CHAPTER 2

LITERATURE SURVEY

A detailed literature search was undertaken as a part of this research work to examine the relevant previous work relating to ignition improver blends to diesel fuel on combustion characteristics, engine performance and exhaust emissions.

2.1 LITERATURE ON COMBUSTION CALCULATIONS

Bertola and Boulouchos (2000) conducted an experiment in the single cylinder research engine with common rail fuel injection system fuelled with different oxygenated hydrocarbons as diesel fuel additives. They concluded that the butylal offers significant advantages over most other oxygenates in that its physical properties are very close to that of common diesel fuel. The results showed that butylal substantially lowers the exhaust gas opacity and the opacity reduction depends on the combustion process conditions and the injection parameters, mainly on the injection pressure. Butylal lowers the premix combustion rate. At constant injected fuel mass flow rate, the NO\textsubscript{x} emissions are not affected from the addition of butylal in diesel fuel. Depending on conditions, sometimes a higher BSEC at same NO\textsubscript{x} emissions is observed.

Kocis et al (2000) investigated the effects of addition of DMM and DMC to diesel fuel in an optically accessible direct injection diesel engine. The study was focused to determine whether the molecular structure of
oxygenated compound affects the production of soot. Soot levels, oxides of nitrogen, carbon dioxide and carbon monoxide concentrations in the engine exhaust were measured using gas analyzers. Oxygenates were blended with diesel to obtain 2% and 4% oxygen by mass. Heat release analysis using the blends showed that the variation of the heat release from diesel was significant, with an increase up to 1.7% in ignition delay and increase in the amount of premixed burn mixture. DMM was more effective than DMC at all blending levels in reducing soot. Reduction in NO\textsubscript{x} of 5 to 17 percent was also observed. No changes in CO levels were observed.

Ayam et al (2001) investigated the performance and emissions of a direct injection Diesel engine operated on 100% butane liquid petroleum gas. The LPG has a low cetane number, therefore DTBP and AHC were added to the LPG (100% butane) to enhance cetane number. Diesel engine operation over a wide range of the engine loads was possible with cetane improvers by changing the concentration of DTBP and AHC several different LPG blended fuels were obtained. In-cylinder visualization was also used in this research to check the combustion behavior. LPG and only AHC blended fuel showed NO\textsubscript{x} emission increased compared to Diesel fuel operation. Experimental result showed that the thermal efficiency of LPG powered Diesel engine was comparable to Diesel fuel operation. Exhaust emissions measurements showed that NO\textsubscript{x} and smoke could be considerably reduced with the blend of LPG, DTBP and AHC.

Hallgreen and Heywood (2001) conducted experiments in a single cylinder direct injection diesel engine to study the effects of oxygenated fuels on combustion and emissions. A matrix of oxygen containing fuels assessed the impact of weight percent oxygen content, oxygenate chemical structure, and oxygenate volatility on emissions. Several oxygenated chemicals were blended with an ultra-low sulfur diesel fuel and evaluated at an equivalent
energy release and combustion phasing. Additional experiments investigated the effectiveness of oxygenated fuels at a different engine load, a matched fuel/air equivalence ratio, and blended with a diesel fuel from the Fischer-Tropsch process. Interactions between emissions and critical engine operating parameters were also quantified.

Kubota et al (2002) studied the diesel engine using the heated fuels in order to activate the fuel before the injection. Two test fuels: The normal diesel fuel and cetane, which have different boiling points, were used. For both normal diesel fuel and cetane, crank angles at ignition and maximum pressure were delayed and the maximum combustion pressure was decreased as the fuel temperature had risen. In case of large and middle mass flow rate of fuel injection, the brake thermal efficiency and brake mean effective pressure were decreased when the fuel temperature was higher than 570 K. However, in the case of small mass flow rate of fuel injection, the brake thermal efficiency was almost independent of fuel temperature. HC and CO concentrations in the exhaust gas emission showed constant values regardless of fuel temperature. However, NO_\textsubscript{x} concentration had gradually decreased as the fuel temperature had risen.

Huang et al (2003) investigated the combustion characteristics and heat release of a direct injection compression ignition engine fuelled with diesel-dimethyl carbonate blends. The study showed that the premixed combustion is prolonged and the duration of the diffusive combustion is shortened with increase in the dimethyl carbonate addition. For a specific brake mean effective pressure, the maximum cylinder gas pressure, the maximum rate of pressure rise and the maximum rate of heat release increase with increase in the DMC addition at medium and high loads, while they exhibit less variation with the DMC addition at small load. Meanwhile, the maximum gas temperature decreased with increase in the DMC addition. The
ignition delay increased while the rapid combustion duration and the total combustion duration showed less variation with the DMC addition. The brake specific fuel consumption increased while the diesel equivalent bsfc decreased and the thermal efficiency increased with increase in the DMC addition. The CO and smoke decreased with increase in the DMC addition, and NO$_x$ does not increase with increase in DMC.

Upatnieks and Muller (2004) conducted an experiment in an optically accessible direct injection diesel engine to study the relationship between combustion processes and engine-out soot using an oxygenated fuel is di-ethylene glycol diethyl ether. The high oxygen content of DGE enabled operation without soot emissions at higher loads than with hydrocarbon fuel. The high cetane number of DGE enabled operation at charge-gas temperatures below those required for current diesel fuels, which may be advantageous for reducing NO$_x$ emissions. The results demonstrated that near-zero engine-out soot emissions could be achieved with the oxygenated fuel, DGE at high engine loads, even under conditions that yield significant in-cylinder soot formation.

Zannis et al (2004) conducted an experiment to determine the effect of oxygen content and oxygenate type on DI diesel engine performance and emissions. The fuels were prepared by blending a biodiesel compound (RME), Diglyme and Butyl-Diglyme with a low sulfur diesel fuel in various proportions. The measurements were carried out at various operating conditions. The experimental findings revealed an increase of in-cylinder pressure due to the increase of cetane number. In addition, a slight increase of bsfc was observed due to the small decrease of fuel heating value with the increase of the oxygen content. A decrease of ignition delay was observed with increasing oxygen content. A considerable reduction of soot, carbon monoxide and unburned hydrocarbon emissions was witnessed while, nitric
monoxide emissions were increased when the oxygen content was increased from 3% to 9%. Similar effects were observed when replacing the rapeseed methyl ester with a mixture of diglyme and butyl-diglyme and the oxygen percentage remained unaltered. As revealed, a reduction of tailpipe soot without overall considerable penalties in bsfc and NO\textsubscript{x} emissions could be achieved in modern DI diesel engines using oxygenated additives at elevated percentages.

Hilden et al (2005) studied the exhaust emission of prototype ultra-low sulfur and oxygenated diesel fuels and determined the emissions performance of a matrix of low sulfur diesel fuels and oxygenate. A 1.3-L DI diesel engine was used in steady state testing. As expected, exhaust gas recirculation was the most effective technique for NO\textsubscript{x} reduction. Conventional sulfur removal process reduced particulate emissions substantially and these particulate emissions could be converted into NO\textsubscript{x} reductions by using higher levels of EGR. On a simulated FDP, this oxygenated fuel simultaneously decreased NO\textsubscript{x} emission by 30% and total particulate emission by 50% compared to a baseline fuel.

Ying et al (2005) studied the combustion and emission characteristics of the DME engine. Smokeless emission could be realized under all operating conditions. It indicated that NO\textsubscript{x} emissions could reduce about 40 percent with less penalty on the brake thermal efficiency of the DME engine. Very promising results with respect to emission, efficiency, durability and combustion noise could be achieved in a DME engine.

Lu et al (2005) investigated the effect of three oxygenated fuels namely ethanol, DMC and DMM on spray characteristics and diesel exhaust emissions. For spray analysis DMM was blended to diesel fuel at blending ratios of 25% and 50% by volume, while for DMC the ratios were 10%, 20% and 30% by volume. The mean axial velocities of DMM-diesel hybrid fuels
were higher when compared to diesel fuel. The lower SMD and higher axial mean velocity with DMM-diesel hybrid fuels were due to the inherent properties of lower kinematic viscosity and surface tension of neat DMM. Concerning exhaust emissions it was reported that the smoke and NOx emissions were reduced markedly with DMC-diesel hybrid fuels. The reductions were higher with the higher percentages of DMC to diesel fuel. The reduction of NOx emissions was due to the shorter combustion duration, while presence of oxygen in hybrid fuels was additional reason for reduction in smoke emissions.

Horn et al (2007) conducted an experiment in a modern direct injection diesel engine fuelled with standard diesel fuel, rapeseed methyl ester and a mixture of 85% standard diesel fuel. Emission analysis results were in accordance with widely known correlations: Increasing exhaust gas recirculation rates lowered NO\textsubscript{x} emissions. Exhaust gas analysis indicated further a strong increase of carbon monoxide, particulate matter and unburned hydrocarbon emissions at high EGR levels. This resulted in lower combustion efficiency. Injection duration was longer for the RME case due to lower fuel energy content. Due to higher fuel viscosity, SMD is increased for RME. RME combustion characteristics can be considered as poor at low load conditions. Premixed heat release was unsteady due to concurrent fuel spray evaporation and premixed combustion.

Yanfeng et al (2007) conducted experiments with a new kind of oxygenated fuel, 2-methoxyethyl acetate of oxygen content of 40.7 wt%. Authors concluded that the cylinder pressure, the rate of pressure rise and the ignition delay change little when the engine run on diesel- 2-Methoxy ethyl acetate blends. The smoke density could be reduced by more than 50% respectively. The emissions of CO and HC also decreased with an increase in
MEA in the blends. The blends have almost no effects on the NOx emissions and the thermal efficiency of the engine increases by 2%.

Iranmanesh et al (2008) conducted an experiment in a single cylinder direct injection diesel engine fueled with neat diesel fuel and addition of 2%, 5% and 20% of diethyl ether to diesel fuel to find out the optimal blend on the basis of performance and emission characteristics. The tests were conducted to investigate the potential of diethyl ether as a supplementary oxygenated fuel in a diesel engine. The heating value of the blends reduces with the addition of diethyl ether. Some tests were repeated up to six times to carry out statistical analysis. The uncertainty associated with measurements was also measured. The results derived at 95% confidence level.

Ren et al (2008) investigated the combustion and emission characteristics of a direct injection diesel engine fueled with diesel-diethyl adipate blends. The results showed that the ignition delay and the amount of heat release in the main combustion duration increase. The diffusive combustion duration and total combustion duration decreased, while the amount of heat release in the diffusive combustion increased with the increase of the oxygen mass fraction in the blends. The diesel equivalent brake specific fuel consumption decreased and the thermal efficiency increased with the increase of the oxygen mass fraction in the blends. The study shows that utilization of diesel-diethyl blends combining with postponing the fuel delivery advance angle can simultaneously decreased both smoke and NOx emissions.

Ren et al (2008) analyzed the combustion characteristics of a compression ignition engine fuelled with diesel-ethanol blends with and without a cetane number improver. They observed that the addition of a cetane number improver was beneficial to the decrease in the ignition delay,
the cylinder peak pressure, the maximum rate of pressure rise and the combustion noise when operating on diesel-ethanol blends.

Wang et al (2008) investigated the engine combustion characteristics of a diesel engine operated on pure diesel and on dual fuel (methanol-diesel). The combustion heat release rate changed from dual peak mode to single peak mode. The centre of the heat release rate curve moved near to TDC under high load conditions, which indicated a better fuel economy. The high methanol mass fraction will realize a simultaneous reduction in both smoke and NO\textsubscript{x} under all operating conditions. Meanwhile, the NO\textsubscript{x} smoke trade-off curve disappeared in combustion of the dual fuel, but CO and HC increase.

Zhu et al (2009) conducted an experiment in a diesel engine to study the combustion, performance and emission of a direct-injection diesel engine fueled with the blends of dimethoxymethane. Results showed that, without changing the fuel supply system and the combustion system of a diesel engine, when using blended fuel with increased DMM percentage, BSFC is higher for a smaller lower heating value of DMM, while thermal efficiency increased a little. For exhaust emission, smoke and CO emission decrease and NO\textsubscript{x} remained almost unchanged, while hydrocarbons increased. For combustion characteristics, peak pressure and pressure rise become slightly higher, ignition delay was longer, which meant more and faster premixed combustion, and the diffusion combustion was faster because of oxygenated fuel. They observed that the diesel engine fueled with 30% DMM blending fuel could obtain satisfactory fuel efficiency and emission level.

Agarwal and Dhar (2010) conducted an experimental analysis for finding out the combustion characteristics, performance and emission of
RBO20 and RBOME20 and mineral diesel. Combustion of RBOME20 was found to be more efficient than mineral diesel but thermal efficiency of RBO20 was inferior to mineral diesel. HC and CO emissions for both RBO20 and RBOME20 were lower than mineral diesel. NOx emissions were comparable for all the three fuels at all load and speed conditions. BSFC for RBO20 was higher than mineral diesel but BSFC for RBOME20 was quite close to mineral diesel. Smoke opacity for both RBO20 and RBOME20 was better than mineral diesel. The experimental investigations revealed that the overall combustion characteristics were quite similar for RBOME20, RBO20, and mineral diesel. For RBO20 and RBOME20, ignition delay was lower compared to mineral diesel. The ignition delay was shorter for RBO20 and RBOME20 compared with mineral diesel; however, the burning rate was relatively slower for RBO20. This detailed experimental investigation suggested that 20% blend of biodiesel as well as 20% rice-bran oil could substitute mineral diesel without any significant modification in medium duty transportation DI diesel engine.

The text written by Pundir (2010) focused primarily on engine combustion processes and the way these influence formation and emission of pollutants. To develop deeper understanding of combustion and engine emission formation potential, the laser based combustion diagnostic techniques being employed for engine combustion research were briefly reviewed in his text book.

Sundarraj et al (2010) investigated a stable ethanol-diesel blended fuel with 10% 1,4 dioxane additive to generate the combustion, performance and emissions data for evaluation of different ethanol content on a single cylinder diesel engine with and without thermal barrier coating. Drastic reduction in smoke density was found with the blends compared to neat diesel
fuel and reduction was still better for coated engine. NO\textsubscript{x} emissions were found to be high for coated engines than the normal engine for the blends. The oxygen enriched fuel increased the peak pressure and rate of pressure rise with increase in ethanol ratio and is still superior for coated engine. Heat release pattern showed higher premixed combustion rate with the blends. Longer ignition delay and shorter combustion duration were found with all blends than neat diesel fuel.

Wu et al (2012) investigated the spray and combustion characteristics of soybean biodiesel in a constant-volume combustion chamber diesel engine. The in-cylinder pressure and heat release rate were measured and the liquid penetration, natural flame emission, and soot formation characteristics were studied via new optical diagnostics. The results showed that the peak pressure decreased with increasing ambient gas temperature and decreasing oxygen concentration for diesel, except that at the oxygen concentration of 15%. For pure soybean biodiesel, a higher peak pressure was obtained at the oxygen concentration of 15% as opposed to that of 18%. A lower heat release rate found for pure biodiesel at the oxygen concentrations of 21% and 18% compared to diesel fuel, while a higher value was shown at the oxygen concentration of 15%. The total soot mass increased with decreasing oxygen concentration and the soot formation duration was longer at a lower oxygen concentration.

From the above literature study, it is observed that only limited results of combustion process of few oxygenates are available and hence in the present work the combustion characteristics of a diesel engine running on three ignition improvers are evaluated to analyze the behavior of the diesel engine.
2.2 LITERATURE ON PERFORMANCE AND EMISSION PARAMETERS

Miyamoto et al (1998) conducted experiments in a single cylinder four stroke direct injection diesel engine with four diesel-oxygenate blends and reported that, the noise reduction was obtained for the oxygenates with higher ignitability (Diglyme and Di-n-butyl ether). They also concluded that there was a complete smokeless operation with simultaneous improvements in NO\textsubscript{x} and total hydrocarbon reduction. Noise reduction and increased thermal efficiency were realized with Diglyme and it was mainly due to increase in the degree of constant volume combustion and the larger increase in number of oxygen molecules by the fuel injection and the combustion efficiency especially at higher loads. NO\textsubscript{x} reduction with these oxygenates was caused mainly by the milder first stage combustion (premixed combustion) and the decrease in mean gas temperature (inherent lower adiabatic flame temperature). Reduction in THC emission and odour intensity under starting condition were much lower with neat Diglyme than with ordinary diesel.

Beatrice et al (1999) tested diglyme blends of 10%, 20% and 30% by volume in a finished summer grade low sulfur diesel fuel in an intercooled Fiat M724 1.9L JTD turbo diesel equipped with an exhaust oxidation catalyst. Exhaust emissions were measured before and after the oxidation catalyst. Smoke number was measured with an AVL smoke meter. The Diglyme blends gave significant reductions in all the emissions. It was noted that EURO III emissions standard could be achieved with the diglyme blends containing 20% and 30% by volume.

Schwab et al (1999) studied the effects of cetane improvers 2-ethylhexyl nitrate (EHN) and di-tertiary-butyl peroxide on exhaust emissions from a 1993 Detroit diesel series 60 heavy duty diesel engine. Both the additives reduce carbon monoxide, oxides of nitrogen and particulate
matter emissions. Emissions reductions were proportional to the cetane number increase induced by the additives.

Litzinger and Stoner (2000) performed a study on diethyl maleate, dibutyl maleate and diglyme in a 4 cylinder 1.9L direct injected Volkswagen turbo diesel. Oxygenates were added to diesel fuel in amounts to achieve 2 wt% oxygen in the blended test fuels. They determined that all the oxygenated fuel blends yielded less soot than the base fuel. The composite NO\textsubscript{x} emissions from the DEM and DBM blends appeared to be slightly higher than that of the diglyme blend. They hypothesize that oxygenates tend to form carbon monoxide prematurely in the reaction zone. They proposed that carbon monoxide react with free radicals such as H, CH\textsubscript{3} and HO\textsubscript{2} to interfere with the precursor reactions that lead to soot formation.

Sirman et al (2000) conducted experiments for different alternative diesel fuels to measure the exhaust emissions in a 2.2L DI diesel engine. Triplicate 13-mode, steady-state test sequences were performed for each fuel, as well as an ASTM D975 low sulfur No. 2 diesel (2DLS) control fuel, which served as the baseline. The alternative fuels include California Reference fuel, a low-sulfur diesel, a Fischer-Tropsch diesel, and three blends: 20 percent Fischer-Tropsch/80 percent low-sulfur diesel; 20 percent biodiesel/80 percent low-sulfur diesel; and 15 percent DMM/85 percent low-sulfur diesel. All six alternative fuel formulations demonstrated benefits by reducing particulate matter (PM) emissions without significant increases in oxides of nitrogen (NO\textsubscript{x}).

Ahmed (2001) tested ethanol blended diesel (e-diesel) in a heavy-duty (HD) and light-duty (LD) compression ignition (CI) engines used in buses, trucks, off-road equipment, and passenger cars. Laboratory and field tests have demonstrated over 41% reduction in PM, 27% reduction in CO, and
5% reduction in NO\textsubscript{x} from a HD diesel engine. Significantly higher emissions reductions are observed from smaller 1.9-L VW TDI engines.

Ball et al (2005) suggested that the oxygenated diesel fuel additives (DBM and TPGME) can be used to lower engine out NO\textsubscript{x} emissions without risking any increase in tailpipe emissions of compounds of toxicological concern. The emissions of toxicologically relevant compounds using two oxygenated fuels were equivalent to or less than emissions from a recognized clean fuel.

Guo et al (2005) conducted experiments with a new oxygenated fuel, methyl 2-ethoxyethyl carbonate (MEEC) by introducing an ether group to DMC molecule. MEEC was blended with diesel fuel from 15% to 25% by volume. For a 25% MEEC blend with full load condition, carbon monoxide was lessened by 29.2 to 40.5% and smoke by 0.3 to 0.5 BSU. NO\textsubscript{x} emissions were also lessened by 15.9% when the 15% MEEC was blended with diesel fuel. Output power of the engine was not noticeably changed with MEEC blends; however 2.5% to 5.5% fuel consumption was increased with 20% MECC. BSEC was improved by 10% when the engine was fuelled with 20% MECC.

Nurun Nabi and Wahid Chowdhury (2006) investigated the diesel combustion and exhaust emissions with additives addition to conventional diesel fuel in a four stroke naturally aspirated direct injection diesel engine. The additives include DGM and liquid cerium. The results show that with the addition of DGM to diesel fuel, BSEC and all diesel emissions are significantly reduced. The volumetric blending ratios of additives to diesel fuel are 25%, 50%, 75% and 100%. All emissions including smoke emissions decrease with the increase in oxygen content in the fuel. The reason for improvement in BSEC with the addition of additives to base diesel fuel is the
improvement of degree of constant volume combustion and the reduction of the cooling loss. Engine noise and odor concentrations are remarkably reduced with diesel-additive blends. Significant improvement in BSEC and exhaust emissions is not only found at medium load condition but also at high load condition.

Boot and Peter Frijters (2007) studied different blends of low-sulfur type diesel fuel with different types of oxygenate. Oxygen mass fraction of the blends varied between 0 and 15%. Tests were performed on a modern multi-cylinder engine equipped with cooled EGR for enabling NOx levels between 2.0 and 3.5 g/kWh on EN-590 diesel fuel. Finally, for some blends, combustion progress and soot illumination was registered when tested on a single cylinder research engine with optical access. The results confirm the importance of oxygen mass fraction of the fuel blend, but at the same time illustrate the effect of chemical structure. In combination with conventional CI combustion with extended ignition delay, such fuel blends will produce extremely low emission levels without the necessity of very high amounts of EGR, suggesting a possible alternative pathway towards clean diesel combustion.

Chen et al (2008) investigated the effect of fuel oxygen on diesel emissions and performance. Authors blended ethanol and biodiesel to diesel fuel. The blending percentages of ethanol to diesel fuel were 10%, 20% and 30%, while the biodiesel percentages were 5% and 10%. Engine torque was reduced and brake specific fuel consumption was increased with blended fuels. NOx emissions were slightly increased or the same as baseline diesel fuel. THC emissions with oxygenated blends were reduced under most operating conditions. CO emissions were increased at low to medium load conditions, but reduced at high load condition.
Kozak and Merkisz (2008) presented the test results of the influence of maleate oxygenated additives to diesel fuel on exhaust emissions. Following the previous tests of glycol ethers, the authors decided to use maleates as oxygenates to obtain greater changes in PM/NO\(_x\) trade-off than the changes obtained as a result of the use of glycol ethers. It was found that in the NEDC maleates at the same concentration as in the case of glycol ethers ensure more favorable changes of PM/NO\(_x\) trade-off and, as a matter of fact, caused greater reduction in PM emissions without the growth of NO\(_x\) emissions, however, at the cost of CO and HC emissions. The tests performed in the FTP-75 confirmed a significantly weaker influence of maleates, both positive (PM) and negative (CO, HC) than in the NEDC. They did not find in both cycles any influence of maleates at the tested concentration upon fuel consumption and CO\(_2\) emissions.

Kapilan et al (2008) conducted experiments with 5 % DEE and found lower carbon monoxide, total hydrocarbon and smoke emissions while a slight improvement in thermal efficiency was observed.

Senthil et al (2011) investigated the performance and emission characteristics of a diesel engine fuelled with 2-Ethoxy ethyl acetate blends. They observed that HC and CO emissions were reduced and brake thermal efficiency had improved. NO\(_x\) emission had increased due to increased peak combustion temperature. Good reduction in smoke was realized with the addition of blends.

From the above literature study, it is observed that only few oxygen containing compounds have suitable properties to provide alternatives to pure diesel fuel in a diesel engine to improve the engine performance and reduce the exhaust emissions.
2.3 LITERATURE ON SIMULATION MODELING

Annand (1963) gives a critical examination of much of the earlier published work, using dimensional analysis to indicate the fundamental weakness in various equations put forward for gas phase heat transfer calculations in reciprocating internal combustion engines and proposing a more satisfactory alternative. The Annand expressions were largely based on turbulent convection considerations. The Annand formulae have constants which may be adjusted to give overall heat transfer values and this can be useful if experience or available information is adequate. The concepts from this literature are used in this work for the calculation of convective and radiative heat transfer.

Benson and Whitehouse (1979) have written a text entitled internal combustion engines. They have presented FORTRAN listings of two programs for simple cycle calculations – one for a compression ignition engine cycle and the other for a spark ignition engine cycle. Methods were also outlined for more complex cycle calculations. In cycle calculations and studies of combustion, heat transfer and gas movement the first law of thermodynamics was frequently used in both closed and open systems. The combustion modeling and the associated gas mixture properties under dynamic conditions have been taken from this text book for the present modeling and analysis.

Watson et al (1986) developed procedures to measure and record cylinder pressure on an individual crank angle basis and obtain an average cylinder pressure trace using an Apple II Plus personal computer. These procedures as well as methods for checking the quality of cylinder pressure data were described. A simplified heat release analysis technique for an approximate first look at the data quality was presented. Comparisons were made between the results of this analysis, the Krieger-Borman heat release
analysis which uses complete chemical equilibrium. The comparison was made to show the suitability of the simplified analysis in judging the quality of the pressure data.

Heywood (1989) has written a text entitled internal combustion engine fundamentals. The main emphasis was on the thermodynamics, combustion physics and chemistry, fluid flow, heat transfer, friction and lubrication processes relevant to IC engine design, performance, efficiency emissions and fuel requirements. The book also contains material on modeling the thermodynamics and fluid dynamics of real engine processes.

Bazari (1992) formulated and developed a model for the prediction of combustion and exhaust emissions of direct injection diesel engines. Diesel engine exhaust emissions including nitrogen oxides, carbon monoxide, unburnt hydrocarbons, soot and particulates had been predicted using a quasi-dimensional multi-zone combustion and emission model. The model was sensitive to fuel injection, turbo charging and engine operating conditions, exhaust gas recirculation, intake swirl and predicted the known trends correctly. The operational range of the model is wide and the computational run time is short, thus making the model most suitable for use with thermodynamically based cycle simulations.

Desantes et al (1996) used a mathematical model to evaluate the effect of diesel engine operating conditions on nitric oxide formation and emissions. The effect of the engine operating conditions was simulated by means of schematical variations of local temperature and fuel–air ratio of the mixture. A computational parametric study was carried out by varying each of the local mixture parameters and characteristic times, either separately or in combinations. The trends obtained show a qualitative agreement with those obtained by other authors from experimental tests on different diesel engines. The analysis of these trends contributes to a better understanding of the
sources of NO diesel emissions and could provide guidelines for cleaner diesel engine design.

Brunt et al (1998) addressed the issues associated with the accurate determination of gross heat release energy. The magnitude of analysis and measurement errors had been quantified using simulated and measured gasoline engine pressure data. This revealed that calculated gross heat release is very sensitive to the assumed ratio of specific heats, charge to wall heat transfer and pressure data errors. Two improved heat release models have been proposed and further investigated and shown to generally give good performance for specific applications although further work was required to fully quantify their accuracy.

Lee (1999) developed a simulation model for a four-stroke direct injection diesel engine. The combustion modeling was based on the assumption that the combustion process was taken to be only a heat addition process and in-cylinder conditions were spatially uniform. The well-known Wiebe’s combustion function and the White house-Way’s heat release model were studied and successfully employed. A comparison between the predicted data on cylinder pressure and heat release and measured data showed the model validation.

Ganesan (2000) in a text entitled “computer simulation of compression ignition processes”, has presented the theory and computer programs necessary for simulating the performance of a conventional hydrocarbon fuelled compression ignition engine. The model described the process occurring within the working fluid of a compression ignition engine and provides an indication of the limits and trends of the performance as a function of some system variables.
Hountalas and Papagiannakis (2000) developed a new model to simulate the operation of dual-fuel diesel engines for the prediction of performance and pollutant emissions. Combustion was initiated by the ignition of the liquid fuel, while the burning rate of gaseous fuel was controlled by its entrainment rate into the burning zone. To validate the model an extended experimental investigation had been conducted on a high speed DI single cylinder test engine. From the analysis of computational data it was revealed that dual-fuel operation results to higher combustion pressures. Concerning engine efficiency it was revealed in general that the replacement of liquid fuel with gaseous results to an improvement of engine efficiency. As far as pollutant emissions were concerned the use of gaseous fuel has a negative effect on NO emissions and a positive on soot. Comparing the calculated and measured values under normal diesel operation a good coincidence was observed for both performance and pollutant emissions.

Curran et al (2001) studied the influence of oxygenates addition using a detailed chemical kinetic model for ignition and soot precursor production and reported that there was a reduction of the production of soot precursors. N-heptane was used as a representative diesel fuel, methanol, ethanol, dimethyl ether, dimethoxymethane and methyl butonate were used as oxygenate fuel additives. The authors have also concluded that, when the overall oxygen content in the fuel blend reached about 30-40 percent by mass, the production of soot precursors fell effectively to zero.

Gao and Schreiber (2001) developed a phenomenological model for analyzing the combustion process in a CIDI engine. The model is used to simulate the combustion process based on empirical correlations to predict the process of fuel jet break-up and evaporation, air entrainment, heat transfer, heat release, soot production and destruction and NO\textsubscript{x} formation. The results from the current model are validated against results taken from experiments.
It is concluded that updating the empirical models in the light of the recent experimental findings would make the model more realistic and could extend its general predictive capabilities at a small increased cost in CPU time.

Tree and Coolers (2001) performed an experiment to measure the NO\textsubscript{x} and particulate emissions of diethyl ether in comparison to diesel fuel. The simple model used to produce the heat release weighted adiabatic flame temperature was successful at predicting all of the measured NO\textsubscript{x} values approximately \( \pm 30\% \). The results indicate that the same kinetic and transport mechanisms were involved in the NO\textsubscript{x} formation for both the fuels and that the flame temperature is the overriding variable of importance.

Yeh et al (2001) investigated the impact of fourteen oxygenates on diesel exhaust emissions, especially particulate matter and NO\textsubscript{x} emission, in a single cylinder heavy duty Caterpillar engine under high and low load conditions. Complementary testing was performed in three vehicles under identical conditions. Reduction in larger PM was found to be more at high load than at low load. Large differences were found between oxygenates at both high and low load conditions and some oxygenates were found to be much more effective than others in reducing particulate matter. In this study, the authors have concluded that the most effective oxygenates on equal oxygen content basis for the particulate reduction were the C\textsubscript{9} – C\textsubscript{12} alcohols.

McCartan et al (2002) employed an accurate engine performance simulation software package to model a benchmark automotive 1.9 litre Turbocharged direct injection diesel engine. The accuracy of the model was scrutinized against actual test results from the engine. This validation included comparisons of engine performance characteristics and also instantaneous gas dynamic and thermodynamic behavior in the engine.
cylinders, turbocharger and ducting. It was seen that there was an excellent agreement in all of these areas.

Charles et al (2003) studied the effects of oxygenates on soot processes in DI Diesel Engines. The oxygenates that were studied are di-butyl maleate (DBM) and tri-propylene glycol methyl ether (TPGME). The experiments were conducted in a constant-volume combustion vessel and a single-cylinder DI diesel engine, each with optical access. Investigation showed that fuels containing the TPGME oxygenate were more effective at reducing soot than those containing the DBM oxygenate. Detailed chemical-kinetic analysis showed that over 30% of the oxygen in DBM was unavailable for eliminating soot precursors. Fuel oxygenation and enhanced charge-gas entrainment were investigated as in cylinder soot reduction strategies in which fuel oxygenation to a given mixture with TPGME or DBM was found to be more effective at reducing soot than enhancing the entrainment of oxygen from the charge gases.

Tamilporai et al (2003) carried out a comprehensive analysis of combustion, heat release, heat transfer and performance in a low heat rejection diesel engine. A model for the prediction of combustion and heat release had been formulated and developed, based on the two zone combustion modeling concept. The combustion model takes into consideration on a zonal basis, the details of spray formation under non-swirl and swirling conditions, spray wall interaction, heat transfer, preparation and reaction rates. The combustion parameters were calculated based on the first law of thermodynamics using energy and enthalpy coefficients. To validate the predicted results, experimental investigations were carried out under identical conditions on a six cylinder direct injection automotive diesel engine under conventional and insulated conditions. The predictions by the computer model, the experimental results and the capability of the model in predicting
engine heat release, cylinder peak pressure, temperature and heat transfer details on zonal and cumulative basis were demonstrated, and the correlation were highly satisfactory.

Kitamura (2003) provided new insights on the mechanism of the smokeless diesel combustion with oxygenated fuels, based on a combination of soot kinetic modeling and optical diagnostics. The chemical effects of fuel compositions, neat oxygenated fuels and oxygenate additives were numerically examined using a detailed soot kinetic model. To better understand the physical factors affecting soot formation in oxygenated fuel sprays, the effects of injection pressure and ambient gas temperature on the flame lift-off length and relative soot concentration in oxygenated fuel jets were experimentally investigated. The computational results showed that the leaner mixture side of soot formation peninsula on the $T$ - $T$ map, rather than the lower temperature one, should be utilized to suppress the formation of PAHs and ultra-fine particles together with the large reduction in particulate mass. The oxygen entrainment estimates coupled with relative soot concentration measurements show a remarkable difference in the average equivalence ratio at the lift-off location leading to no significant soot level between diesel fuel and highly oxygenated fuel.

Ghojel and Honnery (2005) developed a model based on a model designed for both SI and CI engines burning liquid and gaseous hydrocarbon fuels. The model can be used for diesel engines burning water/diesel emulsions and allows for the effect of the presence of inert water in the combustion products on the ratio of specific heats and heating value of the fuel. The output from the model included the apparent heat release, fraction of fuel burned, fuel burning rate, heat losses, indicated parameters and average gas temperature. The model is a suitable tool for quick evaluation and interpretation of the performance of different engines with different
configurations or fuels and for the same engine under variable operating conditions. They have concluded that the model developed is also useful when used to monitor real-time engine heat release characteristics for diagnostic purposes.

Ramadhas et al (2006) developed a theoretical model to analyze the performance characteristics of the compression ignition engine fueled by biodiesel and its blends. In the study biodiesel was produced using unrefined rubber seed oil. A two-step transesterification process was developed for the production of methyl-esters of rubber seed oil. The properties of this biodiesel were closely matching with those of diesel fuel. The performance tests were carried out on a C.I. engine using biodiesel and its blends with diesel as fuel. The effects of relative air-fuel ratio and compression ratio on the engine performance for different fuels were also analyzed using this model. The comparisons of theoretical and experimental results are presented.

Ericson et al (2006) focused the calculation of engine-out NO\textsubscript{x} and engine parameters such as cylinder pressure, temperature and gas flows. A quasi steady gas exchange model is combined with a two zone combustion model. The combustion model uses fuel flow parameters to generate heat release data and calculates the corresponding pressure trace. The temperature and equilibrium concentrations in the zones were calculated by the simplified combustion model and the corresponding NO\textsubscript{x} concentration was given by the original Zeldovich mechanism. The result is a low complexity complete engine model which requires far less computational effort than a CFD model.

Szybist et al (2007) investigated the effect of biodiesel content on homogenous charge compression ignition engine both experimentally and by computer simulation. Experiments were performed using the blends of soy biodiesel in ultra low sulfur diesel, with concentrations ranging from 0 to 50% by volume and equivalence ratios from 0.38 to 0.48. Data from the engine
tests included combustion analysis and exhaust composition analysis with standard gaseous emissions equipment. The zero-dimensional model did a reasonably good job of predicting the combustion event, correctly predicting intake temperature effects on the phasing of both low temperature heat release and the main combustion event.

Hosseini et al (2008) developed a quasi-dimensional model for the compression, combustion and expansion processes in a spark ignition engine. The model was validated against data from a Ricardo E6 single cylinder research engine. The accuracy of the model was first tested with comparison of simulated and experimental data. The model accurately simulated the trends noted experimentally when these parameters varied. After model adjustment for matching the simulated pressure data with experimental data the following results are drawn,

i) Heat transfer model of Annand was found had better influence on matching experimental data than models of Woshni and Eichelberg.

ii) Cylinder wall pressure ($T_w$) was found around 400 °K.

iii) Inlet gas pressure ($P_0$) was found around 95% of atmospheric pressure.

iv) It was found the inlet gas temperature ($T_0$) around 300°K. Combustion duration (CDU) 45 to 50 degrees.

Kim et al (2008) investigated the combustion and emission characteristics of a high-speed direct-injection diesel engine with a common-rail injection system under various operating conditions. In order to analyze the combustion characteristics, several models were used in this study. The prediction of exhaust emissions was conducted using $NO_x$ formation with an extended Zeldovich mechanism and Hiroyasu soot formation with the
Nagle—Strickland-Constable oxidation model respectively. Experimental combustion and emission characteristics were compared with calculated results under various operating conditions, such as injection timing, injection pressure, fuel mass, and engine speed. The calculated results show similar patterns to the experimental results in the cylinder pressure and the rate of heat release. In the emissions characteristics, NO\textsubscript{x} emission decreased as injection timing was retarded and the NO\textsubscript{x} and soot amounts increased with the increase in the injected fuel mass. The calculated soot trends for various injection timings showed different patterns from the experimental trends as the injection timing were retarded.

Masood and Ishrat (2008) developed a two zone code gave reasonably good results which were in good agreement with the experimental values. For all equivalence ratios except for 1.2 and 1.4, the mole fraction of CO\textsubscript{2} increases between 20% and 40% hydrogen substitution and then decreases with further increase in hydrogen percentage. As the value of equivalence ratio increases, the mole fraction of NO\textsubscript{x} decreases for both temperatures of 1500 K and 2000 K. As the hydrogen percentage increases the mole fraction of CO increases, and for more than 1 equivalence ratio, the increase was sharp. The mole fraction of H\textsubscript{2}O increases with hydrogen substitution; this decreased the peak combustion temperatures.

Yoshikawa and Reitz (2008) developed a new nitric oxide (NO\textsubscript{x}) reaction mechanism by adding species, including hydrogen cyanide (HCN) and the CH radical to a reduced chemistry diesel combustion model. The new NO\textsubscript{x} mechanism was implemented into the KIVA/ERC-CHEMKIN code and was found to be able to predict the experimentally observed trend that the amount of engine-out NO\textsubscript{x} decreased as engine load increased, which is not reproduced by the current reduced NO\textsubscript{x} mechanism. The additional species and reactions were also found to influence the prediction of engine-out soot emissions. It is concluded that the new NO\textsubscript{x} reaction mechanism was able to
predict NO\textsubscript{x} emissions more accurately for fuel-rich, high-load diesel engine operating conditions.

Ganapathy et al (2009) developed a two zone thermodynamic model to study the effects of operating parameters on the performance of the diesel engine fuelled with jatropha biodiesel. The results showed that, any change in the rated injection timing decreased the brake thermal and mechanical efficiencies, while retarded timing decreased the peak temperature. The increase in compression ratio increased all the above parameters, while increase in RAF decreased BMEP and peak temperature with both the fuels. The in-cylinder pressure histories computed by the model for the diesel and jatropha biodiesel fueled diesel engine were closer to experimental pressure data than that of the single zone model results.

Kannan and Udayakumar (2009) developed a computer program to simulate the combustion of water diesel emulsion using single zone zero dimensional model for direct injection diesel engine to estimate the heat release rate, cylinder pressure, brake thermal efficiency, brake specific fuel consumption and NO formation. The numerical simulation was performed at different equivalence ratios, engine speeds and water percentages. Experiments also conducted to validate the predicted results of computer simulation. Though the zero dimensional simulation models predicted NO formation during combustion process, the first appearance of NO could not be identified using this method which can be solved by CFD technique.

Ramachandran (2009) presented a thermodynamic model for the simulation of spark ignition engine running on alternate hydrocarbon fuel. The model was based on the classical two zone approach, wherein parameters like heat transfer from the cylinder blow by energy loss and heat release rate were also considered. The model could predict an array of thermodynamic and combustion parameters and easily adapt to any combustion chamber
shape. Due to its simplicity and computational efficiency, the model can also be used as a preliminary test on a wide range of alternate hydrocarbon fuels.

Rajendra prasath et al (2010) developed a computer code using ‘C’ language for compression ignition engine cycle and modified into LHR engine through wall heat transfer model. Combustion characteristics such as cylinder pressure, heat release, heat transfer and performance characteristics such as workdone, SFC and BTE were also analyzed. On the basis of the first law of thermodynamics the properties at each degree crank angle was calculated. The predicted results were validated through the experiments on the test engine under identical operating conditions on a turbocharged DI diesel engine. The simulated combustion and performance characteristics were found satisfactory with the experimental results.

Shabir et al (2010) developed a thermodynamic model to simulate the LHR based extended expansion turbocharged direct injection diesel engine. It included a gas flow model, a heat transfer model and a two zone combustion model. Using the two zone model, the combustion parameters and the chemical equilibrium compositions were used to calculate the nitric oxide formation rate by assuming a modified Zeldovich mechanism. The accuracy of the model was scrutinized against actual test results from the engine. The factors which affect thermal efficiency and exhaust emissions were deduced and their influences were discussed. In the final analysis it is seen that there is an excellent agreement in all of these evaluations.

It is inferred from the above literature study, that there is only a limited research carried out to simulate the diesel engine running on ignition improvers to analyze the combustion characteristics, engine performance and exhaust emissions. Hence in the present work, a simulation code is developed for a diesel engine running on ignition improvers to analyze the performance and emissions.