Chapter 2

LITERATURE REVIEW

2.1 Combustion modeling

Abu-Nada E. et al [1] analyzed spark ignition engine thermodynamically by implementing a theoretical model of Otto cycle, which can use various gas mixtures as a working fluid. The output of the analysis is then compared with those which use air as the working medium with variable temperature specific heats.

Agarwal A. et al [2] studied and evaluated the available single and two-zone turbulent entrainment models of combustion by comparing the performance of the model against the experimental results with reference to a quasi dimensional SI engine simulation. The in-cylinder pressure measurements are compared with the values predicted by different models for the same conditions of operating point by keeping all empirical constants fixed at their calibration values. From this study the two-zone models were found to better predict the engine combustion.

Atsushi Teraji et al [6] developed a TI (time scale interaction) combustion model, considering the turbulence eddy breakups and the characteristic time scale of chemical reactions, for simulation the combustion phenomena to a high degree of accuracy. The developed model was validated by running the engine using diesel and gasoline under a wide range of operating conditions.
Baratta M. et al [9] developed and assessed a combustion simulation code for the prediction of heat release, flame propagation speed and pollutant formation in SI engines. It is based on a multi-zone combustion model that takes the non-uniform spatial distribution of the in-cylinder burned-gas thermochemical properties into account. The proposed approach takes account of the increase of the actual flame front area caused by the wrinkling effect of turbulence and the effects of both radical species and heat transfer across the flame front by fine-scale turbulence eddies. The model presents a new definition of the outer cutoff length scale, based on the flame front area. The predictive model was applied to a multi-valve, fast burn chamber SI engine fuelled by either gasoline or CNG to compare the results with experimental data.

A SI engine simulation model incorporating the geometry of intake and exhaust systems and a single empirical factor correlation for the calculation of turbulent speed of the flame front was presented by Benson R.S. et al [10].

Models and theories of combustion for detonations, deflagrations, ignition, diffusion flames turbulent combustion and propellant combustion developed over the past five decades for the advances anticipated in the near future are reviewed by Buckmaster J. et al [14].

Numerical analysis of the power output, flow field, heat transfer losses scavenging efficiency and unburned hydrocarbon emissions are carried out by Carter M.H. et al [15] by means of a turbulence model (two-equation model) in a spark-ignition, four-stroke, homogeneous-charge engine.

The sensitivity of thermal efficiency and power output to the location of the ignition kernel and the stroke to bore ratio were analyzed using a quasi-
dimensional computer simulation by Curto-Risso P.L. et al [17]. Their simulation results reveal that high power output and efficiency are achievable for centered ignition location in the absence of auto ignition effects.

Dashti Mehrnoosh et al [18] proposed a thermodynamic cycle simulation of a conventional SI engine runs with CNG and gasoline fuels, to predict the power and thermal efficiency and emission concentrations. The first law of thermodynamics was applied to determine in-cylinder temperature and pressure as a function of crank angle. The mass fraction burnt was predicted by a two-zone model for the simulation of combustion process.

Fanhua Ma et al [24] developed a quasi-dimensional model for an SI engine by considering the combustion chamber has two zones separated by the flame front. They investigated the effects of calibration coefficients like turbulent intensity coefficient, the ignition lag coefficient and the Taylor length scale coefficient in the model by conducting experiments at different operating conditions like excess air ratio, ignition timing, fraction of hydrogen enrichment and manifold ambient pressure.

Federico Perini et al [25] developed a quasi-dimensional, two-zone model for the simulation of SI engine combustion process fuelled with methane, hydrogen or their blends by assuming infinitesimal thickness and a simplified spherical geometry for the flame front development. In analyzing the combustion process, attention was given to the description of the chemical and physical phenomena controlling the flame development and the combustion product formation. They also proposed an empirical correlation to estimate the laminar burning velocity and validated the same using experimental data.
Francis T. Connolly and Andrew E. Yagle [27] presented a model by relating in-cylinder pressure with crank angular velocity. (i) by changing the independent variable from time to crankshaft angle so that, a non-linear differential equation model becomes a model with linear first order differential equation. (ii) by developing a stochastic model for combustion pressure, which uses the sum of a deterministic waveform and raised cosine window amplitude – modulated by a Bernoulli-Gaussian random sequence and (iii) by formulating pressure as a state space deconvolution problem, and solving the same using a Kalman-filter based deconvolution at low noise levels.

Hai-Wen G. et al [35] designed and implemented an efficient Multi-Grid (MG) combustion modeling of spark-ignited engine using detailed chemistry and coupled with a GAMUT combustion model for flame propagation. The model was explored for a GDI (Gasoline Direct Injection) engine with knocking combustion. The numerical results of both MG model and the original GAMUT combustion model were compared. It was found that the results of the GAMUT model were more accurate than simple one-zone MG model. While comparing with GAMUT model with both one and two-zone MG model, the two-zone MG models provide much better efficiency and accuracy.

Hakan Bayraktar and Orhan Durgun [2004] [36] developed an empirical correlation for the combustion duration using a quasi-dimensional SI engine model, which takes into account the effect of changes in speed, air-fuel ratio, compression ratio and spark advance on combustion duration. By comparing predicted values with experimental studies the developed model was validated.
Hakan Bayraktar and Orhan Durgan [2005] [37] developed a quasi-dimensional model to predict the cycle performance and exhaust emissions of a SI engine fuelled with gasoline and LPG for a wider range of equivalence ratios and engine speed. The combustion was simulated as a turbulent flame propagation process using the governing equations consisting of first order ordinary differential equations derived for in-cylinder pressure and gas temperature.

Hakan Bayraktar and Orhan Durgan [2003] [38] developed a quasi-dimensional SI engine model. Using this model the parameters that describe the cycle, combustion and engine performance can be calculated for the specific working conditions of any engine.

Hakan Bayraktar [39] observed the effects of ethanol addition to gasoline on spark ignition engine exhaust emission and performance. A test was carried out with the blends containing various volume percentages of ethanol and the results obtained from both experimental and theoretical studies are graphically compared.

Ismet Sezer and Atilla Bilgin [45] developed a QD (quasi-dimensional), two-zone model to study and evaluate the SI engine operation in which the suction process and fluid motions were not considered. The concept of turbulent flame propagation was used to simulate the combustion process and the results of the model were validated by conducting experiments. The effect of parameters like speed, equivalence ratio and spark timing was analyzed in the exergic analysis performed by the model. They found these parameters to have considerable influence on irreversibility, exergy transfer and efficiencies.
Ivan Arsie et al [46] developed a thermodynamic two-zone model for the simulation of performance and emissions in an SI engine with a hierarchical and sequential structure. In order to make the emission models more precise an identification technique based on decomposition approach has been developed, for the definition of optimal model structure with a minimum number of parameters. Comparison of predicted results with the experimental results conducted over more than 300 engine operation conditions showed a satisfactory level of agreement.

Jiri Hvezda [47] developed a simulating tool working on the basis of multi-zone, simple quasi-dimensional method reflecting an actual 3-D combustion chamber geometry by using the specific approach to transfer and transformation of species. To save computational time during the simulation the 3-D combustion chamber geometry is taken into account by means of in-advance created geometrical characteristics.

Juan Mantilla et al [50] presented a phenomenological combustion model using turbulent flame propagation theory developed by Keck and co-workers in 1974 and correlations presented by Bayraktar 2005, to work with gasoline-ethanol blends. New sub-models were introduced for intake valve velocity and combustion efficiency to simulate the effect of compression ratio, spark timing and fuel change. The predicted values of the model are in concordance with both the original work and with experimental results of a Co-operative Fuels Research (CFR) engine.

Kazmi I.H. et al [51] developed a mathematical model to provide a simple system level model for design of model-based control methods and fault diagnostics of IC engine with electronic fuel injection system. Novel
features of this model are: use of constant volume cycle for the approximation of the combustion process; and evidence of fittings equations and constants except only for the estimation of frictional mean effective pressure.

Using the properties of the working fluid, Krzystof Z. Mendera [56] presented a heat transfer model which is capable of calculating the cumulative heat release characteristics of an IC engine.

Long Liang and Rolf D. Reitz [59] developed and implemented a level set method (G-equation) based combustion model incorporating detailed fuel oxidation mechanisms coupled with a reduced NO\textsubscript{X} mechanism are used to describe the chemical processes in KIVA-3V for Spark- Ignition (SI) engine simulations. The flame front in the spark kernel stage is tracked using the Discrete Particle Ignition Kernel (DPIK) model and a progress variable concept is introduced into the turbulent flame speed correlation to account for laminar to the turbulent evolution of the spark kernel flame.

Mahendrakumar Maisuria et al [60] modelled the suction stroke and carried out a simulation using a computer program by calculating the values of mass fraction, volume, pressure, and temperature for each increment in crank angle.

Mohsen Motahari Nezhad et al [63] studied and analyzed the thermodynamic simulation of spark ignition engine combustion process using both single zone and two-zone zero-dimensional model by developing a code in MATLAB Programming Language Software.

Rakopoulos C.D. and Giakoumis E.G. [69] surveyed the publications related to the second-law of thermodynamics and its applications to IC engines. The exergy balance (availability) equations of the engine cylinder
and subsystems are reviewed by providing relations with respect to the
definition of chemical availability, flow and fuel availability, state properties
and dead state. Importance is given to second-law efficiencies and the
irreversibility of various subsystems and processes. A reference is made to
the findings of various researchers, over the past 4 decades in different types
of IC engines like a SI engine, CI engine (direct or indirect injection), naturally
aspirated or turbocharged, during transient and steady-state operations. All
the subsystems (compressor, inlet manifold, after cooler, turbine cylinder,
exhaust manifold), are covered. Explicit comparative diagrams, as well as a	

    Sabre Bougrine and Stephane Richard [80] extended a zero-
dimensional coherent flame model to the combustion of ethanol blended
gasoline for the simulation of knock, heat release and exhaust emission in
spark ignition which mainly relies on the combination of (i) laminar flame
speed correlation, (ii) a modified set of chemical reactions in the flame front
and (iii) an adapted correlation for the ignition delay.

    Serdar Yucesu H. et al [82] conducted experiments in a spark ignition,
single cylinder, four stroke and fuel injection engine run with ethanol–gasoline
blends and studied the effect of ethanol–gasoline blends and test variables on
specific fuel consumption and engine torque. A mathematical model using
ANN was also proposed to calculate the specific fuel consumption and engine
torque based on the RAFR, compression ratio and ignition timing at a
constant speed and at wide open throttle for different fuel densities using the
results of the experimental analysis.
Subba Rao K. et al [84] reported the relative merits of the Eddy Entrainment model over the Reynolds Parameter model in describing the combustion process in a single cylinder spark ignition engine using hydrogen as fuel. From their investigations, it was found that both the models are capable of satisfactorily predicting the performance of hydrogen fuel engines due to (a) higher laminar flame speeds and (b) small quench distance.

Sundeep Ramachandran [85] developed a simple, fast and accurate engine thermodynamic model, based on two-zone approach for the simulation of a spark ignition engine running on alternate hydrocarbon fuel. In modeling the parameters like heat transfer from the cylinder, blow-by energy loss and heat release rate are considered and curve-fit coefficients are then employed to simulate air and fuel data along with frozen composition and practical chemical equilibrium routines.

S. Verhelst and C.G.W. Sheppard [93] comprehensively reviewed a number of papers published on the development of multi-zone thermodynamic engine model to present an overview of multi-zone thermodynamic models for spark ignition engines, their pros and cons, the model equations and sub-models used to account for various process such as turbulent wrinkling, flame development, flame geometry, heat transfer, etc. The authors proposed a unified framework that can be used to compare different sub-models on the same basis, with particular focus on the turbulent combustion model.

Verhelst S. et al [94] developed a two-zone, quasi-dimensional combustion model, using a combination of laminar burning velocity correlation (developed earlier by the authors) and a number of turbulent burning velocity
models, to determine the in-cylinder pressure and temperature in hydrogen engine.

Wen-Po Chaing et al [96] presented a two-state nonlinear engine model for a 4-stroke, single cylinder gasoline engine with respect to electrical throttle control development. Some empirical parameters in the model, such as the volumetric efficiency, are identified using measured operational data from the engine. The steady state performance of the model is then validated by experimental data.

Yousef S.H. Najjar and Abdullah M. Alturki [99], modelled losses due to imperfect construction of the real engine, which includes progressive combustion, valve timing and heat transfer besides engine friction. The presented model was used to convert the output of the fuel-air cycle into net brake performance. Simulation of engine performance was also carried out by varying engine speed, compression ratio and spark advance over a wide range.

2.2 Flame propagation and speed

Balazs Ihracska et al [7] investigated premixed fuel–air flame propagation in a single-cylinder, spark-ignited, four-stroke optical test engine using high-speed imaging. Circles and ellipses are fitted on to image projections of visible light emitted by the flames and are analyzed statistically to evaluate: flame area; flame speed; centroid; perimeter; and various flame-shape descriptors.
Beretta G.P. et al [11] derived a tentative correlation relating $U_T$ and $L_T$ to operating variables and geometry of the engine data. In a transparent piston engine, by synchronized the pressure measurements with high-speed motion picture records of flame propagation have been made. The record show that the initial flame front expansion speed was close to that of a laminar flame. As the flame expands, it accelerates rapidly to a quasi-steady value comparable with that of the turbulent velocity fluctuations in the unburned gas. The data have been analyzed in a model independent way to obtain a set of empirical equations for calculating the mass burning rate in spark ignition engines.

Blizard N.C and Keck J.C. [12] made a survey of relevant literature and indicated that no satisfactory burning law based upon the fundamental principles existed, but empirical functional of the form $X=X(\theta, \theta_s, \theta_d, \theta_b)$ have been used to correlate experimental measurements.

Broustail G. et al [13] proposed a correlation for the laminar burning velocity to estimate any butanol or ethanol blend iso-octane–air mixture from the experimental data. New sets of data of laminar burning velocity are provided by using the spherical expanding flame methodology, in a constant volume vessel and presented the first results obtained for pure fuels (iso-octane, ethanol and butanol) at an initial pressure of 0.1 MPa and a temperature of 400 K, and for an equivalence range from 0.8 to 1.4. New data of laminar burning velocity for three fuel blends containing up to 75% alcohol by liquid volume are also provided.

Feng PengFei et al [26] measured the laminar burning velocity of iso-butanol-air mixtures under different initial conditions of pressures,
temperatures and equivalence ratios using high-speed Schlieren photography and outwardly propagation flame in a constant volume combustion bomb. Based on the analysis of stretched flame propagation speed and stretch rate, the laminar burning velocities and Markstein lengths of iso-butanol-air flames were obtained. An analysis of flame stability and factors influencing flame stability was also carried out.

George A. Lavoie [29] developed a computer model for hydrocarbon emissions from homogeneous-charge, spark-ignition engines in which, the hydrocarbon emission process was treated in terms of a wall quench layer, formed at the moment that the flame touches the cylinder wall, followed by oxidation of unburned hydrocarbons during the expansion and exhaust stroke. The objective of the work was to survey their available experimental data on the quench layer thickness and oxidation rates and to prepare correlations suitable for use in engine-model calculations for the calculation of laminar flame speeds.

Omer L. Gulder [31] compared and evaluated the burning velocity data of different alternative spark ignition engine fuels obtained by various workers in literature. Empirical and semi-empirical correlations, suitable for cycle simulation studies, were presented for laminar burning velocity as a function of mixture strength, unburned mixture temperature, pressure and residual gas fraction by considering different fuels, which include ethanol, methanol, alcohol/water blends, iso-octane/alcohol blends, propane and iso-octane. Experimental data, published data of other workers and the predictions of theoretical thermo-kinetic models have also been considered in correlations.
J. Hacohen et al [34] studied flame speeds during the ignition and combustion processes in a spark-ignition engine by analysing the combustion images in the early stages of the flame kernel development, and the pressure-time history. Simultaneous measurements of engine operating conditions, pressure traces and sequences of combustion images have been made in a single-cylinder four-stroke engine. The early stages of the combustion have been analyzed using stochastic image analysis techniques which can measure the total kernel growth, the local translational velocity of the centroid, the stretching of the flame kernel surface and its roughness. In addition, the fraction of the flame surface area supporting propagation has been determined from the directional variation of flame propagation between successive image frames. From the pressure time history the actual instantaneous flame speed has been derived for the main burn phase and thereafter extrapolated for the ignition phase. Good agreement has been demonstrated between the average value of the derived flame speed and well known correlations.

Hakan Bayraktar [40] theoretically investigated the turbulent flame propagation process in a spark-ignition (SI) engine fuelled with gasoline, ethanol and their blends. A quasi dimensional SI engine cycle model previously developed by him was used to predict the thermodynamic state of the cylinder charge during the cycle. Using this model geometrical features (flame radius, flame front area and enflamed volume) of the flame, combustion characteristics (mass fraction burned and burn duration), cylinder pressure and temperature are predicted as a function of the crank angle.
Based on the study, they concluded that ethanol addition to gasoline up to 25 volume percentage, accelerated the flame propagation process.

**Sodre J.R. [1998]** [48] developed a turbulent flame speed model based on the design and operating parameters of a spark ignition engine and the developed model was calibrated against experiments carried out in an iso-octane-fuelled research engine under different conditions.

**Sodre J.R. [1997]** [49] verified the dependence of the turbulent flame speed and the flame development angle on air-fuel ratio, engine rotational speed, ignition timing and compression ratio with the help of spark ignition engine cycle simulation model and experimental results obtained from an iso-octane-fuelled research engine. The results from this work confirm the existing theories on the influence of engine design and operating parameters on the turbulent flame speed and on the flame development angle, but suggest the way they relate to be better established.

**Liao S.Y. et al [57]** conducted tests for premixed laminar combustion of ethanol–air mixtures in a constant volume combustion bomb to determine the laminar burning velocities of ethanol–air mixtures over a wide range of equivalence ratio at elevated temperatures, by means of the measurements of spherically expanding flames using Schlieren photography technique. Considering the flame stretch and following a linear relation between flame speed and flame stretch, the unstretched laminar burning velocities of ethanol–air flames are expressed as a function of initial temperature and equivalence ratio using a power law correlation. The empirical correlation is also compared with those data available in the literature, the discrepancies being acceptable.
Liberman M.A. et al [58] reported multi-dimensional numerical simulations of knock occurrence in internal combustion engines. Knock occurrence in spark ignition engines was examined within the context of a model of auto ignition of hydrocarbon-air mixture, which has been extended by including chemical reactions for the propagating flames and an extended chemical model for the cool flames. Special attention was given to the influence of the propagating flame on the auto ignition onset.

Metghalchi M. and Keck J.C. [1980] [61] measured the laminar burning velocity of propane-air mixtures in the pressure range of 0.4 to 40 atm and temperature range of 298 K to 750 K for equivalence ratios from 0.8 to 1.5 using a constant volume spherical combustion bomb. A thermodynamic analysis was used to calculate the laminar burning velocity from a pressure-time history of the combustion process and the measured values were correlated using both power law and exponential expressions.

Metghalchi M. and Keck J.C. [1982] [62] measured burning velocities of mixtures of air with methanol, iso-octane, and indolene (RMFD303) using the constant volume bomb method for fuel-air equivalence ratios in the range of 0.8-1.5 over the pressure and temperature ranges p = 0.4atm - 50 atm and T = 298 K - 700K. The effect of adding simulated combustion products to stoichiometric iso-octane-air mixtures were also studied for diluent mass fraction f = 0-0.2 and the results found to fit within ±10% by the functional form \( S_u = S_{uo} (T_u/T_o)^\alpha (p/p_o)^\beta (1-2.1f) \), where \( S_{uo} \) depends on fuel type and equivalence ratio and \( \alpha \) and \( \beta \) depend only on equivalence ratio. In overlapping ranges, the results agree well with those previously reported.
To determine the pressure and temperature histories from mathematical analysis, it is necessary to understand the mechanism of flame propagation and a “burning law” correlation based upon the governing combustion equations would be of great utility in predicting the rate of energy release.

**Piya Ratcharoenpong et al** [65] developed the 1-D combustion model of Spark-Ignition (SI) engines for predicting the effects of various fuel types and compositions on engine performances and fuel consumption at various engine operating conditions without engine modifications. Laminar burning velocity correlations for alternative fuels were used to calculate the combustion duration and the results were validated with experiments conducted in a well-calibrated 4-cylinder gasoline engine.

**Qianqian Li et al** [67] conducted experiments to determine the laminar flame speeds of 2-methyl-1-butanol (2MB)–air mixture at temperatures (K) of 393, 433 and 473, pressures (Mpa) of 0.1, 0.25, 0.5 and 0.75, and equivalence ratios of 0.6–1.8 using the spherically propagating flame. They analyzed flame instabilities using the Lewis number, flame thickness, density ratio and Markstein length, combining with the Schlieren photos and proposed a correlation of laminar flame speed based on their experimental results.

**Ramos J.I.** [74] developed a one-dimensional combustion model, employing constant eddy diffusivity and a one-step chemical reaction, to study the flame propagation in a spark-ignition engine. One-zone and two-zone thermodynamic models have also been developed and applied to study the combustion process in the engine. The results of thermodynamic models viz. the average mixture temperature, the temperatures of the burned and
unburned gases and the flame surface area have been compared with the one-dimensional model results.

**Ranzi E. Et al** [76] collected, consolidated, and reviewed a vast amount of experimental data on the laminar flame speeds of hydrocarbon and oxygenated fuels that have been reported in recent years and analyzed them using a detailed kinetic mechanism for the pyrolysis and combustion of a large variety of fuels at high temperature conditions, to identify aspects of the mechanism that require further revision. The review and assessment were hierarchically conducted, in the sequence of the foundational C\textsubscript{0} – C\textsubscript{4} species.

**Rothrock A.M. and Spencer R.C.** [79] altered the N.A.C.A. (National Advisory Committee for Aeronautics) combustion apparatus to operate as a fuel-injection, spark-ignition engine, and a preliminary study was made of the combustion of gasoline air mixtures at various air-fuel ratios ranging from 10 to 21.6. Using records from an optical indicator and films from a high-speed motion picture camera were the chief sources of data.

**Szabo T. et al** [86] proposed a new correlation describing the laminar burning velocity of hydrogen/air mixtures diluted with steam, as a function of temperature, pressure, and mixture composition. The laminar burning velocity was calculated with the detailed reaction mechanism of Maas and Warnatz (1988) implemented in the code INSFLA and the results obtained were validated against experimental data. A new heuristic approximation based on them was created. The correlation consists of simple mathematical expressions and provides a good approximation of the laminar burning velocity in the range between 200K and 600K for temperature, between 0.1 bar and 10 bar for pressure, and up to 20 mol% steam dilution.
Tomasz Lezanski et al [91] presented some results of visualization researches of combustion system with divided, semi – open combustion chamber for SI engines, using a Rapid Compression Machine (RCM) and Experimental Visualization Engine (EVE). The research results (photographs of combustion sequence, diagrams of in-cylinder pressure histories) during visualization testing with using RCM and EVE are presented.

Vaishali Katre and Bhele S.K. [92] reviewed the laminar burning velocity, one of the most essential parameters for analysis and performance predictions of various combustion engines. They reported the requirement of knowledge of laminar burning velocity of the fuel-air mixture as a function of the mixture strength by a majority of the turbulent combustion models.

Xiao Ma et al [97] investigated laminar burning characteristics of gaseous MF(2-Methylfuran) – iso-octane at varying temperatures and equivalence ratios with an initial pressure of 0.1 MPa in a constant-volume vessel using a high-speed Schlieren photography. The un-stretched flame speeds, Markstein lengths, Markstein number, laminar burning velocities and laminar burning flux of MF – iso-octane under different equivalence ratios and temperatures are then deduced and compared with MF and iso-octane.

Xiaolei Gu et al [98] conducted experimental and numerical studies on laminar burning characteristics of diluted n-butanol/air premixed mixtures by conducting experiments using the spherically expanding flames at different dilution ratios of nitrogen at the initial pressure of 0.1MPa and a temperature of 428 K.
Yuji Ikeda et al [100] applied the optical diagnostic techniques of infrared (IR) absorption and chemiluminescence to a racing engine. The IR sensor mounted in the engine in place of a pressure transducer was able to withstand the operating conditions up to 16,000 rpm with little vibration noise and provided an adequate signal for analyzing the flame propagation speed. In separate tests, two micro Cassegrain (MC) sensors were installed in the cylinder head near the wall to evaluate the cylinder-to-cylinder fluctuations and the flame propagation characteristics. The local air excess ratio (λ) was estimated from the ratios of the emission intensities using the chemiluminescence and the micro Cassegrain system (MCS) after deriving a calibration function. The measured flame propagation speed increased with the engine speed, but the propagation speeds normalized by the piston speed remained at a constant level. The flame propagation speed was influenced by the fluid dynamics of the in-cylinder flow.

Zheng Chen et al [102] conducted a theoretical analysis for a planar premixed flame of binary fuel blends and developed a model for the laminar flame speed. The model depicted the dependency of the laminar flame speed of binary fuel blends on the square of the laminar flame speed of each component. The performance of this model was assessed for methane/hydrogen mixtures.

2.3 Blending

Anada Srinivasan C. and Saravanan C.G. [3] investigated the effects of ethanol and unleaded gasoline with 1, 4 Dioxan blends on the performance and emission of a multi-cylinder SI engine. The results revealed an increase
in brake thermal efficiency and $O_2$ emissions with an appreciable reduction in CO, CO2, HC and NOx emissions.

**Bang-Quan He et al** [8] investigated the effect of ethanol blended gasoline fuels on emissions and catalytic conversion efficiencies in a spark ignition engine with an Electronic Fuel Injection (EFI) system. The results of their investigation revealed that the addition of ethanol to gasoline fuel enhanced the octane number of the blended fuels, and decreased engine-out regulated emissions. The fuel containing 30% ethanol by volume drastically reduced engine-out total hydrocarbon emissions (THC) at operating conditions and reduced engine-out THC, CO and NOx emissions at idle speed and increased unburned ethanol and acetaldehyde emissions.

**Ramesh Kumar C., and Nagarajan G.** [73] quantified the changes in performance and emission characteristics brought by partial thermal insulation on the combustion chamber of a four stroke, spark ignited engine fuelled with E20 ethanol blend. Using a coating of 0.3 mm thick Alumina (Al2O3) on the cylinder head, inlet and exhaust valves. The combustion parameters such as flame development and rapid burn duration are also estimated and compared.

**Simona Silvia Merola et al** [83] investigated the influence of butanol addition to gasoline in a port fuel injection, spark-ignition engine. The experiments were conducted in a single-cylinder optically accessible port fuel injection spark-ignition (SI) engine, with an external boosting device and the effect on the spark ignition combustion process of 20% and 40% of n-butanol blended in volume with pure gasoline was investigated through cycle-resolved visualization.
Wei Yanju et al [95] investigated the effects of different methanol/gasoline ratios on engine power, thermal efficiency and emissions of a three-cylinder, port fuel injection engine using three methanol-gasoline blends containing 10%, 20%, and 85% of methanol by volume.

2.4 Emission modeling

Prabakaran J. et al [66] established an empirical correlation to predict the temperature difference in a vortex tube, using RSM, by conducting experiments applying central composite design at three factor level. The proposed model was found to fit the experimental results with 95% confidence interval.

Rajkumar S. et al [68] developed a model and empirical relationship for the prediction of tensile strength of friction welded AA 1100 aluminium alloy joints by conducting a minimum number of experiments based on five level central composite design of six parameters. Both optimisation of the model and sensitivity analysis were carried out using an RSM technique to maximize the tensile strength.

Rakopoulos C.D. and Michos C.N. [70] developed a zero-dimensional, multi-zone combustion model for predicting the performance and nitric oxide (NO) emissions of a spark ignition engine and validated the same using the experimental data from a multi-cylinder, four-stroke, turbo-charged and after cooled, the SI gas engine running with syngas fuel. The basic concept of the model is the division of the burned gases into several distinct zones, for taking into account the temperature stratification of the burned
mixture during combustion. This is especially important for accurate NO emission predictions, since NO formation is strongly temperature dependent.

Tinault F.V. et al [90] developed a quasi-dimensional model to determine exhaust emissions from Spark Ignition engines based on chemical kinetics for determining CO and NO\textsubscript{X} emissions. The effect of retention in crevices, wall quenching and in-cylinder and exhaust pipe post-flame combustion processes were considered in the model to determine the HC emissions.