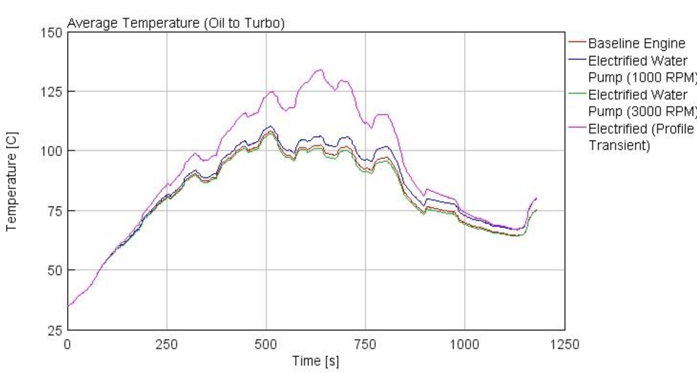



Figure 4. 3: Avg. Temp. (Oil to Turbo)- NEDC

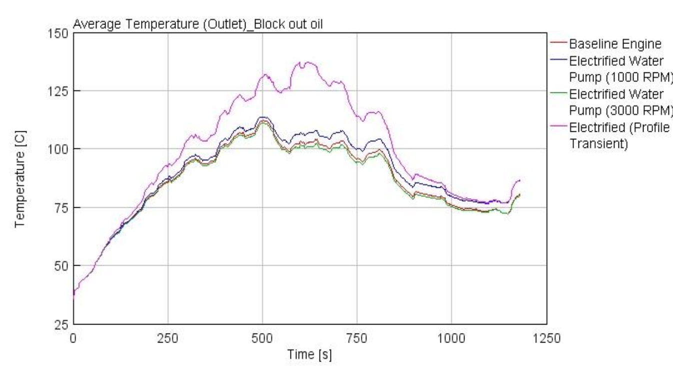



Figure 4. 4: Avg. Temp. (Block out Oil) – NEDC

Oil temperature is mentioned because it is a representative of engine wall temperature. From the circuit diagram of oil system (figure 4.5), the temperature of oil in the oil system circuit is lower than the temperature at the bottom of the engine block sub-system. Because the oil receives heat from the cylinders and then goes to bottom of the engine block "sub-system", the bottom of the engine block can be clearly seen in figure 4.6.

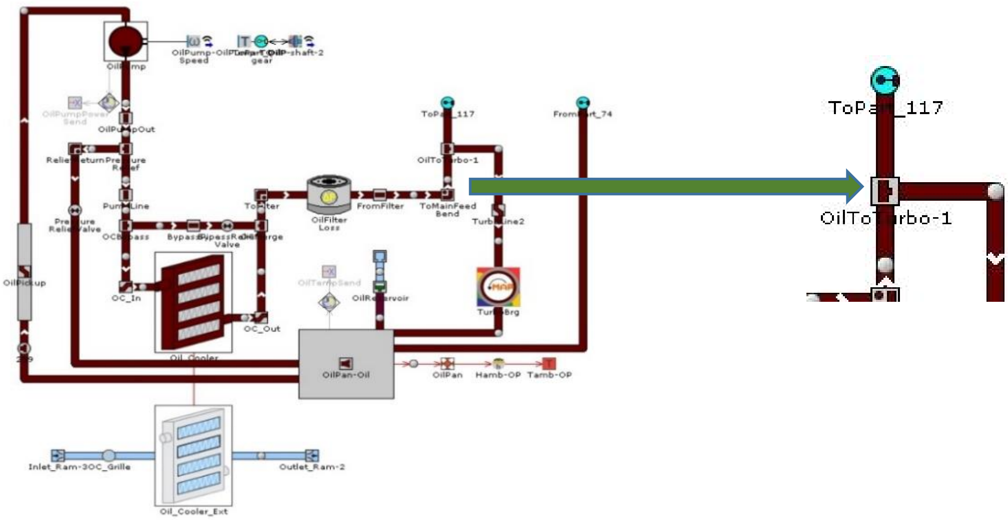



Figure 3.5: Modified Cooling System Circuit

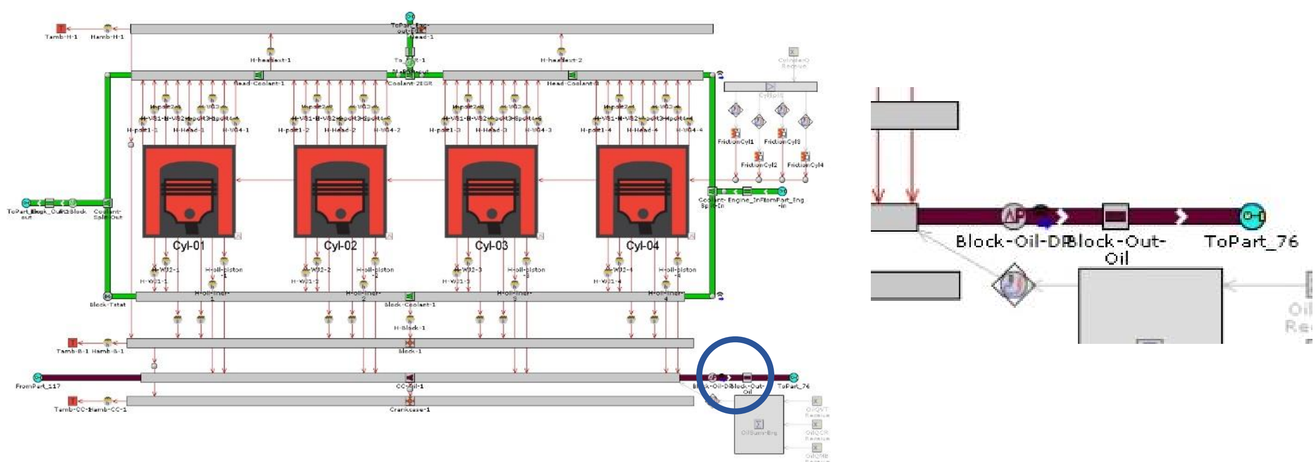
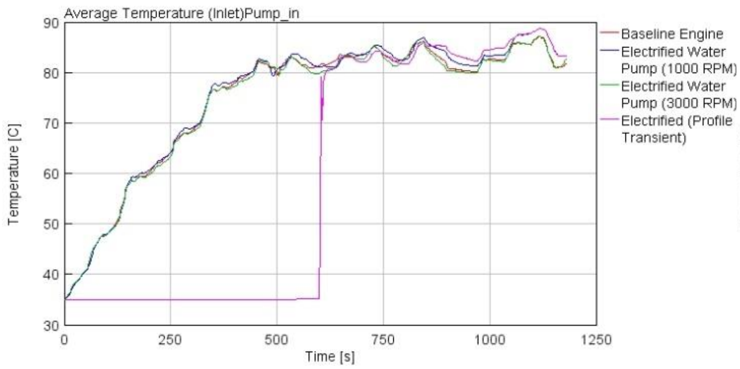



Figure 4. 6: Engine Block Sub-system

Referring to figure 4.7, the average temperatures of water pump inlet of Baseline Engine and water pump running at constant speed of 1000 & 3000 RPM have the similar behavior. In profile transient case, initially the pump running in low speed (i.e. 1 RPM) and the sudden shift of the line is due to the speed changes to 1000 RPM for the remaining half of the cycle.

In figure 4.8, the spike in the case of Profile transient is showing that the temperature of coolant increases with the change in the speed of water pump for the remaining half of the cycle.




*Fi*gure 4. 7: Avg. Temp. (Water Pump-in) - NEDC

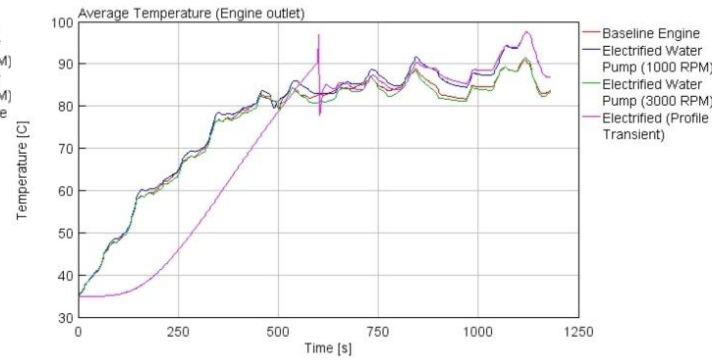



Figure 4. 8: Avg. Temp. (Engine Outlet)- NEDC

Referring to Figure 4.9, the trend of head coolant side is quite reasonable and satisfactory. It shows, when the coolant pump is not running or running very slow the temperature of cylinder head coolant rises to 200$^{o}$C to 300$^{o}$C. Therefore, in the cases of water pump running at constant speed of 1000 RPM and in Profile transient case, we have increased temperature values.

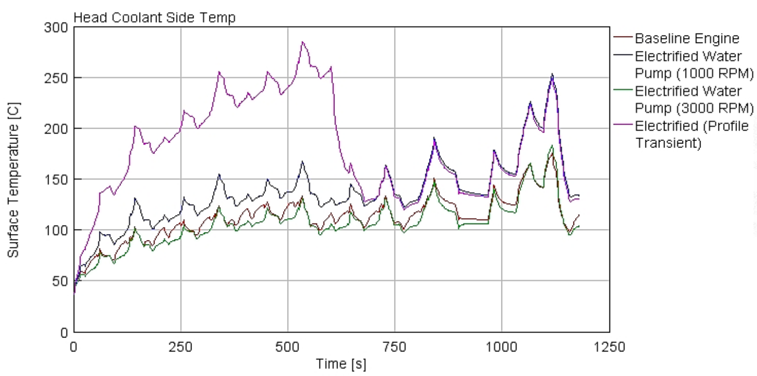



Figure 4. 9: Head Coolant Side Temperature -NEDC

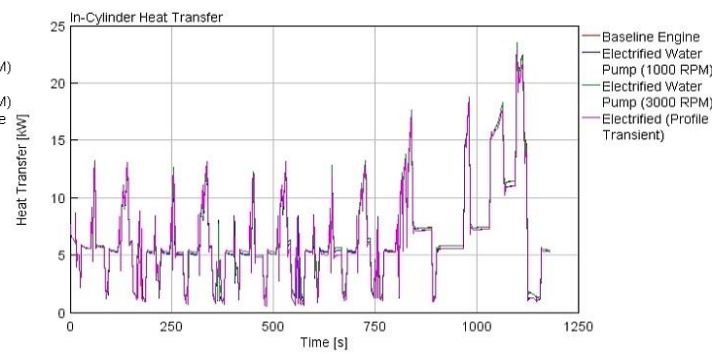



Figure 4. 10: In-cylinder Heat Transfer - NEDC

In figure 4.11 and 4.12, as we can see the comparison graph of radiator flow, the values are smaller in every case because the logic for opening of the valve that controls the flow rate through the radiator is not a closed loop logic, it is based on the temperature of water. There is no controller. There is only a map of opening of valve as afunction of temperature of coolant . It means, if temperature of water becomes higher for e.g. 80$^{o}$C, the valve that controls the flow through the radiator starts to open and the opening degree is defined by lookup table.

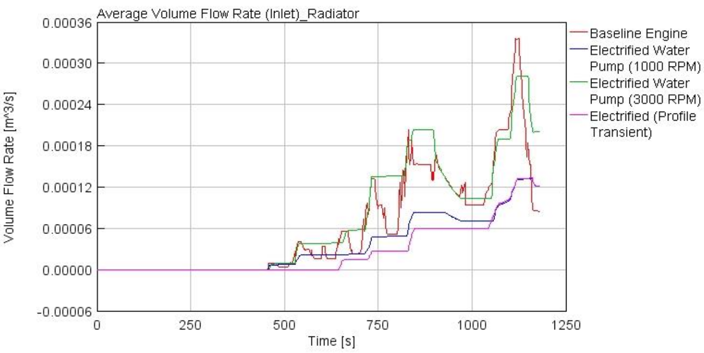



Figure 4. 11: Flow Rate (Radiator-inlet) -NEDC

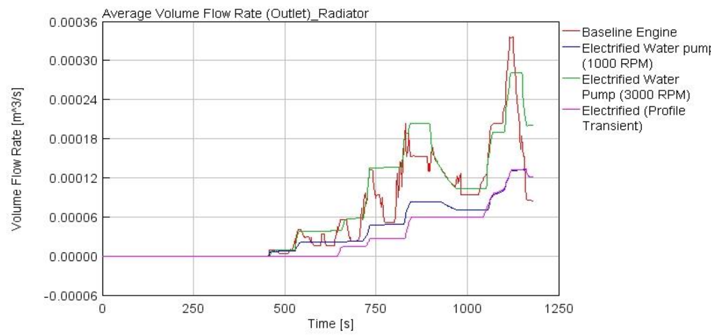



Figure 4. 12: Flow Rate (Radiator-Outlet) -NEDC

Referring to figure 4.13, the fuel flow rate of Baseline engine model is high as compared to different cases of hypothetical /electrified water pump, the high spikes are a clear indication of the increased fuel flow rate of the Baseline Engine throughout the entire cycle. The increased fuel consumption will be clearly observed in terms of values in Chapter 5.

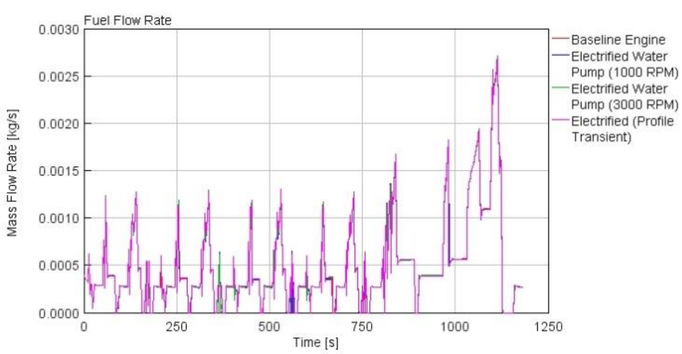



Figure 4. 13: Fuel Flow Rate - NEDC

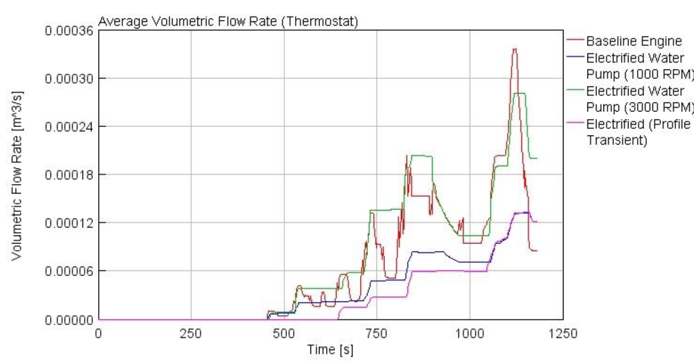



Figure 4. 14: Volume Flow Rate (Thermostat) –NEDC

The simulation results which are compared are just preliminary results and if this activity will be continue in the future, then a proper control strategy for the speed of the pump will have to be identified. We did not have any data to check whether the speed of the pump (i.e. constant 1000 RPM) over the entire cycle would be sufficient to guarantee the cooling system or not. Looking at the trend of the graphical results for oil and cylinder head coolant temperatures, are seemed satisfactory. Which are based on proper hypothesis, which are: the removing of mechanical connection between engine and cooling system, and introduced a function “Wpump_speed” which makes the water pump speed constant throughout the cycle and makes it independent from the speed of engine.

## 4.3. WORLDWIDE HARMONIZED LIGHT VEHICLES TEST CYCLE/PROCEDURE (WLTC):

The WLTC/WLTP (World harmonized Light-duty vehicles Test Procedure/Cycle) is a global harmonized standard for determining the levels of pollutants, $CO_2$ emissions and fuel consumption of traditional and hybrid cars, as well as the range of fully electric vehicles. **[14]**

It aims to replace the previous and regional New European Driving Cycle (NEDC) as the European vehicle homologation procedure. **[15]**

WLTP will introduce much more realistic testing conditions. These include:

- More realistic driving behaviour;
- A greater range of driving situations (urban, suburban, main road, motorway);
- Longer test distances
- Higher average and maximum speeds
- Higher average and maximum drive power
- More dynamic and representative accelerations and decelerations;
- Optional equipment: CO2 values and fuel consumption are provided for individual vehicles as built
- Stricter car set-up and measurement conditions

Simulating the Baseline Engine Model and Electrified Pump Model using entire WLTC /WLTP Cycle. Using this cycle, as it is more dynamic than NEDC and is more representative of real driving conditions. The duration of the entire cycle is 1611 seconds.

### 4.3.1. SIMULATION RESULTS:

Figure 4.15 shows the behavior of water pump speeds in all the four cases. The trend and behavior in each case is similar to that of Transient Warm-up drive cycle using NEDC.

Referring to Figure 4.16, the trend and behavior as we can see the electrified water pump values/cases, the average total power tends to reduce after some time, because isentropic efficiency increases, which resulting in a decrease of power and torque, and the pump speed is constant, which can be clearly seen from figure 4.15. The trend is almost similar to that of NEDC.

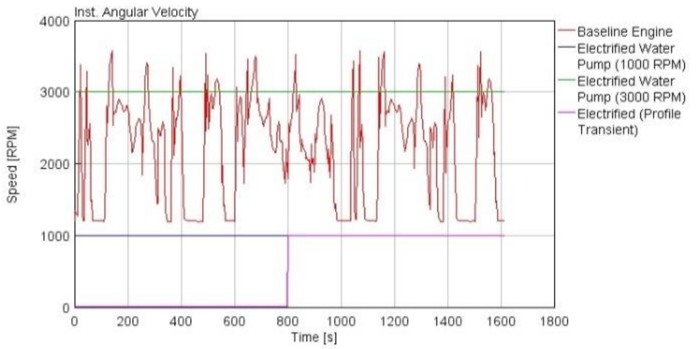



Figure 4. 15: Instant Angular Velocity -WLTC

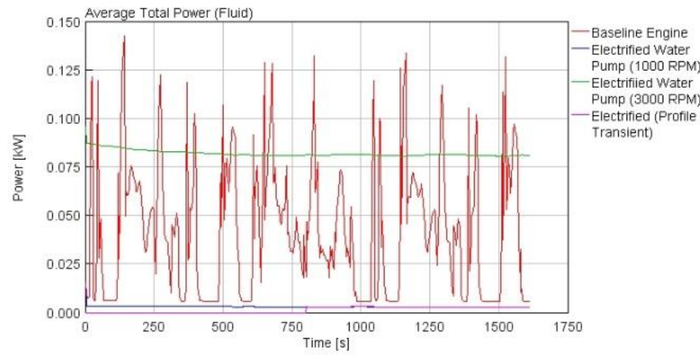



Figure 4. 16: Avg. Total Mechanical Power -WLTC

Referring to Figure 4.17 and 4.18, the oil temperatures are aligned to the expectation, which is related to warm-up phase (cold start phase). Oil temperature increases as the pump speed decreases. By looking at the graphs, it is clear that water pump running at 1000 RPM or in the case of Profile transient, we have an increasing trends of the oil temperature as compared to water pump running at constant speed of 3000 RPM and to the baseline engine model. The trend is showing the similar results as in the Transient warm-up drive cycle using NEDC.

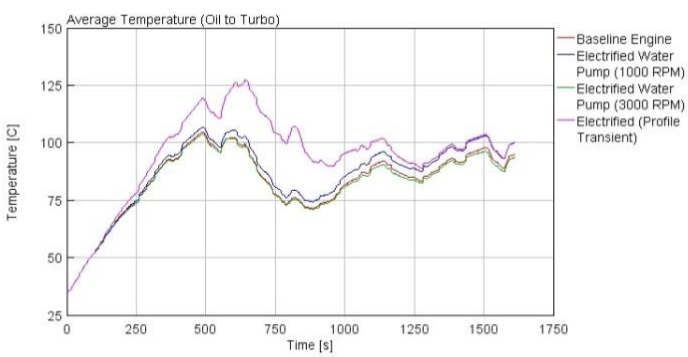



Figure 4. 17: Avg. Temp. (Oil to Turbo) -WLTC

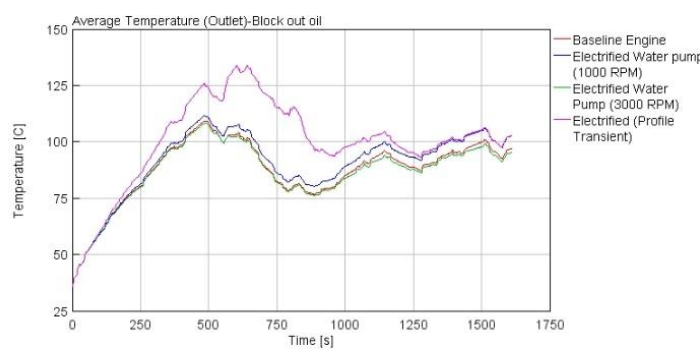



Figure 4. 18: Avg. Temp. (Block out Oil) -WLTC

Referring to figure 4.19, the average temperatures of water pump inlet of Baseline Engine and water pump running at constant speed of 1000 & 3000 RPM have the similar behavior. In profile transient case, initially the pump running in low speed (i.e. 1 RPM) and the sudden shift of the line is due to the pump speed changes to 1000 RPM for the remaining half of the cycle.

In figure 4.20, the spike in the case of Profile transient is showing that the temperature of coolant increases with the change in the speed of water pump for the remaining half of the cycle. Unlike, the simulation result of average temperature of coolant in NEDC, in WLTC the temperature becomes comparatively higher when it is close to half of the cycle.

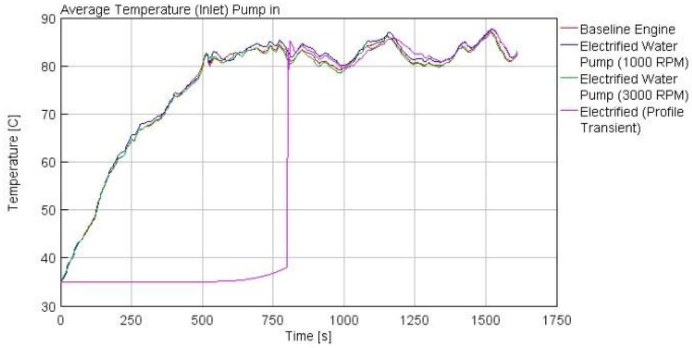



Figure 4. 19: Avg. Temp. (Water Pump-in) -WLTC

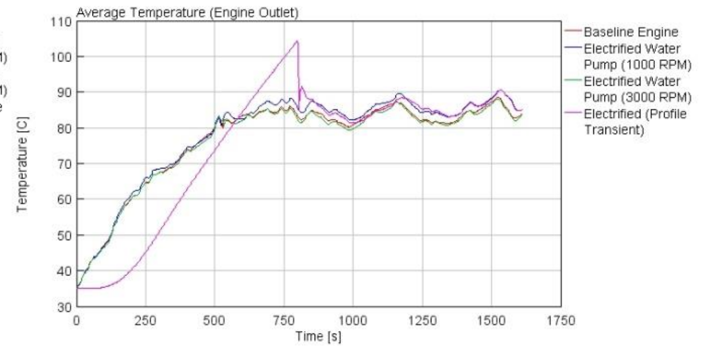



Figure 4. 20: Avg. Temp. (Engine Outlet) -WLTC

Referring to Figure 4.21, the trend of head coolant side is quite reasonable and satisfactory in the case of water pump running at 1000 RPM and in profile transient case. It shows when the coolant pump is not running or running very slow the temperature of head coolant raises to 250°C to 300°C. Therefore, in the cases of water pump running at constant speed of 1000 RPM and in Profile transient case, we have increased temperature values.

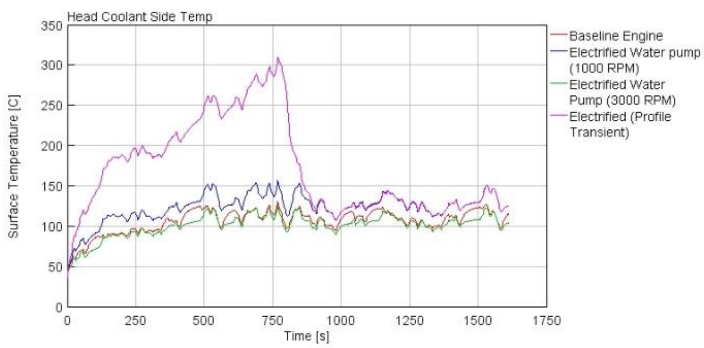



*Figure 4. 21: Head Coolant Side Temp -WLTC.*

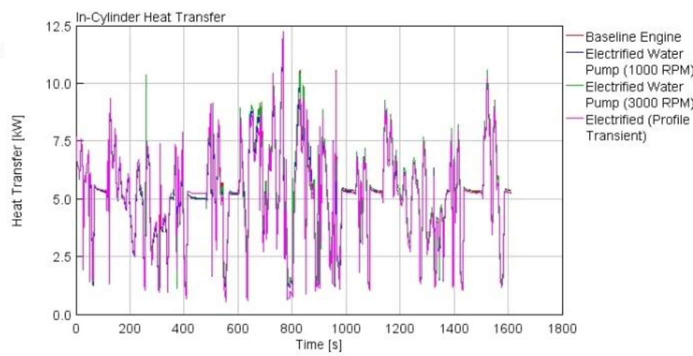



*Figure 4. 22: In-cylinder Heat Transfer -WLTC*

In figure 4.23 and 4.24, as we can see the comparison graph of radiator flow, the values are smaller in every case like in the NEDC .

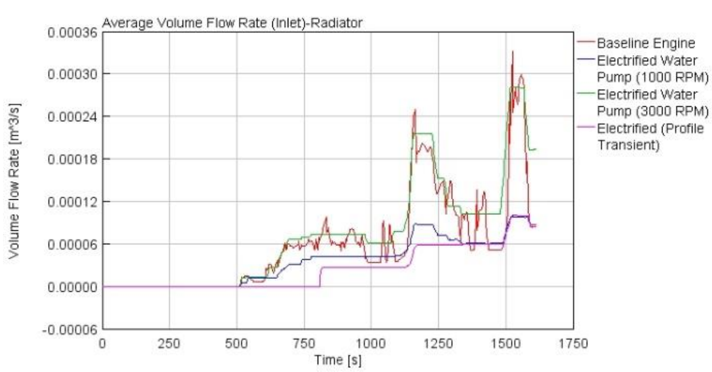



Figure 4. 23: Volume Flow Rate (Radiator Inlet) -WLTC

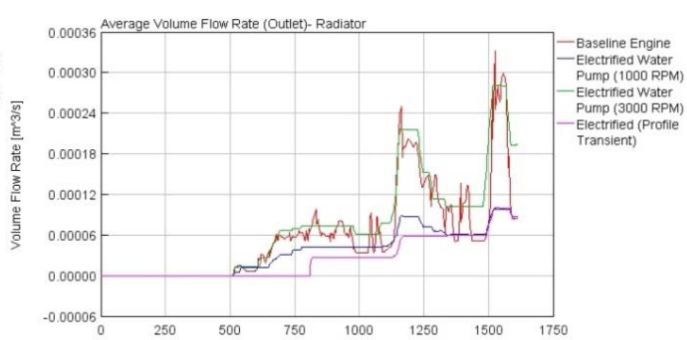



Figure 4. 24: Volume Flow Rate (Radiator Outlet) -WLTC

Referring to figure 4.25, the fuel flow rate of Baseline engine model is high as compared to different cases of hypothetical /electrified water pump, the high spikes are clear indication of the increased fuel flow rate of Baseline Engine throughout the entire cycle. The increased fuel consumption will be clearly observed in Chapter 5.

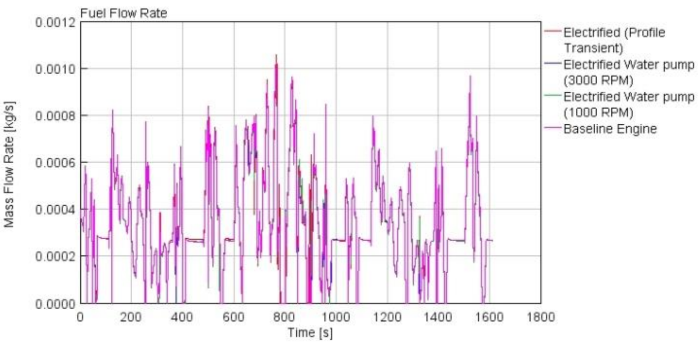



Figure 4. 25: Fuel Flow Rate -WLTC

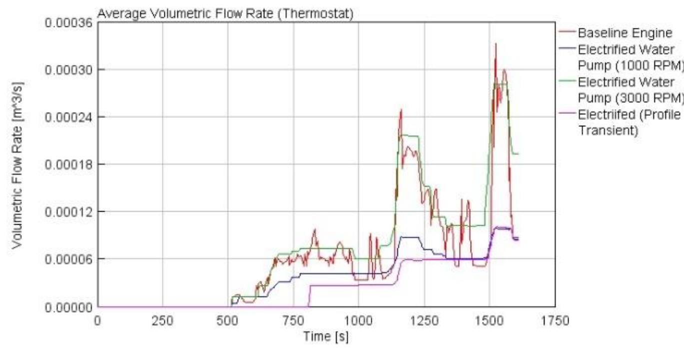



Figure 4. 26: Volume Flow Rate (Thermostat) -WLTC

The simulation results, which are compared, are just preliminary results and if this activity will be continue in the future, then a proper control strategy for the speed of the pump will have to be identified. We did not have any data to check the speed of the pump (i.e. constant 1000 RPM and 3000 RPM) over the entire cycle would be sufficient to guarantee the cooling system or not. Looking at the trend of the graphical results of oil and cylinder head coolant side temperatures, are seemed satisfactory.

# CHAPTER 5: CALCULATIONS AND RESULTS

The intent of this chapter is to estimate the values of electrical power and derived quantities for Hypothetical electric motor and battery for the transient warm-up drive cycle model for different pump speed and cases, and to compare the results with Baseline Engine Model.

## 5.1. ESTIMATION OF ELECTRICAL POWER & OTHER RELATED QUANTITIES FOR HYPOTHETICAL ELECTRIC MOTOR – FOR NEDC:

For the estimation of electrical power absorbed by Hypothetical Electric motor and related quantities, calculations are performed using the values taken from GT-POST (Avg. Mechanical Total Power and Fuel Flow rate values) over the entire cycle. Calculations are performed for NEDC and WLTC.

Also, in cooling system, we have hypothetical electric motor, this electric motor requires electrical power that comes from the battery. This is also estimated by doing calculations.

### 5.1.1. FORMULAS USED FOR CALCULATIONS:

- **ELECTRIC POWER**:

$$P_{elec}, EM = \frac{P\_mech(pump)}{\eta_{EM,ele2mech}} \tag{5.1}$$

Where ŋ is efficiency of electrical to mechanical power and is equal to 0.9.

- **CHEMICAL POWER:**

$$P_{chem}, batt = \frac{P_{elec}, Em}{\eta_{batt,chem2elec}} \tag{5.2}$$

Where ŋ is efficiency of chemical to electrical power and is equal to 0.9.

- **CHEMICAL ENERGY:**

$$\text{Chemical Energy} = \int (P_{chem,batt})\, dt \tag{5.3}$$

- **EXTRA FUEL CONSUMED BY ENGINE TO RECHARGE THE BATTERY:**

$$m_f, chg = \frac{E_{chem}, batt(final)}{HL \ x\ \eta_{engine}\ x\ \eta_{alternator_{mech2elec}}\ x\ \eta_{batt_{chem2elec}}} \tag{5.4}$$

Where $\eta_{engine}$ is the fuel conversion efficiency, which the engine converts fuel into mechanical energy. This value is taken as maximum over the cycle for every case from the GT-POST values, average maximum value is 0.44. HL is the lower heating value of the fuel. For diesel fuel, its value is 42.5 MJ/kg.

Extra fuel consumption is needed, because during the cycle it is necessary that the engine consume extra fuel to recharge the battery.

- **INTEGRAL FUEL CONSUMED:**

$$\text{Integral Fuel consumed} = \int (\text{Fuel Flow Rate})\, dt \tag{5.5}$$

- **CORRECTED FUEL CONSUMED:**

$$\text{Corrected Fuel} = \text{Integral Fuel Consumed} + \text{Extra Fuel Consumed to recharge the battery} \tag{5.6}$$

### 5.1.2. EXTRA FUEL CONSUMED BY ENGINE TO RECHARGE THE BATTERY:

In the expression of extra fuel consumption, there is concept of energy, "It is the energy of fuel spent by engine to recharge the battery".
The fuel energy is converted into mechanical energy by the engine, then this mechanical energy is absorbed by alternator which generates electrical energy and this electrical energy is stored in the battery as chemical energy. Therefore, we have chain of conversions and each conversion is associated with efficiency.

The integral fuel consumed, does not take into account for battery discharge. Therefore, we calculate corrected fuel mass; it is a shift basically. It is the previous value of integral fuel plus extra fuel to recharge the battery ($m_{f,chg}$).

In case of electrified system, the charge of the battery goes down but at the end of the cycle, the engine will recharge the battery in order to maintain original level. And because of this, engine will have to consume extra fuel.

### 5.1.3. HYPOTHETICAL ELECTRIC PUMP @1000 RPM: (FOR NEDC CYCLE)

The summarize tables of calculated values for Electrified Water Pump @ 1000 RPM, Electrified Water Pump @ 3000 RPM and Electrified Water Pump "(Profile Transient) and the related quantities are as follows:

| Time | $P_{mech-pump}$ | $P_{elec\_pump}$ | $P_{chem,batt}$ | $E_{chem\_batt}$ provided by battery during cycle) | Time | Fuel Flow rate | Integral Fuel Consumed | Corrected Fuel Consumed |
|---|---|---|---|---|---|---|---|---|
| sec | W | W | W | J | sec | kg/s | kg | kg |
| 0.5 | 12.87 | 14.30 | 15.89 | 0.00 | 0.15 | 4.0E-04 | 0.0000 | 0.0003 |
| 2.5 | 3.26 | 3.62 | 4.02 | 19.91 | 2.19 | 3.7E-04 | 0.0008 | 0.0011 |
| 4.5 | 3.24 | 3.60 | 4.00 | 27.93 | 4.20 | 3.6E-04 | 0.0015 | 0.0018 |
| 6.5 | 3.24 | 3.60 | 4.00 | 35.93 | 6.11 | 3.5E-04 | 0.0022 | 0.0025 |
| - | - | - | - | - | - | - | - | - |
| - | - | - | - | - | - | - | - | - |
| 1174.5 | 2.91 | 3.23 | 3.59 | 4328.69 | 1174.09 | 2.72E-04 | 0.5688 | 0.5691 |
| 1176.5 | 2.91 | 3.23 | 3.59 | 4335.87 | 1176.03 | 2.71E-04 | 0.5694 | 0.5696 |
| 1178.5 | 2.91 | 3.23 | 3.59 | 4343.06 | 1178.13 | 2.70E-04 | 0.5699 | 0.5702 |
| 1180 | 2.91 | 3.23 | 3.59 | **4348.45** | 1180.07 | 2.70E-04 | 0.5705 | **0.5707** |

Table 5. 1: Electric power and derived quantities (@1000 RPM) – NEDC

**- Extra fuel mass to recharge the battery = 0.000283 kg**

**- Total fuel consumed at the end of the mission/cycle = 0.570 kg**

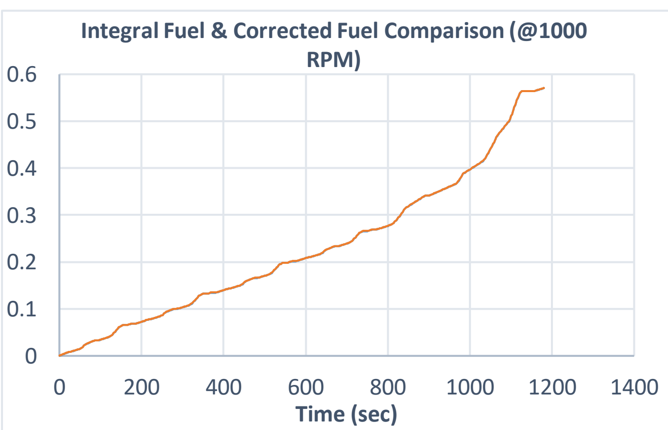



Figure 5. 1: Integral & Corrected Fuel Comparison- 1 (NEDC)

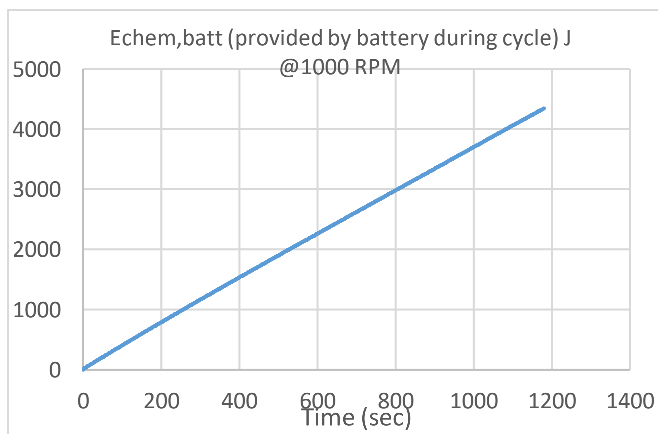



Figure 5. 2: Chemical energy- 1 (NEDC)

From figure 5.2, it is shown that chemical energy is progressively absorbed by the battery. Consequently, battery will discharge on time. Therefore, engine consume extra fuel to recharge the battery

### 5.1.4. HYPOTHETICAL ELECTRIC PUMP @3000 RPM: (FOR NEDC CYCLE)

| Time | $P_{mech\_pump}$ | $P_{elec\_pump}$ | $P_{chem,batt}$ | $E_{chem\_batt}$ provided by battery during cycle) | Time | Fuel Flow rate | Integral Fuel Consumed | Corrected Fuel Consumed |
|---|---|---|---|---|---|---|---|---|
| sec | W | W | W | J | sec | kg/s | kg | kg |
| 0.5 | 95.631 | 106.256 | 118.062 | 0.000 | 0.15 | 3.96E-04 | 0.0000 | 0.0078 |
| 2.5 | 87.218 | 96.909 | 107.676 | 225.739 | 2.19 | 3.75E-04 | 0.0008 | 0.0086 |
| 4.5 | 87.182 | 96.869 | 107.632 | 441.047 | 4.20 | 3.58E-04 | 0.0015 | 0.0093 |
| 6.5 | 87.139 | 96.821 | 107.579 | 656.258 | 6.11 | 3.46E-04 | 0.0022 | 0.0100 |
| - | - | - | - | - | - | - | - | - |
| - | - | - | - | - | - | - | - | - |
| - | - | - | - | - | - | - | - | - |
| 1174.5 | 80.987 | 89.985 | 99.984 | 118878.98 | 1174.1 | 2.74E-04 | 0.572 | 0.579 |
| 1176.5 | 80.961 | 89.957 | 99.952 | 119078.92 | 1176.05 | 2.73E-04 | 0.572 | 0.580 |
| 1178.5 | 80.935 | 89.928 | 99.920 | 119278.79 | 1178.14 | 2.73E-04 | 0.573 | 0.581 |
| 1180 | 80.916 | 89.906 | 99.896 | **119428.65** | 1180.09 | 2.72E-04 | 0.573 | **0.581** |

Table 5. 2: Electric power and derived quantities (@3000 RPM) -NEDC

**- Extra fuel mass to recharge the battery = 0.00777 kg**

**- Total fuel consumed at the end of the mission/cycle = 0.581 kg**

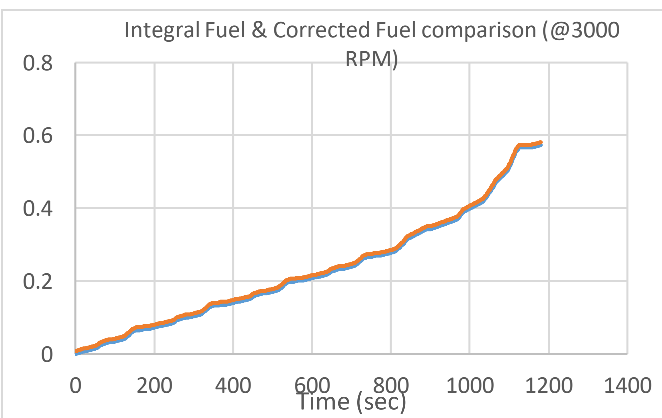



Figure 5. 3: Integral & Corrected Fuel Comparison-2 (NEDC)

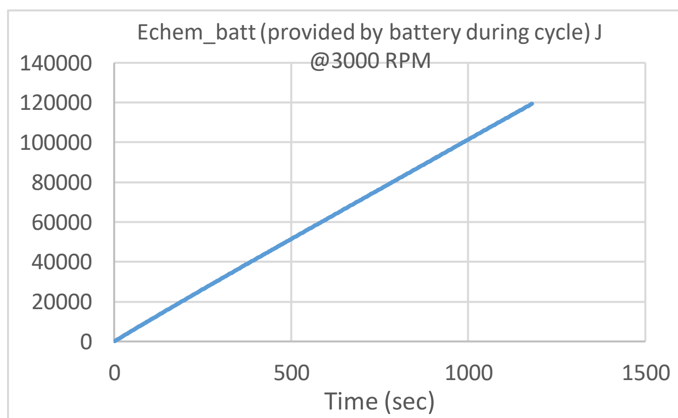



Figure 5. 4: Chemical energy- 2 (NEDC)

### 5.1.5. HYPOTHETICAL ELECTRIC PUMP – PROFILE TRANSIENT: (FOR NEDC CYCLE)

| Time | $P_{mech\_pump}$ | $P_{elec\_pump}$ | $P_{chem,batt}$ | $E_{chem\_batt}$ provided by battery during cycle) | Time | Fuel Flow rate | Integral Fuel Consumed | Corrected Fuel Consumed |
|---|---|---|---|---|---|---|---|---|
| sec | W | W | W | J | sec | kg/s | kg | kg |
| 0.5 | 6.68E-06 | 7.42E-06 | 8.24E-06 | 0 | 0.15 | 3.96E-04 | 0 | 1.35E-04 |
| 2.5 | 2.85E-06 | 3.16E-06 | 3.51E-06 | 1.18E-05 | 2.192 | 3.75E-04 | 0.001 | 9.22E-04 |
| 4.5 | 2.30E-06 | 2.56E-06 | 2.84E-06 | 1.81E-05 | 4.201 | 3.58E-04 | 0.002 | 1.66E-03 |
| 6.5 | 2.33E-06 | 2.59E-06 | 2.87E-06 | 2.38E-05 | 6.110 | 3.46E-04 | 0.002 | 2.33E-03 |
| - | - | - | - | - | - | - | - | - |
| - | - | - | - | - | - | - | - | - |
| 1174.5 | 2.910 | 3.23E+00 | 3.59E+00 | 2.07E+03 | 1174.03 | 2.71E-04 | 0.574 | 0.575 |
| 1176.5 | 2.910 | 3.23E+00 | 3.59E+00 | 2.07E+03 | 1176.12 | 2.71E-04 | 0.575 | 0.575 |
| 1178.5 | 2.910 | 3.23E+00 | 3.59E+00 | 2.08E+03 | 1178.06 | 2.70E-04 | 0.576 | 0.576 |
| 1180 | 2.910 | 3.23E+00 | 3.59E+00 | **2.09E+03** | 1180.01 | 2.70E-04 | 0.576 | **0.576** |

Table 5. 3: Electric power and derived quantities (Profile Transient) - NEDC

**- Extra fuel mass to recharge the battery = 0.000135 kg**

**- Total fuel consumed at the end of the mission/cycle = 0.576 kg**

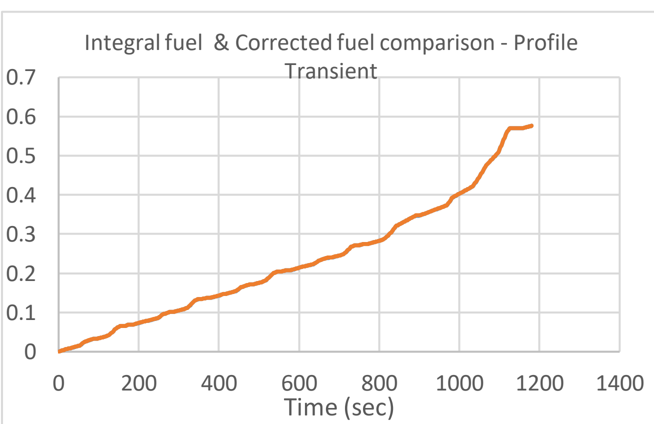



Figure 5. 5: Integral & Corrected Fuel Comparison-3 (NEDC)

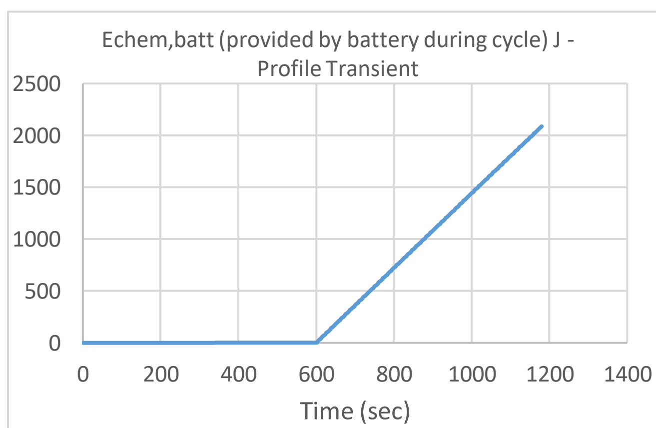



Figure 5. 6: Chemical energy- 3 (NEDC)

Referring to figure 5.6, the flat line from starting until 600 seconds shows that the water pump is running at very slow speed which is almost like OFF state. As explained in the previous chapter, in Profile transient case, the water pump is running at 1RPM in the first half of the cycle, then from half of the cycle until the end of cycle it runs at 1000 RPM.

## 5.2. ESTIMATION OF FUEL CONSUMPTION FOR BASELINE ENGINE MODEL - NEDC:

For the estimation of fuel consumption for Baseline Engine Model / Belted Configuration, calculations have been made using the values taken from GT-POST (Avg. Mechanical Total Power and Fuel Flow rate).

| Time | $P_{mech\_pump}$ | Time | Fuel Flow rate | Integral Fuel Consumed |
|---|---|---|---|---|
| sec | W | sec | kg/s | kg |
| 0.5 | 6.40 | 0.15 | 3.96E-04 | 0 |
| 2.5 | 9.28 | 2.19 | 3.75E-04 | 0.0008 |
| 4.5 | 8.71 | 4.20 | 3.58E-04 | 0.0015 |
| 6.5 | 8.24 | 6.11 | 3.47E-04 | 0.0022 |
| 8.5 | 7.88 | 8.19 | 3.36E-04 | 0.0029 |
| - | - | - | - | - |
| - | - | - | - | - |
| 1174.5 | 5.78 | 1174.05 | 2.74E-04 | 0.574 |
| 1176.5 | 5.76 | 1176.14 | 2.73E-04 | 0.575 |
| 1178.5 | 5.74 | 1178.09 | 2.72E-04 | 0.576 |
| 1180 | 5.73 | 1180.04 | 2.72E-04 | **0.577** |

Table 5. 4: Values of Baseline Engine Model - NEDC

In a real engine or baseline engine, the extra fuel is consumed during the cycle, so in this case it is a distributed extra fuel. Unlike hypothetical electric motor values, in the baseline model the integral fuel consumed at the end of the cycle is considered as the actual fuel consumed at the end of cycle.

## 5.3. RESULTS - (NEDC):

- Looking at the Integral fuel consumed for the Baseline Engine model and corrected fuel consumed of water pump @1000 RPM (Total fuel consumed at the end of cycle) , we have benefit of:

$$\%\textbf{Fuel saving} = \frac{\mathbf{0.577 - 0.570}}{\mathbf{0.577}} = \mathbf{1.21}\%$$

  The calculations provide a sensitivity analysis, which shows that, if you have water pump running at 1000 RPM, then you have a benefit of 1.21% fuel saving.

- Looking at the Corrected fuel consumed (Total fuel consumed at the end of cycle) of Profile Transient case and water pump @ 1000 RPM, we have benefit of:

$$\%\textbf{Fuel saving} = \frac{\mathbf{0.576 - 0.570}}{\mathbf{0.576}} = \mathbf{1.04}\%$$

- Comparing the two cases for the electrified water pump, water pump running at 1000 RPM is more convenient than running in Profile transient case

- From the simulations, we have another benefit in terms of history of Oil temperature of the engine block subsystem. It means the engine warmed up quickly in the case of Hypothetical Electric water pump running at 1000 RPM and in Profile Transient case as compared to Baseline Engine Model.

- In addition, the Oil temperature (Engine Block Subsystem) values are reasonable and satisfactory, because if you reduce the mass flow rate of coolant, the oil temperature increases, which means less heat removed from the engine.

- The calculations which are performed, are just preliminary calculations and if this activity will be continue in the future, then proper control strategy for the speed of the pump will have to be identified. We did not have any data to check the speed of the pump (i.e. constant 1000 RPM and 3000 RPM) all over the cycle would be sufficient to guarantee the cooling system or not. Looking at the trend of the simulation results of different sub-systems' temperature which are already discussed in chapter 4 and the calculations which are performed for fuel consumption, are seemed satisfactory.

## 5.4._ESTIMATION OF ELECTRICAL POWER & OTHER RELATED QUANTITIES FOR HYPOTHETICAL ELECTRIC MOTOR – FOR WLTC:

### 5.4.1. HYPOTHETICAL ELECTRIC PUMP @1000 RPM: (FOR WLTC)

| Time | $P_{mech\_pump}$ | $P_{elec\_pump}$ | $P_{chem,batt}$ | $E_{chem\_batt}$ provided by battery during cycle) | Time | Fuel Flow rate | Integral Fuel Consumed | Corrected Fuel Consumed |
|---|---|---|---|---|---|---|---|---|
| sec | W | W | W | J | sec | kg/s | kg | kg |
| 0.5 | 12.87 | 14.30 | 15.89 | 0.00 | 0.15 | 3.96E-04 | 0.000 | 0.000 |
| 3.5 | 3.25 | 3.61 | 4.01 | 29.85 | 2.86 | 3.69E-04 | 0.001 | 0.001 |
| 6 | 3.24 | 3.60 | 4.00 | 39.86 | 5.70 | 3.49E-04 | 0.002 | 0.002 |
| 9 | 3.24 | 3.60 | 4.00 | 51.85 | 8.33 | 3.36E-04 | 0.003 | 0.003 |
| - | - | - | - | - | - | - | - | - |
| - | - | - | - | - | - | - | - | - |
| 1603 | 2.92 | 3.25 | 3.61 | 5891.52 | 1602.864 | 2.67E-04 | 0.536 | 0.537 |
| 1606 | 2.92 | 3.25 | 3.61 | 5902.34 | 1605.562 | 2.66E-04 | 0.537 | 0.538 |
| 1608.5 | 2.92 | 3.25 | 3.61 | 5911.36 | 1608.411 | 2.66E-04 | 0.538 | 0.538 |
| 1611 | 2.92 | 3.24 | 3.61 | **5920.37** | 1611.111 | 2.66E-04 | 0.539 | **0.539** |

Table 5. 5: Electric power and derived quantities (@1000 RPM) - WLTC

**- Extra fuel mass to recharge the battery = 0.000401 kg**

**- Total fuel consumed at the end of the mission/cycle = 0.539 kg**

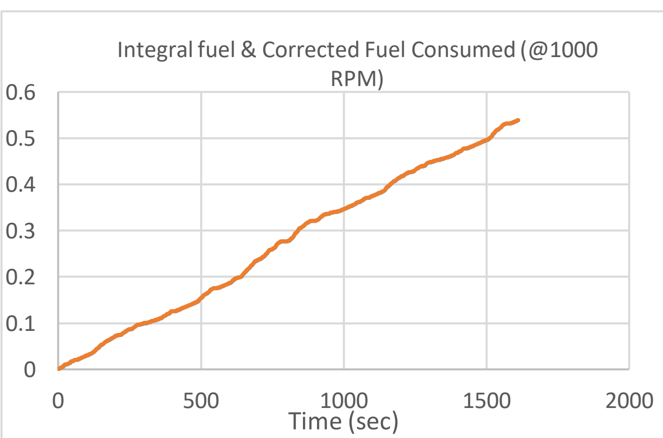



Figure 5. 7: Integral & Corrected Fuel Comparison- 1 (WLTC)

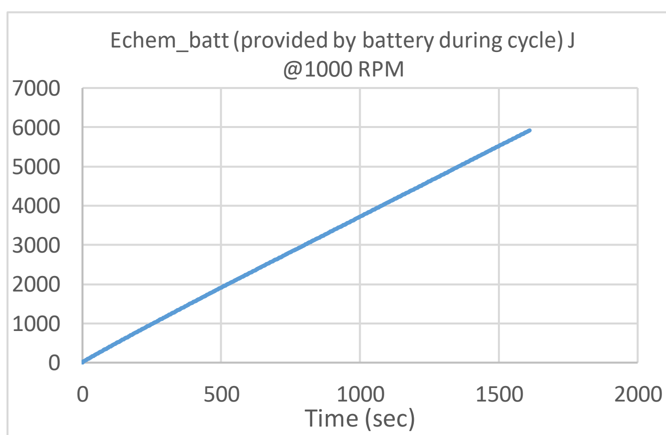



Figure 5. 8: Chemical energy- 1 (WLTC)

### 5.4.2. HYPOTHETICAL ELECTRIC PUMP @3000 RPM: (FOR WLTC)

| Time | $P_{mech\_pump}$ | $P_{elec\_pump}$ | $P_{chem,batt}$ | $E_{chem\_batt}$ provided by battery during cycle) | Time | Fuel Flow rate | Integral Fuel Consumed | Corrected Fuel Consumed |
|---|---|---|---|---|---|---|---|---|
| sec | W | W | W | J | sec | kg/s | kg | kg |
| 0.5 | 95.63 | 106.26 | 118.06 | 0.00 | 0.15 | 3.96E-04 | 0.000 | 0.011 |
| 3.5 | 87.20 | 96.89 | 107.66 | 338.58 | 2.86 | 3.69E-04 | 0.001 | 0.012 |
| 6 | 87.15 | 96.83 | 107.59 | 607.64 | 5.70 | 3.49E-04 | 0.002 | 0.013 |
| 9 | 87.08 | 96.76 | 107.51 | 930.29 | 8.33 | 3.35E-04 | 0.003 | 0.014 |
| - | - | - | - | - | - | - | - | - |
| - | - | - | - | - | - | - | - | - |
| 1603 | 80.97 | 89.96 | 99.96 | 161941.40 | 1602.982 | 2.68E-04 | 0.540 | 0.551 |
| 1606 | 80.93 | 89.92 | 99.92 | 162241.22 | 1605.682 | 2.68E-04 | 0.541 | 0.552 |
| 1608.5 | 80.90 | 89.89 | 99.88 | 162490.96 | 1608.382 | 2.67E-04 | 0.542 | 0.553 |
| 1611 | 80.87 | 89.86 | 99.85 | **162740.62** | 1611.083 | 2.67E-04 | 0.542 | **0.553** |

Table 5. 6: Electric power and derived quantities (@3000 RPM) - WLTC

**- Extra fuel mass to recharge the battery = 0.01107 kg**

**- Total fuel consumed at the end of the mission/cycle = 0.553 kg**

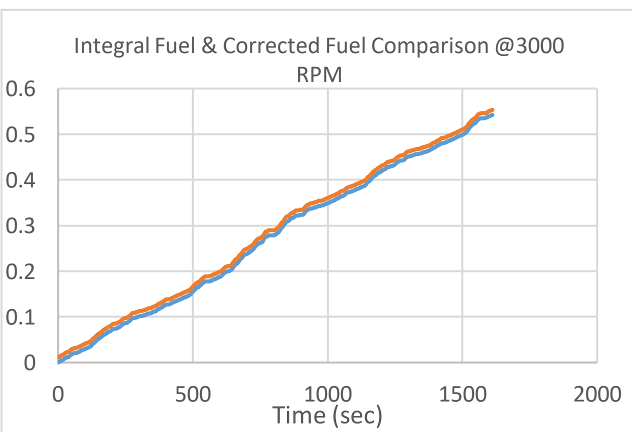



Figure 5. 9: Integral & Corrected Fuel Comparison- 2 (WLTC)

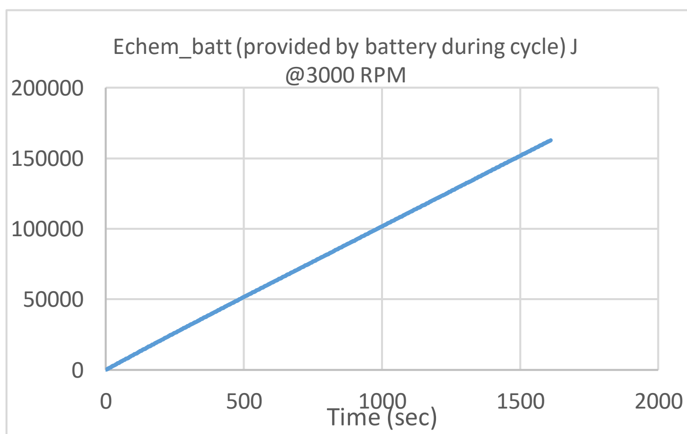



Figure 5. 10: Chemical energy- 2 (WLTC)

### 5.4.3. HYPOTHETICAL ELECTRIC PUMP – PROFILE TRANSIENT: (FOR WLTC)

| Time | $P_{mech\_pump}$ | $P_{elec\_pump}$ | $P_{chem,batt}$ | $E_{chem\_batt}$ provided by battery during cycle) | Time | Fuel Flow rate | Integral Fuel Consumed | Corrected Fuel Consumed |
|---|---|---|---|---|---|---|---|---|
| sec | W | W | W | J | sec | kg/s | kg | kg |
| 0.5 | 5.19E-05 | 5.77E-05 | 6.41E-05 | 0.0000 | 0.15 | 3.96E-04 | 0.000 | 0.000 |
| 3.5 | 2.32E-06 | 2.58E-06 | 2.86E-06 | 0.0001 | 2.86 | 3.69E-04 | 0.001 | 0.001 |
| 6 | 2.43E-06 | 2.70E-06 | 3.00E-06 | 0.0001 | 5.70 | 3.49E-04 | 0.002 | 0.002 |
| 9 | 2.53E-06 | 2.81E-06 | 3.12E-06 | 0.0001 | 8.33 | 3.36E-04 | 0.003 | 0.003 |
| - | - | - | - | - | - | - | - | - |
| - | - | - | - | - | - | - | - | - |
| 1603 | 2.92 | 3.25 | 3.61 | 2893.52 | 1602.94 | 2.67E-04 | 0.542 | 0.542 |
| 1606 | 2.92 | 3.25 | 3.61 | 2904.34 | 1605.638 | 2.66E-04 | 0.542 | 0.543 |
| 1608.5 | 2.92 | 3.25E | 3.61 | 2913.36 | 1608.337 | 2.66E-04 | 0.543 | 0.543 |
| 1611 | 2.92 | 3.25 | 3.61 | **2922.38** | 1611.038 | 2.66E-04 | 0.544 | **0.544** |

Table 5. 7: Electric power and derived quantities (Profile Transient) - WLTC

**- Extra fuel mass to recharge the battery = 0.000197 kg**

**- Total fuel consumed at the end of the mission/cycle = 0.544 kg**

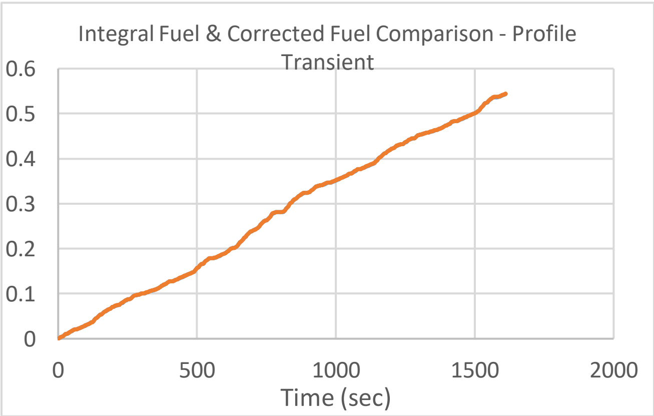



Figure 5. 11: Integral & Corrected Fuel Comparison- 3 (WLTC)

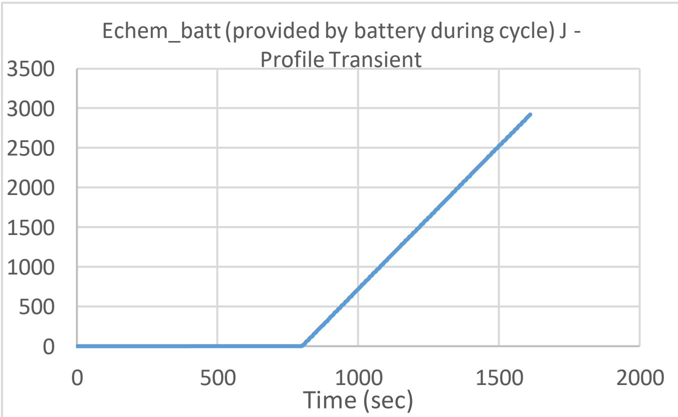



Figure 5. 12: Chemical energy- 3 (WLTC)

## 5.5. ESTIMATION OF FUEL CONSUMTION FOR BASELINE ENGINE MODEL -WLTC:

For the estimation of fuel consumption for Baseline Engine Model / Belted Configuration, calculations have been made using the values taken from GT-POST (Avg. Mechanical Total Power and Fuel Flow rate).

| Time | $P_{mech\_pump}$ | Time | Fuel Flow rate | Integral Fuel Consumed |
|---|---|---|---|---|
| sec | W | sec | kg/s | kg |
| 0.5 | 15.35 | 0.15 | 3.96E-04 | 0 |
| 3.5 | 8.98 | 2.85 | 3.69E-04 | 0.001 |
| 6 | 8.36 | 5.70 | 3.49E-04 | 0.002 |
| 9 | 7.81 | 8.32 | 3.36E-04 | 0.003 |
| 11.5 | 7.43 | 11.14 | 3.24E-04 | 0.004 |
| - | - | - | - | - |
| - | - | - | - | - |
| 1600.5 | 5.71 | 1600.16 | 2.68E-04 | 0.543 |
| 1603 | 5.69 | 1602.86 | 2.68E-04 | 0.544 |
| 1606 | 5.68 | 1605.56 | 2.68E-04 | 0.545 |
| 1608.5 | 5.67 | 1608.41 | 2.68E-04 | 0.545 |
| 1611 | 5.67 | 1611.11 | 2.67E-04 | **0.546** |

Table 5. 8: Values of Baseline Engine Model - WLTC

In real engine or baseline engine, the extra fuel is consumed during the cycle, so in this case it is a distributed extra fuel. Unlike hypothetical electric motor values, in baseline model integral fuel consumed value at the end of the cycle is considered as fuel consumed at the end of cycle.

## 5.6. RESULTS – (WLTC):

- Looking at the Integral fuel consumed for the Baseline Engine model and corrected fuel consumed of water pump @1000 RPM (Total fuel consumed at the end of cycle) , we have benefit of:

$$\%\mathbf{Fuel\ saving} = \frac{\mathbf{0.546 - 0.539}}{\mathbf{0.546}} = \mathbf{1.28\%}$$

  The calculations provide a sensitivity analysis, which shows that, if you have water pump running at 1000 RPM, then you have a benefit of 1.28% fuel saving.

- Looking at the Corrected fuel consumed (Total fuel consumed at the end of cycle) of Profile Transient case and water pump @ 1000 RPM, we have benefit of:

$$\%\mathbf{Fuel\ saving} = \frac{\mathbf{0.544 - 0.539}}{\mathbf{0.544}} = \mathbf{0.92 \simeq 1\%}$$

- Comparing the two cases for the electrified water pump, water pump running at 1000 RPM is more convenient than running in Profile transient case

- From the simulations, we have another benefit in terms of history of Oil temperature of the engine block subsystem. It means the engine warmed up quickly in the case of Hypothetical Electric water pump running at 1000 RPM and in Profile Transient case as compared to Baseline Engine Model.

- In addition, the Oil temperature (Engine Block Subsystem) values are reasonable and satisfactory, because if you reduce the mass flow rate of coolant, the oil temperature increases, which means less heat removed from the engine.

- The calculations which are performed, are just preliminary calculations and if this activity will be continue in the future, then proper control strategy for the speed of the pump will have to be identified. We did not have any data to check the speed of the pump (i.e. constant 1000 RPM& 3000 RPM) all over the cycle would be sufficient to guarantee the cooling system or not. Looking at the trend of the simulation results of different sub-systems' temperature which are already discussed in chapter 4 and the calculations which are performed for fuel consumption, are seemed satisfactory.

# CHAPTER 6: CONCLUSION

This thesis work intends to study the possibility to drive the electrified water pump of a 1.9L light-duty turbo diesel engine by introducing and implementing the hypothetical electric motor and battery model.

Using GT-Power, a new simulation model i.e. Transient Warm-up Drive Cycle Split Cooling has been derived starting from an Engine model already built by GM and validated by Project team of University of Michigan; the following changes to the have been performed:

- Changed the engine geometry i.e. consistent with Starting Model (1.9L Diesel Engine).
- Replaced the valve specifications of the 1.9L engine in the Transient Warm-up Model.
- Changed the diameter and the position of the valves in the "EngCylStruct" sub-model.
- Removing the gear connection of cooling system to the engine just to make speed of the pump independent of engine speed.
- Introduced a function called "Wpump_speed" which is alternative to Electric machine/motor. In this way, the speed of the water pump becomes independent of engine speed, and it works like an electrified pump and it is called as "Hypothetical Electric Motor".
- To clarify or manage the configuration of hypothetical electric motor "Speed Boundary Rot." is considered as a source of speed and it works like an electric motor.

The simulations have been performed for four different cases/strategies in order to analyze the behavior of Transient Warm-up drive cycle model. Initially, the model is simulated with a normal mechanical water pump connection. Then simulated two different constant RPM cases or hypothetical electric water pump cases (i.e. @1000 & 3000 RPM). Finally, introduce another case, which is also a case of electrified water pump, its speed is not constant throughout the entire cycle. For this case, a function called "Profile Transient" is used.

The simulations are performed using New European Driving Cycle (NEDC) and World harmonized Light-duty vehicles Test Procedure/Cycle (WLTC). Using WLTC, because it is more realistic and dynamic driving cycle, it has a greater range of driving situations (urban, suburban, main road, motorway), also it has stricter car set-up and measurement conditions.

According to the simulations performed on both driving cycles using GT-Power, the oil temperatures are aligned to the expectation, which is related to warm-up phase. Oil temperature is mentioned because it is a representative of engine wall temperature. Oil temperature increases as we decrease the pump speed.

By looking at the simulation results, it is clear that water pump running at 1000 RPM or in the case of Profile transient, we have an increasing trends of the oil temperature as compare to the other cases.
Furthermore, calculations have been made the for Hypothetical electric motor and battery of the transient warm-up drive cycle model for different pump speed and cases, and to compare the results with Baseline Engine Model. These calculations are made for the estimation of electrical power absorbed by Hypothetical Electric motor and fuel consumption by the engine.

From the simulations and calculations on the baseline engine model and electrified model, it results that electrified water pump running at 1000 RPM providing the benefit of 1.21% fuel saving as compare to baseline engine when simulating on the NEDC cycle. While, simulating on WLTC it provides the benefit of 1.28% fuel saving as compared to baseline engine.

## 6.1. FUTURE WORK:

Different tests, and experiments have been left for the future due to the model parameters and its different aspects. Future work concerns deeper analysis of particular mechanisms and new proposals to improve the model and to establish whether an electric water pump could have the same beneficial effects as with the hypothetical electric water pump model.

# CHAPTER 7: BIBLIOGRAPHY

[1] Robert D. Chalgren Jr. and David J. Allen, "Light Duty Diesel Advanced Thermal Management", SAE Paper 2005-01-2020.

[2] GT-SUITE "Engine Block Thermal Modeling" tutorial, Version 2018 by GammaTechnologies.

[3] https://www.gtisoft.com/gt-suite-applications/propulsion-systems/gt-power-engine-simulation-software/

[4] https://www.gtisoft.com/gt-suite-applications/thermal-management/vehicle-cooling/

[5] Di Bartolomeo, M., Fatigati, F., Di Battista, D., and Cipollone, R., "A New Approach for Designing and Testing Engine Coolant Pump Electrically Actuated," SAE Technical Paper 2020-01-1161, 2020, doi: 10.4271/2020-01-1161.

[6] Eduardo Gubbiotti Ribeiro, Ayres Pinto de Andrade Filho, João Luiz de Carvalho Meira. WOP Ind. e Com. de Bombas Ltda., "Electric Water Pump for Engine Cooling," SAE TECHNICAL 2007-01-2785 PAPER SERIES E.

[7] Wang, T. and Wagner, J., "A Smart Engine Cooling System – "Experimental Study of Integrated Actuator Transient Behavior," SAE Technical Paper 2015-01-1604, 2015, doi:10.4271/2015-01-1604.

[8] Ramadhas, A. and Xu, H., "Influence of Coolant Temperature on Cold Start Performance of Diesel Passenger Car in Cold Environment," SAE Technical Paper 2016-28-0142, 2016, doi:10.4271/2016-28-0142.

[9] A. E. HERSHEY, University of Illinois, Urbana, "Factors Affecting Diesel-Engine Efficiency and Combustion"**.** Bulletins Nos. 139 and 160 of the Engineering Experiment Station of the University of Illinois, Urbana, Ill.

[10] Zhou, F., Tan, G., Zhou, M., Liu, Z. et al., "Research on Solar Thermal Energy Warming Diesel Engine Based on Reverse Heat Transfer of Coolant," SAE Technical Paper 2020-01-1343, 2020, doi:10.4271/2020-01-1343.

[11] Granitz, C., Ratzinger, J., Eichlseder, H., and Surace, A., "Application of Electrically Driven Coolant Pumps on a Heavy-Duty Diesel Engine," SAE Technical Paper 2019-01-0074, 2019, doi:10.4271/2019-01-0074.

[12] Bitsis, D.C. and Miwa, J., "Optimization of Heavy Duty Diesel Engine Lubricant and Coolant Pumps for Parasitic Loss Reduction," SAE Technical Paper 2018-01-0980, 2018, doi:10.4271/2018-01-0980.

[13] https://en.wikipedia.org/wiki/New_European_Driving_Cycle

[14] https://en.wikipedia.org/wiki/Worldwide_Harmonised_Light_Vehicles_Test_Procedure

[15] https://www.wltpfacts.eu/what-is-wltp-how-will-it-work/