Numerical Simulation of a 2018 F1 Car Cooling System for Silverstone Circuit

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Abstract

The thermal management of a Formula 1 car is a challenging task as it involves multiple components, systems and multiple sources of thermal energy. The present work attempts to model a representative F1 car following 2018 F1 regulations directly linked to the cooling systems requirements and performance. The main purpose of this work is to simulate the steady and transient behaviour of the cooling system when the vehicle is in a qualifying lap, and during the entire race, including the wait in the starting grid and the pit stops. This model includes the sub-models representing internal combustion engine, hybrid powertrain, vehicle, driver and an appropriate cooling system composed of radiators, pumps and expansion tanks. This work validates the cooling system of a representative 2018 F1 car for the Silverstone Circuit. This model is capable of simulating the overall thermal performance of the F1 car for sizing the cooling system for most of the F1 circuits. This paper presents a systematic approach followed for modelling a representative F1 car based on 2018 regulations, methods used for deriving appropriate data from various sources, approach used for validating the model and finally the strengths of the validated model for sizing the cooling system.

Introduction

There are several sources of heat in any kind of vehicle that have to be rejected, however, all these sources can be gathered into two main categories; those sources that only need to be cooled, and those that have not only to be cooled but also to have their temperature controlled and maintained between the proper operational boundaries. One source of heat that does not need an accurate control of its temperature is the braking system. This system only needs to be cooled to keep its temperature below the operational limit of the materials in which the different components of the system have been manufactured. Within the category of source of heat which needs its temperature to be controlled is the power unit of the F1 car. The power unit of a 2018 F1 car is a hybrid power unit consisting of the internal combustion engine (ICE) and the electric unit. This electric unit consists of two electric motors, the motor generator unit-heat (MGU-H) and the motor generator unit-kinematic (MGU-K), and an energy storage or battery (ES).

The main source of heat the cooling system has to receive from is the internal combustion engine. Ideally, the cooling of the engine is against the thermodynamic efficiency. The cooling system steals heat from the combustion chamber that could be used to increase the pressure within the cylinder to extract more work from the engine. However, the cooling system is mandatory in an internal combustion engine due to the limits that materials composing the internals of the engine have regarding higher temperature. From certain temperatures, these components would fail, so the temperature of them has to be kept under safe conditions. In addition, oil loses its lubricating properties when the temperature is higher than around 175º C [1] thus, increasing wear of engine components and conducing to premature failure of the engine.

Developing a cooling system model for a complete vehicle is essential for understanding the interaction between the systems and optimizing the cooling package for the vehicle. Arici, Johnson and Kulkarni [2] simulated the thermal response of the cooling system of an on-highway heavy-duty diesel truck under steady and transient conditions using Vehicle Engine Cooling System Simulation (VECSS) computer code developed originally by Ursini [3] and Chang [4] at Michigan Technological University.

In this work, they were able to predict "the response of the cooling circuit, oil circuit, and the engine compartment air flow when the VECSS is operated using driving cycle data of vehicle speed, engine speed, and fuel flow rate for a given ambient temperature, pressure and relative humidity." Luptowski et al. [5] enhanced VECSS linking it with GT-Power for the engine/cycle analysis model. With the enhanced VECSS (E-VECSS) they predict "the effects of cooling system performance on engine performance including accessory power and fuel conversion efficiency". Along with the engine cycle, components they modelled include the engine manifolds, turbocharger, radiator, charge-air-cooler, engine oil circuit, oil cooler, cab heater, coolant pump, thermostat, and fan. The tool was then applied to develop and simulate the strategy of control of an electric cooling system for a 12.7-liter diesel engine. Mahmoud, et al. [6] integrated all partial thermal systems: gas circuit, cooling circuit, engine oil circuit, engine structure, underhood flow, and passenger compartment through the utilization of an integrated model composed by 1-D thermal network, 1-D engine simulation, 3-D CFD database and vehicle simulation software for analyzing the thermal behavior of the entire vehicle during different cycles.

Thermal management of hybrid electric vehicles is a more complex task due to the increase in the quantity of components and subsystems within the cooling system. Park and Jung [7] model and simulate the cooling system for a virtual heavy-duty series hybrid electric vehicle using Vehicle-Engine SIMulation (VESIM) previously developed by the Automotive Research Center at the University of Michigan. "The model predicts the thermal responses of all cooling system components and the temperatures of the engine and electric component over a realistic driving cycle." The work concludes that it is necessary to provide the vehicle with a dedicated cooling system for electric powertrain components due to the large amount of heat generated from the electric components. Bennion and Thornton [8] modelled an integrated vehicle thermal management system for a hybrid electric vehicle as one way to reduce cost, thermal loads and transfer heat efficiency while increasing the efficiency of the hybrid powertrain reusing available waste heat. This work describes four vehicle configuration including hybrid electric vehicle and plug-in hybrid electric vehicles that are simulated over real-world cycles to obtain data for the heat load analysis.

Scope of the current work

In this work, the cooling system of an F1 will be modelled, including all the subsystems and components. To be able to simulate the cooling system under transient conditions, the hybrid powertrain and vehicle will be modelled to be able to test them against different driving cycles; in this case, it will be a qualification lap and an entire race in the circuit of Silverstone.

Methodology

The design of a cooling system for an F1 is a demanding task that has to be carried out following all the regulations that govern the sport [9]. In addition to the specific regulations for the cooling package, its design has also to take into account the regulations of other components of the car since they interact and transfer thermal energy across the systems. For instance, the maximum pressure a pump can deliver or the maximum energy that the battery can hold can change the overall heat addition or rejection quantity. Therefore, the associated parts and components should be modelled in order to assess the thermal performance of the complete vehicle. The present work employs GT-Suite package for modelling the vehicle and complete cooling system and MATLAB for post processing the simulation output.

Engine

The main source of heat the cooling system has to reject is that coming from the engine. This heat is transferred to the cooling system by two fluids. The main coolant is the water, the fluid in charge of removing excess heat from the cylinder and the head. The second fluid is the oil, used mainly to lubricate engine components like the piston, the camshaft and the crankshaft, but also to remove heat from piston, the turbocharger and other engine components. To know how much heat is transferred from the engine to the cooling system it is necessary to know the power of the engine at every state. To do that, an engine map was introduced into the model. To develop the engine map, the maximum mass fuel flow allowed by the regulation (Article 5.1.4) [9] was the main input to calculate the power at every stage. Moreover, regulations [9] set the boundaries to maximum fuel mass flow rate as shown in Figure 1.

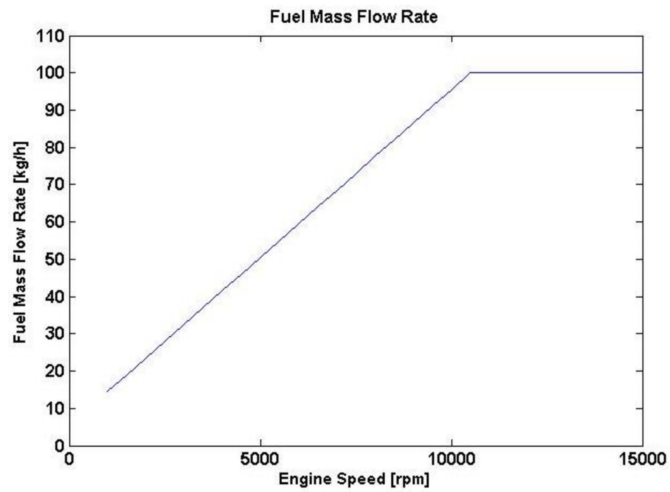

Figure 1. Fuel Mass Flow Rate applying equation in article 5.1.4 and 5.1.5 [9]

Assuming a fuel heat value of 44,600 kJ/kg [10] and assuming appropriate values for thermal, volumetric and mechanical efficiency for every state, the effective power at wide-open throttle can be calculated and is shown in Table 1.The values for thermal, volumetric and mechanical efficiency were taken as assumptions consulting different references as well as to match a maximum BMEP of around 30 bar [11]. Part load characteristics of the engine was derived as a function of mass flow rate air into the system for 0 to 100% air flow rate and are shown in Table 2 and Table 3. Fuel consumption map derived using equation (1) is shown in Table 4.

$$bsfc\left(\frac{}{}\right) \quad \frac{}{\;} \tag{1}$$

Where is the thermal efficiency and the low fuel heat value.

To develop the heat rejection map, it was assumed that the 60% of the waste heat is transferred to the cooling, and the 40% is wasted through the exhaust. For instance, if the thermal efficiency is 40%, the percentage of heat from the fuel that goes to the cooling system would be 36% and the waste heat through the exhaust would be 24%. (Table 5).

Table 1. Effective Power

RPM	Fuel Mass Flow (kg/h)	Indicated Power (kW)	Thermal Efficiency	Volumetric Efficiency	Mechanical Efficiency	Effective Power (kW)
3000	32.5	403	0.4	0.58	0.98	91.5
5000	50.5	570	0.41	0.66	0.97	164
7000	68.5	849	0.42	0.74	0.96	253
9000	86.5	1072	0.42	0.82	0.95	351
11000	100	1239	0.43	0.9	0.95	455.5
13000	100	1239	0.44	0.98	0.95	507.5
15000	100	1239	0.45	1.06	0.95	561.4

Table 2. Engine Map. Power (kW)

RPM	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
3000	9.15	18.3	27.5	36.6	45.8	54.9	64.1	73.2	82.4	91.5
5000	16.4	32.8	49.3	65.7	82.1	98.5	115	131	148	164
7000	25.3	55.4	76	101	127	152	177	203	228	253
9000	35.1	70.1	105	140	175	210	245	280	316	351
11000	45.55	91.1	136.6	182.2	227.7	273.3	318.8	364.4	409.9	455.5
13000	50.75	101.5	152.2	203	253.7	304.5	355.2	406	456.7	507.5
15000	56.14	112.3	168.4	224.6	280.7	336.8	393	449.1	505.3	561.4

Table 3. Engine Map. BMEP (bar)

RPM	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
3000	2.29	4.58	6.87	9.15	11.4	13.7	16	18.3	20.6	22.9
5000	2.46	4.93	7.39	9.85	12.3	14.8	17.2	19.7	22.2	24.6
7000	2.71	5.43	8.14	10.9	13.6	16.3	19	21.7	24.4	27.1
9000	2.92	5.84	8.77	11.7	14.6	17.5	20.5	23.4	26.3	29.2
11000	3.11	6.21	9.32	12.42	15.53	18.63	21.74	24.84	27.95	31.06
13000	2.93	5.86	8.78	11.71	14.64	17.57	20.5	23.42	26.35	29.28
15000	2.81	5.61	8.42	11.23	14.04	16.84	19.65	22.46	25.26	28.07

Table 4. Engine Map. BSFC (g/kWh)

RPM	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
3000	202	202	202	202	202	202	202	202	202	202
5000	197	197	197	197	197	197	197	197	197	197
7000	192	192	192	192	192	192	192	192	192	192
9000	192	192	192	192	192	192	192	192	192	192
11000	187.7	187.7	187.7	187.7	187.7	187.7	187.7	187.7	187.7	187.7
13000	183.4	183.4	183.4	183.4	183.4	183.4	183.4	183.4	183.4	183.4
15000	179.4	179.4	179.4	179.4	179.4	179.4	179.4	179.4	179.4	179.4

Table 5. Heat Rejection Map (%)

RPM	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
3000	36	36	36	36	36	36	36	36	36	36
5000	35.4	35.4	35.4	35.4	35.4	35.4	35.4	35.4	35.4	35.4
7000	34.8	34.8	34.8	34.8	34.8	34.8	34.8	34.8	34.8	34.8
9000	34.8	34.8	34.8	34.8	34.8	34.8	34.8	34.8	34.8	34.8
11000	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2
13000	33.6	33.6	33.6	33.6	33.6	33.6	33.6	33.6	33.6	33.6
15000	33	33	33	33	33	33	33	33	33	33

As the heat rejection map is the total heat rejected to the cooling system, the percentage of heat that goes to the oil and the coolant has to be set by a gain object in the model. This percentage was set to 40% of the total heat going to the oil, and 60% to the water.

EngineBlock-5Mass object in GT-Suite was used for modelling the interaction between the coolant, oil and energy transfer across the boundaries. This object was used to model the coolant and oil volume within the engine block, as well as the engine structure. This object simplifies the engine block into a single volume for coolant and a single volume for oil. The engine structure is represented by 5 thermal masses. Two of these masses are "inner" masses that are connected only to one of the fluid volumes and receive direct heat input (i.e. heat rate to coolant inner mass and heat rate to oil inner mass). The fluid volumes are then connected to the "outer" masses that represent the block, head, and crankcase structure. The outer masses can transfer heat with the ambient environment [12] (Table 6).

Table 6. EngineBlock-5Mass main characteristics

Head Mass	20 kg
Block Mass	50 kg
Head and Block Material	Aluminium 2024-T6
Coolant Volume	3.6 l
Diameter at Inlet. Coolant	42 mm
Diameter at Outlet. Coolant	42 mm
Heat Transfer Area. Coolant	0.138 m^2
Oil Volume	2.5 l
Diameter at Inlet. Oil	35 mm
Diameter at Outlet. Oil	35 mm
Heat Transfer Area. Oil	0.1 m^2
Convective Heat Transfer Coefficient to Ambient	20 W/m^2K
Area for External Convection	0.9 m^2
Block Height	250 mm
Block Average Thickness	10 mm

The cooling system has two circuits. One is the water circuit, and another is the oil circuit. Both have similarities in the layout and the components, but the behaviour is not the same. The oil system is under higher pressure and higher volumetric flow. It also has to run at higher temperatures.

Pumps

Pumps of oil and water circuits have different operating maps. The pump is the responsible for increasing the pressure of the circuit and the responsible for moving the fluid through the pipes, as well as to overcome all the friction and pressure drop of the different components. Both pumps are located before the engine, to assure the pressure and the volumetric flow that reaches the engine is the required. Both pumps are linked directly to the crankshaft through a gear ratio to decrease the speed of the pump, as the maximum speed of these pumps is 5500 rpm.

Radiators

The radiators are responsible for rejecting the heat that oil and water transport. These radiators are air-liquid type, so the water or oil flows inside the tubes and the air passes between those tubes. In this model, the radiators that were chosen were vertical radiators, and the water radiator is bigger in dimensions than the oil radiator (almost the double). To model the radiators, data has to be introduced into the Radiator object of the model. The geometry was designed to fit within the lateral body of the F1, in which the radiators will be located. These radiators will be angled, so they can be taller than the height of the body of the F1 [9]. The main characteristics, the external and internal geometry of the radiator for coolant is shown in Figure 2 and Table 7.

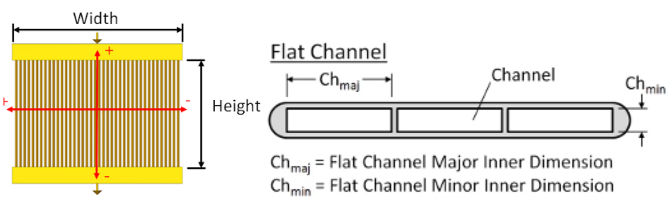

Figure 2. Radiator dimensions

Table 7. Radiator dimensions and characteristics

Heat Exchanger Height	400 mm
Heat Exchanger Width	300 mm
Total Heat Exchanger Depth	50 mm
Number of Rows of Tubes	1
Inlet Connection Diameter	42 mm
Outlet Connection Diameter	42 mm
Dry Mass of Heat Exchanger Material	3.5 kg
Heat Exchanger Material	Aluminium
Flat Channel Major Inner Dimension	19 mm
Flat Channel Minor Inner Dimension	1.5 mm
Tube Wall Thickness	0.1 mm
Number of Channels	2

The data for the heat transfer of the radiator is obtained through testing of the radiator in a test bench [12]. In this work the data for heat transfer introduced into the model is from a typical automotive radiator with the efficiency increased by 5%.

The mass flow of water and oil that flows through the inside of the radiators is given by the pumps, and the air mass flow will be given by the speed of the vehicle.

Thermostats

Thermostats are necessary for the control of the temperature of the coolant fluid especially during warm up, or when the coolant fluid is being overcooled by the radiators. Thermostats consist of a valve with a membrane that moves depending on the temperature of the fluid. Thermostats are connected to the radiator and to another pipe that bypasses the radiator. When the temperature of the fluid is high, the membrane of the thermostat expands and the bypass pipe is closed, so all the fluid goes through the radiators. When the coolant fluid is cold, the membrane of the thermostat is open and the fluid bypasses the radiator, so the coolant fluid is not refrigerated and it warm up faster. In addition, a Bypass thermostat is fitted in the bypass pipe to better control the flow that passes through the bypass. The behaviour of all the thermostats used in this simulation is given in Table 8.

Table 8. Thermostats Behaviour

Oil Thermostat		Water Thermostat		Bypass Thermostat	
T (ºC)	Lift (mm)	T (ºC)	Lift (mm)	Thermostat Lift (mm)	Bypass Lift (mm)
100	0	90	0	0	6
105	0.2	95	0.2	0.2	5.88
108	0.8	98	0.8	0.8	5.58
110	1.8	100	1.8	1.8	4.98
119	8.3	109	8.3	8.3	1.08
121	9.3	111	9.3	9.3	0.48
124	9.8	114	9.8	9.8	0.12
127	10	117	10	10	0

Expansion Tanks

Expansion tanks are required to keep the pressure of circuits at stable levels. In these tanks, there are two volumes separated by a membrane, one filled by air and another by the coolant. When the coolant fluid expands due to the increase in temperature, the fluid expands against the volume of air on the other side of the membrane, so the pressure of the coolant stay the same and the pressure of air increases. These tanks are located just before the pumps, so the fluid in the intake of the pump is always with the same pressure, and the cavitation is avoided. In addition, the regulation (Article 7.5) [9] sets a limit of 3.75 bar-g of maximum water pressure, so it has to be ensured that this limit is not crossed at any moment.

Pressure Losses in the Engine Block

The pressure losses in the engine block both in the water side and in the oil side have to be taken into account when designing the cooling circuit. In this work, the pressure losses data was taken from a typical automotive block [12] with an increase in performance of 10%.

Vehicle

To simulate the real behaviour of an F1 car, a vehicle object in GT-Suite was used alongside with the driver object. 2018 F1 cars are hybrid vehicles, therefore, MGU-K, MGU-H and Energy Storage system were also modelled. The minimum weight of the vehicle used in this model was 728 kg as per Article 4.1 [9]. The drag coefficient was set as 1.0; the lift coefficient as -2.5, the frontal area of the vehicle as 1.3 m^2 and the diameter of the wheels as 670 mm (Article 12.4.2) [9].

Another very important part to model is the transmission and the differential system. To know the gear ratios (GR) of the gears of an

F1 car a video source [13] was used to extract the data of engine speed and vehicle speed. Knowing the diameter of the wheel, the engine speed and the vehicle speed, the gear ratio is calculated using equation (2) and is shown in Table 9.

$$GR = \frac{\left(\frac{2\pi N}{60}\right)}{\left(\frac{V_{veh}}{D_{wheel}/2}\right)} \tag{2}$$

Where N is the engine speed in rpm, V_{veh} is the vehicle speed in m/s and D_{wheel} is the diameter of the wheel in *m*.

Table 9. Total Gear Ratio

Gear	1	2	3	4	5	6	7	8
GR	17.24	15.06	12.14	10.02	8.36	7.23	6.61	5.6

Defining a Final Drive Ratio in the differential of 5.6, the gear ratio of each gear would be as shown in Table 10

Table 10. Transmission Gear Ratio

Gear	1	2	3	4	5	6	7	8
GR	3.08	2.69	2.17	1.79	1.49	1.29	1.18	1

Driver

The driver is the person who has to govern the vehicle and specify the behaviour of the car, like the speed, acceleration, gear number, etc. In this case, a speed will be imposed to the driver to drive the vehicle, and the driver has to operate the throttle and brake pedals to follow that imposed speed. The cycle the vehicle has to follow will be defined in the test part of this work. The gearshift strategy as shown in Table 11 will be imposed by engine speed.

Table 11. Gearshift Strategy

Gear	2	3	4	5	6	7	8
Up-Shift	14000	14500	14500	15000	15000	15000	15000
Down-Shift	80000	10500	10500	10500	10500	10500	10500

Hybrid System

The hybrid part of an F1 consists of a Motor Generator Unit – Heat (MGU-H), a Motor Generator Unit – Kinetic (MGU-K) and an Energy Storage (ES) system. To model these components, the rules of FIA have to be followed, because they set boundaries in total energy stored and energy flow. MGU-K model follows Article 5.2.3 [9]. The maximum power that the MGU-K can deliver is 120 kW (Appendix 3) [9]. Thus, the final torque map for the MGU-K based on this regulation will be as shown in Figure 3:

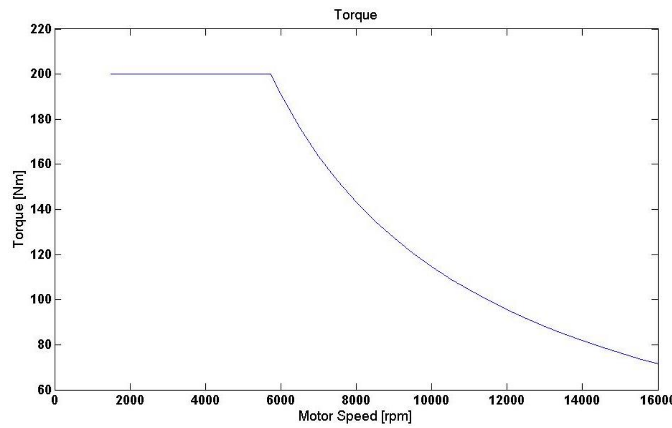

Figure 3. MGU-K Torque

The MGU-H does not have a limit in power, however 60 kW was the assumption that has been taken for the maximum power that the MGU-H can harvest from the turbo when the vehicle is at full power. The battery was modelled based on regulations, Article 5.12.5 [9]. This regulation also states that the difference between the maximum and the minimum state of charge of the ES may not exceed 4 MJ at any time the car is on the track. Thus, the maximum time the MGU-K can deliver 120 kW can be calculated using in equation (3).

(3)

Taking all of that into account, and after various tests to match the time the battery lasts with the MGU-K developing 120 kW, and without exceeding the limit of 1000 V ruled by Article 5.12.5 [9], the battery was modelled. In addition, as the cells produce a large amount of heat, a cell thermal model was created, and the battery is cooled by the cooling system. Figure 4 shows the cooling system layout, Figure 5 shows the vehicle layout and Figure 6 shows the complete layout of the entire model.

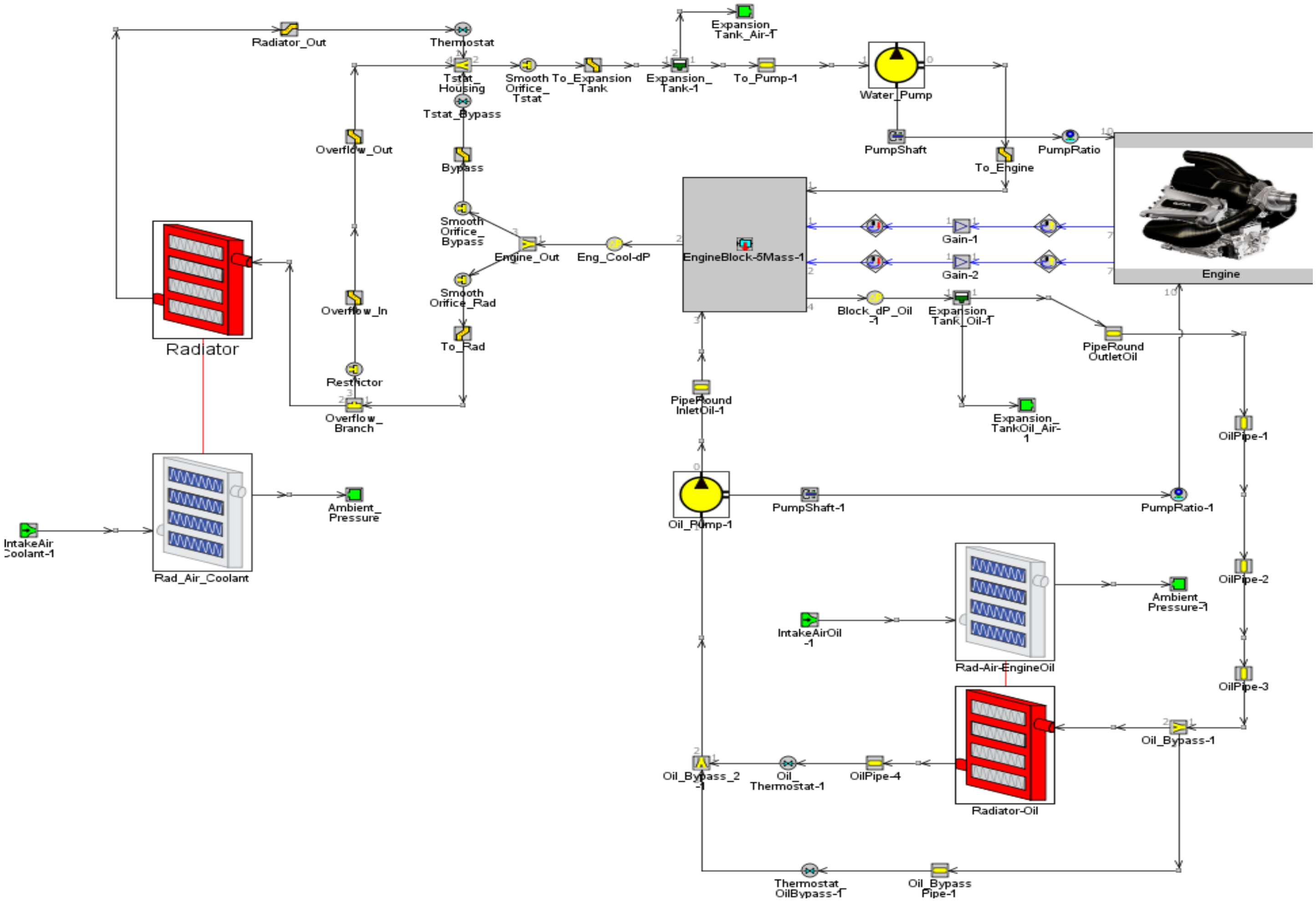

Figure 4. Cooling System Layout modelled as per 2018 Formula One Regulations

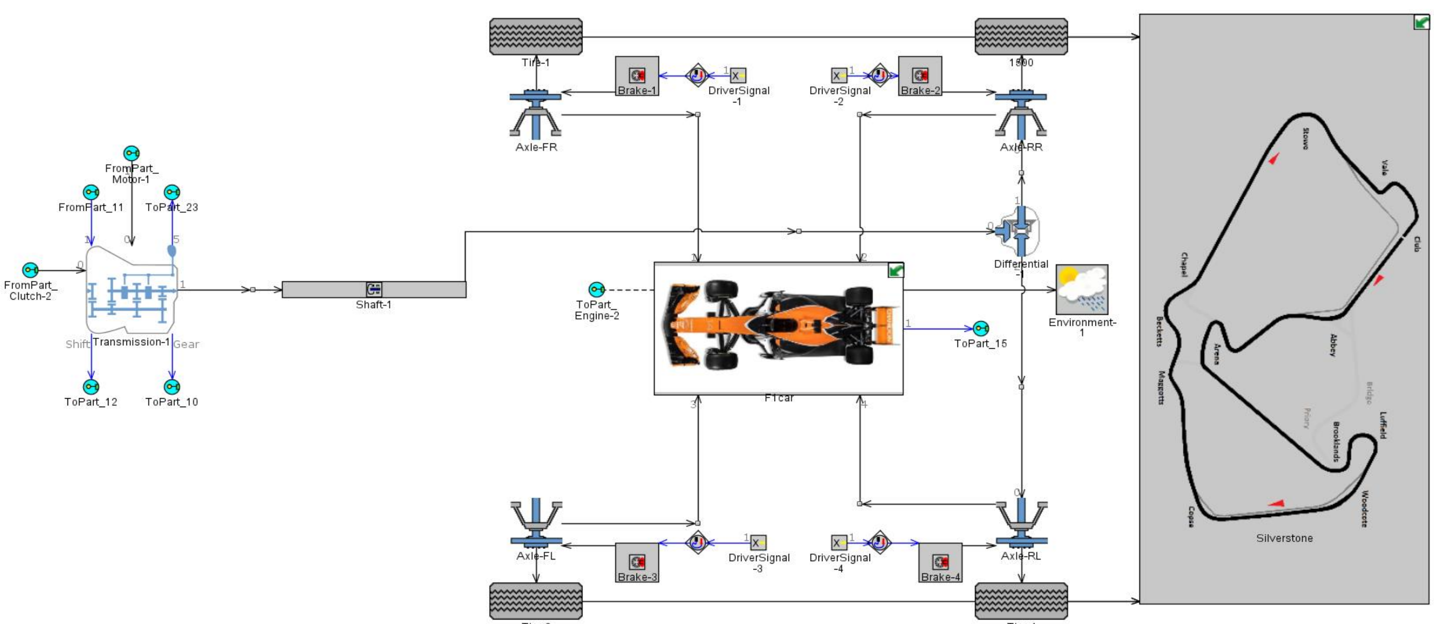

Figure 5. Vehicle Layout modelled as per 2018 Formula One Regulations

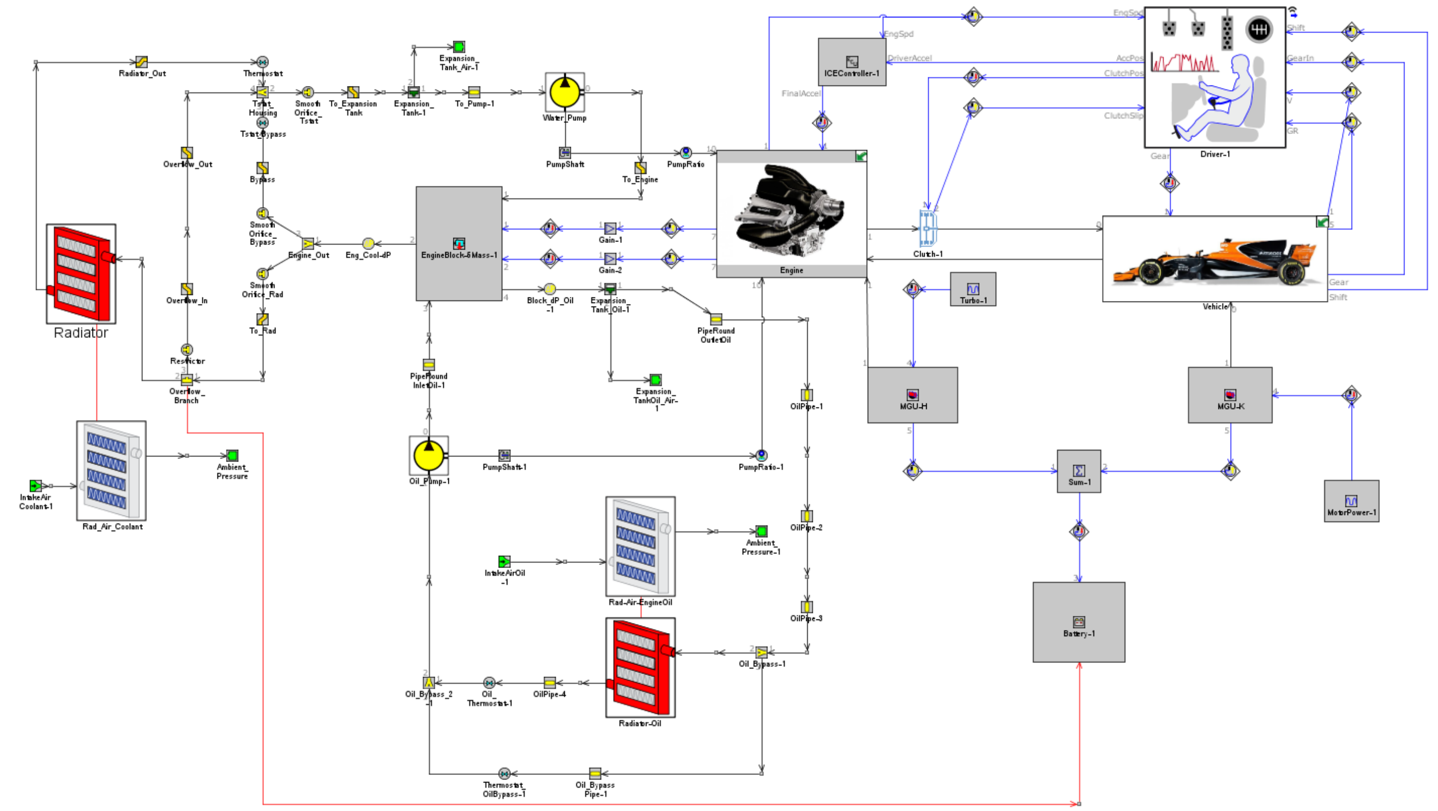

Figure 6. Complete Layout modelled as per 2018 Formula One Regulations

Simulating test conditions

The first set of simulations were carried out at steady state vehicle operating conditions by fixing the vehicle speeds at 100 km/h, 200 km/h and maximum vehicle speed. The second set of simulations were carried out under transient vehicle operating conditions, considering qualification lap, and a complete race in the Silverstone circuit.

Qualification Lap

Vehicle speed trace for simulating qualification lap in Silverstone was acquired by analysing video recording of the race data [13]. The vehicle starts from the pit lane, with water and oil temperature of 90º C and it makes the launch and warming up lap at 80% of the maximum speed possible in every part of the circuit. The state of charge of the battery in the pit lane is 0.8; the MGU-H will harvest energy until the state of charge of the battery will be close to 1.

Then, the vehicle run the qualification lap trying to follow the speed profile introduced into the model (Figure 7). The MGU-K will deliver 120 kW (Appendix 3) [9] with the engine at full throttle, and it will harvest energy during the hardest braking. In addition, the MGU-H will harvest energy while the engine is at full throttle to control the speed of the turbine of the turbocharger, and it will give energy to the turbocharger before the accelerations to speed up the compressor and avoid turbo-lag. After the qualification lap, the vehicle will go back to the pit lane at 80% of the maximum speed and the MGU-K will harvest 20 kW of energy at every second. The full cycle is shown in Figure 7.

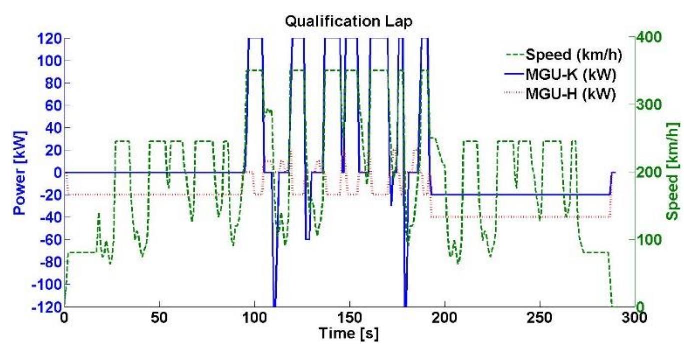

Figure 7. Characteristics of the Qualification Lap. Speed curve is the target speed the driver will try to achieve and not the actual speed.

Race

The second test is to validate the cooling system for a complete race in Silverstone circuit. The vehicle will start from the starting grid; it will do the warm-up lap, regenerating energy until a state of charge of the battery of almost 1. Then it will stop in the starting grid for 21 seconds until the green light and the start of the race. The pit stop strategy includes total of 2 stops, the first one in the lap 15, and the second one in the lap 35. This race consists of 52 laps.

From the start to the lap 8 the electric motor will be used more, discharging the battery until almost zero SOC (relative SOC as battery is never empty or full). In the lap 8, when the tyres are more worn and the vehicle is already in a constant position in the classification, the electric motor will be used less, and will harvest more energy to recharge the battery. The electric motor will be used more after the first change of tyres, often and the battery will be discharged faster during some laps. From the lap 27, the system will recover more energy to charge the battery. In the lap 35, the second pit stop will be made. The battery will be charged until full charge the next laps, so the last laps the electric motor can deploy more energy for the final part of the race. When the race is finished, the car will go back to the box.

Results and Analysis

Steady State

The simulation output for three steady state vehicle operating conditions at 100 km/h, 200 km/h and maximum vehicle speed are analyzed. Figures 8-10 shows the temperature and coolant volumetric flow rate at these operating conditions.

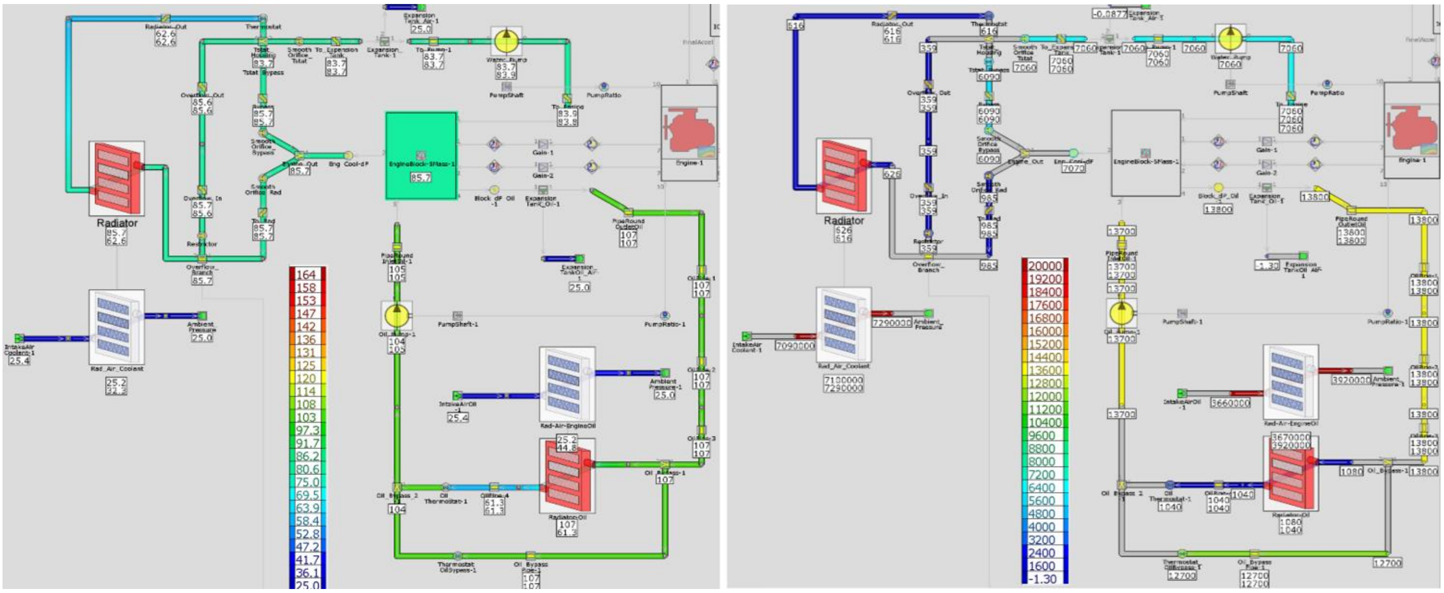

Figure 8. Temperature (ºC) (left) and Volumetric flow rate (l/h) (right) at 100 km/h

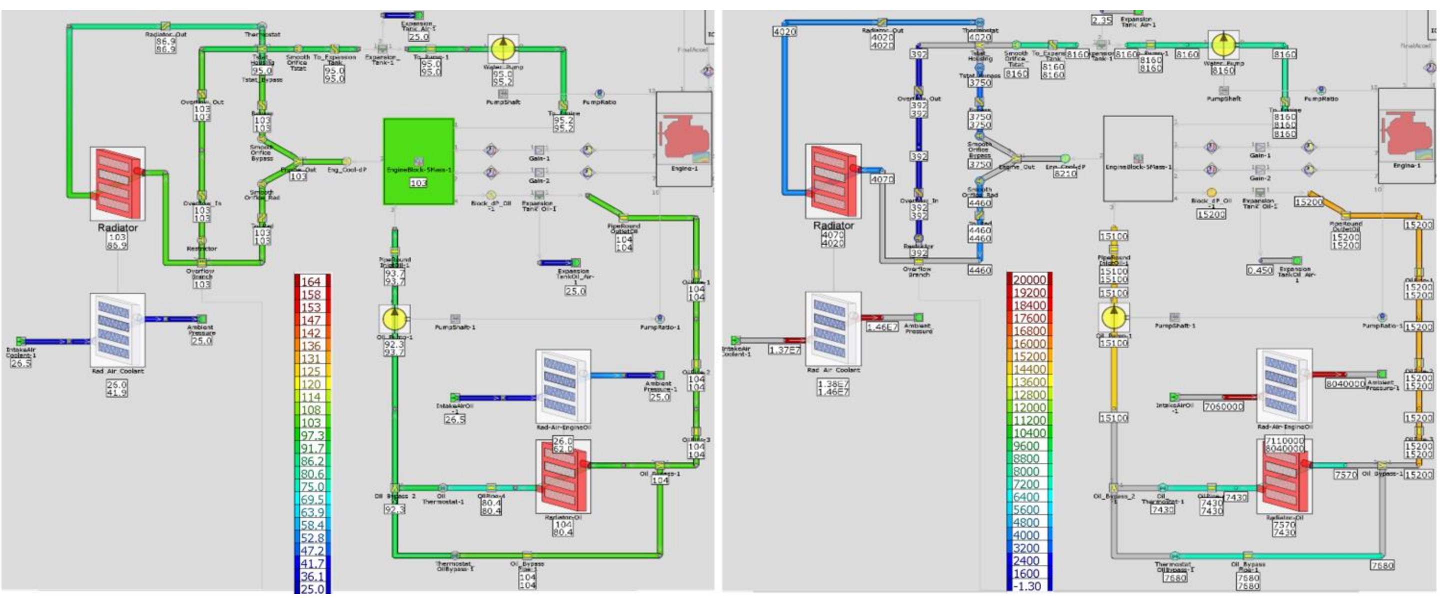

Figure 9. Temperature (ºC) (left) and Volumetric flow rate (l/h) (right) at 200 km/h

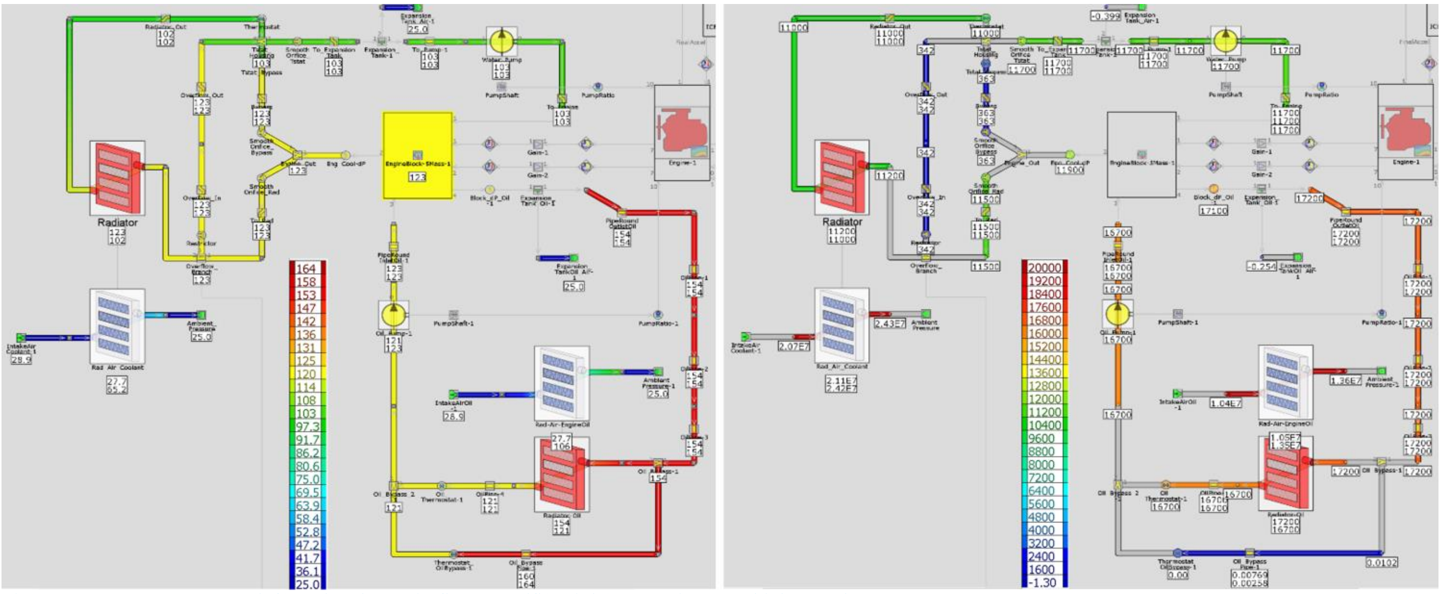

Figure 10. Temperature (ºC) (left) and Volumetric flow rate (l/h) (right) at maximum vehicle speed

At 100 km/h operating condition, the temperature of the water is below 90º C so only 600 l/h go through the radiator, the main part of the water flows through the bypass. In the oil circuit, only 1,000 l/h flow through the radiator and 12,700 l/h flow through the bypass.

When the vehicle speed is 200 km/h, the temperature is around 100º C so half of the flow of water and oil passes through the radiator, and the other half flows through the bypass as shown in Figure 9.

At maximum speed, all the flow of water and oil is cooled by the radiators, as both temperatures are high. However, it is a temperature in which a F1 engine can work, so even at full throttle the engine does not overheat and the cooling system is able to reject enough heat to assure the reliability of the engine. Thus, the radiators and cooling system are well designed and dimensioned. Figure 11 shows the vehicle speed over time, to know which is the maximum vehicle speed at full throttle. Figure 12 shows the pressure of the coolant, being less than 4.75 bar-a as per Article 7.5 [9]

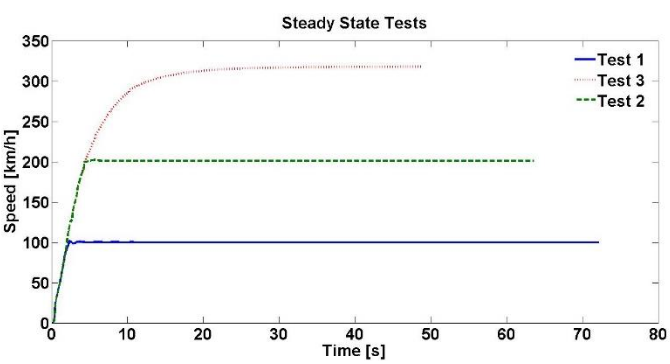

Figure 11. Vehicle Speed for the three different tests

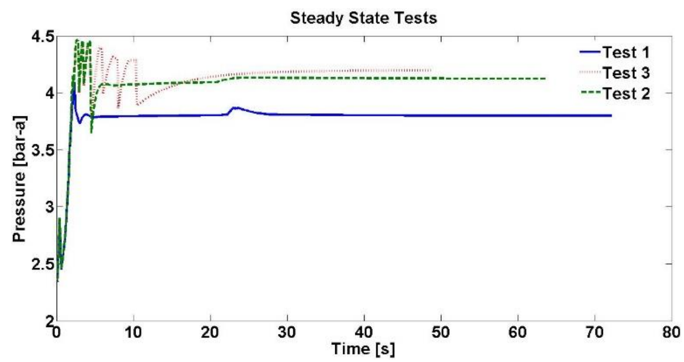

Figure 12. Coolant Pressure for the three different tests.

Transient State

Qualification Lap

In the transient state, the most important value is the temperature and pressure of the coolant and oil, that have to stay between and upper and lower limit to ensure the reliability of the engine. Figure 13 and Figure 14 show the temperature and pressure of both fluids respectively and the vehicle speed at every second.

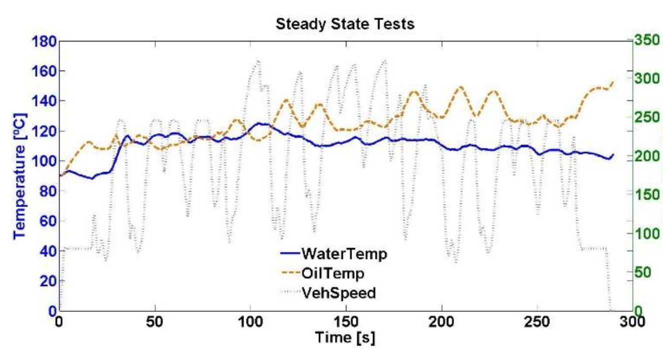

Figure 13. Temperature of Water (Coolant) and Oil against Vehicle Speed

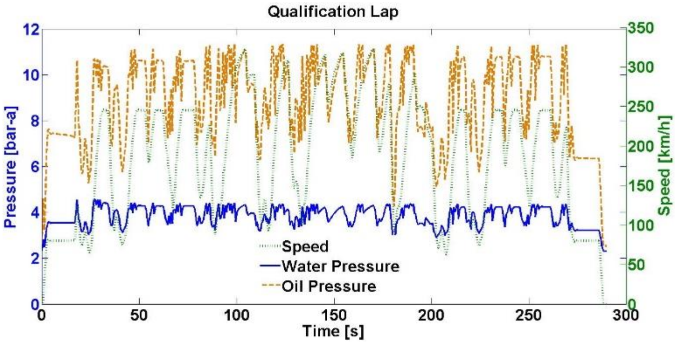

Figure 14. Pressure of Water (Coolant) and Oil against Vehicle Speed

As it can be seen, the temperature of the water is more constant regardless of the vehicle speed, this is because the increase in heat due to the increase in power of the engine is compensated with the increase in air flowing through the radiators and the increase in the speed of the water pump. Therefore the amount of heat generated and the heat rejected is similar at most vehicle operating conditions.

Figure 13 also shows that the temperature of the oil increases when the vehicle speed decreases and vice versa. As the radiator for the oil is smaller, the heat rejected by it is more dependent on the vehicle speed, therefore, when the vehicle speed is high, more heat is rejected and the temperature decreases.

The pressure of the water and the oil (Figure 14) is dependent on the engine operating speed, as both pumps are permanently linked to the flywheel. In fact, when the vehicle speed is increasing and the pressure decreases is because the driver has shifted a gear upward.

In the qualification lap, the battery also heats the water, as it is giving and receiving energy from the MGU-K and MGU-H. This scenario is shown in Figure 15.

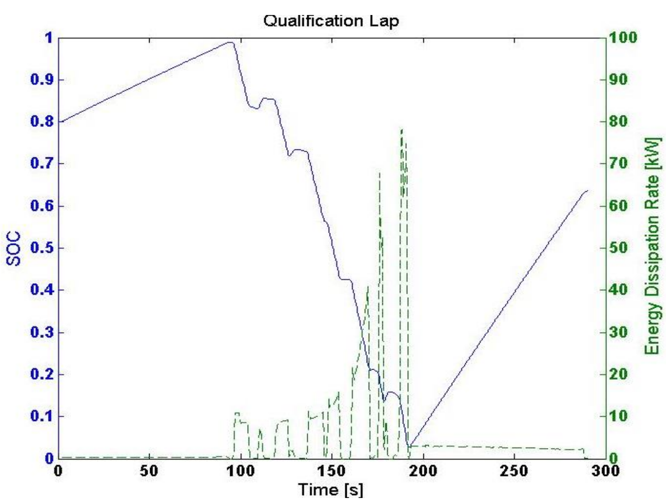

Figure 15. SOC and Energy Dissipation Rate of the Battery

Race

This test is done to assure the cooling system is able to control the temperature of the engine in a complete race. During the stay at the starting grid, the cooling system may have difficulties in keeping the water and oil at the desired temperature, as the engine is running and the vehicle has no forward speed. Similarly, the pit stop scenarios are also a tough test for the cooling system. In addition, the thermal inertias that the engine block and the components have can play an important role in a real race. The operating performance of the energy storage system, battery, during this race is shown in Figure 16.

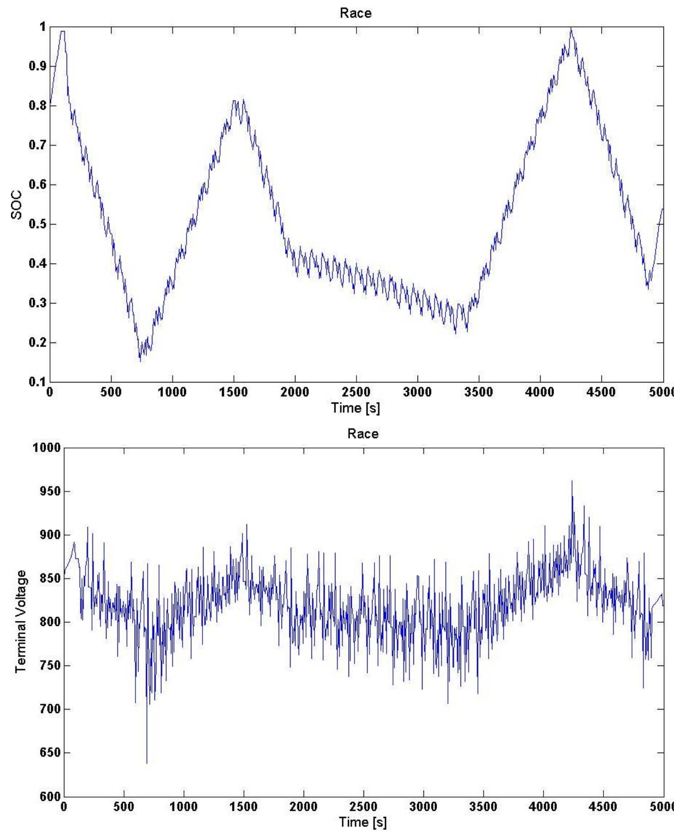

Figure 16. SOC (up) and Terminal Voltage (down) of the battery

The temperature and pressure of the water and oil are shown in Figure 17 and Figure 18.

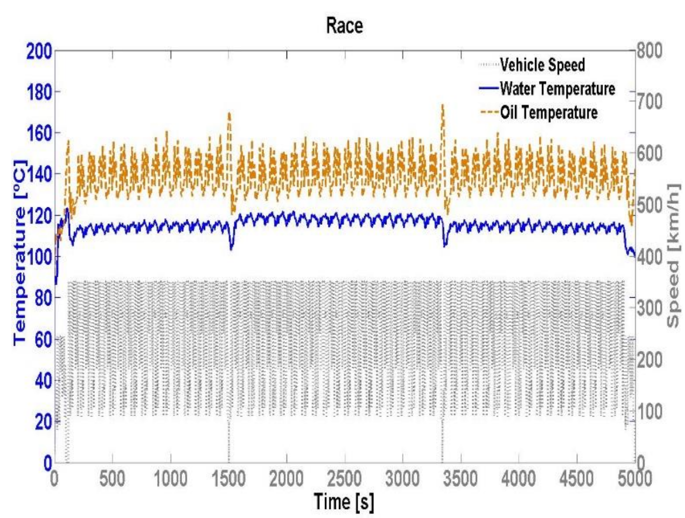

Figure 17: Water and Oil Temperature during the race

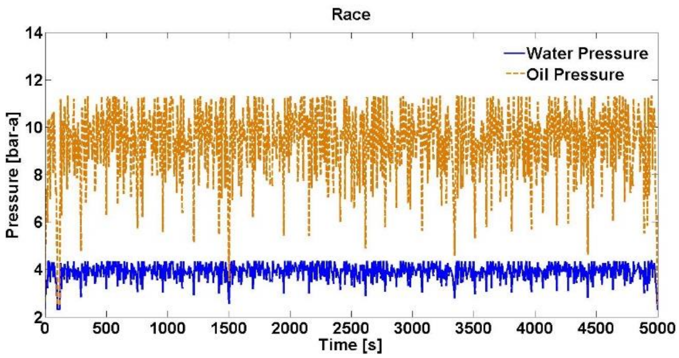

Figure 18. Water and Oil Pressure during the race

As it can be seen in Figure 17, the water temperature is maintained between 100 and 120º C , only at the waiting on the starting grid, the water rise up to 125ºC, nevertheless, at 4 bar of absolute pressure the chances of boiling the coolant is negligible. The temperature of the oil varies around 140ºC, reaching more than 160ºC at the pit stops for very brief moments. The statistics from the race are shown in Table 12. The vehicle model do not exceeded the fuel consumption limit of 105 kg (Article 30.5) [9].

Table 12. Main statistics from the race

Time	5000
Mass of Fuel consumed [g]	87549.9
Volume of Fuel consumed [l]	115.807
Fuel Consumption Rate [kg/h]	63.04
Brake Energy Output [kWh]	477.4167
BSFC [g/kWh]	183.4
Total Distance Traveled [m]	302878
Average Vehicle Speed [km/h]	218.1
Average Fuel Consumption [g/km]	289.1
Average Fuel Consumption [g/mi]	465.2
Average Gas Mileage [l/100km]	38.2
Average Gas Mileage [km/l]	2.6
Average Gas Mileage [US mpg]	6.2

Summary

The main objective of this paper was to develop a virtual model of an entire F1 car to test the cooling system under steady and transient operating conditions. The model consist of many subsystems of an F1 car, including internal combustion engine, electric powertrain and dynamic and static characteristics of the vehicle. In addition, driver behaviour and track characteristics have also been included.
The components and subsystems are constrained by 2018 F1 regulations. Most of the data required for modelling the vehicle is deducted theoretically for meeting 2018 regulations. The model was validated using the track data obtained from onboard camera.

Steady state tests have shown the capacity of the cooling system for maintaining the temperature of oil and water within the working limits even at maximum engine load and at low or high speed operating conditions. Transient state tests have been made to reproduce a qualification lap and an entire race. Results showed cooling system is able to change its behaviour fast enough to keep up with the changes in thermal load and vehicle speed.
The model has proven to be reliable for designing and sizing the cooling system of an F1 for Silverstone circuit. The use of this model to size and test the cooling system of an F1 car for different circuits can save time and cost.

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