



Laser-assisted homogeneous charge ignition in a constant volume combustion chamber

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ABSTRACT

Homogeneous charge compression ignition (HCCI) is a very promising future combustion concept for internal combustion engines. There are several technical difficulties associated with this concept, and precisely controlling the start of auto-ignition is the most prominent of them. In this paper, a novel concept to control the start of auto-ignition is presented. The concept is based on the fact that most HCCI engines are operated with high exhaust gas recirculation (EGR) rates in order to slow-down the fast combustion processes. Recirculated exhaust gas contains combustion products including moisture, which has a relative peak of the absorption coefficient around 3 μm . These water molecules absorb the incident erbium laser radiations ($\lambda = 2.79 \mu\text{m}$) and get heated up to expedite ignition. In the present experimental work, auto-ignition conditions are locally attained in an experimental constant volume combustion chamber under simulated EGR conditions. Taking advantage of this feature, the time when the mixture is thought to “auto-ignite” could be adjusted/controlled by the laser pulse width optimisation, followed by its resonant absorption by water molecules present in recirculated exhaust gas.

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1. Introduction

The automotive industry is striving hard to reduce the fuel consumption and harmful engine out emissions. These harmful emissions are products of incomplete combustion except oxides of nitrogen, which are combustion products formed due to high temperature prevailing in the combustion chamber. There are two distinct approaches to reduce these emissions and fuel consumption; the first is to improve the conventional internal combustion concept and the second is to develop a new combustion concept. Homogeneous charge compression ignition is a new combustion concept. In a homogeneous charge compression ignition (HCCI) engine, air and fuel are premixed to form homogeneous mixture and as soon as the piston reaches top dead centre (TDC) during the compression stroke, the mixture auto-ignites at multiple locations in combustion chamber simultaneously, releasing heat at a very rapid rate in relatively much smaller combustion duration. This new combustion concept combines the advantages of both, gasoline and diesel combustion (spark ignition (SI) and compression ignition (CI)), i.e., the high efficiency of a diesel engine and

low soot emissions of a gasoline engine. However, unlike either of these combustion concepts, combustion occurs simultaneously throughout the combustion chamber rather than in the form of a definite flame front traversing through the combustion chamber as in the case of a SI engine or mixing controlled combustion of fuel droplets as observed in a CI engine.

HCCI combustion was first discovered as an alternative combustion concept for two-stroke internal combustion engines by Onishi et al. [1]. A profound increase in the level of research and development of this technology took place in the last decade due to huge potential benefits, it offers. This has been directly attributed to significant potential of this technology for enhancing engine fuel economy and reducing emissions for automobiles/engines.

HCCI combustion is achieved by controlling the temperature, pressure, and composition of the fuel–air and exhaust gas recirculation (EGR) mixture so that it spontaneously auto-ignites in the engines. The control system for this is fundamentally more challenging as compared to a spark plug/fuel injector used in SI/CI engines. For HCCI, the control of ignition timing is extremely critical. The recent advancements in electronic engine controls have enabled consideration of HCCI combustion for application in commercial engines. In spite of this, several technical challenges still remain to be resolved in order to make HCCI engines practical

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to a wide range of applications and viable for high volume production. Some of the important challenges include: (1) controlling auto-ignition timing and rate of combustion over a wide range of engine operating conditions, (2) extending the operating range of HCCI to include high engine loads, (3) cold-start capabilities and quick transient response and (4) minimizing hydrocarbon and carbon monoxide emissions.

Controlling the operation of a HCCI engine over a wide range of speeds and loads is the most difficult technical challenge. HCCI is affected by the fuel-air mixture composition, its time-temperature history, and to a lesser extent on cylinder pressure. Several potential control methods have been proposed to control HCCI combustion; e.g. varying the amount of EGR [2,3], using a variable compression ratio (VCR) [4], and using variable valve timing (VVT) to change the effective compression ratio/ or the amount of hot exhaust gases retained (internal exhaust gas recirculation; IEGR) in the cylinder.

HCCI combustion is dominated by the rate of local chemical kinetic reactions [5], with no requirement for flame propagation. This notion has been supported by spectroscopic data indicating that the order of radical formation in HCCI combustion corresponds to self-ignition rather than flame propagation [6,7]. Recent analytical developments also support the view that HCCI combustion is dominated by chemical kinetics, and an analytical method based on this premise has had considerable success in predicting HCCI combustion and emissions [8]. If a truly homogeneous mixture exists at the time of combustion, turbulence has little direct effect on HCCI combustion, but it may have an indirect effect by altering the temperature distribution and the boundary layer thickness near the cylinder walls. Small temperature difference inside the cylinder has a considerable effect on combustion due to the sensitivity of chemical kinetics to temperature. As a result, heat transfer and mixing are important in attaining the condition of the charge suitable for ignition.

The control of combustion phasing in a HCCI engine is done by manipulating the pressure and temperature conditions by regulating the intake valve closure (IVC). Since cylinder contents follow a polytropic process during the compression stroke, all thermodynamic states during compression are known once the conditions at IVC are fixed. Control strategies for HCCI engines will have to utilize some form of closed loop control and adjust the valve timing to change the in-cylinder residual gas levels (IEGR) to obtain the desired combustion phasing. The problem arises when the piston reaches TDC position during the compression stroke and suitable conditions for auto-ignition have not been achieved. In such a situation, there are not many options, which can be exercised to stimulate ignition. Thus, lack of direct ignition control is a serious issue for HCCI combustion and engine development.

Kopecek et al. [9] investigated using laser to generate plasma to assist the HCCI combustion and thereby having some degree of control over the HCCI combustion. It was also demonstrated that the laser plasma could sustain HCCI combustion even at much lower inlet temperature than normally required. One of the other problem that exists with HCCI combustion concept is the exact definition of the start of the auto-ignition, which is very sensitive to variations in the inlet temperature and mixture inhomogeneity.

A new concept of a resonant 'start of auto-ignition' initiated by a focused-pulsed laser beam with a wavelength around $3\ \mu\text{m}$ is presented in this manuscript. The concept is based on the fact that most HCCI engines are operated with high EGR rates in order to slow-down the rapid combustion (auto-ignition), which gets completed within few crank angle degrees (CAD) close to the top dead centre during the end of the compression stroke/early expansion stroke. This research investigates experimental feasibility of this concept by simulating EGR in a constant volume

combustion chamber by adding known quantity of water (moisture) thus slowing down the combustion assisted by laser absorption.

Around $3\ \mu\text{m}$ wavelength range, different cheap and reliable laser systems are available commercially, which can be used for engine applications. For the first demonstration of this concept, a flash lamp-pumped Er,Cr:YSGG (erbium, chromium-doped yttrium scandium gallium garnet) laser ($\lambda = 2.79\ \mu\text{m}$) was used in the present experiments.

2. Experimental setup

For the demonstration of this concept, experiments were carried out in a constant volume combustion chamber. The internal diameter and length of the combustion chamber were 70 and 220 mm, respectively. Combustion chamber is heated up to 473 K (200 °C) for every test run. Liquid fuel (n-heptane) can be injected using an injection needle into the combustion chamber through the septum located at the top of the combustion chamber. Moisture is required to simulate EGR in the chamber, hence water can also be injected into the heated chamber using the same septum. The water quickly evaporates because the temperature inside the combustion chamber is maintained at 200 °C. Before every injection, the combustion chamber was evacuated to avoid possibility of any residual fuel/moisture. After fuel/water injection, the chamber was filled with air up to calculated chamber pressure. The experimental setup can be seen in Fig. 2.

As ignition source, a flash lamp-pumped Er,Cr:YSGG laser ($\lambda = 2.79\ \mu\text{m}$) with pulse duration of approximately 100 μs , fixed frequency of 20 Hz and variable average power of up to 6 W has been used in the present investigation. Pulse width of 100 μs is however quite long to produce a non-resonant breakdown of gas molecules. This laser has maximum pulse energy of 300 mJ per pulse. This laser system is normally used for dental applications. The beam profile was nearly Gaussian. The laser beam was guided through a fibre into combustion chamber where it was collimated using an uncoated CaF_2 lens ($f = 20\ \text{mm}$) to a beam radius of approximately 5 mm. The beam was again focussed into the combustion chamber at a point using another uncoated CaF_2 lens ($f = 80\ \text{mm}$) attached to the sapphire window of the combustion chamber. Inside the chamber, laser pulse energy was absorbed by the water molecules which stimulate/initiate the auto-ignition of the cylinder charge. Initially, laser beam was introduced into the combustion chamber without focussing on a point. In this condition, auto-ignition of fuel-air mixture was not achieved.

In the present study, initial chamber filling pressures between 6 and 8 bars and auto-ignition temperatures between 230 and 245 °C have been investigated. Air-fuel equivalence ratio is varied between 0.8 and 1.5 and water content up to 0.3 ml. Laser energy per pulse was also varied to investigate the effect of pulse energy on the ignition initiation.

Initially, the experiments were carried out to ensure the effect of moisture addition to the chamber contents in order to ascertain its effect on ignition. Experiments were carried out in the constant volume combustion chamber with cylinder contents (without water addition) and it was found that transmitted laser intensity was almost same as that of the incident laser intensity and there was hardly any laser absorption by the cylinder contents, suggesting that the fuel-air mixture does not absorb the incident laser energy. In this experiment, combustion of the cylinder contents did not take place. The same experiment with identical experimental conditions was repeated with cylinder contents having moisture. It was observed that approximately 96–97% of the incident laser energy was absorbed by the constituents of the combustion chamber, leading to combustion of fuel-air mixture.

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