CHAPTER – 2
LITERATURE REVIEW

2.1 GENERAL

By harnessing the pros and cons of combustion chamber temperatures, internal combustion engines are developed. Here temperature difference puts a major impact on efficiency. If the gas energy is utilized to an utmost level the efficiency could be improved. To provide the same researches preferred limited cooled diesel engine. This provides a clear understanding of how to improve efficiency, which is enhanced by diminishing heat losses.

2.2 CONCEPT REVIEW

After thorough study of literature and analyzing brainstorming sessions the following report is made.

Myers et al., [2] had worked on properties which in turn effect on the transfer of heat and also on various efficiencies related to the IC engines and this marks first of its kind effort on adiabatic engines after 25 years of Kirloskar’s research. He clearly mentioned the pros and cons of his research. This is very much useful for researchers for further developments.

One of the earliest investigations on the low heat rejection concept was conducted by Griffiths [10]. In his thermodynamic simulation model, he increased the combustion chamber wall temperature and studied its effects on thermal efficiency and heat rejection. In his analysis he found that only 25% of the reduction in heat rejection is recovered as work. About 61% of this reduction appears in the exhaust and 14% is lost in intercooler.

Adiabatic engine research was disseminated to the world when the Cummins engine Co. collaborated with the US Army tank in 1978, - Tank-automotive and Armaments Command (TACOM) in pursuing the adiabatic engine concept. In one of their earliest attempts, Kamo et al., [12] had reported using Hot Pressed Silicon
Nitride (HPSN) and Lithium Alumina Silicate (LAS) as the insulating material. The main disadvantage of using LAS is its low material strength. Although HPSN has good high temperature strength, the conductivity has left much to be desired.

After careful study of literature research work is much focused on four-stroke compression ignition engines. Valland et al., [33] had proved divergence from four strokes maximizes the benefits and also they clearly cited two stroke engines entail maximum efficiency. They have shown that there is a 9% increase in exhaust energy for the two-stroke cycle and 6% increase for the four-stroke cycle.

Dalvi et al., [42-44] had described the effect of adding various stabilizers (CaO, MgO, Y₂O₃) on sintering and stabilization of zirconia. They had found out, from their experiments, that for uncalcined mixtures the sintered bulk density was higher when CaO is used as a stabilizer. But, when the mixture was calcined at 1600°C, Y₂O₃ stabilized zirconia is far more superior. Hence, for high temperature applications, as required in internal combustion engines, Y₂O₃ stabilized zirconia is preferred.

In their paper in 1983, Kamo et al., [46] had leveraged maximum benefits with the use of Partially Stabilized Zirconia (PSZ). The PSZ powder was deposited on the engine components by the plasma spraying technique. Experiments were carried out on a 450 HP turbo compound reported a specific fuel consumption of 228 gms / bhp-hr. With this research they showed that green house gases are reduced in line with smoke emission levels.

Tovell [55] came forward with his idea of computer-simulated model, which showcased effects of heat losses in the performance of the diesel engine. He prototyped the model, by comparing the engine, with and without insulation on direct injection diesel engine. He reported a 7.5 % reduction in fuel consumption on eliminating cooling system completely. He has found that the largest reduction in fuel consumption can be obtained by insulating the piston crown or cylinder head. He has also reported a drop in hydrocarbons, particulate and smoke emissions and rise in NOₓ emissions and exhaust temperature and a reduction in engine noise.
Wallace et al., [57] had reported the use of heat resisting materials on the adiabatic engine concept. At the University of Bath, they replaced the standard piston crown by heat resisting crown made of nimonic material with air gap to derive maximum benefits from heat loss. The aluminium piston skirt and crown are joined together with the help of spacer ring, which is interchangeable. They also developed a finite element analysis for calculating the heat flows, temperature distribution and stress analysis. The analysis made clear evidence of increase in piston temperature to 400°C.

Alkidas et al., [61] had also reported some research work on the air-gap insulated piston. In their design, the piston crown was made of Inconel, which has high temperature strength and relatively low thermal conductivity. The crown was attached by four bolts with disk springs to maintain a sufficient clamping load despite dimensional changes due to thermal expansion. The effective thickness of the air gap was about 4 mm. The diameter of the air gap was made as large as possible to minimize the heat flow area.

In their paper published in 1984, Kamo et al., [62] focused their research in attaining full-fledged volumetric efficiency with effective heat resisting ceramic materials. They concluded this research session by noting the material requirements to be implemented for adiabatic engines. Due to limitations of lubricating oil failures, they turned out their research importance to friction losses, which put up to 50%.

French [64] had conducted an extensive literature review on the subject of adiabatic engine. He has developed a simple model for this survey, based on air cycle, which describes the reduction in coolant heat loss as a function of the ceramic dimensions and engine operating conditions. He even compared the results of his model with experimental results published in the literature. In his analysis he found that increasing the insulating material thickness follows the law of diminishing returns (i.e. a 2 mm layer of zirconia will reduce heat loss by 48% and a 8 mm thick zirconia layer is require to reduce the heat loss by 78%).
Wade et al., [74] had concentrated much on the area of the combustion chamber above the piston rings. Their research was focused on insulated steel piston for the development of limited cooled engine. They made significant efforts to study the pollution impact on diesel engines and fuel consumption at part load operating conditions. The major pollutants namely hydrocarbons and particulate matter have been reduced to 7%. They also faced problems like lubricating oil failure at elevated temperatures and drop in volumetric efficiency due to change in densities. They also reported impacts made due to nitrogen oxide emissions.

Lumby et al., [81] had reported the development of a new ceramic material syalon (Si-Al-O-N) for engine applications. Though this material was superior to zirconia in many aspects such as rupture modulus, tensile strength, compressive strength, young’s modulus, hardness, the coefficient of thermal expansion and thermal conductivity left much to be desired. Hence syalon can be used for high temperature applications but not as an insulating material.

Morel et al., [82] had formulated strategy to work considering the structural parameters related to diesel engines and these embark a new correlation [83] regarding heat transfer and proper mixing of charge inside the engine cylinder as well as combustion gas velocities. They focused on the effects of different insulation approaches and insulating materials placed at several positions within the combustion compartment.

In their analysis they found that the piston and head receive about 81% of the total heat transferred. Hence insulating the piston and head should be given first priority. In the liner, the top portion (i.e. 1/6th of the total liner length) receives most of the heat transferred through the liner. Hence insulating the top portion of liner is recommended because insulating the whole liner increases the liner temperature, which in turn reduces the volumetric efficiency.

Arunachalam et al., [122] had conducted several experiments on the performance of limited cooled engine with diesel as fuel. He has also conducted tests to see whether the high temperatures encountered in an insulated engine allowed the
use of low cetane number fuels. In his experiments, he found that with full insulation, fuels with 25 as cetane number could be used. With partial insulation, fuels having 35 as cetane number can be used, above which the engine started missing.

Engine tests were conducted by Pawar et al., [208] on the ceramic-coated engine components. Experiments were carried out on a comet (VCT-10) type, 10 HP, 1500 rpm water cooled twin cylinder, diesel engine with fully instrumented for the measurement of engine output, speed, fuel consumption, air flow rate, heat transfer rate to the coolant, exhaust gas temperature and smoke density. Engine tests were conducted with the ceramic-coated engine components. The piston top with stainless steel bowl press fitted into the combustion chamber with two mm air gap insulation thermal barrier and valves were coated with materials namely Calcia Stabilized Zirconia (CSZ) by the use of plasma spray techniques. They noticed suppression in smoke emissions in limited cooled compression ignition engines. Maximum reduction in smoke density was found in 80% to 100% load range. They also reported that the turbo compound system was essential for taking full diesel advantage of insulated semi adiabatic engine.

Researcher by name Mirari et al., [215] in latest experimentation report showed 7% improvement in brake specific fuel consumption using single cylinder DI diesel engine with necessary insulation in combustion chamber. The study showed useful results compared to metallic engine in terms of better combustion and fuel efficiency.

The study report from Domingo et al., [223] showed that cylinder heat rejection reduction causes temperature increase in insulated engine in line with convective heat transfer.

2.3 INTRODUCTION TO VEGETABLE OILS

It is time to change from diesel engines to alternate fuel engines as pollution is posing a major constraint to the modern era and due to renewable issue of petroleum products. The following points emphasize the need for alternative fuels.
i) As global economies have already declared red alert to fossil fuels, the researchers started to make a comprehensive study to develop engines compatible with alternate fuels.

ii) There is an exponential growth in the automobile vehicles; hence the fuel requirements would go up day by day.

iii) The rising prices and diminishing reserves of petroleum products have led to intensive studies.

Though these vegetable oils seem to be beneficial they do not cope up with thermal efficiency standards made by diesel engines and also they make contributions to pollution [68, 101,102, 108, 178, 194, 204].

It is the need of hour to discuss the benefit of switching to alternative fuels coming to this the most useful solution is vegetable oil, which is obtained from rural areas. IC engine advent marked the time to study about them. In spite of benefits availed from them researchers started to use them in only recent years.

2.4 SCIENTIFIC PROPERTIES OF VEGETABLE OILS

Due to technological impacts made by industrial revolution several illusions were cleared off regarding development of diesel engines using alternate fuels and researchers started to extract a semi drying oil from seeds using a methodological processes and finally seeds get processed through these processes and oil extraction is made.

The oil extraction contains mixtures of organic compounds, which comprises of simple and compound structures. Some inorganic compounds of heavy metals are also present. Most of the hydrocarbons present in the vegetable oils are not simple aromats but they also belong to turpine class. They are usually fatty esters of glycerol (triglycerides). Because of greater density, their heat value is comparable to diesel. Heat value decreases with increasing unsaturation as a result of fewer hydrogen atoms. High stoichiometric ratio is attained due to oxygen in molecular form presence. The properties of these oils depends very much on many factors like
refining techniques, the extent of refining, oil seed growing climate and therefore may contribute to variations in test results [218].

Researches finally gave fruitful results based on vegetable oil implementations as they do not contain sulphur and several hazards of pollution are caused mainly by sulphur, which form a major consequence to acid rains. And also would take away more CO₂ from the atmosphere for its production than will be added to atmosphere.

2.5 VEGETABLE OILS AS ALTERNATE TO DIESEL

Until today only a few number of studies are conducted which proved to be worthwhile demonstrations regarding performance and emission related analysis of D.I engine coated with ceramic. These experimental studies also provided better efficiency in line with base line engine.

For this research analysis some peculiar oils are selected among vegetable oils namely Rice bran, Karanj, Peanut, Rapeseed, Sunflower and Soyabea are among them. Though these provide better alternatives to D.I engines they mainly possess defects related to nozzle deposits, which put a great limit to efficiency and performance. Apart from above discussed limitations vegetable oils are easy to make refining than crude oil.

To know more loopholes regarding viscosity properties researcher Gerhard Vellguth et al., [45] set some specific tests to evaluate vegetable oils and he came to know that they contribute more viscosity and low calorific value than diesel.

Some of the vegetable oils, which are also being investigated as alternative fuels, are Palm oil, Neem oil, Babussa oil, Linseed oil, Cottonseed oil and Jatropha oil etc. Neither of the above fuels is well suited for use in diesel engines, and ignition improver and ignition assistance devices have commonly been used. Apart from these, they also produce aldehydes and ketones in their exhaust emission, which create associated environmental and health troubles.

Another researcher by name Goering et al., [26] made studies by experimenting eleven vegetable oils to know the best among them as alternate fuel
and soya been, sesame oil, cotton seed oil, corn oil, rapeseed oil are proved to be beneficial.

Another researcher Bruwer et al., [23] studied the properties of renewable resource using sunflower oil and showed power loss of around 8% after testing operation of thousand hours. He replaced injector pump and fuel injector to decrease power loss. And again after operation testing of 1300 hours the deposits of carbon is similar to 100% diesel fuel engine with exception in case of injector tips.

The researchers made more thrust to analyze properties of sunflower oil at various temperatures and Tahir et al., [32] noted that it shows 14% higher viscosity than diesel fuel. This showed similar performance to CI engine with slight decrease in fuel usage and also sunflower oil is prone to oxidize and after oxidation gum and wax traces are left out on equipment, which leads to failure of engine.

Another researcher by name Schoedder et al., [31] showed effects on engine by using rapeseed oil and it produced mixed results and has energy outputs in par with diesel fuel in short term results while long term tests contradicted short term test results and started to show difficulties after 100 hours of test conduction due to formation of deposits on engine components. So long term test results have proved to be beneficial and these are insisted to be carried out by investigators.

The testing process is carried with thirty distinct vegetable oils on CI engine since 1900’s [19]. The preliminary results showed these could be used as substitutes in place of diesel. Prolonged operation with raw vegetable oils leads to carbonization of engine components, which in turn causes failure of engine. Reduction in coking and extension in engine line can be obtained by using blends of vegetable oil with diesel.

**2.5.1 Complications of using fuel as Vegetable Oils in Conventional Engine**

Though with minor modifications these alternate vegetable fuels can be used in compression ignition engine, but there are certain problems associated with their high viscosity and high carbon residue. The enhanced viscosity nature of vegetable oil
causes complications in pumping and atomization, leading to poor performance of the engine.

The implication faced by vegetable oils is loss of potential to handle spark ignition engine flammability needs and these are same as cetane rating in diesel engine. Lowered power, combustion distortion, poor spray, wear problem as well as high smoke are some of the complications caused by these vegetable oils, while noise, odor and cold start are some other problems in these oils. Vegetable oils show more reactivity than diesel fuels due to increase of molecular weight, reduction in volatility as well as unsaturation. This increases oxidation and polymerization reactions as shown in literature.

After a thorough review of the literature it is observed that there are operational, longevity problems with the vegetable oil engines. The main complications associated with these engines are operational and durability related problems where performance, ignition and starting capability fall into operational related problems while formation of deposit, injector carbonization as well as sticking and oil lubricating dilution fall into durability problems [40].

When crude vegetable oils are used for prolonged duration they show fuel filter choking due to increase in viscosity and presence of insoluble in crude oil. Fuel spray pattern [220] is influenced by vegetable oil viscosities.

Due to high viscosity in vegetable oils when fuel is injected into the compressed air it leads to improper mixing of air and fuel due to poor atomization. Many researchers had faced the same while using vegetable oil as an alternate fuel. Due to this combustion efficiency reduces and in turn leads to loss of power and efficiency. In medium duty vehicles fuel from fuel injector injects fuel on the walls of the cylinder and erodes the lubricating oil presented on the walls. This causes lubricating oil failure in diesel engines, which in turn reduces mechanical efficiency. In most of these vegetable oils the kinematic viscosity is more and it is 15 times higher than that of diesel. Researchers suggested some of the methods to use vegetable oil as an alternate fuel to give better performance and these methods include
modifications of the engine, multi fuel injection, use of high temperature fuels and use of limited cooled engine. They also suggested fuel modifications like use of fuel blends, pyrolysis, transesterification and polymerization reduction by hydrogenation.

2.5.2 Blend Analysis on Vegetable Oil Fuel

By providing supplementation with diesel these vegetable oils shows compatible as diesel fuel. They show privilege of using as diesel alternative because they have free mixing characteristics with diesel fuel in present engines without the need of modifications in engine design. So to get more beneficial results researchers [27, 192] tried out various possibilities of mixing vegetable oils in proportionate blends.

Two researchers by name Ziejewski et al., [38] performed engine testing using blend of sunflower oil and diesel in equal proportions but the result is unsuccessful due to carbon formation on engine components like piston rings, intake ports and injectors which leads to sudden failure.

In their paper published in 1998, Beg et al., [199] research is conducted using linseed oil and necessary performance and emission parameters are reported. The utmost portion of piston was provided with insulation by yttria Partially Stabilized Zirconia (PSZ) with a bond coat of alumino-boro-silicate in a dedicated process instead of normally used plasma spray process. Results show that brake specific fuel consumption increases both in linseed-diesel oil blends and esterified linseed oil at different compression ratios and injection timings compared to 100% diesel operation. NOx level decreases whereas CO level increases in different blends compared to clean diesel operation. They had shown that there was an increase in smoke density for blended oil compared to esterified linseed oil and neat diesel oil.

Varaprasad et al., [210] had reported some research work on adiabatic engine, and improved the design by inducing necessary air spaces in liner top portion and in the piston. In their design, the piston was made in two parts, with a crown of super alloy of superni-90 having low thermal conductivity screwed to aluminium body of piston. They provided the top portion of the liner with an insert of superni-90 super
alloy. They reported 2.3% enhancement in Brake thermal efficiency and 8% decrease in BSF intake for various proportions of diesel-methanol mixtures.

2.5.3 Vegetable Oil Heating

One of the techniques to reduce viscosity is by heating the vegetable oil. For attaining good atomization and combustion viscosity, fuel injector is important. With a high fuel viscosity, fuel spray can impose upon the walls of the combustion chamber resulting in late burning and combustion. If heated to very high temperatures, low viscosity of the fuel can result in poor fuel droplet penetration and low combustion.

Dhinagar et al., [116] reported improved performance and low emissions by heating vegetable oils to temperature of 80 to 110°C. Therefore, these oils are to be heated to an optimum temperature for improved performance.

It was observed by Stumborg, Mark et al., [190] that several proponents affect the oil properties and test results and to name some among them are techniques of refining, climate of seed growth and seed variety.

2.5.4 Esterification Impact on Fuel Modification

Esterification is the method of transformation of vegetable oils to esters such as methyl and ethyl alcohols, which are known as Bio-Diesels. This process eliminates all the complications posed with vegetable oil [28]. The main asset of using vegetable oil esters is safety measures associated with them than diesel fuels.

This vegetable Ester oils offer good performance improvement when used in place of base vegetable oils [75, 91, 143, 153, 154, 167, 188, 186,182, 184,225, 226].

However, the performance can be further improved by using vegetable oil with low volatile, high viscous characteristics and low volatile vegetable oil esters in LHR engines [155, 1170, 205, 219].
2.6 INTRODUCTION TO LOW HEAT REJECTION ENGINE

When combustion chamber walls are provided with insulation the CI engine can be referred to as a Low Heat Rejection (LHR) engine. Ceramic coating was used to insulate piston, cylinder head, liner, valves etc. Theoretically this insulation reduces heat lost to cooling water and also gives conversion of more energy to useful mechanical work. Keeping this view in idea, several researchers [17, 59, 71, 90, 99, 109, 115, 107, 145, 152] have been working on these engines since 1978.

Two researchers by names Kamo et al., [15] belonging to Tank-automotive and Armaments Command (TACOM) Company had done speculating work by presenting a new concept on LHR Engines. The thrust to this research has gained importance since then. The research is aided by ceramic materials development undergone in the past 20 years and this made footsteps to the advanced adiabatic engines.

Theoretical work has been done besides limited experimental work. New analytical tools were developed for engine cycle analysis and design of ceramic components. Detailed review of the literature on both theoretical and experimental works is given in detail in the following sections.

2.6.1 Heat Balance in a Conventional CI and LHR Engines

By burning of fuel, heat is generated in the combustion chamber. In a conventional Compression Ignition (CI) engine fuel consumption gives clear picture of how effectively work is produced and how the losses take place during the transfer of this work to the output shaft [59]. As the load on the engine varies, the magnitude of the losses are also varies [1, 5, 20].

The LC Engine [11, 58, 135, 166, 162, 173, 172, 224] insulation provides minimization in heat transfer in combustion chamber using high temperature materials. Because of insulation the inside engine temperatures would tend to rise and at full load, un cooled combustion chamber wall temperatures could be as high as
1000-1500°C. However, this is not an impossibly high temperature from the point of view of strength but would be different from the lubricant point of view [82].

If the cooling is not employed there may be possibility of elimination of water circulating pump, fan and radiator [16, 18] resulting in a considerable saving in power and reduction in the weight of the engine. However, reduced heat losses to coolant will raise the exhaust gas temperatures.

2.7 IMPROVED FUEL ECONOMY IN LHR ENGINE

In limited cooled engines combustion phenomena and heat transfer affects due to reduced ignition delay and quantity of earlier combustion and due to this combustion duration increases. As heat release rate in the primary combustion stage reduces there would be drop in volumetric efficiency. However researchers claimed the mean temperature of combustion chambers increase in parallel to temperature of the working gases. Due to this there will be reduction in volumetric efficiency and cylinder pressure rate.

The in-cylinder convective heat transfer of the ceramic insulated LHR Engine did decrease in some cases [34, 85, 108, 193]. Yet, the fuel consumption rate of some LHR Engines rose. Many researchers [141, 150, 159, 163] attribute this to the deteriorated fuel combustion. It is evident that the deterioration of fuel combustion of LHR Engines is mainly caused by the shortened ignition delay. Because of insulation in LHR Engines, the in-cylinder temperature and the combustion side surface temperature increases greatly, which makes the pumped heat effect more serious. After being inhaled into the cylinder of LHR Engines, the fresh air gets more heat than it does in conventional CI engines, so its pressure and temperature are much higher at the end of the compression. Consequently, after being injected into the cylinder of LHR Engines, fuels can finish the physical and chemical preparation stages more quickly before ignition. It follows that the ignition delay is shorter and the fuel injection quantity into the cylinder during the ignition delay is much smaller. To improve the performance of LHR Engines, there are two effective methods, which can be adopted. One is to outspread ignition delay and the other is to boost injection rate
of fuel. Therefore, fuels, which have low cetane number, should be selected to prolong the ignition delay of LHR Engines. Therefore, the improvement in combustion process of LHR Engines would reduce the fuel consumption rate [165].

Xiaobo Sun et al., [168] suggested several methods to increase the fuel injection rate. One of the methods is to raise the opening pressure of the needle valve, which increases the fuel injection rate. It follows that the fuel quantity injected into the cylinder during ignition delay increases. In addition, the outlet velocity and the outlet pressure of the fuel flow, and the length of visible spray increases. Since the air resistance to the spray will increase relatively the cone angle and the turbulence of spray will increase. So the mixing quality of fuel with air will improve. All these factors mean that an increased quantity of well-mixed combustible gases would be present before ignition. Single cylinder D.I engine is considered for and observed that the fuel consumption rate drops by 2.55% as the injection pressure varied from 19.61 MPa to 23.5 MPa. It is also found that the fuel intake capacity reduces by 4.16% as the cross section area of a multi-orifice nozzle is increased.

Fuel pump plunger diameter is increased to improve the fuel injection rate is also found in the literature. In addition to the three methods discussed so far, other methods such as raising the speed of the cam axle can also increase the fuel injection rate. However, improving the performance of LHR Engines is complex because many factors are involved which vary from one engine to another.

Roy Kamo et al., [41, 111] had demonstrated the compliance of adiabatic engine concept specific to TACOM/Cummins and presented worthy results out of them for fuel efficiency enhancement. This uncooled model of adiabatic engine uses a metal composition and minimized coatings of ceramic on engine parts and gives boost up to technical backdrop of engine. The thought of using efficient ceramics in an adiabatic engine offers new ways to explore.

There are few experimental investigations perhaps because of the difficulties encountered and the considerable amount of time, money and effort involved in setting up the apparatus.
The insulated engine of Cheng et al., [136] consistently had shown poor performance at all loads. They carried out experiments on LHR Engine with zirconia-coated insulation on cylinder head and piston. They reported poor performance at all the engine loads and higher bsfc up to 17%.

The Woschni et al., [120] investigation also showcased reduced performance in LHR engine, even though the trend is not clear as in the case of brake specific fuel consumption. They attribute the poor performance to enhanced heat transfer in the cylinder, which is caused by a drastically increased convective heat transfer coefficient, which in turn is resulted from high cylinder surface temperatures.

Havstad et al., [92] conducted research with constant A/F ratio on inline base engine provided with insulation and without insulation. There is improvement of thermal efficiency by 9% and heat transfer by 30% with insulated engine. The heat carried by the exhaust is utilized to improve the volumetric efficiency.

Moore et al., [97] study indicates that insulation in combustion chamber occurs in four forms. They are coolant elimination, increasing oil pan temperature, insulation of piston and cylinder proved effective means of reducing rejection of heat.

Researcher by name Aldidas et al., [103] suggested to improve fuel mixing and combustion as fuel efficiency of LHR engines is related to base line engine and sometimes better than this. Observation is also made regarding ignition delay reduction; duration as well as increase in diffusion combustion for uncooled engines and these results compared to conventional cooled engines. He also made suitable implementations to the existed design to enhance better fuel efficiency outcomes in LHR and also he made hypothesis related to optimize injection system as mere insulation in insufficient for conversion of cooled engine to LHR version.

Kobori et al., [158] studies revealed that the main factor in limited cooled engine is fuel economy. They concluded in their research that fuel economy shows better results at rated loads compared to higher loads. This complication is due to higher temperature of the combustion chamber walls and increase in temperature of the fuel sprayed from the nozzle.
Theoretical analysts [14, 67] predict definite improvement in the thermal performance with increased insulation and numerical studies support it almost unanimously, but experimental investigations cast serious doubts on the validity of the predictions and some even proved it wrong [147]. The research has not produced fruitful results in spite of spending great deal of time on LHR engines. Some investigations indicate that engine insulation causes an increase in the in-cylinder heat transfer while as others points to the opposite. In a nutshell, their findings are inconclusive at best and contradictory at worst.

2.8 EMISSIONS IN LHR ENGINE

Wade’s et al., [119] experimental investigations showed, the shortening of the ignition delay tends to reduce NO\textsubscript{x} emission as it decreases the proportion of the premixed combustion phase. This difference in NO\textsubscript{x} emission behavior depends on which of these two competing conditions prevail. There was a significant increase in NO\textsubscript{x} emission of Kamo et al., [46] LC Engine.

The HC formation mechanism is determined by the speed of the engine. At lower speeds bulk quenching is predominant and at higher speeds the oil cracking in engines is predominant. Experiments carried out by Kamo et al [196] on a single cylinder LHR Engine found that there was not much difference in HC and CO emissions compared to standard CI engine [9, 61, 149].

The smoke and particulate emissions of LHR Engines are increased in some cases and decreased in some investigations carried out by researchers [137, 148, 179, 197, 202]. In high temperature combustion, a prolonged diffusion combustion phase is generally associated with an increase in the exhaust smoke emission [156]. The high combustion temperature, on the other hand, tends to reduce soot formation and enhance soot oxidation. At a high temperature condition, soot emission will either increase or decrease depending on which of the two preceding trends is the more dominating influence. The results obtained by Wade et al., [74] and Alkidas et al., [39, 133] show significant reduction in smoke emission. Thring et al., [100] in his experiments noticed higher smoke levels.
2.9 THERMAL BARRIER COATINGS

The insulation of the engine leads to the engine processes of compression and expansion to approach that of an adiabatic process, but cannot attain 100 percent adiabatic condition. Ideal heat rejection is not possible as no material with 100% is available in nature, so limited cooled engine is the best term than adiabatic engine. Due to reduction of heat losses, the energy preserved can partly appear as increased power output [66, 70, 79, 78, 89]. Due to hot environment inside the cylinder the ignition delay and combustion duration are reduced and thus enabling the use of low cetane, low volatile fuels like vegetable oils and vegetable oil esters in low heat rejection engines.

To reduce heat losses of an adiabatic engine the following four methods have been adopted.

1. Using air as the insulating medium [77]
2. Combustion chamber surface coatings with ceramic materials [104, 113]
3. Providing solid ceramic inserts in the engine structure [157]
4. Employing full ceramic components [65, 87, 125, 128]

The following are the important characteristics of insulating materials for use in adiabatic engine [30, 35, 130, 123, 181].

i) High thermal insulation
ii) Higher thermal expansion coefficients
iii) High thermal shock resistance
iv) High strength at elevated temperatures
v) Low friction and wear properties
vi) Low cost

Providing insulation could protect the inherent limitation of the material with high temperature gradient. This insulation also eliminates the intricate cooling system thereby reducing the overall weight of the engine, which in turn increases performance. Insulation of diesel engines with thermal barrier coatings has the following objectives.
i) Reducing specific fuel consumption, emission and noise

ii) Eliminating cold start problem and enhancing the engine life

iii) Carrying multi fuel ability

Different materials like Silicon Nitride [6, 13], Silicon Carbide [54, 53], Magnesia-PSZ [47], Chromium Oxide [63], Titanium, Fiber reinforced Aluminium [169] were found experimented but the results are not encouraging. PSZ coatings were reported to be good insulating material by many researchers [36, 69, 80] as its thermal conductivity is lowest among the other materials.

Thermal shock resistance, coefficient of thermal expansion and thermal conductivity are essential for the selection of a good insulating material. Most of the ceramics are brittle due to loss of consistency in the ceramic layers as well as loss of coating substrate. To obtain good barrier coating plasma spray ceramic powder [187,216,221] is covered as top layer of bond coating. Modern techniques play a significant role in this process apart from old methods and these new methods include laser glazing, electron beam vapor deposition etc. The analysis in this literature [209] has been made by considering mullite coatings and stabilized zirconia sprayed with plasma.

Chromium oxide and aluminium oxide have been excellent materials for abrasion resistant coating applications. These ceramic materials are not directly coated on combustion chamber components because of their brittle behavior. These are stabilized with yttria and alumina for better stabilization so that it gives good bonding between combustion components and ceramics. In most of the investigations researchers had faced complications with ceramics as insulating materials.

Timoney et al., [72] conducted research on various types of ceramics including Partially Stabilized Zirconia (PSZ) for deriving benefits related to prevention of cooling losses. He suggested Lithium Aluminium Silicate (LAS) was the best insulating material due to resistance to thermal shocks in addition to very low coefficient of thermal expansion.
Pradheeram et al., [29] studied the analysis of compressed ignition single cylinder four-stroke engine with an air gap piston. He optimized the thickness of air gap at 2 mm for efficient operation. He observed that the performance was better than the standard diesel engine.

R.Kamo et al., [24] defined the requirements of possible ceramic materials in his research and discussed the selection of ceramic materials in combustion chamber components, which puts significant impact on the performance of the engine.

Wade et al., [74] used 1 mm thick Partially Stabilized Zirconia (PSZ) as insulating material on the walls of the cylinder liner head and exhaust wall. He also incorporated 2mm air gap between piston crown and skirt as air acts as an insulator because of low thermal conductivity. As significance of these experiments the fuel efficiency raised to 4% at maximum load and 7% at part loads. They have applied a modest boost pressure to the uncooled engine intake airflow to compensate for the reduction in volumetric efficiency.

Dale R.Tree et al., [183] performed studies with Mullite as insulating material on cylinder liner, head and valves and zirconia stabilized with yttria on the piston. From this he plotted characteristics based on indicated specific fuel consumption versus average heat release with above specified insulators. Both the zirconia coated and mullite coated pistons showed an increase in heat release duration over the uncoated piston at advanced injection timing.

Krishnamoorthy et al., [112] conducted research on multi fuel method in a ceramic insulated direct injection diesel engine and concluded brake thermal efficiency improvement and emission reduction.

Parker et al., [116] conducted experiments on an air gap insulated piston using bolted and welded/roll bonded designs for their dual fuel mode engine and obtained better results.

Moffat et al., [96] suggested an upper limit not exceeding 50% reduction in heat loss, through piston for long-term durability. Ceramic coatings are being used as
thermal barriers to insulate the combustion chamber for hot combustion gases. Though researchers claimed PSZ as best insulator in terms of low thermal conductivity, high strength and low thermal expansion their experimental results are not satisfactory due to brittle behavior possessed by PSZ.

2.9.1 MULLITE AS HEAT RESISTING MATERIAL

Mullite is a material that is manufactured by combining Alumina with Silica, fused together during sintering, in various combinations to produce a family of materials known as mullite for the dense materials and porous mullite or corundum for the porous grades.

Synthetic Mullite (Al$_2$O$_3$–SiO$_2$) products are available in both impervious and porous forms. Densely sintered (impervious) mullite combines high strength with good thermal shock resistance. Porous mullite has a reasonably high strength combined with low thermal expansion giving improved levels of thermal shock.

Mullite ceramics with high thermal shock and operating temperatures up to 2910°F (1600°C) are used in furnaces, heaters, electrical insulation, wear and corrosion resistant applications. Stock is available in rods, mullite tubes, insulators, thermocouple protection sheaths and crucibles.

2.10 TURBO-CHARGING AND TURBO-COMPOUNDING

Turbo-charging is more promising in LHR Engines due to the high exhaust temperatures. In turbo-charging technology the exhaust pipe and turbine valve have to be dimensioned and valves have to be timed in such a way that the pressure in the exhaust pipe rises above the boost pressure when the exhaust valve opens (pre-release), but drops below the boost pressure towards the end of the exhaust stroke, during the scavenge period. With improvements in component efficiency, the turbo-charger with LHR Engine looks to be the best combination for vehicular applications.

In a turbo-compounded adiabatic CI engine, air enters from the compressor to the insulated high temperature combustion chamber. After combustion some of the energy is converted into piston work. The high temperature, high pressure gas is then
expanded through two turbine wheels and as much as possible remaining energy can be recovered. The first turbine drives the compressor and the second turbine is connected by gears to the engine crankshaft to further increase the useful power output of the engine. 10 to 15% reduction in fuel consumption is possible with this method. This method can be incorporated easily in large commercial vehicles. Similar attempts were made by Kawamura et al., [177] and many other researchers report useful extraction of exhaust energy. Kamo et al., [12] reported that the results obtained from a turbo-charged engine operated at constant BHP, showed very little change in SFC, though an increase in exhaust temperature was noted.

Shigeharu Kobori et al., [158] reported in his paper that the increased exhaust gas enthalpy could be utilized and additional work can be extracted. This conversion of enthalpy into additional work is one of the major objectives in the LHR Engine concept, could be made possible by a turbo compound system, thus improving the fuel economy of the LHR Engine system.

Toyamma et al., [56] carried out investigations on a turbo compound engine. Their results show that there is a 13.5 percent improvement at rated power. Further there is a 1.5 percent gain in thermal efficiency because of elimination of fan.

R.Kamo et al.,[161] elaborately conducted investigations on low heat rejection engines and suggested the type of high performance ceramics used in turbo compounding engines to withstand high operating temperatures and to reduce heat loss. He recovered the heat loss, which is carried by exhaust gases through compounding system. The exhaust gas enthalpy of diesel engine can be used in an auxiliary boiler for vapour generation to run a turbine, which is geared to the crankshaft. This concept makes use of the well-known rankin cycle system. This increases the total horsepower by 24% and full load indicated thermal efficiency increase from 37 to 46%. The combination of both turbo-compounding and organic rankin cycle system would be possible in LHR Engine by virtue of its high exhaust temperature. Such a combination gives an indicated thermal efficiency of over 50%.
2.11 TRIBOLOGY

Lubrication problem [114,118,213] is considered as the great barrier to LHR engines. As the top piston ring encounters high temperature, lubricating oil deteriorates to a greater extent in an insulated engine [185]. Oil becomes unstable due to surface and high gas temperatures. This may lead to emission problems also. The liner will wear out faster under these temperatures due to the loads transmitted through a fluid that has a much-decreased viscosity. Three types of synthetic oils are under development. They are polyesters, polyphenol ethers and poly perfluoro alkyl ethers.

Tests on partially insulated single cylinder, water cooled engine was carried out by Krishna Moorty et al., [112]. He varied the insulation levels by changing different pistons with different crown materials. Good results were obtained using densified plasma spray iron titanate for cylinder liner coating vs plasma sprayed molybdenum compound for piston ring.

Experimental study of the development of tribological surface coatings for military engine applications was carried out by Lloyd S. Kamo et al., [207]. They used treated porous iron oxide/titanium oxide (Fe$_2$O$_3$/TiO$_2$) and molybdenum (Mo) based composite thermal sprayed coatings with chemical binders to improve coating strength, integrity, and tribological properties. This process dramatically decreases open porosity to form an almost monolithic appearing coating at the surface. This densification process improves the plasma spray layers, mechanical properties, reduces the friction coefficient of the coating layer and improves coating wear resistance. Good results were obtained using densified plasma spray Iron titanate for cylinder liner coating vs plasma sprayed molybdenum compound for piston ring. They also attempt the methods of post treatment of thermal sprayed coatings as a means of various coatings.

Currently, there exist well known solid lubricant materials, based upon the low friction coefficients they provide include PTFE Teflon (Poly Tetra Flouro Ethylene), carbon graphite, boron nitride, Tantalum, Tungsten, Molybdenum disulphides or Diselenides, and so forth. Unfortunately, these materials are either not stable, have
limited life times, or can not survive at elevated temperatures as found in LHR Engine operating environments. For this reason, hybrid solid lubricant type materials have been under development in an effort to achieve basic survival at these predicted temperatures. It is important to understand and realizes the significance of hybrid coating because it utilizes existing proven low cost technology. Furthermore, it is simple, and shows potential for a wide range of materials, and promise for more rapid processing. The cross combining of slurry binders with thermal sprayed coatings is a good match as water soluble liquid binders penetrate open porosity in the thermal sprayed coating layer.

Gaydos et al., [143] used some solid lubricants for high temperature ring cylinder applications. Important conclusions of their findings are given below.

i) Three types of sintered materials they used had high wear rates
ii) Lower wear rates were observed with molybdenum alloy and with chromium oxide plasma coatings
iii) Lithium fluoride appeared to be a more effective solid lubricant than calcium fluoride
iv) Low friction values were observed at temperatures higher than 500°C

2.12 NUMERICAL STUDIES

The greater effort is focused to analyze the nature of performance and emission characteristics on engine when modeled with in-cylinder and ceramic barrier coatings [57, 98, 110, 126, 164]. Some report real or potential beneficial effects for in-cylinder ceramic coatings on engine performance and emissions. Further, it appears that thin coatings might be better than thick ones [37]. Others report that in-cylinder ceramic coatings have detrimental effects on fuel mixing and combustion and therefore make performance and emissions worse. It is not that any of these reports are necessarily wrong, but it is unlikely to get successful results by just applying the coating to a combustion chamber, which has been designed to work optimally without the coating. There is a need to carefully consider the effects that the coating has on the combustion process and potential design changes to take best advantage of the effects.
A full-fledged analytical method to describe the heat transfer process for a bowl in piston geometries was developed by Thomas Morel et al., [86]. They used convection, radiation heat transfer models, steady state heat conduction and with thermodynamic cycle models for the analysis. The analytical method was applied to an insulated diesel engine designs. And with the analytical method, the insulating materials affect on engine performance can easily be studied.

Christine H. Moore et al., [97] had carried out cycle simulations on a diesel engine and predicted the effect of barrier coatings on engine heat rejection. They claim that the benefit of ceramic insulation is enhanced on components where there was little variation in surface temperature across the component.

Woschni et al., [131] predicted the influence of soot deposits on combustion chamber walls. They claim that the conventionally cooled diesel engine is to a certain extent can be treated as adiabatic engine as the soot layer acts as a thermal barrier. However, the surface temperature increases, the flame burns near to the wall and therefore the insulating layer burns off.

The poor performance of ceramic engine components may be partly due to the brittle nature of the material and partly ignorance of its basic limitations and properties as reported by French [64]. His studies suggested the areas where ceramics are to be employed. Ceramic tappet followers would probably reduce engine friction in turn improves the fuel economy. Similar improvements may be obtained with ceramic pads on the running surfaces of the piston. A silicon carbide liner would be an alternative method of achieving the same effect, but the reliability of this material in a high stress environment is doubtful.

Researchers by names Ravindra Prasad et al., [117] investigated on direct injection diesel engine using analytical methods with the help of oxide based ceramic material provided with a coating of 2mm thickness on piston they found that there would be around 20% of heat loss reduction through the piston.

The effect of wall quench distance on wall heat transfer coefficient was studied by Mark Jennings et al., [151]. Their calculations of heat transfer during
combustion in a constant volume chamber revealed that, in spite of changes in quench distance, total heat transfer during the combustion period decreased with increasing wall temperature for quench distance in the range expected to occur in diesel engines. They predicted that the total heat transfer for the combustion period decreases with increasing the wall temperature regardless of changes in quench distance. Piston-induced compression heating of the near wall gas or flame quench distance reduction can cause heat transfer to increase with wall temperature. This prediction helps substantially for the development of ceramic insulated diesel engines.

2.13 SCOPE OF PRESENT WORK

Based on the previous work the following specific remarks are noted. From this the main point to infer is insulation increases, efficiency in terms of thermal means of compression ignition engine. The life to this research has been based on the reduction in noise, hydrocarbon as well as improvement in fuel consumption due to reduced pressure rate. By utilizing low cetane fuels, demand for imported petroleum products can be suppressed. Maximum heat loss occurs through piston and cylinder head. Hence the insulation of these components significantly contributes to the increased thermal efficiency and exhaust gas enthalpy. The analysis shows that only 9% improvement in brake thermal efficiency has shown so far. Therefore still there is a lot of scope to increase the thermal efficiency.

Many of the works reported in the literature concentrated on the experimental works but the theoretical works are very limited. The theoretical models are important because they are based on the mathematical analyses, which are standard. To overcome these failures a model should be developed with mathematical analysis by taking parameters related to study performance with various insulation levels.

In view of the growing prices of conventional petroleum fuels, the suitability of running LC engines with vegetable oils have also been shown with experimental work. Hence is the present work.

Therefore, a unique endeavor to analyze the properties with lubrication at higher temperatures with an objective to develop an efficient LC Engine provided
with efficiency is made. From the base oil supplied by refineries, special lubricants are developed.

To leverage maximum advantages from this research, various variants of insulation concentrations are tried out and the best one is chosen. These all variants are tried out with diesel to make analysis in performance criteria. It is planned to study the effects of various insulation levels and to identify the best method of insulation. Out of all the configurations tested, the performance of the LC-3 Engine having mullite as insulating material for cylinder head and valves with air gap liner and Brass crown Aluminium piston was the finest. Hence, such configuration is used for further investigations. Newly developed lubricants are blended with different additives and tested in the best LC-3 Engine configuration. An attempt is made on number of turbulent grooves on brass piston crown to study the performance of engine to increase the rate of turbulence. In the TG-03 engine, selected vegetable oils are tried with optimum number of grooves to study the performance.

Objectives of the research work:

- Conversion of enthalpy into additional work.
- Reducing specific fuel consumption, emission and noise.
- Eliminating cold start problem and enhancing the engine life.
- Unique endeavor to analyze the properties with lubrication at higher temperatures with an objective to develop an efficient LC (Limited Cooled) engine.
- To find the proper turbulent grooved piston crown to be used for better turbulence.
- Carrying multi fuel ability.

2.13.1 Insulation of The Engine Components

The priority to this research is stressed on insulation parameters related to how much insulation can be provided on the combustion chamber parts. Out of those combustion parts main emphasis is made on only certain portions, which includes piston, cylinder liner and valves. Parts of the combustion chamber surfaces, namely,
liner and piston crown were insulated. The cylinder liner was insulated by a thin sleeve of mild steel fixed around the cylinder liner providing a thin layer of air (2 mm) adjacent to the liner. A special effort has also been made to use the piston crown with air insulation as a heat regenerator. Design is focused on choosing a versatile piston crown with two millimeters air-gap and spreading it over the surface area of the piston. By providing piston insert with air-gap, the crown forms as a reservoir of heat and hence acts as a heat regenerator. By a suitable method the crown is attached to the piston body. Two types of pistons were designed and fabricated with the aim of utilizing its higher heat regenerative capacity. They are aluminium piston with aluminium crown and aluminium piston with brass crown. Tests were conducted on a 3.68 kW Kirloskar direct injection single cylinder 4-stroke, vertical, water-cooled diesel engine. Specifications of the engine are summarized in Appendix-I.

Tests were mainly designed to cover various operations of the engine particularly different modes and to name some among them were normal and insulation modes. All the experiment is carried over at fixed speed of 1500 rpm. Necessary measurements like exhaust and lubricating oil temperatures, fuel consumption etc. were made. Design and efficiency covers major portion in diesel engines and to get best out of them, the characteristics like pressure rate, peak pressure, ignition delay, exhaust temperature, brake thermal efficiency, heat loss to cooling water, lubricating oil temperature and volumetric efficiency were assessed for different modes of operation.

During experimentation, it is observed higher exhaust gas temperatures provided with various combinations of insulated components acts as medium for exhaust gases heat flow.

2.13.2 Special Lubricants and Additives

Common problem associated with LC engines is a lubrication oil failure. Due to high cylinder operating temperatures, the lubricating oil may crack at the top ring reversal point. Frictional losses would tend to go up because of lubricating oil failure. As a result, engine emissions may also go up. The liner will wear out faster as the top
ring temperature reaches $350^\circ C$ to $600^\circ C$. Therefore it is planned to study the problems due to the failure of lubricating oil. To overcome stumbling outcomes, design is tested with advanced lubricating oils and report on frictional losses and performance characteristics are made in LC Engines. These oils have shown improved performance with the addition of paratone, Teflon based additives.

### 2.13.3 Suitability of Vegetable oils In LC Engines

Based on the literature survey it can be inferred that wide range of vegetable oils were investigated in CI engines and the researches have reported the detailed analysis of the blends and pure vegetable oils in compression ignition engines in terms of performance characteristics. The research put forth two problems namely more viscosity and less volatility and they also noticed nozzle blocking, cold starting, high smoke, seizure of piston. All these problems are persisting even with use of esterified oils in engines. Though theoretical implementations are made practical implementations of any vegetable oil engine is not showcased. To develop an efficient vegetable oil engine much research is needed.

In addition, the effect of the higher heat generated in the combustion space due to the adiabatic condition and also due to higher calorific values, the suitability of various vegetable oils was also studied with varying quantities of diesel. The present investigations are planned carefully. For this purpose five different vegetable oils are selected. Experiments are carried out in TG-03 engine owing to the excessive hotness of an adiabatic engine. Comparison normal mode operation is chosen for making performance analysis. When a standard diesel engine is converted to an adiabatic diesel engine, the frictional power increases than the normal diesel engine. The increase in frictional power might be due to the breakdown of lubricating oil film between the liner and the piston due to the reduced viscosity of oil at the higher temperature and also due to the higher thermal expansion of aluminium piston compared to cast iron liner at elevated temperatures. Different methods have been tried out in this work to solve the above problems. The results of all these investigations are reported in detail in the following chapters.