Chapter - 1

Introduction

1.1 Background

Many technical developments have been introduced to meet the requirements of low fuel consumption and CO_2 emission in vehicles. Concerning the energy distribution as shown in Fig.1.1, in the vehicle, only around 35% of the total fuel energy finally becomes mechanical work which is used for driving the vehicle. However, 30% of the total energy input is brought away by the coolant of the engine cooling system and another 35% of the energy is lost to the exhaust gases. If one could optimize the energy wasted in the coolant or the exhaust gases, then the efficiency increases and hence the fuel consumption and the CO_2 emission (this is also proportional to the fuel consumption) could be reduced.

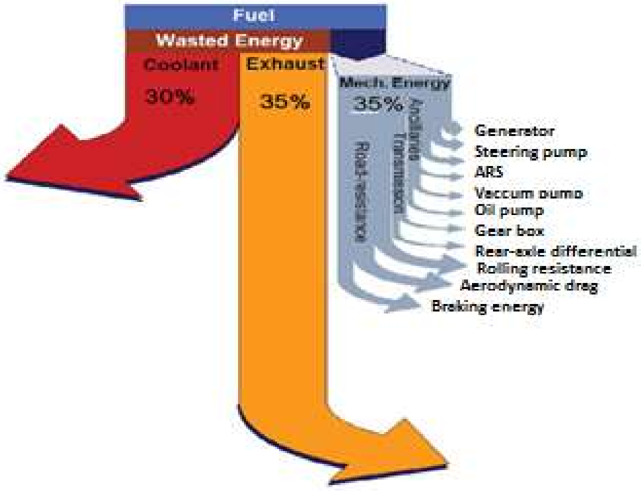

Figure 1.1: Energy distribution in a vehicle [1]

If the engine cooling system cannot take away the heat quickly, the engine working temperature will increase. More fuel will be consumed and the life time of the engine will be reduced due to the high working temperature in the engine.

On the contrarily, a good engine cooling system can reduce the time of the engine start and warm up processes, in which the engine reaches its optimal working temperature [2]. A lot of hydrocarbon (HC) and carbon monoxide (CO) are produced during the starting and warming up period [3]. Cooling of an engine is necessary for the following reasons [3, 4]:

(i) During combustion process of an IC engine, peak gas temperature goes up to 2500K. The temperature of the inside surface of the cylinder walls is usually kept below 200°C to prevent deterioration of the oil film. High temperature of the lubricating oil may result in physical and chemical changes in the oil and cause wear and sticking of the piston rings, scoring of the cylinder walls or seizure of the piston.

(ii) During the process of converting thermal energy into mechanical energy, high temperatures are produced in the cylinder head and walls, piston and valves. Heat absorbed by these components increase their temperatures. The uneven temperature distributions cause uneven expansion of various engine parts, hence causing thermal stresses in the components of the engine. High thermal stresses cause fatigue and cracking of the components. Therefore, the temperature must be kept less than about 400°C for cast iron and about 300°C for aluminium alloys.

(iii) The temperature of the cylinder head must also keep below 220°C. If the cylinder head temperature is high, this may lead to overheated spark-plug electrodes causing preignition in SI engines. Preignition results in a loss of efficiency and increases the cylinder head temperature to such an extent that engine failure or complete loss of power may result.

Even excessive cooling is undesirable for the following reasons [3]:

(i) Starting of the engine will be difficult at low temperatures. The engine must be kept sufficiently hot to ensure smooth and efficient operation.

(ii) Vaporization of the fuel will be reduced at low temperatures, preventing formation of a homogeneous mixture with air. It may cause poor combustion and also increase fuel consumption.

(iii) Excessive cooling provided to the combustion chamber walls will lower the average combustion gas temperature and pressure, which in turn reduces the work per cycle transferred to the piston.

(iv) Friction will be increased because of high viscosity of lubricating oil at lower temperatures.

(v) The sulphurous and sulphuric acids are formed from the oxidation of sulphur present in the fuel during the combustion process. These acids may condense at low temperatures and corrode the cylinder surfaces. To prevent condensation of acids, the coolant temperature should be greater than 70°C.

Removing heat is highly critical in preventing an engine and engine lubricant from thermal failure. On the other hand, it is desirable to operate an engine as hot as possible to maximize the thermal efficiency. Thus, an efficient engine cooling system is significantly important for the fuel consumption of vehicles. In automobile industry pump circulating cooling system is mainly used. The advantages of it are [4],

(i) More uniform cooling of cylinder barrels and cylinder heads due to the flow of coolant through jackets. It reduces the temperatures of the cylinder head and valve seats, permitting the use of higher compression ratios in SI engines for a given cylinder size. It results in higher power output per cylinder volume.

(ii) The liquid-cooled engine can be made more compact with appreciably smaller frontal area to reduce air resistance.

(iii) The fuel consumption of high compression liquid-cooled engines is lower than that of air-cooled engines.

As shown in Fig.1.2, the pump circulating cooling system mainly consists of liquid i.e coolant to absorbed heat from the engine and reject to the ambient through a heat exchanger i.e radiator. Hence, the radiator and the coolants are the two important components of automotive cooling system.

1.2 Automotive Radiator

The purpose of the radiator is to cool the water that has absorbed heat from the engine. It is a compact heat exchanger with both fluids unmixed, in which coolant passing downwards through the tubes and efficiently cooled by the forced flow of atmospheric air.

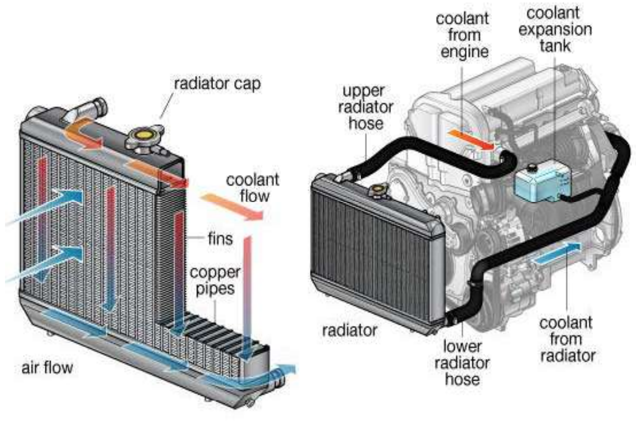

Figure 1.2: Pump circulating cooling system [4]

The radiator consists of a radiator core, with its water-carrying tubes and large cooling area, which are connected to a receiving tank (end cap) at the top and to a dispensing tank at the bottom. Between the tanks there is the core, which divides the coolant into thin streams. In operation, the coolant flows from the inlet to the outlet through many tubes mounted in a parallel arrangement. The fins conduct the heat from the tubes and transfer it to the air flowing through the radiator by a fan. 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. 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.

1.2.1 Radiator fin surfaces

The main requirement for any heat exchanger is to transfer the required amount of heat with a very high effectiveness. In order to increase the heat transfer rate by assuming that the heat transfer coefficient cannot be changed, the area or the temperature differences have to be increased. In reality, it may not be much meaningful to increase the temperature difference because for both cases either to supply the hot fluid at high temperature or cold fluid at lower temperature extra work has to be done. Furthermore, increasing the temperature difference more than enough will cause unwanted thermal stresses on the metal surfaces between two fluids. This usually results in the deformation and also decreases the life span of those materials. As a result of these facts, increasing the heat transfer surface area generally is the best engineering approach.

The above requirements have been the motivation for the development of a separate class of heat exchangers known as compact heat exchangers. These heat exchangers have a very high heat transfer surface area with respect to their volume and are associated with high heat transfer coefficients. Typically, the heat exchanger is called compact if the surface area density (β) i.e. heat transfer surface area per unit volume is greater than $700 m^2/m^3$ in either one or more sides of two-stream or multi stream heat exchanger [5].The compact heat exchangers are light weight and also have much smaller footprint, so they are highly desirable in many applications.

Types of fin surfaces are classified as follows,

Plain fin: Plain fins are most common of all compact cores used in compact heat exchangers. Triangular and rectangular cross section passages are most common in it, although any desired shape can be given to the fins [5], considering only manufacturing constraints.

Wavy fin: Wavy fins are uninterrupted fin surfaces having cross-sectional shapes similar to plain fins, but involves cyclic lateral shifts perpendicular to the flow direction [5]. The resulting wave form provides effective interruptions which causes the flow direction to change periodically and consequently, the boundary layer separates and reattaches periodically around the trough regions to promote enhanced heat transfer; increased pressure drop penalty is also accompanied. Heat transfer is enhanced due to creation of counter-rotating vortices while the fluid passes over the concave wave surfaces. Its heat transfer and pressure drop characteristics lie between plain and offset strip fins. The friction factor continues to fall with increasing Reynolds number.

Offset strip fin: It is a type of interrupted surface, which can be visualized as a set of plain fins cut normal to the flow direction at regular intervals and each segment being offset laterally by half the fin spacing [5]. Surface interruption enhances the heat transfer by two mechanisms. First, it prevents the continuous growth of thermal boundary layer by periodically interrupting it. Second, at above the critical Reynolds number, oscillations in the flow field in the form of vortices shed from the trailing edges of the interrupted fins, which enhance local heat transfer by continuously bringing in fresh fluid towards the heat transfer surfaces. But this enhancement is accompanied by an increase in pressure drop. The heat transfer performance of an offset strip fin is often as much as times than that of a plain fin surface of comparable geometry, but at the expense of higher pressure drop.

Louvered fin : Louvered fin is also an interrupted fin in which small segments of the fins are slit and rotated 20 to 45 degrees relative to the flow direction [5]. The fin surfaces are cut and bent out into the flow stream at frequent intervals in a louver fashion for breaking up the boundary layers and enhance the heat transfer. Its performance is either similar to or better than offset-strip fins. The multi-louvered fin has the highest heat transfer enhancement relative to pressure drop in comparison with most other fin types. An important aspect of louvered fin performance is the degree to which the flow follows the louver.

Perforated fins: This surface geometry is made by punching a pattern of spaced holes in the fin material before it is formed into flow channels. The channels may be triangular or rectangular in shape with either round or rectangular perforations [5]. If the porosity of the resulting surface is sufficiently high, enhancement can occur due to boundary layer dissipation in the wake region formed by the holes. The performance of the perforated fin is less than that of a good offset strip fin, and thus the perforated fin is rarely used today. Perforated fins are now used only in limited number of applications such as a tabulator in oil coolers.

Pin fin: In a pin fin exchanger, a large number of small pins are sandwiched between plates in either an inline or staggered arrangement. Pins may have a round, an elliptical, or a rectangular cross section. Due to their low compactness and high cost per unit surface area compared to multi-louvered or offset fins, these types of finned surfaces are not widely used nowadays. Due to vortex shedding behind the pins, noise and flow-induced vibration are produced, which are generally not acceptable in most heat exchanger applications. The potential application of pin fin surfaces is at low flow velocities (Re<500), where pressure drop is negligible. Pin fins are used as electronic cooling devices with free-convection flow on the pin fin side.

1.2.2 Radiator fin materials

Air-water heat exchangers are commonly employed in high output internal combustion engine cooling. The resistance to convective heat transfer on the air side of the heat exchangers dominates in the design of these heat exchangers. Large numbers of metal fins are used to provide additional surface area on the air side of the heat exchangers to lower the total convective thermal resistance. These fins are generally made of aluminium having thermal conductivity of 160 - 250 W/m-K.

Carbon foam and graphite foam fin: Compared to aluminium and copper, porous carbon-foam and graphite foam are having higher effective thermal conductivity. Thermal conductivity of foam depends on the porosity, which is normally in between 0.7 and 0.9 using the current foaming process. Due to its big specific surface area, a porous medium at a small size might be a good choice for the development of new compact HEXs. The carbon foam and graphite foam has channels in a corrugated pattern (Fig.1.3). 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 aluminium which also provides the structural support and mounting locations.

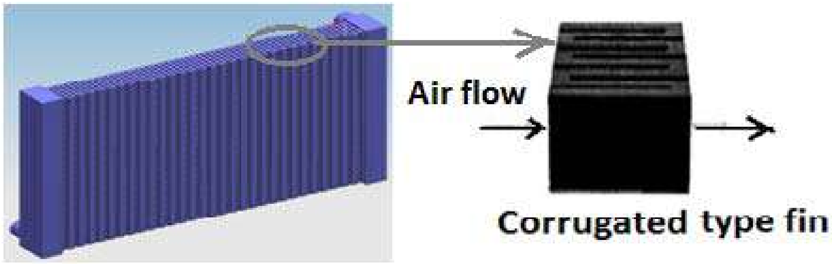

Figure 1.3: Carbon foam fin [6]

The main advantages of carbon foam and graphite foam fins are they provide a large surface area per unit volume due to large and numerous pores. This large surface area will increase the surface area exposed to the air and thus reduce the air side resistance along with reduced weight when compared to conventional materials used in current radiators (aluminium or copper). However, the disadvantages are due to small pores, these fins can become clogged with road debris or insects, but a filtering screen should keep the foam clean for our application. It also requires additional bracing for support.

1.3 Radiator coolants

Cooling is one of the important processes for maintaining and enhancing the operational performance of the system as a result caused by the increase in power and reduction in size and weight in future products. To enhance the cooling rate, increasing the surface area by addition of fins is the earliest approach but this approach of increasing heat transfer already reached to their limit. The conventional fluids, such as water and EG have been proven to have poor convective heat transfer performance due to comparatively lower thermal conductivity. In order to reduce pumping power requirement and to achieve higher cooling capacity, higher compactness and effectiveness of heat transfer systems are necessary.

Nanofluids : Recently, there has been considerable research outlining superior heat transfer performances of nanofluids in automotive radiator. Nanofluids are superior as a heat transfer agent over conventional fluid (Water + EG). The idea behind the development of nanofluids is to improve the heat transfer coefficient and to minimize the size of heat transfer equipments for conservation of material and energy. Nanofluids have invented a new path in the field of thermal engineering and are taken to be a new generation fluid for dissipation of heat in many fields such as transportation, electronics, medical, nuclear, food, space vehicles and manufacturing of many other products. With the use of nanofluids, about 10-20% of heat transfer enhancement can be achieved.

Hybrid nanofluids : The most important exclusivity of hybrid nanofluid refers to composition of two variants of dispersed nanoparticles in a base fluid. Thus, when materials of particles are chosen properly, they could enhance the positive features of each other and cover the disadvantages of just one material. Alumina has beneficial properties such as chemical inertness and a great deal of stability. Al_2O_3 also exhibits lower thermal conductivity with respect to metallic nanoparticles. Aluminium, zinc, copper and other metallic nanoparticles encompass great thermal conductivities. However, the use of metallic nanoparticles for nanofluid applications is limited due to the stability and reactivity. According to these features of metallic and non metallic nanoparticles (such as Cu), a nanofluid based on Al_2O_3 nanoparticles can enhance the thermophysical properties of this mixture. However, the application- oriented researches of hybrid nanofluids are limited.

New radiator coolants : Recently, research has been carried out with sugarcane juice and citrus lemon juice brines [154] are used as radiator coolant and seem to be slightly better in terms of both heat transfer and pumping power than water and nanofluid. In overall, both sugarcane juice and citrus lemon juice brine are seem to be potential substitutes of water hence hybrid nanofluid can be also potential candidate as engine coolant.

1.4 Aims and objectives

Due to the increasing power requirement and the limited available space in the vehicles, it is extremely difficult to increase the size of the heat exchangers (HEXs) placed in the front of the vehicles. Hence, the overall aim of this study is to increase the performance of the automotive radiator. In general here are few methods which can applicable for that are,

- By using coolant having low freezing point, high boiling point and high heat transfer coefficient.
- By using various plain fin heat transfer surfaces such as louvered fins, wavy fin and rectangular fins etc.
- By using high thermal conductive materials in the formation core of automotive radiator such as graphite foam and carbon foam etc.
- By changing the position of the heat exchanger. i.e counter current flow heat exchangers and combination of cross and counter flow radiator configuration.

By using above methods the objectives are

(i) Determination of thermophysical properties of selected coolants by theoretical and experimental analysis.

(ii) Theoretical performance analysis of automotive radiator using various mentioned coolants for louvered, wavy and rectangular fin radiators.

(iii) Theoretical performance analysis of optimum PG brine (25% PG brine) and optimum PG brine based nanofluid and hybrid nanofluids in rectangular fin automotive radiator.

(iv) Theoretical performance analysis of radiator using graphite foam, carbon foam, aluminum, copper, and aluminum foam as fin materials.

(v) Theoretical performance analysis for improvements in radiator by using different configuration as cross flow (conventional), counter flow and combination of cross and counter flow (CCFC).

(vi) Experimentation on radiator performance on wind tunnel based radiator experimental set up using water, optimum PG brine, PG brine based hybrid nanofluids as coolant.

(vii) Experimentation on cooling system (engine with radiator) performance using water, optimum PG brine, PG brine based nanofluids and hybrid nanofluids as coolants for evaluating the energy distribution fractions.

(viii) CFD analysis of rectangular fin radiator with water, 25% PG brine, 25% EG brine, nanofluids and hybrid nanofluid as radiator coolants.

1.5 Outline of the thesis

The thesis has been divided into eight chapters. After an introduction and overview, **Chapter 2** contains a comprehensive review of literatures on radiator performance with different coolants such as water, EG, PG, nanofluid and hybrid nanofluids, with different fins surfaces such as louvered, wavy and rectangular, with different fin materials of aluminium, copper, graphite foam, carbon foam, aluminium foam and also with different configuration and radiator positions.

Chapter 3 contains the evaluation of thermophysical properties of base fluid as water, EG, PG sugarcane juice, optimum PG brine, various nanofluid, hybrid nanofluids and comparison of their theoretical and experimental results comparison. However, **Chapter 4** presents the theoretical performance of above mentioned various coolants for louvered, wavy and rectangular fin automotive radiator. A new coolant i.e optimum PG brine (25% PG) has been introduced which results the nearly same performance as water at higher temperature. Also, performance analysis have been carried out with optimum PG brine based nanofluids and hybrid nanofluids. Also, it contains the theoretical performance analysis for various fin materials i.e aluminium, copper, carbon foam, graphite foam, aluminium foam with their performance comparisons and the results for performance improvement with different radiator positions

Chapter 5 presents the experimental performance determination of conventional coolants and with optimum PG brine based hybrid nanofluid and their performance comparisons on wind tunnel based radiator experimental set up. **Chapter 6** contains the detailed design and fabrication of a prototype radiator set up coupled with engine assembly and experiments carried with above mentioned coolants and compared with engine performance at different loads .

Chapter 7 dedicated to the CFD analysis for rectangular fin radiator with coolants i.e 25% EG brine based nanofluid, 25% EG and their air and coolant flow patterns and also recommendation of future works. Finally, **Chapter 8** presents the conclusions of the above mention chapters for different coolants, fin materials, fin surfaces and positions of radiator with theoretical, experimental and numerical analysis in CFD for the performance improvements in automotive radiator.