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Review and recent developments of laser ignition for internal combustion engines applications

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A B S T R A C T

Performance of future ignition system for internal combustion engines should be reliable and efficient to enhance and sustain combustion stability, since ignition not only initiates combustion but also influences subsequent combustion. Lean burn systems have been regarded as an advanced combustion approach that could improve thermal efficiency while reducing exhaust gas emissions. However, current engines cannot be operated sufficiently lean due to ignition related problems such as the sluggish flame initiation and propagation along with potential misfiring. A high exhaust gas recirculation engines also has similar potential for emissions improvement, but could also experience similar ignition problems, particularly at idle operation. Similarly, ignition is an important design factor in gas turbine and rocket combustor.

Recently, non-conventional ignition techniques such as laser-induced ignition methods have become an attractive field of research in order to replace the conventional spark ignition systems. The fundamentals of conventional laser-induced spark ignition have been previously reviewed. Therefore, the objective of this article is to review progress on the use of such innovative techniques of laser-induced ignition including laser-induced cavity ignition and laser-induced multi-point ignition. In addition, emphasis is given to recent work to explore the feasibility of this interesting technology for practical applications concerning internal combustion engines.

Contents

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1. Introduction

With increasing restrictions being placed on emissions from modern reciprocating engines as well as increasing demands for higher engine efficiency [1–8], the traditional spark ignition system could face its practical durability limit, as well as its effectiveness cap where igniting ultra-lean fuel/air mixtures is concerned [3]. By shifting to leaner fueling conditions, cooler combustion can be maintained, through which nitric oxides (NO_x) emissions can be dramatically reduced in engines [4–8]. Higher thermal efficiencies can also be achieved due to lower heat loss and higher compression efficiency [6–8]. The increasing of in-cylinder pressure at the time of ignition allows the engine designer to increase the engine efficiency by increasing the power per unit piston area. Such increases in in-cylinder pressure and leaning of the fuel/air mixture are currently limited by the durability of the ignition system and its ability to ignite leaner mixtures at higher pressures.

With conventional spark ignition systems performing well at normal operating conditions, the energy supplied by ignition systems is well above the minimum ignition energy (typically in the order of several tenths of mJ) compared to the order 1–10 mJ of minimum ignition energy required for most hydrocarbons, depending on the mixture strength. However, some future developments in spark ignition engines may require significantly higher spark energies such as those for lean burn high compression ratio engines used for large bore lean burn natural gas fueled engines. Similar ignition energies are required for engines which use alternative fuels such as methane (CH_4), for multi-fuel engines which use a variety of liquid fuels, for low temperature starting of alcohol fueled engines and even for homogeneous charge gasoline engines to enhance early flame growth and improve tolerance to the higher rates of exhaust gas recirculation (EGR) used to reduce NO_x emissions.

However, higher spark energies do not always improve ignitability, but they also decrease spark plug lifetime through increased electrode erosion [9]. Electrode erosion may inherently increases the maintenance cost incurred by users and hence quickly negates any benefits gained. Furthermore, the electrodes act as a thermal energy sink, by taking away a considerable portion of discharge energy thereby reducing the amount of energy that is transferred to the gas for ignition [2]. The development of lean charge associated with fast burn engines requires enhanced ignition devices, through which proper means for increasing the rate of burn of lean mixtures can be obtained. A durable high-energy electrode-less ignition system is therefore a desirable option for overcoming this limitation in higher efficiency ultra lean mixture reciprocating engines [10–12].

For this purpose, various ignition systems have been proposed [9,13,14]; these include high-energy spark plugs, plasma jet igniters, rail plug igniters, laser-induced ignition, flame jet igniters, torch jet igniters, pulsed-jet combustion, and exhaust gas recirculation ignition systems. Many of these systems have features which improve the delivery of ignition energy to the combustible mixture or allow the ignition energy to be dispersed throughout the combustible charge [9]. Among these, laser sources for initiating combustion have many potential advantages and have become an attractive field of research in order to replace the conventional electrical discharge systems [1–8,10–21], despite some limitations that still exist.

Laser-induced spark is a reasonable point energy source in which the amount of energy, the rate of its deposition and ignition timing can be controlled precisely. It also permits the choice of optimal ignition location, which is not easy in conventional ignition systems. In addition, the absence of a material surface in the vicinity of the ignition location minimizes the effect of heat loss during flame kernel development and hence, the lifetime of a laser ignition system is expected to be significantly longer than that of conventional spark ignition systems [21]. Furthermore, for equivalent amounts of system input energy delivered to the spark, the laser ignition system provides a much larger initiating spark volume as compared to an electrical spark [2]. Moreover, laser ignition is capable of providing multi-point ignition sites [19,20,22–24], that can be controlled to ignite a gaseous combustible mixture either sequentially or simultaneously rather comfortably as compared to conventional electric ignition systems using spark plugs. These characteristics not only provide valuable research areas but also, if the overall size of laser units can be reduced sufficiently, potentially improve practical igniters, albeit requiring suitable windows for laser beam access.

Recently, the conventional techniques and fundamentals of laser-induced ignition have been reviewed extensively [9,25,26]. Therefore, the objective of this paper is primarily to examine and review developments with the innovative techniques of laser-induced ignition and to identify promising systems which might aid in the development of future combustion related applications. In this regard, only a brief review of laser-induced ignition fundamentals is included while more detailed comments on the present developments of new laser-induced ignition techniques including laser-induced cavity ignition and laser-induced multi-point ignition is presented. In addition, recent work concerning applications of laser-induced ignition to practical engines is covered.

2. Fundamentals of laser-induced ignition

Laser-induced ignition has been tested and/or used for a wide variety of applications in many practical combustion devices including, ignition of gaseous fuels in internal combustion engines [2,5–8, 27,28]; ignition of high explosives [29,30]; ordnance [31–33] and rocket motors [34,35]; ignition of liquid fuel sprays [36–39] as used in turbines [40,41] and jet engines [42]; flameholders and stabilizers for supersonic combustion applications [43].

Fundamentally, there are four different mechanisms by which laser light can interact with a combustible mixture to initiate an ignition event. They are referred to as thermal initiation, photochemical ignition, resonant breakdown, and non-resonant breakdown [25,26]. The relative importance of each mechanism depends on the wavelength of the laser beam used.

2.1. Thermal initiation

Thermal ignition is initiated when low energy long wavelength laser radiation is incident on a target material that is a strong absorber, solid or gaseous, in a gaseous combustible mixture [2]. Thermal initiation utilizes infrared (IR) laser energy to vibrationally and/or rotationally excite a specific highly absorbing species within the combustible mixture to induce ignition. Ignition takes place when the target absorber transfers sufficient energy to the combustible mixture to cause autoignition.

Although laser equipment are readily available to such a thermal ignition system, they are rather impractical due to their requiring a portions of the system to be sacrificial, similar to erosion in spark plug electrodes, whether it is a fuel additive or a part of the engine. Moreover, as reported by Ronney [25] and Phuoc [26], breakdown-type sources are probably ruled out for line-source ignition studies because of the focusing required to obtain breakdown.

2.2. Photochemical ignition

Photochemical ignition occurs when a high energy photon dissociates a molecule allowing the ionized constituents to react with the surrounding gases [2]. This type of ignition mechanism is similar in concept to the thermal ignition regime; however the