Study on Performance Evaluation of Automotive Radiator

JP Yadav[1*] and Bharat Raj Singh[2]

ABSTRACT

A complete set of numerical parametric studies on automotive radiator has been presented in detail in this study. The modeling of radiator has been described by two methods, one is finite difference method and the other is thermal resistance concept. In the performance evaluation, a radiator is installed into a test-setup and the various parameters including mass flow rate of coolant, inlet coolant temperature; etc. are varied. A comparative analysis between different coolants is also shown. One coolant as water and other as mixture of water in propylene glycol in a ratio of 40:60 is used. It is observed that that the water is still the best coolant but its limitation is that it is corrosive and contains dissolved salts that degrade the coolant flow passage.

Keywords: *Radiator, coolant, thermal resistance, nano-fluids, carbon-foam fins.*

1. INTRODUCTION

The demand for more powerful engines in smaller hood spaces has created a problem of insufficient rates of heat dissipation in automotive radiators. Upwards of 33% of the energy generated by the engine through combustion is lost in heat. Insufficient heat dissipation can result in the overheating of the engine, which leads to the breakdown of lubricating oil, metal weakening of engine parts, and significant wear between engine parts. To minimize the stress on the engine as a result of heat generation, automotive radiators must be redesigned to be more compact while still maintaining high levels of heat transfer performance.

In an automobile, fuel and air produce power within the engine through combustion. Only a portion of the total generated power actually supplied to the automobile with power, the rest is wasted in the form of exhaust and heat. If this excess heat is not removed, the engine temperature becomes too high which results in overheating and viscosity breakdown of the lubricating oil, metal weakening of the overheated engine parts, and stress between engine parts resulting in quicker wear, among the related moving posts . A cooling system is used to remove this excessive heat. Most automotive cooling systems consist of the following components: radiator, water pump, electric cooling fan, radiator pressure cap, and thermostat. Of these components, the radiator is the most prominent part of the system because it transfers heat. As coolant travels through the engine's cylinder block, it accumulates heat. Once the coolant temperature increases above a certain threshold value, the vehicle's thermostat triggers a valve which forces the coolant to flow through the radiator. As the coolant flows through the tubes of the radiator, heat is transferred through the fins and tube walls to the air by conduction and convection.

2. AUTOMOTIVE RADIATOR

A radiator is a type of **heat exchanger**. It is designed to transfer heat from the hot coolant that flows through it to the air blown through it by the fan. Most modern cars use aluminum radiators. These radiators are made by brazing thin aluminum fins to flattened aluminum tubes. The coolant flows from the inlet to the outlet through many tubes mounted in a parallel arrangement. The fins conduct the heat from

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the tubes and transfer it to the air flowing through the radiator. The tubes sometimes have a type of fin inserted into them called a **turbulator**, which increases the turbulence of the fluid flowing through the tubes. If the fluid flows very smoothly through the tubes, only the fluid actually touching the tubes would be cooled directly. The amount of heat transferred to the tubes from the fluid running through them depends on the difference in temperature between the tube and the fluid touching it. So if the fluid that is in contact with the tube cools down quickly, less heat will be transferred. By creating turbulence inside the tube, all of the fluid mixes together, keeping the temperature of the fluid touching the tubes up so that more heat can be extracted, and all of the fluid inside the tube is used effectively. Radiators usually have a tank on each side, and inside the tank is a transmission cooler. From fig. 1 the inlet and outlet shown where the oil from the transmission enters the cooler. The transmission cooler is like a radiator within a radiator, except instead of exchanging heat with the air, the oil exchanges heat with the coolant in the radiator.

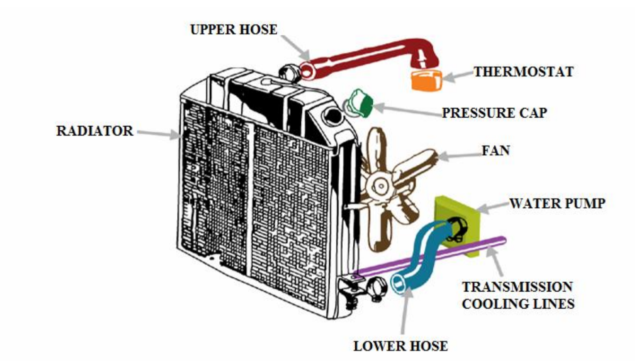

Fig. 1: Parts of cooling system

2.1 *Working of Radiator*

The pump sends the fluid into the engine block, where it makes its way through passages in the engine around the cylinders. Then it returns through the cylinder head of the engine. The thermostat is located where the fluid leaves the engine. The plumbing around the thermostat sends the fluid back to the pump directly if the thermostat is closed. If it is open, the fluid goes through the radiator first and then back to the pump [1].

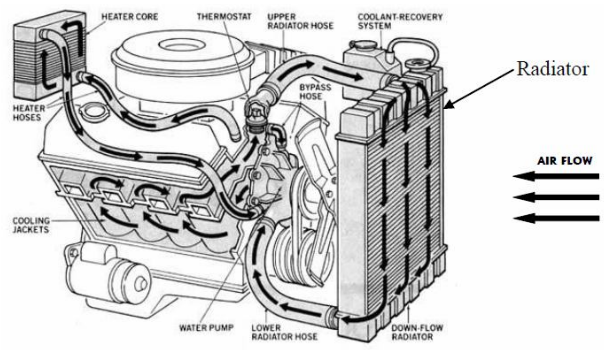

Fig. 2: Working of Radiator

There is also a separate circuit for the heating system. This circuit takes fluid from the cylinder head and passes it through a heater core and then back to the pump. On cars with automatic transmissions, there is normally also a separate circuit for cooling the transmission fluid built into the radiator. The oil from the transmission is pumped by the transmission through a second heat exchanger inside the radiator, as shown in fig.2.

2.2 *Cooling System and Antifreeze*

An automobile's cooling system is the collection of parts and substances (coolants) that work together to maintain the engine's temperature at optimal levels. Comprising many different components such as water pump, coolant, a thermostat, etc, the system enables smooth and efficient functioning of the engine at the same time protecting it from damage. While it's running, an automobile's engine generates enormous amounts of heat. Each combustion cycle entails thousands of controlled explosions taking place every minute inside the engine. If the automobile races on and the heat generated within isn't dissipated, it would cause the engine to self-destruct. Hence, it is imperative to concurrently remove the waste heat. While the waste heat is also dissipated through the intake of cool air and exit of hot exhaust gases, the engine's cooling system is explicitly meant to keep the temperature within limits. The cooling system essentially comprises passages inside the engine block and heads, a pump to circulate the coolant, a thermostat to control the flow of the coolant, a radiator to cool the coolant and a radiator cap controls the pressure within the system. In order to achieve the cooling action, the system circulates the liquid coolant through passages in the engine block and heads. As it runs through, the coolant absorbs heat before returning to the radiator, to be cooled itself. Next, the cooled down coolant is re-circulated and the cycle continues to maintain the engine's temperature at the right levels.

2.3 Automotive use of antifreeze

The term engine coolant is widely used in the automotive industry, which covers its primary function of convective heat transfer. When used in an automotive context, corrosion inhibitors are also added to help protect vehicles' cooling systems, which often contain a range of electrochemically incompatible metals (aluminum, cast iron, copper, lead solder, etc). Antifreeze was developed to overcome the shortcomings of water as a heat transfer fluid. In most engines, freeze plugs are placed in the engine block which could protect the engine if no antifreeze was in the cooling system or if the ambient temperature dropped below the freezing point of the antifreeze. If the engine coolant gets too hot, it might boil while inside the engine, causing voids (pockets of steam) leading to the catastrophic failure of the engine. Using proper engine coolant and a pressurized coolant system can help alleviate both problems. Some antifreeze can prevent freezing till - 87^{0}C.

3. ANTIFREEZE AGENTS

3.1 Methanol

Methanol, also known as methyl alcohol, carbinol, wood alcohol, wood naphtha or wood spirits, is a chemical compound with chemical formula CH_3OH (often abbreviated MeOH). It is the simplest alcohol, and is a light, volatile, colourless, flammable, poisonous liquid with a distinctive odor that is somewhat milder and sweeter than ethanol (ethyl alcohol). At room temperature it is a polar liquid and is used as an antifreeze, solvent, fuel, and as a denaturant for ethyl alcohol. It is not very popular for machinery, but it can be found in automotive windshield washer fluid, de-icers, and gasoline additives to name a few.

3.2 Ethylene glycol

Ethylene glycol (IUPAC name: ethane-1, 2-diol) is an organic compound widely used as an automotive antifreeze and a precursor to polymers. In its pure form, it is an odorless, colorless, syrupy, sweet tasting liquid. However, ethylene glycol is toxic, and ingestion can result in death.

Fig. 3: Ethylene glycol

Ethylene glycol solutions became available in 1926 and were marketed as "permanent antifreeze," since the higher boiling points provided advantages for summertime use as well as during cold weather. They are still used today for a wide variety of applications, including automobiles. Being ubiquitous, ethylene glycol has been ingested on occasion, causing ethylene glycol poisoning. Coolant containing ethylene glycol should not be disposed of in a way that will result in it being ingested by animals, because of its toxicity. Many animals like its sweet taste. As little as a teaspoonful can be fatal to a cat, and four teaspoonfuls can be dangerous to a dog. In some places it is permitted to pour moderate amounts down the toilet, but there are also places where it can be taken for processing.

3.3 Propylene glycol

Propylene glycol, on the other hand, is considerably less toxic and may be labeled as "non-toxic antifreeze". It is used as antifreeze where ethylene glycol would be inappropriate, such as in food-processing systems or in water pipes in homes, as well as numerous other settings. It is also used in food, medicines, and cosmetics, often as a binding agent. Propylene glycol is fig. 4 is "generally recognized as safe" by the Food and Drug Administration (FDA) for use in food. However, propylene glycol-based antifreeze should not be considered safe for consumption. In the event of accidental ingestion, emergency medical services should be contacted immediately.

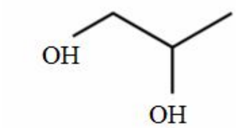

Fig. 4: Propylene glycol

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Propylene glycol oxidizes when exposed to air and heat. When this occurs lactic acid is formed.[5]. If not properly inhibited, this fluid can be very corrosive. Protodin is added to propylene glycol to act as a buffer, preventing low pH attack on the system metals. It forms a protective skin inside the tank and pipelines which helps to prevent acid attack that cause corrosion. Besides cooling system breakdown, biological fouling also occurs. Once the bacterial slime starts, the corrosion rate of the system increases. In systems where a glycol solution is maintained on a continuous basis, regular monitoring of freeze protection, pH, specific gravity, inhibitor level, color and biological contamination should be checked routinely. Propylene glycol should be replaced when it turns reddish in color.

4. FUNCTIONS OF ANTIFREEZE

Engine antifreeze and additive mixture for automobile radiator are meant to:

4.1 *Reduce cooling system corrosion*

Every automotive cooling system will corrode eventually, but this mixture of antifreeze and additive will make the overall process of corrosion slow therefore, increasing the life of cooling system.

4.2 *Reduce cavitation*

In large diesel engines, air or tiny bubbles in the coolant can cause serious problems or engine overheating. So, for a diesel vehicle, it is highly recommended that a cavitation reducing engine coolant must be used.

4.3 *Buffer the acidity of your engine coolant*

The more acidic an engine coolant, the more quickly it can corrode and damage the cooling system and automobile radiator.

4.4 *Raise the boiling point of the engine coolant*

A higher boiling temperature means that the coolant can cool better as the engine gets hotter. It also reduces the chance of blowing a head gasket.

5. TESTING SETUP OF AUTOMOTIVE RADIATOR

In the performance evaluation of radiator a test apparatus is prepared in as shown test diagram fig.5 & test model fig. 6 which a radiator, fan, flow meter, heating element, pump, two thermocouples, digital meters for conversion of thermal emf into digital form are used.

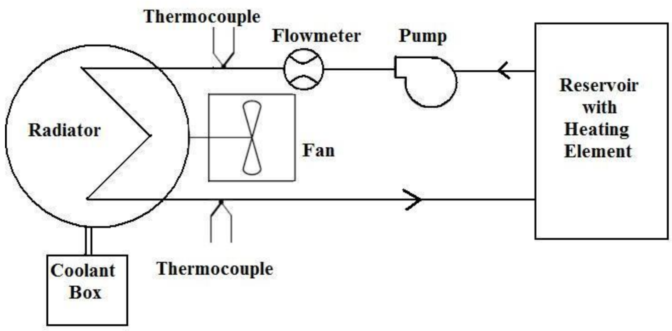

Fig. 5: Schematic diagram of test setup

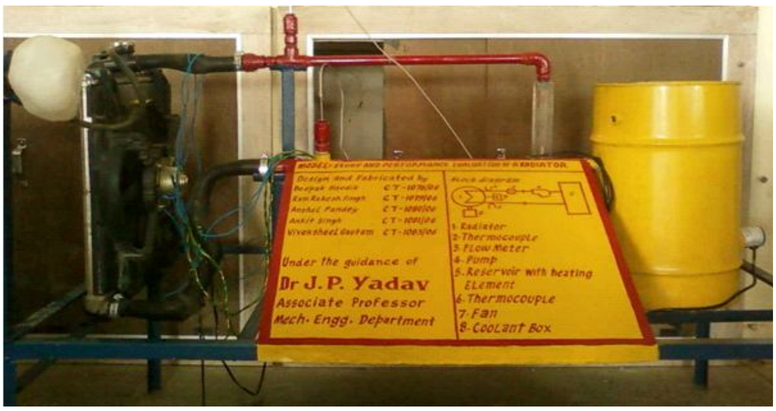

Fig. 6: Testing model of project

The various components used are described below.

- **Reservoir with heating element:** In the test apparatus the hot water acting as the coolant taking heat from the engine block is provided here the help of a heating element fixed into the reservoir container. In this container the water is heated up to the range of 65-75^{O}C
- **Pump:** The 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. After this the flow rate is measured with the help of a flow meter.
- **Rotameter:** A rotameter is a constant pressure drop, variable area flow meter. It consists of a tapered metering glass tube inside of which located a rotor or active element (float) of the meter. The tube is provided with inlet and outlet connections. The specific gravity of the float or bob material is higher than that of the fluid to be metered. On a part of a float spherical slots are cut which cause it (float) to rotate slowly about the axis of the tube and keep it centered. Owing to this spinning accumulation of any sediment on the top sides of float is checked. However, the stability of the bob may also be insured by using guide along which the float winds slight. When the rate of flow increases the float rise in the tube and consequently there is an increase in the annular area between the float and the tube. Thus, the float rides higher or lowers depending on the rate of flow.
- **Thermocouples:** The most common electrical method of temperature measurement uses the thermocouple. It is based upon see-back effect i.e. when two dissimilar metals are jointed, these forms two junctions and if these junctions are maintained at different temperatures than an emf is produced and this emf depends on the temperature difference. Therefore in thermocouple emf plays thermometric property, the property which helps in holding in finding out the temperature is named as the thermometric property.
- **Radiator:** The radiator is a type of heat exchanger in which the coolant looses heat by convection and conduction phenomenon occurring in the tubes of radiator. The radiator is generally made up of aluminum metal because of its light weight and high thermal conductivity.
- **Fan:** A fan is installed just behind the radiator so as to increase the cooling capacity of the radiator. When the temperature of the coolant increases because of constant acceleration the fan starts operating, sucking in the air through the fins of the radiator. This fan is controlled by an ECU (Engine Control Unit). In the apparatus the fan runs continuously to give an effect of a moving vehicle.
- **Coolant bottle:** The coolant bottle serves here an important function of controlling the coolant from overflowing. When the fluid in the cooling system heats up, it expands, causing the pressure to build up. The cap is the only place where this pressure can escape, so the setting of the spring on the cap determines the maximum pressure in the cooling system. The cap is actually a pressure release valve, and on cars it is usually set to 15 psi. When the pressure reaches 15 psi, the pressure pushes the valve open, allowing coolant to escape from the cooling system. This coolant flows through the overflow tube into the cooling bottle. This arrangement keeps air out of the system. When the radiator cools back down, a vacuum is created in the cooling system that pulls open another spring loaded valve, sucking water back in from the cooling bottle to replace the water that was expelled.

5.1 Testing procedure

In the test apparatus the heating element will be acting as a source of heat which will act just like an engine in an automobile. This heating element will heat up the coolant to a temperature range of 80^{O}C - 120^{O}C. After heating, the hot water is pumped with the help of a pump in to the radiator. At the outlet of the pump a rotameter is installed to measure the mass flow rate of the hot coolant. The flow to rotameter is controlled by a controlling valve, which helps in obtaining different mass flow rate of the hot coolant. Then the inlet temperature to radiator is calculated by installing one thermocouple at inlet and is digitalized by one digital meter. The hot water then flows through the radiator core. Here with the help of a fan cold air is sucked in, which helps in decreasing the temperature of the coolant flowing through the radiator. Then, the temperature at outlet is measured by a second thermocouple. After this the coolant from outlet is returned to the reservoir where it again becomes hot by the action of heating element and is re-circulated in the flow circuit to maintain the continuity of flow.

During testing, firstly water is taken as a coolant. It is circulated at a mass flow rate of 5 LPM (liter per minute). The fan is rotated at a speed of 6000 rpm. After this the temperature of hot coolant at the outlet is recorded at particular inlet coolant temperatures. These readings are taken twice, at the first time by rotating the fan at 6000 rpm and at the second time by stopping the fan. After this first round of data recording the coolant is changed. This time water is replaced with a mixture containing 60% propylene glycol and 40% water. Here the mass flow rate is maintained at the same level as before and the fan is also circulated with the same speed of 6000 rpm. The temperature of the hot coolant at the inlet is also maintained at the previous values and the corresponding temperature values of the hot coolant at the outlet are recorded. After the process of this initial data recording the mass flow rate is varied by keeping the temperature of the hot coolant at inlet fixed at 80^{O}C. The different mass flow rate values include values from 5.0 LPM, 5.5 LPM, 6.0 LPM to 8.5 LPM. At these varying mass flow rates the corresponding outlet temperature values of the hot coolant is recorded. The above readings are taken with water as well as with mixture of 60% propylene glycol and 40% water one by one acting as coolants.

5.2 Assumptions

The results obtained are based on the following assumptions:

a) Velocity and temperature at the entrance of the radiator core on both air and coolant sides are uniform.

b) There are no phase changes (condensation or boiling) in all fluid streams.

c) Fluid flow rate is uniformly distributed through the core in each pass on each fluid side. No stratification, flow bypassing, or flow leakages occur in any stream. The flow condition is characterized by the bulk speed at any cross section.

d) The temperature of each fluid is uniform over every flow cross section, so that a single bulk temperature applies to each stream at a given cross section.

e) The heat transfer coefficient between the fluid and tube material is uniform over the inner and outside tube surface for a constant fluid mass flow rate.

f) For the extended fin of the radiator, the surface effectiveness is considered uniform and constant.

g) Heat transfer area is distributed uniformly on each side

h) Both the inner dimension and the outer dimension of the tube are assumed constant.

i) The thermal conductivity of the tube material is constant in the axial direction.

j) No internal source exists for thermal-energy generation.

k) There is no heat loss or gain external to the radiator and no axial heat conduction in the radiator.

l) Thermal conduction parallel to the flow direction of both the wall and the fluids are equal to zero.

m) Humidity is 71%.

n) Wind velocity is 4 km/hr.

o) Room temperature is 30^{O}C.

5.3 *Mathematical Relations*

In the test the following mathematical equation has been used.

$$\text{Effectiveness of radiator } (\varepsilon) = \frac{\text{Actual heat Transfer}}{\text{Maximaum heat transfer}}$$

$$= \frac{mc\, C_{pc}(t_{ci} - t_{co})}{ma\, C_{pa}(t_{ci}/t_{ai})}$$

Where, m_c = mass flow rate of coolant in kg/s
m_a = mass flow rate of air in kg/s
Cp_c = specific heat capacity of coolant at constant pressure in kJ/kg K.
Cp_a = specific heat capacity of air at constant pressure in kJ/kg K.
t_{ci} = input temperature of coolant.
t_{co} = output temperature of coolant.
t_{ai} = input temperature of air.

$$\text{At 1LPM } m_c = \frac{1}{1000 \times 60}\ m^3/s = \frac{1000}{1000 \times 60} \text{ (for water)}$$

$$= \frac{1062}{1000 \times 60} \text{ kg/s (for water + propylene glycol)}$$

Cp_c = 4.18 kJ/kg K (for water) = 3.39 kJ/kg K (for 40% water + 60% propylene glycol)
Cp_a = 1.005 kJ/kg K
m_a = 1.49 kg/sc

The radiator fan rotates with 6000 rpm and its radius is 14 cm and effective pitch is 8 inches and it has 2735.28 CFM (cubic fit per minute)

$$1 \text{ CFM} = \frac{(1\,ft)^3}{1\min} = \frac{(1\,ft)^3}{1\min} \times \frac{(0.3048m)^3}{1\,ft} \times \frac{1\min}{60s} = \frac{0.3048m^3}{60s} \approx 4\text{-}79 \times 10^{-4}\ m^3 s^{-1}$$

5.4 *Influence of coolant mass flow*

A graph is plotted graph showing the variation of effectiveness and cooling capacity by the variation of coolant flow rate. Coolant flow rate has been plotted on X-axis and the effectiveness and cooling capacity has been plotted at the primary and secondary Y-axis. The temperature of inlet coolant has been maintained at 80°C. By the graphs plotted it is observed that effectiveness and the cooling capacity of the radiator has direct relation with the coolant flow rate. With an increase in the value of inlet cooling flow rate there is corresponding increase in the value of the effectiveness and cooling capacity.

One thing which needs to be noted is that the graph of water is above the graph when mixture has been used as the coolant. This is because the specific heat capacity of the water is very much greater than the mixture. So, if it is required to increase the cooling capacity with the mixture then its mass flow rate is to be increased. Same is true with the plot of effectiveness against the coolant mass flow rate.

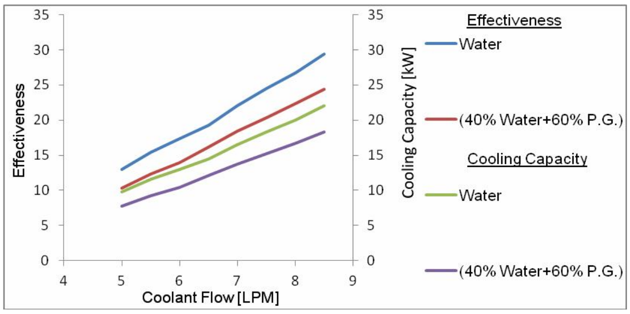

Fig. 7: Effectiveness and Cooling Capacity Versus Coolant Flow of Radiator

5.5 Influence of coolant inlet temperature

In the following graphs the variation of the variation in the cooling capacity and outlet temperature of hot coolant is plotted against the inlet temperature of hot coolant. On the X-axis inlet temperature of hot coolant is plotted. The cooling capacity and the outlet

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temperature are plotted on primary and secondary Y-axis. The first graph is plotted when the fan is rotating at a speed of 6000 rpm and the second graph is plotted by considering it to be stationary. After observing the first graph it is found that with the increase in the inlet temperature of the coolant the cooling capacity of the radiator increases. Also, with the increase in the inlet temperature of the coolant the temperature range of operation increases rapidly i.e. at higher ranges of temperature operation the difference between the inlet and the outlet temperature of coolant increases rapidly. This happens because the heat transfer between ambient and radiator surface takes place by two phenomenon's one is conduction and the other is convection. In both these process the heat transfer is directly proportional to the temperature difference i.e. higher the temperature difference between two medium higher will be the heat transfer.

The second graph has been plotted by considering the fan to be stationary. As expected with the increase in the value of inlet coolant temperature the cooling capacity of the radiator increases. This is due to the fact that the specific heat capacity of the water is very much greater than the mixture. This fact can also be seen by a sharp difference in the reading at the corresponding values of coolant inlet temperature. In the case of variation of outlet temperature with the inlet temperature of coolant, there is not so much difference since the effect of forced convection is negligible. Hence the two graphs are almost coincident.

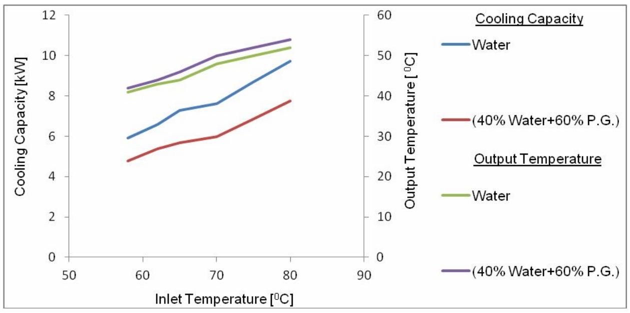

Fig.8 : Cooling Capacity and Output Temperature versus Inlet temperature of Radiator with Fan

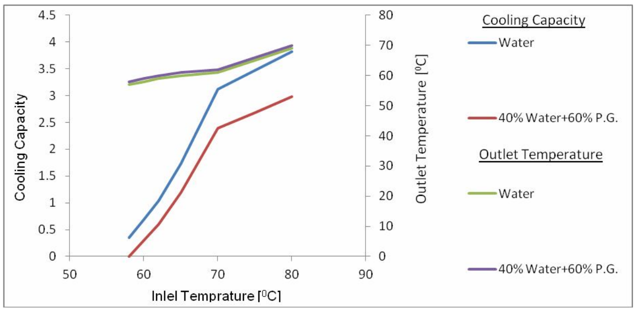

Fig. 9: Cooling Capacity and Output Temperature versus Input Temperature of Radiator without Fan

6. CONCLUSION

A complete set of numerical parametric studies on automotive radiator has been presented in detail in this study. The modeling of radiator has been described by two methods, one is finite difference method & the other is thermal resistance concept. By a detailed literature survey a number of recommendations have been provided for the development of a more effective & compact radiator. All these recommendations are listed in the future scope section. These recommendations demand changes from the range of the geometrical parameters to the extent of coolant composition. In the performance evaluation of the radiator, a radiator is installed into a test-setup and the various parameters including mass flow rate of coolant, inlet coolant temperature etc. are varied. Then the corresponding value of the effectiveness and outlet coolant temperature are reversed. These values are then plotted in the 3-axis graphs and their behavior is studied.

In the testing, a comparative analysis between different coolants has also been shown. Here, one of the coolants is used as water and other as mixture of water in propylene glycol in a ratio of 40:60. Here a big difference in the cooling capacity of the radiator is seen when the flowing coolant from water is changed to mixture. This is on the account of a very high value of specific heat of water in comparison to the mixture. It therefore can be concluded that the water is still the best coolant but its limitation are that it is corrosive and contains dissolved salts that degrade the coolant flow passage. By making a mixture with ethylene glycol its specific heat is decreased but its other properties are enhanced. It also increases the boiling temperature of water and decreases freezing temperature also. But if the mixture is to be as effective as that of the water then its mass flow rate should be increased.

All the formulas used in the calculation are listed in the testing results and discussion section. Hence on the basis of the study it is concluded that:-

- The cooling capacity and the effectiveness are in direct relation with the inlet temperature of hot coolant i.e. with an increase in the value of inlet coolant temperature the cooling capacity & the effectiveness of the radiator increases respectively.
- The cooling capacity and the effectiveness are also in direct relation to the mass flow rate of the coolant.
- All these results have been calculated by taking the fan speed at 6000rpm.

During our testing we have taken the maximum fluid inlet temperature at 80^{O}C. So, the values of effectiveness are lower at this low temperature. Whereas in actual the inlet coolant temperature to the radiator is very much higher than experimented. Therefore, the nature of the graph needs to be concentrated on and not the specific values. Same is true for the other plots also

7. FUTURE SCOPE

7.1 Use of nano-fluids

A three-dimensional laminar flow and heat transfer with two different nano-fluids, Al_2O_3 and CuO, in an ethylene glycol and water mixture circulating through the flat tubes of an automobile radiator can also be numerically studied to evaluate their superiority over the base fluid. In radiators, which are vital component in the control of the engine temperature in automobiles, a liquid (commonly water – glycol mixture) is to be cooled by air. The liquid flows in flat tubes while the air flows in channels setup by fin surfaces. With recent developments in Nanotechnology has been widely used in traditional industries because materials with grain size of nanometers posses unique optical, electrical and thermal properties etc. Recently, nano-particles can be dispersed in conventional heat transfer fluids such as water, Ethylene glycol, Engine oil. It produces a new class of high efficient heat exchange fluids called Nano-fluids [4]. Many experimental and theoretical analyses are carried and found these new heat exchanger coolants are excellent. Nusselt number in turbulent and laminar flows of different nano-fluids (Al_2O_3 + H_2O, Cu + H_2O; etc) have been found, showing that these fluids possess very high thermal properties than conventional coolants.

7.2 S-shaped fins

Numerical studies have showed that the fin shape affects the thermal-hydraulic characteristics of the radiator with S-shaped fins. The fin angle effect, guide wing effect, fin width effect, fin length effect, and fin roundness effect were studied. The guide wing effect was studied while changing the radial position and circumferential fin arc length. Narrower fins produce more heat transfer area per unit volume but worsen the fin efficiency more than the wider fins. In the S-shaped fin model, the narrowest fins showed the largest heat transfer rate. A longer fin length reduces the stream bend and pressure drop that occurs because of the stream bend. The fin length effect was less than the other fin effects if uniform flow was realized in the channel. Fin roundness at the head and tail edge of the fins minimally affect the heat transfer performance but greatly affect the pressure drop performance. From the real fin shape manufactured by chemical etching, the pressure drop is increased by about 30%. Lesser fin roundness is preferred to reduce the pressure drop.

7.3 Increasing turbulence of coolants

The effectiveness of the radiator can be increased by employing turbulence promoters. First the heat transfer in plain fin arrangements was investigated to determine the influence of corner radii of bent metal sheets of the ribs. The Reynolds number range extended from 500 to 3000, and a transition from laminar to turbulent flow was observed at about Re=2000. The ducts with the smallest radii resulted in the highest Nusselt number for a given Reynolds number, Nu exceeding that of ducts with the largest radii by about 15%. However, a comparison of the investigated geometries in terms of the volume goodness factors showed that the ducts with the greatest radii were most advantageous.

Second, the influence of circular segment shaped turbulence promoters in staggered, non staggered and inclined arrangements was examined, the determination of average Nusselt number showed that the non staggered geometries deliver the highest heat transfer rates. The best volume goodness factor was achieved with the staggered arrangement.

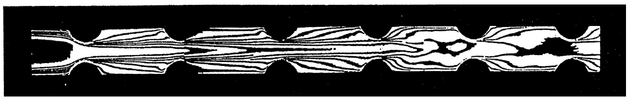

Fig. 10: Flow pattern in non staggered arrangement

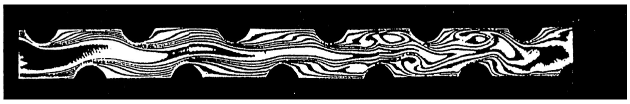

Fig. 11: Flow pattern in staggered arrangement

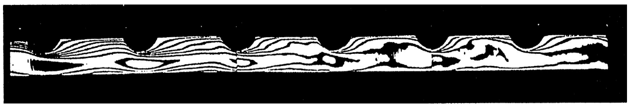

Fig. 12: Flow pattern in aligned arrangement

7.4 Use of carbon-foam fins

One more modification which can be employed is to replace aluminum fins with carbon foam channels. Due to the thermal properties of carbon foam (k = 175-180 W/mK for carbon foam with 70% porosity), along with increasing the amount of heat rejected, we will be able to reduce the overall size of the radiator while simultaneously increasing the surface area exposed to the air, thus reducing the air side resistance. Figure below shows our new design concept.

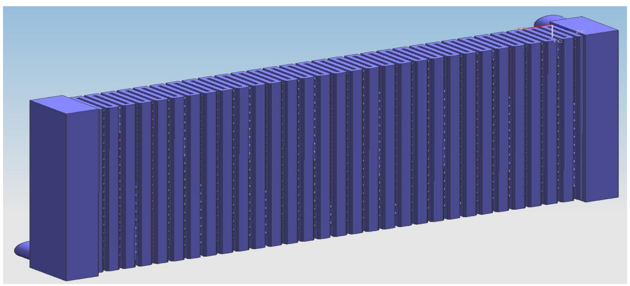

Fig.13: Carbon foam films

The carbon foam has channels in a corrugated pattern. This corrugation channels air into the slots and forces the air through the carbon foam. Also, there are many tubes which are arranged in a parallel design. They provide support for the carbon foam as well as contain the necessary volume of coolant. The end caps are made out of aluminum and also provide structural support and mounting locations. Overall, this design concept is a simple design which will meet most of our customer requirements, including dissipating 147 kW of heat with an inlet fluid temperature of 85°C, decreasing the overall volume.

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