Propulsion and Power Research 2016;5(1):1–21

HOSTED BY

http://ppr.buaa.edu.cn/

Propulsion and Power Research

www.sciencedirect.com

ORIGINAL ARTICLE

Review: laser ignition for aerospace propulsion

Steven A. O'Briant[a], Sreenath B. Gupta[b], Subith S. Vasu[a,*]

[a]*Department of Mechanical and Aerospace Engineering, Center for Advanced Turbomachinery and Energy Research, University of Central Florida, Orlando, FL, 32816, USA*
[b]*Argonne National Laboratory, Argonne, IL, 60439, USA*

Received 13 November 2014; accepted 2 July 2015
Available online 23 February 2016

KEYWORDS

Laser ignition;
Ignition limit;
Scramjet;
Gas turbines;
Rocket;
Plasma ignition;
Propulsion

Abstract Renewed interest in the use of high-speed ramjets and scramjets and more efficient lean burning engines has led to many subsequent developments in the field of laser ignition for aerospace use and application. Demands for newer, more advanced forms of ignition, are increasing as individuals strive to meet regulations that seek to reduce the level of pollutants in the atmosphere, such as CH_x, NO_x, and SO_2. Many aviation gas turbine manufacturers are interested in increasing combustion efficiency in engines, all the while reducing the aforementioned pollutants. There is also a desire for a new generation of aircraft and spacecraft, utilizing technologies such as scramjet propulsion, which will never realize their fullest potential without the use of advanced ignition processes. These scenarios are all limited by the use of conventional spark ignition methods, thus leading to the desire to find new, alternative methods of ignition.

This paper aims to provide the reader an overview of advanced ignition methods, with an emphasis on laser ignition and its applications to aerospace propulsion. A comprehensive review of advanced ignition systems in aerospace applications is performed. This includes studies on gas turbine applications, ramjet and scramjet systems, and space and rocket applications. A brief overview of ignition and laser ignition phenomena is also provided in earlier sections of the report. Throughout the reading, research papers, which were presented at the 2nd Laser Ignition Conference in April 2014, are mentioned to indicate the vast array of projects that are currently being pursued.

*Corresponding author. Tel.: +1 407 823 3468.
E-mail address: subith@ucf.edu (Subith S. Vasu).

Peer review under responsibility of National Laboratory for Aeronautics and Astronautics, China.

http://dx.doi.org/10.1016/j.jppr.2016.01.004

1. Overview of laser ignition

Ignition is defined as the transformation process of a combustible material, from an unreactive state to a self-propagating state, where the ignition source can be removed without extinguishing the combustion process [1]. In the past century, electrical sparks have been the predominant form of accomplishing this process. The desire to achieve a more advanced form of ignition stems from the need to acquire a more efficient ignition of combustible materials, while avoiding undesirable explosions during the process. According to Cardin et al, ignition can be summarized in three successive stages [2]. First, the spark creates initial ignition conditions for energy deposition. The initial breakdown phase results in microsecond scale emissions, followed by a glow discharge phase which deposits most of the energy. The spark is then fully ionized and contains plasma with highly reactive chemical species. After breakdown, the plasma grows and cools. High discontinuities exist between the spark and outer environment, such as temperature and pressure, which lead to the development of a shock wave around the plasma. The shock wave is extremely energetic but cannot ignite the surrounding mixture due to a short propagation time. In the second stage of ignition, the flame develops depending on the initiation of the chemical reactions, which determines whether or not the transition from a kernel of hot gas to a self-sustained flame kernel is possible. Radicals are vital to the ignition process and must be produced in an appropriate quantity during the initiation of the chemical reaction to permit successful ignition of the flame kernel. The final stage of ignition is flame kernel propagation, which leads to flame growth and wrinkling.

According to classical combustion theory, two modes of flame propagation exist, known as deflagrations and detonations [1,3,4]. Deflagrations are characterized by subsonic propagation rates with approximately uniform pressure across the front and reduced density behind the front. Deflagrations may be thought of as thermal conduction waves sustained by a chemical heat release. As opposed to deflagrations, detonations have supersonic propagation rates relative to unburned material. There are substantial pressure increases across the front with a slightly increased density behind it. Detonations may be represented by shock fronts sustained by a chemical heat release. Deflagrations are the primary form of flame propagation in practically all combustion engines and systems. Though some papers [1] have suggested detonation as a form of propulsion for aircraft (such as a pulse detonation engine), detonation is typically an unwanted characteristic in aerospace applications, and steps are usually taken to prevent deflagration-to-detonation transitions (DDT).

Lewis and von Elbe [3] provide a phenomenological description of deflagrations in premixed gases. If ignition energy is greater than the minimum ignition energy (MIE, E_f), at the time when peak temperature decays to the adiabatic flame temperature, T_f, heat is generated in the kernel quicker than it is lost via conduction to the unburned mixture. A steady, self-sustaining deflagration wave results from this ignition and consumes the remaining combustible mixture. However, if the amount of energy is at a subcritical level, below the MIE, and is delivered to the combustible mixture, the resulting flame kernel decays at a rapid rate. This is because the heat and radicals are lost, away from the surface of the kernel, and dissociated species recombine faster than they are regenerated. A realistic conclusion is such that the MIE must be sufficient to raise a sphere of gas, whose radius is the characteristic flame thickness, δ_f, to the adiabatic flame temperature. Typical values of E_f are 0.4 mJ for stoichiometric CH_4-air mixtures and 0.02 mJ for stoichiometric H_2-air mixtures [3]. An estimation for the MIE of deflagration can be seen below in Eq. (1) [1,5], where ρ_f refers to the density and c_p is the specific heat at constant pressure.

$$E_f \approx \frac{4\pi}{3}\delta_f^3 \rho_f c_p \left(T_f - T_0\right) \tag{1}$$

Measurements by McNeill et al. [6] performed on combustion ignition processes by electrical and non-resonant laser sparks describe how spark formation and the subsequent flows (prior to combustion) contribute to minimum ignition energy values. The MIE for laser sparks is found to be higher than electrical sparks, due to the higher energy cost of creating a laser spark and because of efficient removal of the energy absorbed in laser sparks to regions outside the nominal ignition kernel. However, before that study, there were a wide range of MIE values being reported, with no paper published relating the interrelated breakdown and shock phenomena as contributors to a system's ignitability. McNeill et al. found several factors that influence higher MIE's in laser spark ignition. First, additional energy is required for laser breakdown to create a seed electron at the beam focus in order to heat plasma. At threshold, the energy alone can be higher than the thermal MIE, but the breakdown energy could be reduced using a two wavelength system. The existing relationship between laser breakdown energy and lens focal length suggests that with a very short focal length, the MIE for laser spark ignition may approach that of an electrical spark ignition. Certain resonant laser ignition schemes, where a laser is tuned to a transition of a fuel, allows photolysis of combustible fuel mixtures, lowering the required energy for ignition. Secondly, laser sparks are more efficient at generating shocks which propagate omnidirectionally. This is mainly due to equilibration, a condition where a shock wave develops after energy delivered to the plasma electrons transfers to the ions. Denser laser spark plasmas make equilibration more efficient than typical electrical sparks, thus collisional processes prevail and radiative losses are lower. Thirdly, most of the stored laser energy is carried out of the nominal ignition-kernel volume by the shock, and no additional heating occurs after the shock departs. Normally, supplemental heating occurs in the ignition-kernel volume for electrical sparks, but this effect is absent for laser ignition, contributing to a higher MIE.