Development of Alternative fuels for HCCI Engine Technology

1st P.V.Ramana, 2nd B.Umaheswar gowd, 3rdD.maheswar

1stResearchScholar –2nd professor,3 3rd professor
1st 2nd 3rd Mechanical Engineering
1st and 2nd JNTU Anantapur-Mechanical 3rd MNREC-professor principal -SangaReddy, india

***Abstract*—The consumption of conventional fuels are increasing from year to year and leading to faster depletion of fuel reserves. So it becomes necessary to improve the technology to minimize the consumption and substituting alternative fuels for future development and also to minimize the exhaust gas emissions. Stringent emissions standards that are being enforced in many countries around the world are encouraging vehicle manufacturers to meet such emissions norms as EURO 5, the ACEA agreement and EURO 6.Due to the stringent emission norms, the research in the field of internal combustion engines in general and diesel engines in particular gathered huge importance and also increasing demand on fuel consumption. So high demands are there on large gas engines and attention placed in the areas of performance, fuel consumption and emissions. One way to reach this goal is by introducing new combustion concept engine like Homogeneous Charge Compression Ignition (HCCI) engines promise high thermal efficiency combined with low levels of nitric oxide and particulate matter emissions. However, due to the absence of an immediate means of triggering ignition, stable operation over a wide range of conditions and transient control have proven most challenging and have so far prevented commercialization by opening up new technical avenues, such as micro-hybridization and bio fuels. Most alternative fuel conversions involve reconfiguring a gasoline or diesel vehicle or engine to operate on natural gas, propane, alcohols, or on a blend of conventional and alternative fuels. Use of clean alternative fuels opens new fuel supply choices and can help consumers address concerns about fuel costs, energy security, and emissions. HCCI engines can operate on gasoline fuel, diesel fuel and most of alternative fuels. HCCI combustion is achieved by controlling the temperature, pressure, and composition of the fuel and air mixture so that it is a spontaneously ignites in the engine. This control system is fundamentally more challenging than using a spark plug or fuel injector to determine ignition timing as used in SI and DI engines, respectively. The purpose of this study is to summaries the alternative fuel effect on the HCCI engine combustion process**

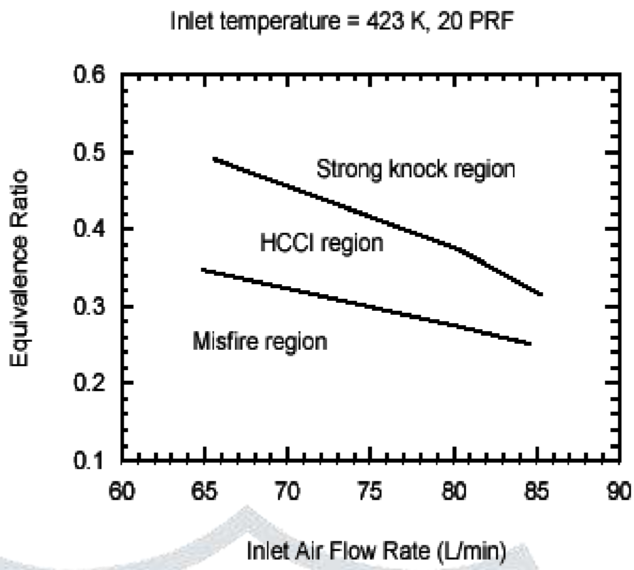
***Key words*— HCCI, CI, SI, alternate fuels, VVT, DME, VVA**

1. INTRODUCTION

The entire surface transport of India is based on petroleum fuel, but its availability is of growing concern. The production of domestic crude has been declining and the transport system has been increasingly dependent on imported crude oil to meet its needs. There is a growing concern that the world may run out of petroleum based fuel resources. All these make it imperative that the search for alternative fuels is taken in right earnest. Alternative fuels, particularly sustainable bio fuels, have been identified as one of the key elements in helping achieve this goal. Bio fuels derived from sustainable oil crops such as jatropha, camelina and algae or from wood and waste biomass can reduce the overall carbon footprint by around 80% over their full lifecycle. The information about alternative fuel vehicle and engine conversions where conversion systems modify vehicles and engines so that they can run on different fuels than the ones for which they were originally designed. Most alternative fuel conversions involve reconfiguring a gasoline or diesel vehicle or engine to operate on natural gas, propane, alcohols, or on a blend of conventional and alternative fuels. Use of clean alternative fuels opens new fuel supply choices and can help consumers address concerns about fuel costs, energy security, and emissions.

2. ALTERNATIVE FUELS

Many fuels have been studied for their performance in HCCI engines; idea used a dual mode (spark ignited/HCCI) two stroke engine to investigate gasoline methane, propane, methanol, ethanol and dimethyl-ether. HCCI operation was conducted in a natural aspirated engine with high levels of trapped residual gas. The equivalence ratio was in a range 0.7-1.2; a regime equivalence ratio was necessitated by low 6:1 compression ratio of the engine. HCCI operation could not be achieved with methane and propane and could achieve with varying degrees of success with the other fuels. Gasoline, methanol and ethanol could be operated at low load in HCCI mode, but transition to spark ignition was necessary to achieve higher load.Dimethyl-Ether (DME) could only be operated in HCCI mode. At higher load or equivalence ratio sever knock would occur.



Alternative fuels are derived from resources other than petroleum. Some are produced domestically, reducing our dependence on imported oil, and some are derived from renewable sources. Often, they produce less pollution than gasoline or diesel.

2.1Biodiesel: An alternative fuel formulated exclusively for diesel engines, biodiesel is made from vegetable oil or animal fats. Biodiesel is to petroleum diesel fuel what ethanol (E85) is to gasoline: a substitute fuel made from biomass, which means that it is inherently renewable and, in itself, it contributes nothing to carbon-dioxide loading of the atmosphere. Biodiesel commonly uses soybean or canola oil as its base, but animal fat or recycled cooking oil can also be used. To speed its market introduction, and dilute its additional cost over petroleum diesel fuel, the initial commercial product being studied is a blend of 20% biodiesel and 80% petroleum diesel fuel, whence B20. As noted above, B20 can be stored and dispensed in exactly the same manner as petroleum diesel fuel; in addition, diesel-powered vehicles require no modification at all to run on B20 or even higher blends. Thus any diesel-powered truck or bus is, potentially, already an alternative-fueled vehicle! For example, an ordinary used Winnebago was "converted" into the Veggie Van simply by pouring homemade biodiesel into its tank. Since biodiesel is not a fossil fuel, as noted above, it can cut greenhouse-gas emissions as well as ordinary pollutants (particularly soot) by displacing petroleum diesel fuel.

2.1.2 Preparation of biodiesel

To prepare the biodiesel in a room temperature

1. Take 200ml of methanol into the glass blender pitcher. Add 3.5grams NaOH (lye). This reaction produces sodium meth oxide, which must be used right away or else it loses its effectiveness (like NaOH) it can be stored away from air or moisture, but that might not be practical for a home setup.
2. Mix the methanol and sodium hydroxide until the sodium hydroxide has completely dissolved (about 2 minutes), and then add 1litre of vegetable oil to this mixture.
3. Continue blending this mixture (on low speed) for 20 – 30 minutes.
4. Pour the mixture into a wide – mouth jar and see the liquid starts to separate out into layers. The bottom layer will be glycerine. The top layer is the biodiesel.
5. Allow at least a couple of hours for the mixture to fully separate to keep the top layer as biodiesel fuel and glycerin is separated.

2.1.3 Biodiesel stability and its self life

All fuels have a self-life that depends on their chemical composition and storage conditions. The chemical stability of biodiesel depends on the oil from which it was derived. Biodiesel from oils that's natural contains the antioxidant to copherol or vitamin (E) (eg: rapeseed oil) remain usable longer than biodiesel from other types of vegetable oils. According to at least one source, Stability is noticeably demised after 10days and the fuel may be unusable after 2 months. Temperature affects fuel stability in that excessive temperature may denature the fuel.

2.2 Blends: Blends are mixtures of traditional and alternative fuels in varying percentages, like biodiesel blends of B5 or B20. Blends can be thought of as transitional fuels since they work with current technologies while paving the way for future integration. Blending amounts of alternative fuel with conventional fuel is an important option for reducing petroleum consumption. Examples of low-level fuel blends include E10 (10% ethanol/90% gasoline), B5 (5% biodiesel/95% diesel), and B2 (2% biodiesel/98% diesel). Blends can also consist of two types of alternative fuels, such as hydrogen and compressed natural gas (HCNG), which can be a combination of 20% hydrogen/80% CNG. B20 (20% biodiesel/80% diesel) and E85 (85% ethanol/15% gasoline) are not considered low level blends. These are 1.Biodiesel blends 2.Ethanol Blends 3.Hydrogen/Natural Gas Fuel Blends.

Table 1: shows Blends of Biodiesel

Biodiesel	Petrodiesel	Type
100% Biodiesel	0% Petrodiesel	B100
80% Biodiesel	20% Petrodiesel	B80
50% Biodiesel	50% Petrodiesel	B50
20% Biodiesel	80% Petrodiesel	B20
5% Biodiesel	95% Petrodiesel	B5

Fig 1: Different types of blends

2.3 Ethanol: Ethanol (ethyl alcohol) is an alternative fuel made from corn, grains or agricultural waste and is used primarily as a supplement to gasoline. Ethanol, or grain alcohol, is produced by fermenting biomass, commonly corn (though other, lower-value feedstocks have been tested in an effort to reduce costs, like brewery waste and cheese-factory effluent--bleach). It is thus inherently a renewable resource, and contributes nothing in itself to greenhouse-gas loading of the atmosphere (and with efficient modern farming techniques, there's still an improvement even when you add in the petroleum-based fuel burned to plow the fields, make the fertilizer, etc.). As an alternative motor vehicle fuel, it is usually blended in a mixture of 85% ethanol, 15% unleaded gasoline, whence E85. (It is also used in up to 10% blends with gasoline (gasohol) to oxygenate the gasoline, and this mixture can be used by most modern gasoline vehicles.) Ethanol, as noted above, is a renewable resource that contributes nothing in itself to global warming concerns. Like methanol, it can be blended with any amount of gasoline in the tank of a flex-fuel vehicle, which is what automakers are selling these days. In fact, starting with the 1999 model year, some automakers are making every one of certain vehicle models capable of using E85 in any mixture with gasoline, at no extra charge.

2.4 Hydrogen: Hydrogen is an elemental gas that is extracted from other compounds, not manufactured in the traditional sense like other fuels. Hydrogen does not occur free in nature; it can be made by "re-forming" natural gas or another fossil fuel, or by using electricity to split ("electrolyze") water into its components of oxygen and hydrogen. In this sense, hydrogen is like electricity: the energy to generate it can be obtained from sources ranging from the burning of high-sulfur coal to pollution-free photovoltaic cells (solar cells). Hydrogen has been called the "most alternative" of the alternative fuels: if it is made by electrolysis of water using electricity from a nonpolluting source like wind or solar power, then no pollutants of any kind are generated by burning it in an internal combustion engine except for trace amounts of nitrogen oxides, and if it is used in a fuel cell then even these disappear. Furthermore, no greenhouse gases are generated because there's no carbon in the fuel. All that comes out the vehicle's exhaust is drinkable water! Using hydrogen as the "battery" to store energy from a nonpolluting, renewable source would result in a truly unlimited supply of clean fuel. The advantage of using hydrogen to store energy rather than a battery pack is that a hydrogen tank can be refilled in minutes rather than recharged in hours, and it takes less space and weight to store enough hydrogen to drive a given distance on a single refueling than it does to carry enough battery capacity to go the same distance on a single recharging. The battery-electric drive train uses energy more efficiently, and can handle the vast majority of daily commute-and-errands driving that people do, but for long trips hydrogen could prove to be a lot more convenient.

2.5 Methanol: Methanol (methyl alcohol) is an alternative fuel made from woody plant fiber, coal or natural gas and is used primarily as a supplement to gasoline. Methanol is typically made from natural gas; though it is possible to produce it by fermenting biomass (this is why it is sometimes called "wood alcohol"), this is not economically competitive yet. Because it is easier to transport natural gas to a distant market by converting it to methanol, which is a liquid at ordinary temperatures and pressures, than by chilling and liquefying it or by building a long pipeline, some petroleum-exporting countries are looking at exporting their "waste" natural gas (which they currently "flare off" in huge flames visible from the Space Shuttle!) by converting it to methanol; however, most of the natural gas that goes into methanol in the United States is still domestically produced. For reasons to be explained below, most fuel methanol in this country is sold as a blend of 85% methanol with 15% unleaded premium gasoline, whence "M85". In the not-too-distant future, "neat" (100%) methanol may be the preferred means of storing hydrogen for fuel-cell electric vehicles.

Alcohol fuels like M85 are perhaps the most "transparent" alternative fuels to the user, i.e., they are the least distinguishable from gasoline in how you buy and use them, which should ease acceptance. The fuel system of a car or truck only needs to be slightly changed (somewhat different materials, bigger fuel injectors, and a fuel composition sensor) in order for it to run on M85, and recently automakers have been offering M85 vehicles at no extra cost over their gasoline counterparts (or even for slightly less money), though at present automakers seem to be more interested in ethanol (E85).

2.6 Natural Gas: As already known crude petroleum is composed of hydrocarbons. It contains some amount of water, sulphur and other impurities. Petroleum when mixed with natural gas produces a highly volatile liquid. This liquid is known as natural gasoline. When this petroleum natural gas mixture is cooled, the gasoline condenses. The natural gas can be compressed and then called compressed natural gas (CNG)

Natural gas can be used as a motor fuel in two forms: compressed natural gas (CNG) and liquefied natural gas (LNG). CNG used to run automobile vehicles just like LPG.Compressed natural gas fuel feed system is similar to liquefied petroleum gas (LPG) fuel feed system . CNG conversion kits are used to convert petrol driven cars into CNG driven cars .It is very easy on the engine, giving longer service life and lower maintenance costs. CNG is the least expensive alternative fuel (except electricity) when you compare equal amounts of fuel energy, and, in my experience at least, its price has been relatively steady. A gasoline-gallon-equivalent of 130-octane natural gas as would have paid for a gallon of 92-octane unleaded gasoline. Even with the natural-gas price spikes of the last few years, have found the price of CNG to be less volatile, and on average lower, than that of gasoline.

2.7Propane and butane: propane and butane are obtained from oil and gas wells. They are also the product of the petroleum refining process. For automobiles engines two types of LPG are used. One is propane and other is butane .some times, a mixture of propane and butane is used as liquid petroleum gas in automobiles. Liquefied petroleum gases are compressed and cooled to form liquid. This liquid is kept in pressure tanks which are sealed. And is a by-product of natural gas and crude oil refining.

Liquefied petroleum gas, as the name suggests, is partly a byproduct of petroleum refining. It consists of hydrocarbons that are vapors, rather than liquids, at normal temperatures and pressures, but which turn liquid at moderate pressures; its main constituent is propane, and it is sometimes referred to by that name.

Because it's so widely available, LPG is the least "alternative" of alternative fuels if "alternative" equates to inconvenience, and most of the alternative fuel used in the United States is LPG. (One might also say, given LPG's dominance of the alternative-fuel market, that it's the most alternative fuel...) In order to liquefy the fuel, it is stored in sturdy tanks at about 20 times atmospheric pressure; since these are much tougher than typical sheet-metal or plastic gasoline tanks, and since they have a built-in shutoff valve to seal the tank if the fuel lines start leaking, LPG is safer than gasoline. (The tanks are a permanent part of the vehicle, unlike barbecue-grill tanks, so they are immune to the usual cause of LPG fires, which is leakage due to the operator's failure to hook the tank up properly.) It is also somewhat cheaper than gasoline in most places at most times, when you compare the price of a gallon of gasoline with the price of the somewhat larger volume of LPG needed to drive the same distance.

Because LPG enters the engine as a vapor, it doesn't wash oil off cylinder walls or dilute the oil when the engine is cold, and it also doesn't put carbon particles and sulfuric acid into the oil. Thus an engine that runs on propane can expect a longer service life and reduced maintenance costs. (Incoming liquid gasoline cools the combustion chamber and a valve as it vaporizes, so you might expect, for example, that you'd need a valve job more often on an LPG-burning engine because the gaseous fuel doesn't give this cooling effect. However, modern valve and valve-seat materials, designed for unleaded gasoline, don't have problems with the "dry" fuel. More recently, direct injection of LPG in the liquid state, with attendant cooling effect as well as improved emissions control, is being tested.) Its high octane rating (around 105) means that power output and/or fuel efficiency can be increased, without causing detonation ("knocking"), in a vehicle that isn't required to run on gasoline as well.

2.8 P-series Fuel: Although they are not yet widely used or manufactured, P-series fuels were added to the list of Energy Policy Act (EPAct) recognized alternative fuels in 1999.

On basis of above availability of different fuels there is wide scope to develop alternating fuels to suit the requirement of HCCI engine technology.

3. HCCI IS A PROMISING TECHNOLOGY

Considering the type of engine; gasoline engine could operate cleaner than diesel engine, however diesel engine shows higher in thermal efficiency. This inspires the idea of hybrid among two common type of engine so far. It calls “HCCI” concept i.e.

Homogeneous Charge Compression Ignition. However, HCCI combustion works with gasoline diesel and most alternative fuels, giving it a major advantage for future developments.

In HCCI engines, the fuel and air are premixed to form a homogeneous mixture before the compression stroke. As a result, the mixture ignites throughout the bulk without discernable flame propagation due to occurrence of auto ignition at various locations in the combustion chamber (multi-point ignition). This may cause extremely high rates of heat release, and consequently, high rates of pressurization [3-5]. In HCCI engines, auto-ignition and combustion rate are mainly controlled by the fuel chemical kinetics, which is extremely sensitive to the charge composition and to the pressure and temperature evolution during the compression stroke, therefore HCCI combustion is widely assumed to be kinetically controlled [13, 12, 15]. The main objective of HCCI combustion is to reduce soot and NO_X emissions while maintaining high fuel efficiency at part load conditions [40, 16]. In some regards, HCCI combustion combines the advantages of both spark ignition (SI) engines and compression ignition (CI) engines [16, 9]. The results from experiment and simulation show that the HCCI combustion has a low temperature heat release and a high temperature heat release, and both heat releases occur within certain temperature ranges. The low temperature heat release is one of the most important phenomena for HCCI engine operation and the occurrence of it depends chemically on the fuel type [1-2].

However there are certain number of obstacles and problems in its application that have not been resolved. These problems are the control of ignition and combustion, difficulty in operation at higher loads, higher rate of heat release, higher CO and HC emissions particularly at light loads, difficulty with cold start, increased NO_X emissions at high loads and formation of a completely homogeneous mixture [3-5]. The lack of a well-defined ignition timing control has led a range of control strategies to be explored. Numerous studies have been conducted to investigate HCCI combustion control methods such as intake air preheating [4, 6, 7], Variable Valve Actuation (VVA) [14], Variable Valve Timing (VVT) [41], Variable Compression Ratio (VCR) [8] and EGR rate [1]. Moreover many studies also focused on the effects of different fuel physical and chemical properties to gain control of HCCI combustion [9, 19- 21].

HCCI engines can be considered as newcomers even though the research was initially by Onishiet al. in 1979, as reported in [48]. Investigators worldwide are developing HCCI engines as this technology has not matured sufficiently. They can be used in either SI or CI engine configurations with a high compression ratio (CR). HCCI engines work without the help of diesel injectors or spark plugs and can achieve high engine efficiency with low emission levels. General Motors Corporation (GM) has unveiled a prototype car with a gasoline HCCI engine and it was claimed that it could cut fuel consumption by 15% [23]. The engine is able to virtually eliminate NOx emissions and lowers throttling losses which assists better fuel economy [11].

A great deal of work has been done in recent years and the research area has extended to all aspect of the combustion process. It has been gradually presenting a picture of energy saving and cleaner exhaust emissions. Increasing environmental concerns regarding the use of fossil fuels and global warming have prompted researchers to investigate alternative fuels.

HCCI has high fuel flexibility and can be applied for a wide range of fuels with different octane/cetane numbers. The combustion process of a HCCI engine has little sensitivity to fuel characteristics such as lubricate and laminar flame speed. Fuels with any Octane or Cetane number can be burned, although the operating conditions must be adjusted to accommodate different fuels, which can impact efficiency. An HCCI engine with variable compression ratio or variable valve timing could, in principle, operate on any hydrocarbon or alcohol liquid fuel, as long as the fuel is vaporized and mixed with air before ignition. Besides gasoline[17] and diesel fuel [18], a variety of alternative fuels, such as methanol [20], ethanol [22,23], natural gas [24], biogas [26], hydrogen [25], DME [20] and their mixtures [33-35], including also gasoline and diesel mixtures and different mixtures of iso-octane with heptane [27], have been experimentally proved as possible fuels for HCCI combustion in both two-stroke and four-stroke engines.

4. ALTERNATIVE FUELS FOR HCCI ENGINE – AN ANALYSIS

Extensive experimental research shows that the engine exhaust emissions and fuel efficiency of modern diesel engines indicate several unfavorable conditions for biodiesel fuels when the engines are operated in conventional high temperature combustion cycles. The homogeneous charge compression ignition (HCCI) is an alternative combustion concept for internal combustion engines. The HCCI combustion engine offers significant benefits in terms of high thermal efficiency and ultra low emissions (NO_x and PM).Fuels can be described by various combinations of chemistry, boiling points, or physical Properties. The significance of kinetics in modelling advanced combustion modes like HCCI has been well-recognized. Overall, HCCI engine generally responded well to fuels of lower octane, higher sensitivity, lower aromatics and higher olefins, with boiling points in the lower range of those evaluated. One of the advantages of HCCI combustion is its intrinsic fuel flexibility. HCCI combustion has little sensitivity to fuel characteristics such as lubricate and laminar flame speed. Fuels with any octane or cetane number can be burned, although the operating conditions must be adjusted to accommodate different fuels, which can impact efficiency. The study focuses on to investigate the effect of different fuels used in HCCI on combustion characteristic. In order to study the fuel effect, a comparative study [30] was carried out with four types of fuel combinations to control the combustion process of HCCI engine. The fuels used were Gasoline (A-92, A-95, A-98), Diesel fuel (Diesel-45, Diesel-50, Diesel-55), Natural-Gas (NG), single-and dual-component mixtures of the gasoline and diesel primary reference fuels (iso-octane and n-heptane). Combinations between these fuels were used, such as: Natural-Gas with DME (Dimethyl Ether), gasoline with DME, diesel fuel or paraffin hydrocarbons with Natural-Gas.

4.1 Effect of using different fuels combinations on the performance of HCCI is given as follows

Auto ignition timing may be controlled by blending low cetane number fuel (natural gas) with high cetane number fuel (DME).Dimethyl ether is an ideal fuel additive for natural gas(NG) HCCI because has a small ignition delay, and because DME has similar reaction chemistry to methane and DME does not tend to soot formation

Combination of fuel mixtures

1. Diesel 45- with NG
2. Diesel 50-with NG
3. Diesel 55- with NG
4. NG with DME
5. A-95with DME
6. A-98 with DME
7. A-92 with DME
8. $C_N H_{2N+2}$ with DME (N=1-4)
9. CN H_{2N+2} with NG (N=5-10)

Table 2. Properties of Fuels

Attribute	Diesel fuel	Natural Gas(NG)	Dimethyl Ether
Cetane number(CN)	40 -59	<6	<55
Auto ignition temperature ^{0}C	250	650	235
Stoichiometric Air fuel ratio	14.6	16.86	9
Calorific Value(KJ/Kg)	$42.5x10^3$	$49.9x10^3$	$28.8x10^3$

Homogeneous mixtures of two different fuels, which have different ignition characteristics, were used in a compression ignition engine to control the ignition and to improve the thermal efficiency. By varying the composition of the fuel mixture, the ignition timing can be controlled as shown in the following Figure.

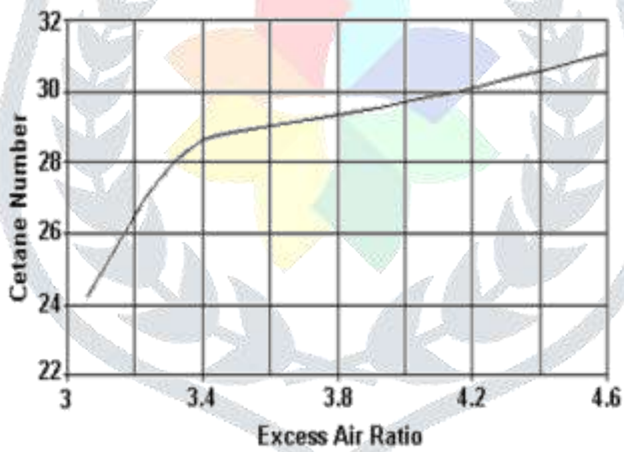


Fig 2 : Relation between CN and λ_{total} at Ta = 320 K, ε = 17.7 for maximum brake thermal efficiency (BTE).

The Fig. shows that the Cetane Number of the mixture increase with increasing the total excess air ratio of Natural-Gas and DME, therefore, by controlling the fuel cetane number, we can control the combustion process of HCCI engine, and this will happen by using a combination of two different fuels. The combustion process of a homogeneous charge compression ignition engine is very sensitive to a substantial influence of a fuel cetane number on cycle indication parameters. A method for controlling physical and chemical composition of a fuel (a usage of a mixed two-component fuel with a component fraction changed in accordance with a known relationship, for example in dependence on mode parameters of an engine) was chosen as a basic operation method for a working process of HCCI engine.

Natural-Gas (NG) with Dimethyl Ether (DME)

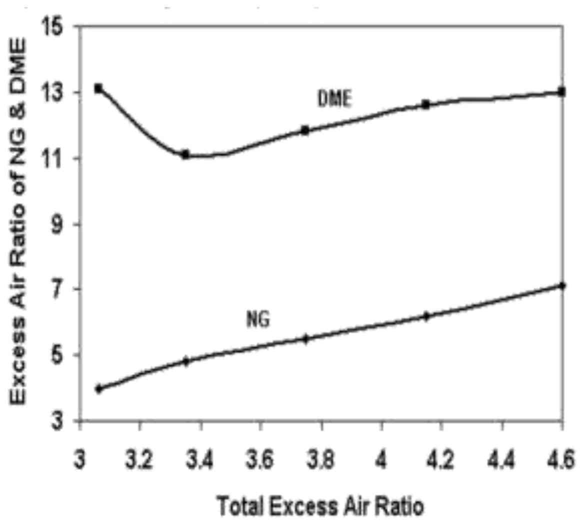


Fig 3: Relation between total excess air ratio (λ_{total}) and excess air ratio of NG + DME A-98 with DME

Homogeneous mixtures of two different fuels like Natural-Gas with Dimethyl Ether (DME), A-98 with DME, CnH_{2n+2} with DME, Diesel-45 with Natural-Gas and others, which have different ignition characteristics, are used in a compression ignition engine to control the ignition and to improve the thermal efficiency. By varying the composition of the fuel mixture, the ignition timing can be controlled

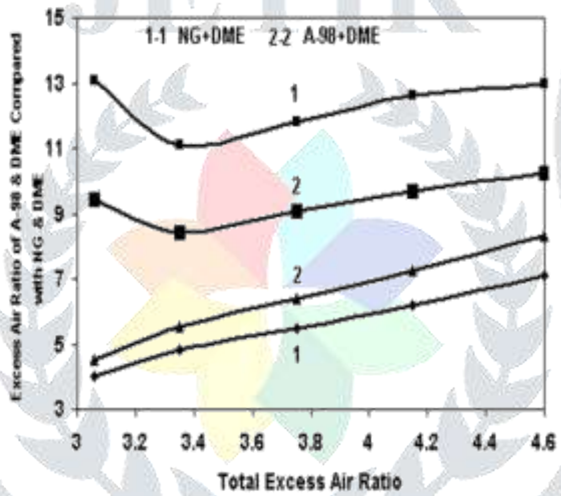


Fig 4. Relation between total excess air ratio (λ_{total}) and excess air ratio of NG + DME & A-98 + DME C_nH_{2n+2} with DME , [n = 1…4]

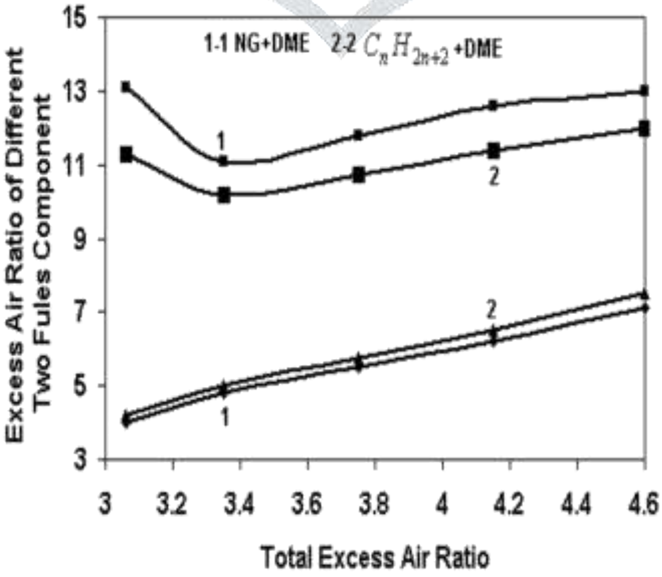


Fig 5. Relation between total excess air ratio (λ t_{otal}) and excess air ratio of NG + DME & CnH2n+2 + DME Diesel-45 with Natural-Gas

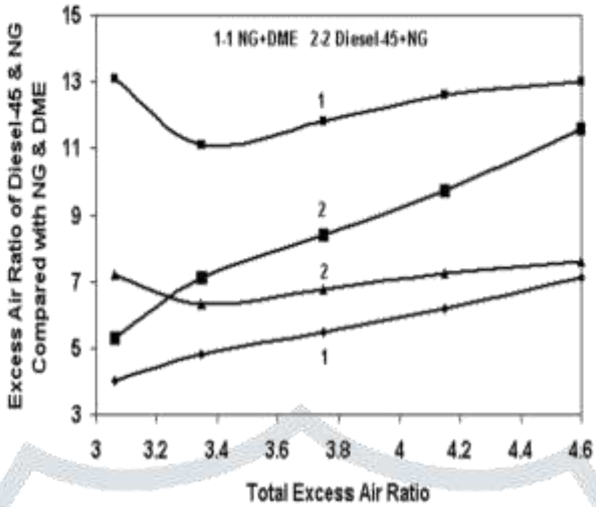


Fig 6. Relation between total excess air ratio (λ $_{total}$) and excess air ratio of NG + DME & Diesel-45 with Natural-Gas Diesel-55 with Natural-Gas

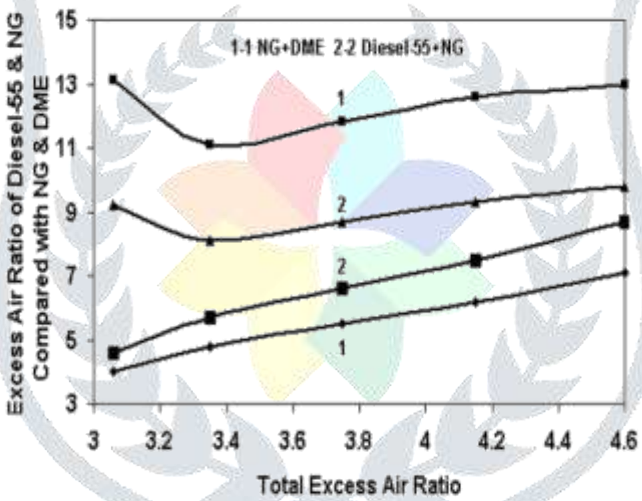


Fig 7. Relation between total excess air ratio (total λ) and excess air ratio of NG + DME & Diesel-55 with Natural-Gas $C_n H_{2n+2}$ with Natural-Gas, [n = 5…10]

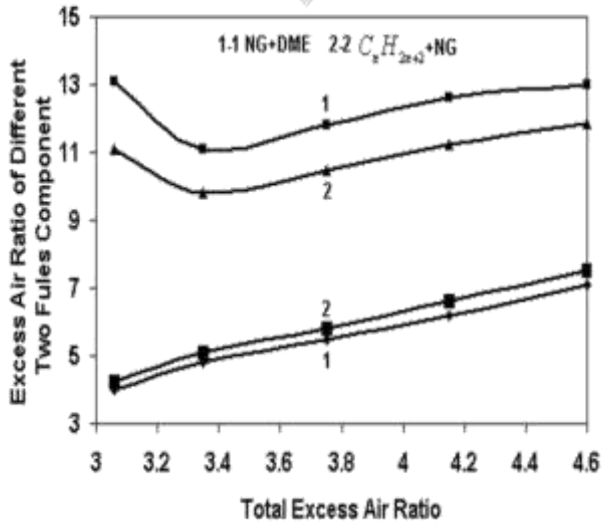


Figure 8. Relation between total excess air ratio ($\lambda\ t_{otal}$) and excess air ratio of NG + DME & $C_n H_{2n+2}$ with Natural-Gas

As shown from the above Fig. that HCCI has been achieved with multiple fuels. Fuels with any Octane or Cetane number can be burned. It was shown that a tested engine can be used for realizing HCCI process with different components of a mixed fuel (a natural gas, a di methyl ether, benzenes with a different octane number, a diesel fuel, individual hydrocarbons providing range for changing Cetane number of a mixed fuel in limits of 24 - 31) and regulation relationships for these components providing maximum efficiency were used to improve the combustion behaviour, control the ignition timing and improve the thermal efficiency of the HCCI engine. Results analyzed that the possibilities of using fuels with different physical and chemical properties in HCCI engines to control the ignition timing and to control the combustion process.

HCCI engines can operate using any type of fuel as long as the fuel can be vaporized and mixed with air before ignition [38]. Since HCCI engines are fully controlled by chemical kinetics, it is important to look at the fuel's auto ignition point to produce smooth engine operation. Different fuels will have different auto-ignition points. Fig.8 shows the initial intake temperature required for the fuel to auto ignites when operating in HCCI mode. It is clearly seen that methane requires a high intake temperature and high compression ratio to auto-ignite, as does natural gas because its main component (typically in a range of 75%-95%) is methane.

It is easily adapted for use as a fuel due to its wide availability, economic and environmental benefits [38]. Its high auto-ignition point gives it a significant advantage over diesel-natural gas operation by maintaining the high CR of a diesel engine and lowering emissions at the same time [38-32]. It was found that methane is suitable for high CR engine operations[40] and results from a four stroke HCCI engine simulation have shown that methane did not ignite if the intake temperature was less than 400K with CR=15 [37]. Where methane will only auto-ignite with intake temperature less than 400K when CR>18.

If the Indicated Mean Effective Pressure (IMEP) is increased, it can reduce the intake temperature required on a HCCI engine. Increasing the CR has the same effect [36]. However, the intake temperature required for hydrogen is lower than that for natural gas in HCCI engines without increasing the IMEP or the CR [35]. This is due to hydrogen having a lower density than natural gas. Hydrogen can operate as a single fuel in a HCCI engine but it works in an unstable condition and is prone to generate knocking [33]. It has the highest diffusivity in air, about 3-8 times faster, which leads to fast mixing [32] and the intake charge can be considered homogeneous when mixed with air [31]. Its net heating value is almost 3 times higher than diesel (119.93 MJ/kg compared to 42.5 MJ/kg) with a high self-ignition temperature to initiate combustion (858 K) [33]. Hydrogen and natural gas are mainly used as fuel additives or even as a single fuel in IC engines due to their practicality and availability. Car manufacturers are producing cars powered by fuel-cells (using hydrogen), as well as engines operated with compressed natural gas (CNG). They are purposely built to reduce emissions and be more economical than gasoline and diesel. Iso-octane is used as a surrogate fuel for gasoline in engine experiments while n-heptane is used for diesel [49]. Hydrogen and natural gas are mainly used as fuel additives or even as a single fuel in IC engines due to their practicality and availability. Car manufacturers are producing cars powered by fuel-cells (using hydrogen), as well as engines operated with compressed natural gas (CNG). They are purposely built to reduce emissions and be more economical than gasoline and diesel. Iso-octane is used as a surrogate fuel for gasoline in engine experiments while n-heptane is used for diesel [31]. Alcohol-derived fuels are not widely used due to their complexity to produce.

HCCI engines have some features of both spark ignited (SI) engines and Diesel engines. HCCI engines, like SI engines, are generally premixed and very lean at fuel-air equivalence ratio, <0.5; thus they produce very low NOx and particulate matter (PM) emissions. Yet, HCCI engines typically have high compression ratios, leading to high efficiency similar to that found in Diesel engines. In an SI engine, the combustion event is initiated by a spark, and the timing of the spark is routinely adjusted by an onboard computer called an electronic control unit (ECU). Similarly, the combustion event in a Diesel engine is initiated by injection of the Diesel fuel and the injection time and duration is variable. However, the HCCI engine does not have a spark plug or direct fuel injection; the combustion event occurs when the cylinder contents are hot enough (approximately 1000-1200 K) for a long enough time (order ~ 1 millisecond).

The effect of biodiesel content on HCCI engine performance and emission characterization has been studied where combustion experiments are performed in a two cylinder engine, in which one cylinder operates in HCCI mode while other operates in a conventional diesel engine cycle. The basic requirement of the HCCI engines of homogeneous mixture of fuel and air is fulfilled by port fuel injection strategy, in which an external mixing device is used for fuel vaporization. This fuel vaporizer provides highly premixed charge of fuel and air. HCCI engine is operated with various blends of biodiesel (B20, B40, B60 and B80) and 100% biodiesel (B100). Experimental results of engine tests included combustion and exhaust composition at different engine load and speed conditions. A partial flow dilution tunnel is used for particulate sampling, which are further analyzed for various metal concentrations in biodiesel HCCI particulates vis-à-vis diesel HCCI particulates.

5. RECENT TRENDS IN HCCI TECHNOLOGY

The biggest challenge of HCCI in gasoline engines is controlling the combustion process. With spark ignition, the timing of the combustion can be easily adjusted by the power train control module, with control of the spark event. That is not possible with HCCI's flameless combustion. [51] The mixture composition and temperature must be changed in a complex and timely manner to achieve comparable performance of spark-ignition engines in the wide range of operating conditions. That includes extreme temperatures--both hot and cold--as well as the thin-air effect of high-altitude driving. To overcome this, designers could use an engine that uses gasoline but switches between spark ignition and diesel-style compression ignition when required, reports (subscription required).If successful, Bosch estimates that a gasoline engine with HCCI and existing technologies such as turbo charging and stop-start systems could be up to 30 percent more fuel efficient than a conventional engine of the same performance. Its first prototype engine will be a 2.0-liter GM Ecotec unit fitted with a supercharger, a turbocharger, direct fuel injection, a stop-start system, variable valve timing, and HCCI compatibility. Researchers hope their prototype will be as powerful as GM's 3.6-liter V-6 but with the 30 percent target for a reduction in fuel consumption. Unfortunately, the technology still appears to be in its early days as the prototype engine won't be completed until sometime in 2014, meaning any commercial release may not appear until closer to the end of the decade.

The Volkswagen Golf 2012 satisfies the lust for performance and stability of the drive with its inbuilt technology that's an appropriate remedy for all types of engine wants [46]. The ability to the two012 Golf Volkswagen is delivered by a 2.0 liter turbocharged four-cylinder that's capable of deployed a horsepower of 266. Emptor will are confronted with the selection of either choosing a conventional six-speed manual transmission and VW's DSG dual-clutch automated manual. The quality all wheel drive permits for a sure-footed handling and thus ensures a snug drive. However, the all wheel drive has been reworked for livelier response and to form all the ability go rearward straightforward. With a sharper handling and quicker acceleration, the Volkswagen Golf 2012 could be a much-desired machine that's positively price investment. The 2012 Golf Volkswagen also will expertise the HCCI engine. HCCI engine could be a petrol engine that behaves a lot of sort of a diesel engine. The behavior of the engine depends on compression primarily needed for bound conditions. The 7-speed DSG can mark the prevalence of the Golf Volkswagen 2012 engine. The automotive has 3 wheelbases, namely, short for the hatchbacks, midsize for Jetta, Tiguan and Golf Variant and Long for Touran and Tiguan XL. The capability to carry baggage is additionally probably to travel up accordingly. The 2012 Golf can have a baggage capability of 405 litres.

Surprisingly, Mazda is passing on today's popular trend of downsized, turbocharged engines—say, a 1.4-liter turbo instead of this 2.0-liter [45]. The company says the next generation of gasoline engines, which will employ HCCI essentially firing a gasoline engine like a diesel, without using the spark plugs—will erode the benefits of downsized engines. Smaller engines reduce pumping losses by operating at a higher load (the throttle is open further) more often. In the same way, HCCI engines will have to flow more air to realize the fuel-saving, lean-combustion benefits of that cycle. Mazda claims that if it downsized the Sky family of engines they wouldn't be able to flow enough air for HCCI without upsizing once again. Plus, as Mazda rightly points out, adding a turbocharger and an intercooler is quite a pricey proposition.

6. FUTURE DIRECTION OF HCCI

It is expected that the vehicle density will increase significantly in coming future, therefore more strict emission regulations has to come. It is very important to make the compulsory use of the control techniques in the vehicles to meet the emission standards. The future study to be focused is on the development of alternative diesel emission control techniques based on the future Indian emission standards. Many challenges remain before HCCI engines are practical. HCCI combustion has several main difficulties. These difficulties include "control of combustion timing," "limited power output," "homogenous mixture preparation," "high unburned Hydrocarbon (HC) and carbon monoxide (CO) emissions," and "weak cold-start capability" HC and CO emissions of HCCI engine are relatively higher in comparison with those of diesel engines . Some potential exists to mitigate these emissions at high load by using direct in-cylinder fuel injection to achieve appropriate partial-charge stratification. However, in most cases, controlling HC and CO emissions from HCCI engines will require exhaust emission control devices where fuel optimization was not used. Catalyst technology for HC and CO removal is well understood and has been standard equipment on automobiles for many years. However, the cooler exhaust temperatures of HCCI engines may increase catalyst light-off time and decrease average effectiveness. As a result, meeting future emission standards for HC and CO will likely require further development of oxidation catalysts for low-temperature exhaust steams. However, HC and CO emission control devices are simpler, more durable, and less dependent on scarce, expensive precious metals than are and PM emission control devices. Thus, simultaneous chemical oxidation of HC and CO in an HCCI engine is much easier than simultaneous chemical reduction of and oxidation of PM in a Compression-Ignition Direct-Injection (CIDI) engine.

At cold start, the compressed-gas temperature in an HCCI engine will be reduced because the charge receives no preheating from intake manifold and the compressed charge is rapidly cooled by heat transferred to the cold combustion chamber walls. Without some compensating mechanism, the low compressed-charge temperatures could prevent an HCCI engine from firing. Various mechanisms for cold-starting in HCCI mode have been proposed, such as using glow plugs, using a different fuel or fuel additive, and increasing the compression ratio using variable compression ratio (VCR) or variable valve timing (VVT). Perhaps the practical approach would be to use Spark Assisted Compression Ignition (SACI) approach as a bridge to the gap between HCCI and SI engines. For engines equipped with VVT, it may be possible to make this warm-up period as short as a few fired cycles, since high levels of hot residual gases could be retained from previous spark ignited cycles to induce HCCI combustion. Although solutions appear feasible, significant research and developing will be required to advance these concepts and prepare them for production engines.

The problem of high HC and CO emissions in HCCI is also linked to control of combustion timing since HC and CO emissions highly depend on the location of ignition timing. Despite the plurality of different proposed solutions, each of the proposed solutions has its own drawbacks. Variable intake temperature, variable intake pressure, and variable coolant temperature have slow response time, while VCR and VVT are technically difficult to implement. Practicality and cost effectiveness are the main concerns with most of the proposed options such as water injection and modulating two or more fuels

One of the major challenges of HCCI is controlling the combustion timing. Combustion timing is defined as the crank angle at which 50% heat release occurs, often called CA50. Each stroke of the piston in the cylinder occurs over 360 crank angle degrees. The point of peak compression is called top dead centre (TDC) and engine timings are referred to in times of degrees after top dead centre (ATDC). Another issue for HCCI engines is that pressure rise occurs very rapidly, because auto ignition occurs nearly simultaneously throughout the combustion chamber. This rapid pressure rise can lead to noise, and potentially damaging knocking conditions within the engine. By avoiding the detrimental effects of rapid pressure rise, an increase in the power output of HCCI engines can be achieved. Better understanding of the HCCI combustion process can be greatly aided by exploration of the chemical processes occurring in the combustion process, such as the effect of fuel structure on combustion timing. It is possible to observe combustion characteristics of the fuel-in-air charge by collecting exhaust samples at different combustion timing. Combustion timing is determined by a number of different parameters, such as equivalence ratio, intake manifold pressure, and intake manifold temperature. The primary influence on combustion timing is the intake manifold temperature of the fuel-in-air mixture inducted into the engine combustion chamber. HCCI research has continued over the past 15 years. Experiments have been conducted in four-stroke engines operating on fuels as diverse as gasoline, diesel, methanol, ethanol, LPG, natural gas, etc. with and without fuel additives, such as iso-propyl nitrate, dimethyl ether (DME), di-tertiary butyl peroxide (DTBT) etc.. From these investigations and many others in the past five years it appears that the key to implementing HCCI is to control the charge auto ignition behaviour which is driven by the combustion chemistry. Even more than in IC engines, compression ratio is a critical parameter for HCCI engines. Using high octane fuels, the higher the compression ratio the better in order to ignite the mixture at idle or near-idle conditions. However, compression ratios beyond 12 are likely to produce severe knock problems for the richer mixtures used at high load conditions. It seems that the best compromise is to select the highest possible CR to obtain satisfactory full load performance. The choice of optimum compression ratio is not clear; and it may have to be tailored to the fuel and other techniques used for HCCI control. An HCCI engine with VCR or VVT could, in principle, operate on any hydrocarbon or alcohol liquid fuel, as long as the fuel is vaporized and mixed with the air before ignition. The importance of turbulence/chemistry interactions on the global ignition event and emissions in HCCI engines has been demonstrated using multidimensional simulations. For lean, low-temperature operating conditions, engine-out NOx levels are low, NOx pathways other than thermal NO are dominant, engine-out NO 2/NO ratios are high, and in-cylinder in homogeneity and unmixed unless must be considered for accurate emissions predictions. Combustion timing is determined by a number of different parameters, such as equivalence ratio, intake manifold pressure, and intake manifold temperature. The primary influence on combustion timing is the intake manifold temperature of the fuel-in-air mixture inducted into the engine combustion chamber. Devices such as electrical heaters, heat exchangers, and exhaust gas recirculation (EGR) control the intake manifold temperature(Tin).The composition of the fuel also plays a major part in the ignition process, as different fuels possess different auto ignition characteristics. Yet still the study should focus more on the technical feasibility of burning blends of natural gas, hydrogen, and DME to improve engine performance, efficiency, and emissions (NOx, CO, CO2, THC, and PM are of interest). Cold-start of the HCCI engine will be handled with the micro-pilot F-T synthetic diesel fuel injection. All engine performance parameters (i.e. indicated mean effective pressure, indicated specific fuel consumption, temperatures, pressures, flow rates, etc.) and emissions (NOx, CO, CO2, THC, CH4, and O2) data to be analyzed. Despite the advantages in terms of higher overall fuel efficiency and lower emission (compared to conventional IC engines), the HCCI engine suffers from several drawbacks such as the difficulty to control ignition timing, low power density, poor performance at high loads, and high un burnt hydrocarbon emissions [50]. Those technological difficulties are a considerable impediment to a wide-spread adoption of HCCI technology and they are topic of current research. Charge stratification, i.e. the introduction of controlled in homogeneities in the temperature and composition of the HCCI charge, is considered a viable solution to the difficulties mentioned above. The presence of in homogeneities in the charge (or stratification) is a challenge to current HCCI modelling methods. The Relative Flow Modelling Laboratory at KAUST is involved in the development of computationally affordable methodologies to numerically predict ignition in an HCCI engine with a thermally and mixture stratified charge. Additionally, we perform research in the fundamentals of the ignition process in HCCI engines under stratification.

REFERENCES

[1]L. Shi, Y. Cui, K. Deng, H. Peng, Y. Chen., " study of low emission homogeneous charge compression ignition (HCCI) engine using combined internal and external exhaust gas recirculation (EGR),'' International Journal of Energy, 31, 2665–2676, 2006.

[2] M. Sjoberg, J. E. Dec, "Comparing late-cycle autoignition stability for single- and two-stage ignition fuels in HCCI engines,'' Proceedings of the Combustion Institute, 31, 2895–2902, 2007.

[3] N.K. Miller Jothi, G. Nagarajan, S. Renganarayanan, "LPG fueled diesel engine using diethyl ether with exhaust gas recirculation,'' International Journal of Thermal Sciences, 47, 450-457, 2008.

[4] D. S. Kim, Ch. S. Lee, "improved emission characteristics of HCCI engine by various premixed fuels and cooled EGR,'' International Journal of Fuel, 85, 695–704, 2006.

[5] X. C. Lu¨, W. Chen, Z. Huang, "A fundamental study on the control of the HCCI combustion and emissions by fuel design concept combined with controllable EGR. Part 1. The basic characteristics of HCCI combustion,'' International Journal of Fuel, 84, 1074-1083, 2005.

[6] J. Chang, Z. Filipi, D. Assanis, T-W Kuo, P. Najt, R. Rask., "Characterizing the thermal sensitivity of a gasoline homogeneous charge compression ignition engine with measurements of instantaneous wall temperature and heat flux,'' International Journal of IMechE, 2005.

[7] P. Yaping, T. Manzhi, G. Liang, L. Fafa, L. Hua , G. Yingnan, "Study the ethanol SI/HCCI combustion mode Transition by using the fast thermal management system, ''Chinese Science Bulletin, vol. 52, no. 19 , 2731-2736, 2007.

[8] J. Olsson, P. Tunestal, B. Johansson, S. Fiveland, R. Agama, M. Willi , D. Assanis,"Compression Ratio Influence on Maximum Load of a Natural Gas Fueled HCCI Engine,'' SAE, 02P-147, 2002.

[9] J. Ma, X. Lü, L. Ji, Z. Huang, "an experimental study of HCCI-DIcombustion and emissions in a diesel engine with dual fuel,'' International Journal of Thermal Sciences, 47, 1235-1242, 2008.

[10] A. S. Premier. (2007, May 17, 2010). HCCI could cut fuel consumption by 15%. Advanced Materials and Processes, P. 27.SREC2010-F2-2 8

[11] A. S. Premier. (2004, May 17, 2010). And they're not hybrids: HCCI engines could bring breakthrough fuel efficiency. Machine Design (21), 43-44.
[12] J.J. Hernandez, J. Sanz-Argent, J. Benajes, S. Molina, “selection of a diesel fuel surrogate for the prediction of auto-ignition under HCCI engine conditions,’’ International Journal of Fuel,87, 655–665, 2008.
[13] A. C. Alkidas, “Combustion advancements in gasoline engines,’’ International Journal of Energy Conversion and Management, 48, 2751- 2761, 2007.
[14] C. S. Daw, R. M. Wagner, K. D. Edwards, J. B. Green, “Understanding the transition between conventional spark-ignited combustion and HCCI in a gasoline engine,’’ Proceedings of the Combustion Institute, 31, 2887–2894, 2007.
[15] X. C. Lu¨, W. Chen, Z. Huang., “a fundamental study on the control of the HCCI combustion and emissions by fuel design concept combined withcontrollable EGR. Part 2. Effect of operating conditions and EGR on HCCI combustion,’’ International Journal of Fuel, 84, 1084-1092, 2005.
[16] M. Yao ,Z. Chen,Z. Zheng,B. Zhang,Y. Xing., “Study on the controlling strategies of homogeneous charge compression ignition combustion with fuel of dimethyl ether and methanol,’’ International Journal of Fuel, 85, 2046-2056, 2006.
[17] Jacques L., Dabadie J., Angelberger C., Duret P., Willand J., Juretzka A., Schaflein J., Ma T., Lendresse Y., Satre A., Schulz C., Kramer H., Zhao H., Damiano L., Innovative Ultra-low NOx Controlled Auto-Ignition Combustion Process for Gasoline Engine: the 4-SPACE Project. SAE Technical Paper Series 2000, SAE 2000-01-1837.
[18] Ryo H., Hiromichi Y., HCCI Combustion in DI Diesel Engine. SAE Technical Paper Series 2003, SAE 2003-01-0745.
[19] M. Canakci, “An experimental study for the effects of boost pressure on the performance and exhaust emissions of a DI-HCCI gasoline engine,’’ International Journal of Fuel, 87, 1503-1514, 2008.
[20] Zheng Z., Yao M., Chen Z., Zhang B., Experimental Study on HCCI Combustion of Dimethyl Ether (DME) / Methanol Dual Fuel. SAE Technical Paper Series 2004, SAE 2004-01-2993.
[21] A report to the U.S. Congress, “Homogeneous Charge Compression Ignition (HCCI) Technology ’’, 2001.
[22] Yap D., Megaritis A., Wyszynski M. L., An Investigation into Bioethanol Homogeneous Charge Compression Ignition (HCCI) Engine Operation with Residual Gas Trapping. Energy & Fuels 2004, 18, 1315-1323.
[23]Yap D., Megaritis A., Wyszynski M. L., An Experimental Study of Bioethanol HCCI. Combustion Science and Technology 2005 (subm Feb).
[24] Jun D., Iida N., A Study of High Combustion Efficiency and Low CO Emission in a Natural Gas HCCI Engine. SAE Technical Paper Series 2004, SAE 2004-01-1974.
[25] Stenlåås O., Christensen M., Egnell R., Johansson B., Mauss F., Hydrogen as Homogeneous Charge Compression Ignition Engine Fuel. SAE Technical Paper Series 2004, (04SFL-229).
[26]Wyszynski M. L., Megaritis A., Karlovsky J., Yap D., Peucheret S., Lehrle R. S.,Xu H., Golunski S., Facilitation of HCCI Combustion of Biogas at Moderate Compression Ratios by Application of Fuel Reforming and Inlet Air Heating. Journal of KONES Internal Combustion Engines 2004, 11, (3-4).
[27] Christensen M., Hultqvist A. Johansson B., Demonstrating the Multi Fuel Capability of a Homogenous Charge Compression Ignition Engine with Variable Compression Ratio. SAE Technical Paper Series 1999, SAE Paper 1999-01-3679.
[28] Chen Z., K., M., O., M., Y., T., Experimental Study of CI Natural-Gas/DME Homogeneous Charge Engine. SAE Technical Paper Series 2000, SAE 2000-01-0329.
[29] Toshio S., Yoshitaka O., HCCI Combustion of Hydrogen, Carbon Monoxide and Dimethyl Ether. 2002, SAE 2002-01-0112.
[30] S. V. Gusakov, Mahmoud Mohamed El-Ghobashy El-Hagar, Thermal Engineering and Internal Combustion Engine Department Fuel requirements for HCCI engine operation "design of the high thermal efficiency HCCI engine running on DME".
[31] J. M. G. Antunes, R. Mikalsen and A. P. Roskilly, "An investigation of hydrogen-fuelled HCCI engine performance and operation," Int J Hydrogen Energy, vol. 33, pp. 5823-5828, Oct 2008.
[32] S. Aceves and D. Flowers, "Engine shows diesel efficiency without the emissions," ed: Lawrence Livermore National Laboratory, 2004.
[33] S. B. Fiveland and D. N. Assanis, "A Four-Stroke Homogeneous Charge Compression Ignition Engine for Combustion and Performance Studies," SAE Paper 2000-01-0332, 2000.
[34] Masahiro S., Masato K., Ali M., Kiyoshi K., Shingo E., Knock Characteristics and Performance in an SI Engine With Hydrogen and Natural-Gas Blended Fuels. SAE Technical Paper Series 2004, SAE paper No. 2004-01-1929.
[35] N. Saravanan and G. Nagarajan, "An experimental investigation on hydrogen fuel injection in intake port and manifold with different EGR rates," Energy Environ, vol. 1, pp. 221-248, 2010.
[36] P. M. Duc and K. Wattanavichien, "Study on biogas premixed charge diesel dual fuelled engine," Energy Convers Manage, vol. 48, pp. 2286- 2308, Aug 2007.
[37] R. G. Papagiannakis and D. T. Hountalas, "Combustion and exhaust emission characteristics of a dual fuel compression ignition engine operated with pilot Diesel fuel and natural gas," Energy Convers Manage, vol. 45, pp. 2971-2987, Nov 2004.
[38] Karim GA. Hydrogen as a spark ignition engine fuel. Int J Hydrogen Energy 2003:28:569–577.
[39] J.M. Gomes Antunes, R. Mikalsen, A.P. Roskilly ,Sir Joseph Swan Institute for Energy Research, Newcastle University, United Kingdom. An investigation of hydrogen-fuelled HCCI engine performance and operation
[40] L. Xingcai, H. Yuchun, Z. Linlin, H. Zhen, “Experimental study on the auto-ignition and combustion characteristics in the homogeneous charge compression ignition (HCCI) combustion operation with ethanol/nheptane blend fuels by port injection,’’ Fuel, 85 , 2622–2631, 2006.
[41] K. Yeom, J. Jang, Ch. Bae, “Homogeneous charge compression ignition of LPG and gasoline using variable valve timing in an engine,’’ International Journal of Fuel, 86, 494-503, 2007.

[42] X. Lü, L. Ji, L. Zu, Y. Hou, C. Huang, Z. Huang, "Experimental study and chemical analysis of n-heptane homogeneous charge compression ignition combustion with port injection of reaction inhibitors,'' International Journal of Combustion and Flame, 149, 261-270, 2007.
[43] VW Golf – VW Southtown Utah, www. http://volkswagenutah.wordpress.com, 14th June 2011.
[44] A. Dubreuil, F. Foucher, Ch. Mounaı¨m-Rousselle, G. Dayma ,Ph. Dagaut, "HCCI combustion: Effect of NO in EGR,'' Proceedings of the Combustion Institute, 31, 2879-2886, 2007.
[45] Dave vanderwerp, "Mazda Skyactiv-G and Skyactiv-D Engines in Detail" www.caranddriver.com, August 2010.
[46] Sam Abuelsamid, "GM HCCI Engine can operate at idle", www.green.autoblog.com, 26th Jun 2008.
[47] M. F. Yao, Z. L. Zheng and H. F. Liu, "Progress and recent trends in homogeneous charge compression ignition (HCCI) engines," Prog Energy Combust Sci, vol. 35, pp. 398-437, Oct -2009.
[48] K. Inagaki, T. Fuyuto, K. Nishikawa, K. Nakakita, I. Sakata, "combustion system with premixture-controlled compression ignition,''R&D Review of Toyota CRDL Vol.41 No.3, 2006.
[49] J.-O. Olsson,et al., "Compression Ratio Influence on Maximum Load of a Natural Gas Fueled HCCI Engine," SAE Paper 02P-147, 2002.
[50] Antunes JMG, Roskilly AP. The use of H2 on compression ignition engines. In: Third European congress on economics and management of energy in industry, 6th–9th April 2004.
[51] "Bosch Hard At Work On Sparkless Ignition HCCI Engine", Seek mind (motor authority),24thJanuary2012,http://www.seekmind.com/2012/01/bosch-hard-at-work-on-sparkless.html