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Cooling Performance Analysis and Improvement in the Cooling Sytem of SAE-Supra Vehicle

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Abstract

The present paper presents performance analysis and improvement in cooling system of SAE-Supra Vehicle. SAE-Supra vehicle is meant for participating in the competition of formula one student edition event. The vehicle was built keeping in mind all the rules and regulations of the event. Among numerous rules, one rule was to use air and water as the only coolant for radiator and no other substance. Though the car is dynamically fit and performed well during the event but there was a heating issue in the engine which needed to be solved. This paper presents the thermal analysis of engine and cooling system of SAE-Supra Vehicle. An improvement is suggested to cool the engine efficiently. The results are verified after conducting several experiments on the SAE-Supra Vehicle.

Keywords: SAE-Supra Vehicle, Cooling System, Air Vent, pump.

INTRODUCTION

SAE-SUPRA event was organized by SAE-INDIA. The event comprised of various static and dynamic rounds. The team registered for this event and initial task was to fabricate a formula 1 car (student edition). The main event was held at Gautam Buddha International Circuit dated June 26, 2017 to July 01, 2017.The team fabricated a formula student edition car as per FSAE guidelines. Team name – Speed Wagon Cruisers. Vehicle name – Vencenova. Fabrication of a Formula 1 car (student edition) is a gigantic task and requires a deep understanding and process undertaking of different sub sections. One of the sections out of this was cooling system which had various components including radiator, water pump, hose pipe and water storage chamber. Basically, heat of the engine is absorbed by the water jacket which is then cooled by radiator using water and the heated water is then cooled by air, water is recirculated back to the radiator. In SUPRA vehicle the engine is placed at the rear side, so the radiator compartment has to be situated near it. The amount of air passing through radiator and engine is comparatively very less as compared to the radiator situated in front of the vehicle.

So, there is a need of designing a good air vent system around the radiator for passing good amount of air through radiator so that proper cooling of the engine can be obtained.

LITERATURE REVIEW

FSAE rules

As per FSAE (Formula Society of Automotive Engineers) rules the cooling system of the car must comply with the FSAE Rules [1]. In the 2017 FSAE Rules, the specifications relating to the cooling system are that there must be a "firewall to separate the driver compartment from all the components of the fuel supply, the engine oil, the liquid cooling systems and any high voltage system" (T4.5.1. 2017 fsae rulebook), the "cooling or lubrication system must be sealed" (T8.2.1 2017fsae rulebook), "any catch can on the cooling system must vent through a hose with a minimum internal diameter of 3 mm" (T8.2.4 2017fsae rulebook), and "no power device may be used to move or remove air from under the vehicle except fans designed exclusively for cooling" (T9.4 2017fsae rulebook). Also, "water-cooled engines must only use plain water.

FSAE-A competition

The Formula Society of Automotive Engineers – Australasia (FSAE-A) [2] competition is the Australasian arm of the international event run by the Society of Automotive Engineers, where teams of students are challenged to conceive, design and fabricate a small formula style race car. Since 2005, engine overheating has been a primary concern for the Melbourne University Racing (MUR) team at the Formula SAE-A Endurance Event, which has lead to both performance and reliability issues. The engine cooling systems are critical for the car to run smoothly, a failure in the cooling system would mean a failure in the overall car. Use of a cooling system with excess capacity does not provide a solution either as this adds unnecessary cost and weight. Many factors contribute to overheating; the most critical is the inadequate management of airflow through the radiator. As the FSAE-A event is held during the summer months, temperatures on the track can rise considerably.

Previous MUR teams have fallen victim to this overheating issue at FSAE-A competitions. In 2008, alone, two engines were damaged because of poor heat management. Consequently, previous MUR drivers have been unable to perform competitively during the endurance event for fear of overheating and damaging an engine. Critical variables that may be manipulated to solve heat management issues include

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radiator size, airflow through the radiator and water flow rate through the radiator. It is widely accepted that air flow rate plays a major role in providing heat transfer.

PROPOSED METHODOLGY

The car was fabricated as per rules mentioned in the FSAE rulebook but the major flaws which came to notice was the position of radiator and its air back flow. Following steps show the approach to solve the problem of heating issue:

Heating problem issue

⇩

Objective

⇩

Heat generation analysis

⇩

Design and analysis of side vent

⇩

Cooling system analysis

(theoretical basis and experimental basis)

Figure 1. Fabricated car – Vencenova

1. Heating issue

The heating problem may be attributed to mainly two reasons – the first one is the use of DUKE 390 engine in the SAE Supra vehicle. DUKE 390 engine is generally cooled by a coolant called ethyl glycol which gives the sufficient cooling to the engine. However, according to FSAE rules the coolant must not contain any chemical and therefore it has been mandated that only air and water can be used for cooling of the engine. The second reason is improper position of radiator. It was observed that negative pressure difference was developed at the inlet of previous radiator position which was causing air to flow from backward and, hence, there was excessive heating problem in the vehicle.

2. Objective

The objective is to design a side vent in order to increase the mass flow rate of air in a directed flow on the radiator core and to increase the mass flow rate of water so that required amount of heat could be removed from the water jacket of the engine.

3. Heat generation analysis

To estimate the heat generation through combustion chamber and its distribution through different auxiliary's system we must first obtain the Brake Power vs Engine RPM from the available literature [3]. Various assumptions [4] are to be taken for the calculation of heat flow through the combustion chamber and amount of heat being taken by the water from the water jacket. These assumptions are as follows-

- Brake power taken as 75 percent of the indicated power.
- Indicated power is taken as 25 percent of the heat generated due to combustion in combustion chamber.
- 35 percent of the heat generated is carried by cooling water.
- Ambient temperature taken as 25 °C or 298 K.

Table 1: Heat generation analysis

Engine Speed (RPM)	Brake Power (kW)	Heat Generation (kW)	Heat transferred to coolant (water) (kW)
4000	30.8	57.6	20.1
5000	35.3	65.9	23.0
6000	50.0	93.4	32.6
7000	71.2	133.1	46.5
8000	79.9	149.2	52.2
9000	92.7	173.1	60.5
10000	82.2	153.5	53.7

The heat generated, and heat transferred to the cooling water is obtained from the above table.

4. Design and analysis of side vent

Position of radiator was changed to frontal facing the air flow directly and a side vent was put for directed air flow. Side vents are structure which have directional flow of air towards the radiator and engine. This enhances cooling capacity of engine. Also, it increases the downforce. Following design parameters were considered while fabricating the side vent-

- Max frontal area to ensure max flow rate of air through vent inlet.

- Converging throat should be aligned with respect to the roll cage of the vehicle.
- The angle of convergence and divergence must be according to the angle of roll cage with respect to the horizontal.
- The width of the side vent should not exceed the track width (from the roll cage till trackwidth line).

Figure 2. Frontal facing radiator

Air Side Vent Dimensions:

- Frontal Area: 33 cm x 30.48 cm
- Radiator core dimension: 29 cm x 16 cm
- Radiator thickness = 2.5cm

Figure 3. Vencenova car with side vent

Flow simulations were performed using Solidworks 2016 edition to estimate the velocity at the radiator core. The following figure shows the velocity profile at radiator core:

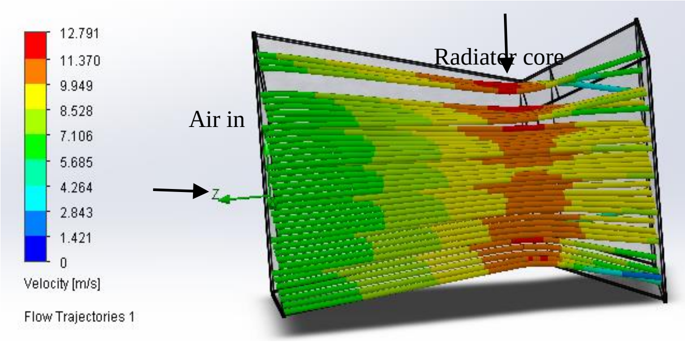

Figure 4. Velocity at radiator core at the inlet velocity of 5.72 m/s at side vent

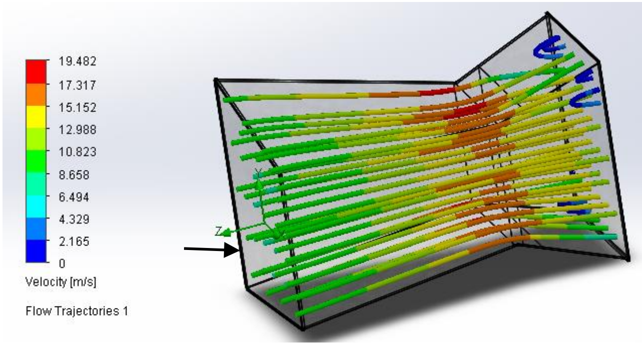

Figure 5. Velocity at radiator core at the inlet velocity of 8.58 m/s at side vent

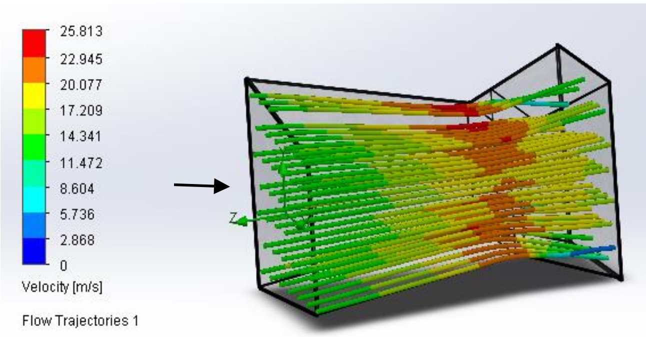

Figure 6. Velocity at radiator core at the inlet velocity of 10.2 m/s at side vent

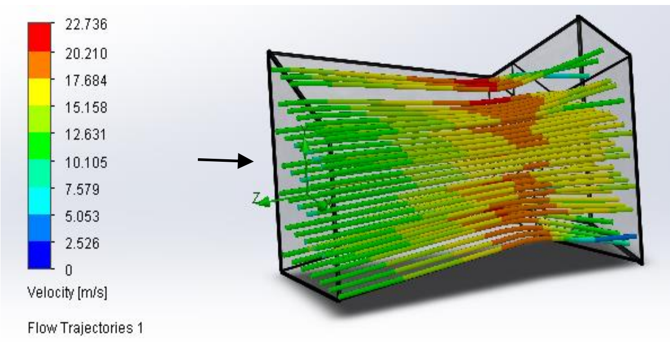

Figure 7. Velocity at radiator core at the inlet velocity of 11.47 m/s at side vent

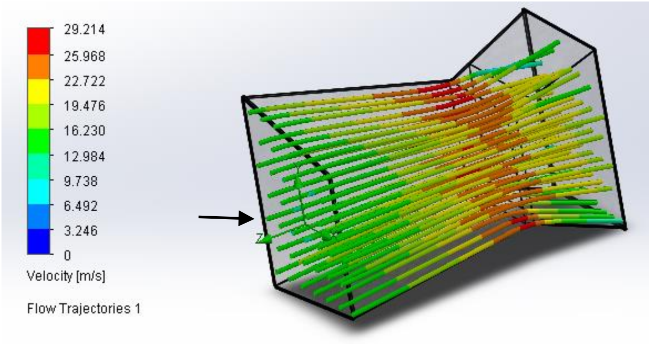

Figure 8. Velocity at radiator core at the inlet velocity of 12.9 m/s at side vent

The above figure shows the simulation results for different inlet velocities. The following table shows the velocity at the radiator core that will be used in Reynold's number calculation.

Table 2. Velocity at radiator core at given engine rpm

Engine speed (RPM)	Inlet velocity (at 1st gear) m/s (km/hr)	Velocity at radiator core (m/s)
4000	5.72 (20.6)	12.79
5000	7.16 (25.8)	16.07
6000	8.58 (30.9)	19.48
7000	10.02 (36.1)	22.73
8000	11.47 (41.3)	25.81
9000	12.90 (46.5)	29.21
10000	14.33 (51.6)	32.61

Velocity of car at 9000 rpm engine speed

$=(\pi dN/60)$ x (primary reduction) x (secondary reduction) x sprocket reduction

= (3.14x 0.5842 x 9000/60) x (30/80) x (15/45) x (12/32)

= 12.9 m/s = 46.5 km/h

Where, d = diameter of wheel = 0.5842 m

5. Cooling system analysis

Following parameters to be estimated for design of cooling system

a) Mass flow rate of water from the pump
b) Mass flow rate of air for cooling system

Theoretically the mass flow rate of water from the pump is calculated and then later on it will be compared with the experimental value.

As the DUKE 390 water pump characteristic is not directly available, therefore for calculation purpose, values were estimated from a similar engine Yamaha R5. Hence the water pump characteristic for theoretical calculation is as follows:

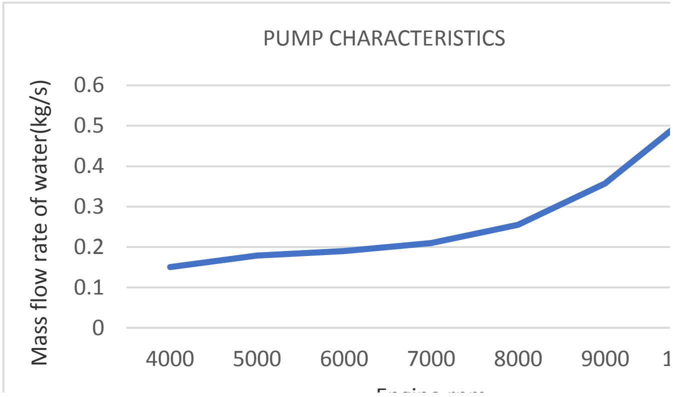

Table 3 Pump characteristics

Engine speed (RPM)	Mass flow rate of water (kg/s)
4000	0.1600
5000	0.1792
6000	0.1897
7000	0.2100
8000	0.2552
9000	0.3571
10000	0.5300

In KTM DUKE 390 Radiator-

No. of tubes =19

Dimension = 39cm x 16cm x 2.5 cm

Radiator core dimension = 29cm x 16cm

No. of radiators used – 2

i. Equation of heat transfer to cooling water

$$Q = m_w C_{water} \Delta T$$

Where,

Q- Heat transferred to cooling water

m_w – mass flow rate of water from single tube of the radiator

m_a – mass flow rate of air through radiator

C_{water} - specific heat of water

$\Delta T = T_2 - 30$

The water temperature (T_1) at radiator outlet is taken as 30 °C. The corresponding value of water temperature from engine outlet will vary.

T_1 be the temperature of water coming out of the radiator.

T_2 be the inlet temp of water at radiator.

T_3 be ambient temperature = 25 °C

T_4 be the temperature of air after passing through the tube of radiator.

ii. Convective heat transfer coefficient, h

Nusselt number empirical relation is used –

$Nu = z (Re)^a (Pr)^b$

- R_e (Reynolds number) = $\rho VL / \mu$
- Pr (Prandtl number) = $\mu C_p / k$
- z, a, b are empirical coefficients
- z= 0.664, a = 0.5, b = 0.33 (assuming air flowing over flat plate with length = tube width of the radiator,2.5 cm)
- V – mean velocity of air at radiator core
- L – characteristic length, here, 2.5 cm

Properties of air [5] -
- ρ – Density of fluid
- μ - Dynamic viscosity
- C_p= specific heat capacity of air
- k= thermal conductivity of air

iii. T_4 can be calculated using following relation

Q = hA(LMTD)

Where, LMTD
$= ((T_2 - T_4) - (T_3 - T_1)) / \ln (((T_2 - T_4)/ (T_3 - T_1))$

iv. $Q = \text{mair } C_{air} \Delta t$

Here, $\Delta t = T_4 - T_3$

Also, it is to be noted that heat transferred by water to the cooling air will be same, therefore:

$$Q = m_w C_{water} \Delta T = m_{air} C_{air} \Delta t = hA(LMTD)$$

Using above equations, the mass flow rate of air is calculated at different engine rpm and shown in the table:4:

Table 4. Mass flow rate of air required

RPM	Velocity (at 1st gear) (km/hr)	Mass flow rate of air (kg/s)
4000	20.6	1.26
5000	25.8	1.71
6000	30.97	2.10
7000	36.13	2.50
8000	41.29	2.91
9000	46.45	3.48
10000	51.61	3.81

6. Experiments and Validation

The experiments were performed on the SAE-Supra vehicle to measure the mass flow rate of water, the measured values are shown in the Table-5 below:

Table 5. Reading for flow rate of water using single pump

RPM	Volume of water (ml)	Time (s)	Flow rate of water from one radiator (kg/s)	Flow rate from two radiators (kg/s)	Temp (T_2) of water coming out from engine water jacket (°C)
4000	275	10	0.027	0.055	74.0
5000	365	10	0.036	0.073	76.4
6000	398	10	0.039	0.079	78.5
7000	447	10	0.044	0.089	79.8
8000	513	10	0.051	0.102	81.2
9000	597	10	0.059	0.119	83.0
10000	615	10	0.062	0.123	81.6

The above table gives us the results of the mass flow rate of water from single pump which is inside the engine compartment. As it can be seen that required mass flow rate of water obtained from pump characteristic curve was much more than the value that has been obtained during the experiment. Hence, 2 number of pumps were employed for the sake of maximum heat removal from the engine. Table-6 given below tells us about the excessive heat which occurred due to insufficient mass flow rate of water and why an extra pump was needed for effective heat extraction.

Table 6. Excess heat causing heating issue

RPM	Heat to be taken away by cooling water (Calculated theoretically) (kW)	Heat taken away by cooling water (found experimentally) (kW)	Excess heat causing heating issue (kW)
4000	20.15	12.89	7.26
5000	23.08	17.84	5.23
6000	32.68	20.15	12.53
7000	46.58	23.12	23.45
8000	52.22	27.14	25.07
9000	60.57	32.48	28.09
10000	53.71	32.43	21.27

This excess heat can be removed by using additional water pump and the corresponding heat from the radiator can be removed by air flowing across the radiator. Therefore, result due to addition of extra pump were obtained and then air flow rate passing through the radiator core was evaluated at the radiator core for experimental validation of the same.

Table 7. Reduction in temperature with addition of new pump

RPM	Volume of water (ml)	Time (s)	Flow rate of water from one radiator (kg/s)	Flow rate of water from two radiators (kg/s)	Temp (T_2) of water coming out from engine water jacket (°C)
4000	1299	10	0.13	0.26	66.17
5000	1375	10	0.137	0.275	67.66
6000	1362	10	0.136	0.272	69.56
7000	1487	10	0.149	0.297	71.23
8000	1553	10	0.155	0.311	74.9
9000	1568	10	0.156	0.313	75.5
10000	1626	10	0.163	0.325	76.7

In the above table the experimental values of flow rate of water are shown using a secondary pump.

The mass flow rate of air estimated is shown in the Table-8 at different speed of the car:

Table 8. Mass flow rate of air at different speed

Car velocity (km/hr)	Mass flow rate of air (kg/s)
20.6	0.98
25.8	1.29
30.9	1.65
36.1	2.58
41.3	2.74
46.5	2.93
51.6	3.01

RESULTS AND DISCUSSIONS

It is observed that the heating issue of the engine was due to the insufficient flow of water and air. The flow rate of water is increased with the addition of a pump. Therefore, the heat is extracted from the engine sufficiently to cool it properly. The air flow rate is increased by modifying the side air vent. The required mass flow rate of air and mass flow rate of air through side air vent is shown in the table-9 below:

Table 9. Estimation of % deviation in results

Car velocity (km/hr)	Required mass flow rate of air (kg/s)	Mass flow rate of air through air vent (kg/s)	% Deviation
20.6	1.26	0.98	22.4
25.8	1.71	1.29	24.84
30.9	2.1	1.65	21.82
36.1	2.57	2.58	-0.34
41.3	2.91	2.74	5.74
46.5	3.48	2.93	15.82
51.6	3.81	3.01	20.81

It can be seen that the deviation in the mass flow rate of air through side air vent and required mass flow rate is varying in the range of 0 to 25 % approximately. These deviations may be attributed to the assumptions taken in the calculation of required mass flow rate. Therefore, an improvement in the cooling system is being made by modifying the side air vent and addition of one more water pump. After these modification in the SAE-Supra Vehicle it has been observed that the engine is now cooled properly.

CONCLUSION

The problem of heating issue in the SAE Supra vehicle has been investigated in the present paper. Heat generation in the engine was estimated. The cause of heating was mainly due to the insufficient water flow rate in the coolant chamber and improper design of side air vent. The addition of a water pump increased the heat removal from the water jacket of the engine, henceforth, improving the heat removal from the engine. The design of side air vent and its analysis showed that there was improvement in mass flow rate of air at radiator core, therefore, improvement in cooling system. After modifying the SAE-Supra vehicle with the addition of water pump and improved design of side air vent, the cooling performance was improved. The results show the satisfactory cooling of the engine.

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