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ORIGINAL ARTICLE

# Review: laser ignition for aerospace propulsion

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**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.



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## 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, $\delta_f$, 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 $\rho_f$ refers to the density and $c_p$ is the specific heat at constant pressure.

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

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.

### 1.1. Fundamentals of the laser ignition process

According to Ronney [1], laser ignition can be characterized into four categories. Thermal initiation is the first of these types, where no electrical breakdown of gas occurs. In thermal initiation, the laser source heats up a solid target or excites vibrational/rotational modes of different gas molecules. The second type is non-resonant breakdown, which is considered by Tauer et al. [5] to be the most appropriate mechanism for ignition. In non-resonant breakdown, the electrical field strength of a focused laser beam is enough to cause an electrical breakdown of a gas, and is most similar to standard electric spark discharges. A main difference between laser ignition and spark ignition is that small amounts of vapor, dust, and microparticles can reduce the breakdown field strength by orders of magnitude, whereas electrical spark discharges are not usually affected by such phenomena. The third type of laser ignition is resonant breakdown, which is similar to non-resonant breakdown, but includes a non-resonant multiphoton photodissociation of a molecule, followed by a resonant photoionization of atoms created by the previous photodissociation. The final type of laser ignition is photochemical ignition, in which a single photon, typically in the UV range, undergoes dissociation after being absorbed by a molecule. Direct heating of the gas may occur, but due to the species being in thermal non-equilibrium, they may recombine with themselves or other molecules.

When applying the concept of laser ignition to actual application, laser-induced optical breakdown for the use of igniting combustible gas mixtures may be done by using laser ablation ignition (LAI) or laser plasma ignition (LPI) [5]. In laser ablation ignition, a laser beam focuses on a target, generating optical breakdown once the intensity in the focal region exceeds a certain threshold. In laser plasma ignition, the concept is the same, but the laser beam is tightly focused into the combustion chamber, and the plasma is formed in free space as opposed to a target in laser ablation. Typically, this threshold for plasma formation in LPI is one hundred times greater than target surfaces in LAI. Laser ablation is typically employed for use in rocket engines and spacecraft designs because, just as in chemical rockets, thrust is produced from the resulting reaction force. Plasma ignition on the other hand, is typically found in internal engines, since ignition of the plasma drives moving parts, such as in a cylinder. In either case, plasma formation is based on ionization of atoms and molecules around the focal point followed by acceleration of ionized electrons. This causes collisions with more neutral atoms of molecules.

### 1.2. Aerospace applications

Applying the concept of laser ignition to extreme flight regimes, such as supersonic and hypersonic flows, is one of the most challenging, yet fruitful pursuits in the field of aviation. There are many benefits to all areas of aerospace study. Possibilities include multiple ignition positions in time and space, precise ignition timing, controllability of input energy and its duration, more stable combustion, ignition of leaner fuel mixtures, and ignition of high pressure mixtures [7]. Generation and maintenance of a laser is also much less than other forms of ignition, making the prospect of laser ignition promising from an economic standpoint. In supersonic and hypersonic engines, such as scramjets, internal regions where combustion occurs can receive energy instantaneously through laser igniters, without using electrodes, found in conventional ignition methods. Since the laser ignition system is electrodeless, there are no cooling effects associated with electrode use [8]. Laser use also allows the laser radiation energy to focus its intensity directly on the jet fuel, creating a spark [9,10]. Laser ignition offers several advantages in internal combustion engines as well, such as the absence of electrodes which disturb the cylinder geometry (thus quenching a flame kernel), and variable ignition positions within the combustion cylinder [7].

Using a laser ignition system with the aforementioned benefits would allow for progress in the field of hypersonic aviation. An aircraft travelling at hypersonic speeds can cover immense ground in a short period of time. For example, a hypersonic aircraft travelling at Mach 5 can cover 7600 miles in roughly a 2 hour time frame. Considering that the distance between Los Angeles and Tokyo is approximately 5400 miles, a hypersonic flight carrying commercial goods and/or passengers over the Pacific Ocean can be completed in almost 90 minutes; a huge improvement over the current average 11 hour flight. Though several commercial platforms have been proposed, such as the Zero Emission Hyper Sonic Transport (ZEHST) and the SpaceLiner, no company currently operates a supersonic or hypersonic transport vehicle for commercial purposes. Laser ignition offers to help advance technological capabilities in this field, which would enable for further commercial development.

The concept of laser ignition and propulsion may also be applied to space travel. Multi-mode engines with built-in scramjet capabilities would allow for quick, cost-effective travel outside Earth's atmosphere. Small microsatellites, weighing between 1–10 kg, can also benefit by using onboard laser propulsion, such as the laser-electrostatic hybrid acceleration thruster [11], which is discussed later in this report. Ground-to-orbit launch vehicles are also proposed using laser propulsion, which would allow rockets a high specific impulse, higher thrust, and a lower propulsion weight.

A high-speed engine also has numerous military applications. A scramjet engine can be utilized in next generation ICBMs (Intercontinental Ballistic Missile) and military aircraft, which would be able to reach distant battlefields across the globe in minutes, rather than hours. The United States Air Force (USAF) has experimented with the viability of air-breathing, high-speed scramjet propulsion in the form of the X-51A Waverider. During its final flight

**Figure 1** X-51A Waverider attached to B-52 mothership. (*source:* United States Air Force).

in 2013, the X-51A was dropped via B-52 and used a solid rocket booster for its initial stage of flight, travelling over 230 nautical miles in six minutes at Mach 5, setting a record for the longest hypersonic air-breathing flight ever. The X-51A can be seen in Figure 1, attached to its mothership, a B-52 Stratofortress. Though the X-51A does not utilize laser ignition, it nonetheless demonstrates the importance of further researching laser ignition, which will help perfect scramjet technology.

The large range of flight conditions experienced by ramjets and scramjets greatly affect how future high-speed aircrafts are designed. The conditions for safe flight may be defined as the flight envelope, with both an upper and lower limit. At higher Mach numbers ($M > 15$), nonequilibrium flow in the region following leading shock waves can influence compression ramp flow, reducing fuel injection efficiency, as well as mixing and combustion efficiency [12]. This leads to large decreases in engine performance and sets the upper limit of the flight envelope at a dynamic pressure of roughly 0.25–0.5 atm. At lower Mach numbers ($M < 3$), it is shown that ramjet operation is insufficient due to poor compression ratios from airflow deceleration. This, alongside thermal and structural limitations, set the lower boundary of the flight envelope, and are limited by a dynamic pressure of 1 atm. Using laser igniters can extend the boundaries of the flight envelope, as plasma-assisted ignition can stabilize ultra-fast combustion at higher Mach regimes ($M = 10$–$20$) and higher altitudes, making it possible to reach regions of low dynamic pressures (0.05–0.2 atm) [12].

## 2. Advanced ignition in aerospace systems

Several categories of engines can benefit from laser ignition. Though all engines could potentially benefit from more advanced ignition methods, such as laser-induced plasma ignition, This section describes the following aeronautical and space applications:

1. Gas turbines, including discussions on new laser "spark plugs" and microwave assisted ignition and their effects on kernel formation.
2. Plasma-assisted ignition, using both conventional electrical spark ignition and laser-induced ignition.
3. Ramjet/scramjet applications and progress thus far, including sections on geometric variances and different fuel characteristics.
4. Space applications, to include studies on laser ablation, applications in rocket design and satellite microthrusters.

### 2.1. *Gas turbines and gas engines*

Laser ignition may be used in various applications besides high-speed, hypersonic aircraft. Examples include standard internal combustion engines, such as in automobiles and aircraft, as well as industrial combustion facilities which generate large amounts power. There are several patents [13,14] which have already expressed possible uses for their inventions in turbojet, turbofan, turboprop, and gas turbine applications. There are also studies, discussed below, that aim to develop a laser "spark plug" that is miniature in size and can fit directly on an internal combustion engine. Pursuing laser ignition in gas turbine systems helps to realize the added benefits of higher engine efficiency and lower pollutant levels in engines that are already in wide scale use today. This section offers to summarize the most current works in the above areas with a focus on gas turbines, gas engines, and methane-air mixtures.

In high-power gas engines, it is often desirable to minimize service effort and keep maintenance to a minimum. Lamp-pumped lasers employ short lifetime arc lamps which are usually changed every 200 to 600 hours. Their optical alignment drifts over time as well, leading to increases in downtime. Laser output usually suffers since frequent realignments are needed. Diode-pumped solid-state lasers offers to remedy these issues, as these lasers convert most of their electrical input into laser light. Diode-pumped lasers contain a higher electrical efficiency, require less cooling water, operate from lower-voltage power supplies, are more compact, and provide many years of uninterrupted operation. These advantages all serve to keep repair and maintenance costs down.

Expanding on earlier work done in 2000 [15], Kopecek et al. [16] performed further experiments in a 2005 study on methane-air mixtures at high pressures and high temperatures using solid-state lasers via non-resonant optical breakdown. Since laser energy is deposited on the order of nanoseconds, generated shock waves and asymmetric shapes of the flame kernel greatly influence combustion, leading to the desire to determine qualitative and quantitative properties of laser ignition using diagnostic methods. Very lean fuel mixtures with an air/fuel-equivalence ratio of up to $\lambda = 2.2$ were successfully ignited with a Q-switched Nd:YAG (neodymium doped yttrium aluminum garnet) laser. However, only ratios below $\lambda = 2.0$ were found to be of practical use (due to increases in ignition delay time and lower peak pressures). This is considerably leaner than

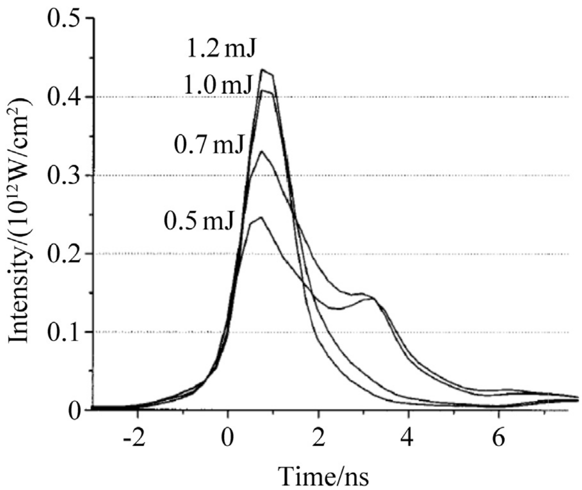



**Figure 2** Averaged shapes of transmitted pulses based on input energy [16].

the limits imposed by ignition via conventional spark plugs (a limit of $\lambda = 1.8$ for commercial gas engines). A compact diode-pumped laser could easily replace a conventional spark plug and provide the required pulse energy (4 to 6 mJ) for mixtures up to $\lambda = 1.8$. Time-resolved transmission measurements were taken in the paper, giving an indication for the ideal pulse shape of future laser-ignition systems, as shown in Figure 2 below. This ideal pulse shape should have a very steep increase for effective plasma formation, followed by a smooth descent to sustain the plasma as long as possible to heat up the flame kernel. The minimum ignition energy was found to decrease as the mean pressure increased. Kopecek et al. demonstrated the usefulness of laser ignition by combusting an air/fuel mixture in one cylinder of a 1 MW natural gas internal combustion engine. A 5 ns pulsed Nd:YAG laser at 1064 nm was used to ignite the mixture. The engine worked successfully during a test period of 100 hours with no interruption at a ratio of $\lambda = 1.8$. A minimum $NO_x$ emission value was achieved at $\lambda = 2.05$ (where $NO_x = 0.22$ g/kWh).

Studies conducted by Michael et al. [17], Wolk et al. [18], and Hayashi et al. [19] provide a possible alternative process to methane-air combustion: laser-initiated microwave-enhanced ignition. There are several advantages by adding sequential microwave pulses following ignition, such as lower laser energy requirements, reduction in the ignition delay time, and a large ignition volume. This type of ignition is only limited by microwave wavelength and seed ionization profile (the placement of a seed laser, pulsed for initial ionization). Adding sequential microwave pulses after ignition allows additional deposits of energy into the flame zone, increasing the kernel growth rate. Through early numerical simulations [17], energy densities deposited by the laser and microwave pulses estimate that microwave deposition is several orders of magnitude stronger than laser energy deposition. A preliminary investigation on the effect of rapid microwave pulse trains on ignition kernel formation and growth show there is a considerable increase in growth rate when the addition of energy takes place in the first few milliseconds after ignition. Wolk et al. theorize that flame enhancement results from non-thermal chemical kinetic enhancement from energy deposition to free electrons in the flame front, and induced flame wrinkling from excitation of plasma instability. It is shown from these findings that flame enhancement is negligible above an initial pressure mixture of 3 bar (conducted in a constant volume chamber). Hayashi et al. demonstrate that the microwave-enhanced plasma technique extended plasma life and lowered the minimum pulse energy for laser ignition. This is true for a wide range of excess air ratios (0.6 to 1.54).

Findings from Michael et al. show two kernel growth rates seen in Figure 3: (a) represents the kernel without additional microwave pulses, while (b) has added microwave pulses at 1 and 2 ms. Figure 4 shows kernel growth rates with no microwave pulses in the top row, and additional microwave pulses in the bottom row, at several millisecond intervals [18]. In both figures, there is a significant increase in the diameter of the kernel in the bottom row of image, indicating the valuable potential of microwave-enhanced ignition.

Knowledge of the minimum ignition energy is essential to the application of laser ignition in the aforementioned methane-air combustion studies. A recent study by Peng et al. [20] tackles the issue of measuring the MIE in high pressure methane-air mixtures in premixed turbulent combustion conditions (similar to Kopecek et al.). A high-pressure, double-chamber (high-pressure outer chamber and a high-pressure fan stirred mixing chamber) explosion facility, characterized by turbulent properties and

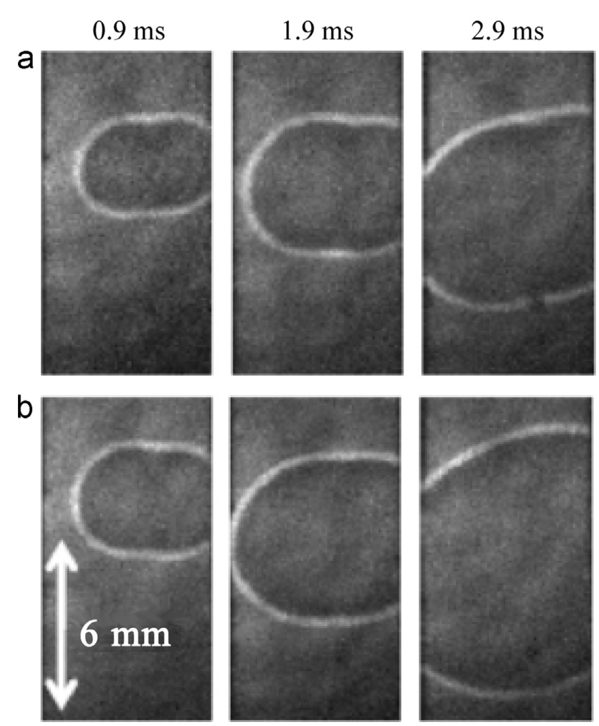



**Figure 3** Shadowgraph of kernel growth rates, $\lambda = 0.8$ [17] (reprinted with permission).

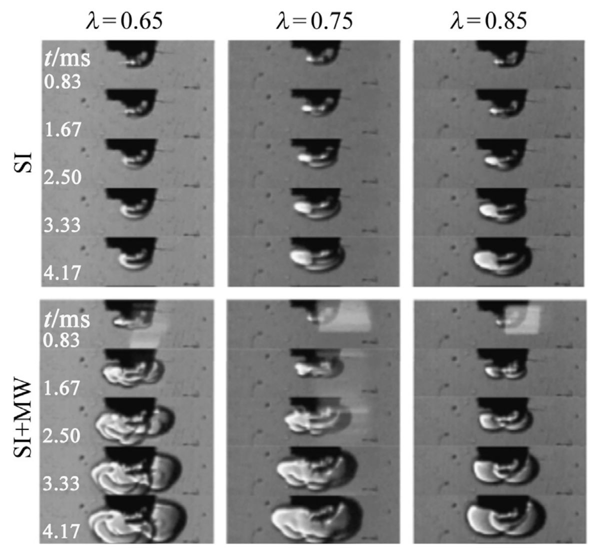



**Figure 4** Schlieren imaging of kernel growth rates, $\lambda=0.65$, 0.75, 0.85 [18] (reprinted with permission).

controllable ignition, was used to measure the MIE and flame kernel formation. Findings indicate that MIE decreases significantly with increasing pressure at any given turbulence (agreeing with findings in Kopecek et al.), but increases with increasing turbulence at a fixed pressure. By varying the turbulence in the system, three modes of flame kernel development are observed, similar to laminar, turbulent-flamelet, and distributed flames. The mechanism of flame kernel formation depends on the surface diffusivity ratio between turbulence and the chemical reaction, represented by the value $Pe^*$. $Pe^*$ is the reaction zone Péclet number with pressure correction. The modified reaction zone $Pe^*$, introduced in this paper, is shown below in Eq. (2), with $p/p_0$ representing the ratio of test pressure to atmospheric pressure.

$$Pe^* = Pe\left(\frac{p}{p_0}\right)^{-1/4} \tag{2}$$

The author recommends a model based on the balance of local ignition energy input and heat losses of ignition kernels in high-pressure turbulent environment to predict MIE transitions at elevated pressures. This model, however, does not consider the unsteadiness of the full ignition process.

In contrast to performing combustion experiments in an enclosed, double-chamber explosion facility, Cardin et al. [2] conducted a similar set of experiments meant to analyze the ignition process of lean, highly turbulent, premixed methane-air flows in a vertical open wind tunnel. During preliminary studies, it was discovered that during plasma cooling, the net increase in radical emissions defined a characteristic chemical time (corresponding to the initiation of chain-branching reactions), which increased significantly with the equivalence ratio in ultra-lean mixtures. Based on the evidence in this part of the experiment, it was concluded that the time required to reach a self-sustaining chemical reaction after breakdown is constant at equivalence ratios $\lambda > 0.7$. In subsequent tests, the MIE values at different equivalence ratios experienced a transition when the turbulence intensity was increased, thus leading to a much larger amount of energy being required to ignite the flow. This is the same observation as experienced with the earlier study by Peng et al. [20]. Before the transition, the smallest time scales of turbulence were larger than the time of initiation of the chain-branching reactions, indicating that the hot kernel and turbulence reaction occurred after the time of initiation of chemical reactions. Larger amounts of deposited energy are required to compensate for turbulent dissipation in order to achieve a self-sustaining flame, due to the hot kernel/turbulent interaction during cooling. Turbulent diffusivity also played an impact on the MIE/$MIE_0$ ratio ($MIE_0$ equaling the minimum energy in laminar flow), which dramatically increased with increasing values of $Pe^*$ after passing the aforementioned transition. This led to significant heat losses, thus requiring more energy to ignite the flow at higher turbulent regimes.

Drawing from prior research in 2007 and 2008 [21–23], McIntyre et al. [24] present a study focusing on the ignition and operation of a single cylinder research engine (filled with either natural gas of hydrogen augmented natural gas) which utilizes a new laser diode end pumped, passively Q-switched laser. A commercial laser spark plug system is sought to increase combustion efficiency at leaner mixtures, and the fiber optic coupled end pumped laser spark plug developed by the researchers is stated as a significant advanced toward producing this system. The work presented extends research performed on a side pumped laser to the development of an end pumped laser system with greatly improved operational characteristics. The new end pumped laser was packaged in such a fashion that the laser was relatively insensitive to heat and vibration, allowing the system to be directly attached to the test engine. The end pumped laser spark plug was mounted directly to the engine and operated at 1800 rpm (as opposed to earlier works, in which the spark plug was detached from the engine and operated at 600 rpm) for 10 hours. Engine emission data taken during the experiment showed that $NO_x$ concentration increased with increasing equivalence ratio due to increasing combustion temperatures. $CO_2$ concentration levels increased and overall hydrocarbons decreased with increasing equivalence ratio as well, due to more complete ignition and combustion. The researchers also added 20% hydrogen (by volume) to the natural gas, which produced results that concurred with the researcher's expectations. $NO_x$ concentrations increased with an increasing equivalence ratio, $CO_2$ concentrations reduced across all equivalence ratios (due to overall availability of carbon in the fuel mix being diluted by hydrogen), and total hydrocarbons decreased since methane was completely burned, and the remaining unburned hydrogen did not add to the concentration of unburned hydrocarbons. These results were due only to stoichiometric variations in the trials. As far as advantages of utilizing the laser spark plug, the experiment showed that the laser-ignited engine performed just as well as conventional spark ignition, but with the added benefit of smoother operation and an extension on the lean mixture limit in both natural gas and hydrogen augmented natural gas. Future works by the authors will include distribution of optical pumping energy to laser plugs in multiple cylinders.

The main driver for achieving a laser ignition system that is cost-effective and has a long lifespan is the pump laser being used. Schwarz et al. [25] compared two pumping concepts for laser ignition in their study for the use of laser spark plugs. The two main concepts studied by Schwarz et al. were edge emitters in combination with gas fibers and VCSELs (vertical cavity surface emitting lasers) in combination with a pump lens. 806 nm edge emitters proved promising at the start of their study; however, system costs proved to be too large and catastrophic optical damage occurred. Using a VCSEL in laser ignition allowed the omission of glass fibers, which reduced cost and increased lifetime value. This concept proved to be the more fruitful of the two, as it did not fail and met their customer's requirements of a long life span and relatively low cost. Groneborn et al. recently performed optimizations on VCSEL power arrays, improving the epitaxial design and the geometrical array layout, reducing the required device area by 50%. A complete pump module that delivers a 500 W pulse output is designed to fit into a 23 mm diameter, small enough for an engine, allowing for low cost, reliable systems as mentioned above.

In addition to different laser ignition systems, studies performed by Yamaguchi et al. [26] provide insight and experimental data on two point laser ignition and conventional spark plug ignition in a single cylinder, lean burn gas engine. With an equivalence ratio of $\lambda = 0.8$, two-point ignition showed a more rapid rise in pressure as compared to single point ignition. The widest stable operational range is achieved with two-point laser ignition (when compared with two point spark plug ignition), and yielded higher thermal efficiency and superior IMEP (indicated mean effective pressure) stability. Further studies by Shiono et al. [27] investigate two-point laser-induced sparks from the perspective of flame kernel formation. During flame kernel formation, a third "lobe", which is a geometric description of the flame kernel itself, may appear. This lobe, which is a characteristic behavior of laser ignition, is not observed at a pressure of 1 MPa for focal point gaps of 0, 1, and 2 mm. Typically, the presence of a third lobe helps with initial flame development. The growth of the flame kernel however, is clearly enhanced at 1 mm with a 1 MPa pressure in the absence of the third lobe.

Saito et al. [28] recently performed tests with laser-induced ignition in an internal combustion engine using an inert gas dilution. In a previous study by the authors, it was found that the in-cylinder pressure and rate of heat release rose faster with laser ignition over spark ignition, leading to a more stable operation of the engine at high EGR (exhaust gas recirculation) fractions utilizing laser ignition. Confirming earlier studies, laser ignition allowed for faster flame propagation, leading to a shorter ignition delay time. At high dilution rates, the operation of the gasoline engine was more stable with laser-induced ignition over conventional spark ignition, and had a larger IMEP.

An alternate method of studying fundamental laser ignition is via a spherical bomb, as described by Vasu et al. [29]. The high-pressure (up to 140 atm), high-temperature spherical facility is optically accessible on 4 sides for schlieren imaging and laser ignition, and was inspired by studies conducted by Farrell et al. [30]. This setup can be seen in Figure 5 and similar apparatus are widely used in literature. Gupta, Bihari and Sekar [31] used a laser ignition rail under lean-burn conditions in a 6 cylinder natural gas engine. This engine was able to run in a lean-burn condition of $\lambda = 1.76$ using laser ignition, as opposed to $\lambda = 1.6$ allowed by conventional ignition. Preliminary results showed that laser ignited combustion allowed for a 60% reduction in $NO_x$ emissions with a 0.8% increase in brake thermal efficiency. There are observable increases in CO and UHC, but are easily reduced with after-treatment systems. Other technologies in conjunction with laser ignition may be needed to achieve the target thermal efficiency of 50%.

As stated earlier, the demand for alternative fuels has increased in recent years. A study by Rahman et al. [7] investigated the use of hydrous ethanol, an alternative liquid fuel, in internal combustion engines via laser ignition. Anhydrous ethanol, which is less than 1% water, is more costly than gasoline, as there is a significant amount of energy required during distillation and dehydration process. Wet ethanol, or hydrous ethanol, may prove a promising alternative to anhydrous ethanol (and possibly gasoline) as it improves the associated energy balance and may reduce costs. Laser ignition is utilized in the experiment due to the advantages it offers, such as the ignition of leaner fuel mixtures, more stable combustion, and variable ignition positions within a combustion chamber. A Q-switched Nd:YAG laser with a 532-nm nanosecond pulse generated the spark in the transient ethanol fuel spray. It was observed

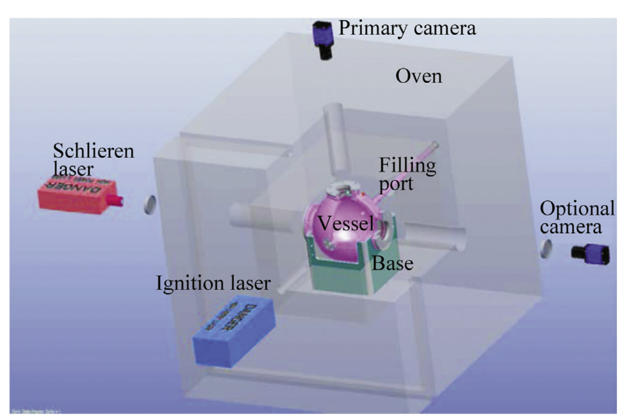



**Figure 5** Spherical bomb configuration, situated in thermcraft XSB-12-12-18-1C 6 kW oven.

that flame luminosity and development with subsequent propagation became weaker and slower, with increases in ignition delay times, at higher water content values. At 20% water content by volume, pressure rise and rate of heat release is practically similar to that of pure ethanol. Incomplete combustion occurred for stratified charge of hydrous ethanol where laser ignition proved feasible up to 30% water fraction volume. At 40% and 50% volume fraction, misfire occurred. This is different compared to a comparative study by Mack et al. [32] in which hydrous ethanol was studied using conventional spark ignition methods in an homogenous charge compression ignition (HCCI) engine. According to Mack et al., stable operation occurred at 40% water fraction, which is higher than the limit of stable operation in laser ignition (30%). This leaves this area of study open on the subject of laser ignition of hydrous ethanol to match the higher performance of conventional spark ignition methods.

A more complex geometry pertaining to gas turbine combustors is swirl flames. Some data from the previous decade are available [33,34], but in all, little work has been done on ignition studies in swirl configurations. As a study addressing innovative solutions for the development on new combustors in aircraft engines, research performed in 2013 by Cordier et al. [35] considered two swirl numbers and investigated their impact on the laser ignition process. The researchers demonstrated that the efficiency of the ignition location (how successful ignition is in various locations) is controlled by both local flow properties and by the flame surface development, which are linked by typical kernel trajectories within the combustion chamber. During long development times, the flame was observed to potentially cross into zones presenting high levels of turbulence, leading to partial or full extinction of the flame. Flame development and stabilization was largely controlled by the cold flow field (flow not ignited and without reaction), implying that location of ignition may be selected based on combustor cold flow. No correlation between local turbulent kinetic energy and ignition probability was observed, as opposed to the results found in the previous studies performed by Marchione and El-Rabii et al. [33,34].

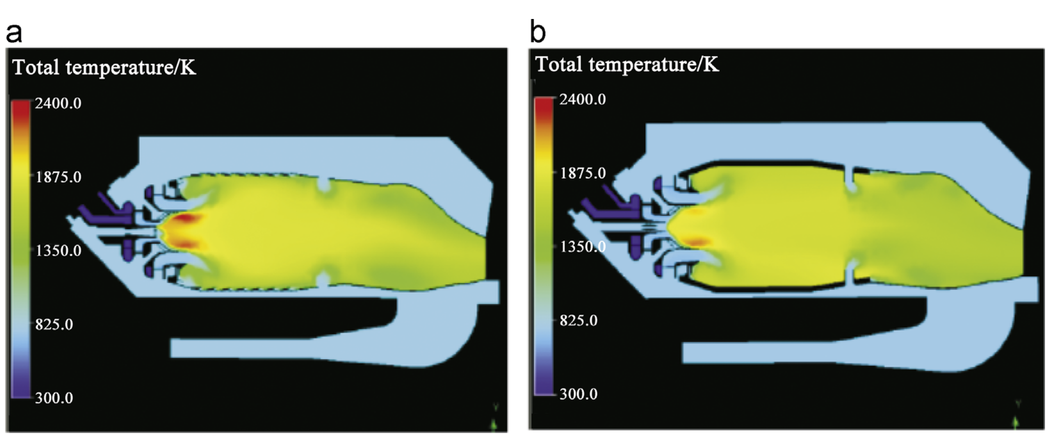
Though not entirely devoted to laser ignition, a study performed by Serbin et al. [36] investigated the possibility of improving gas turbine performance through plasma assisted combustion, and warrants discussion. Using computational fluid dynamics (CFD) and mathematical modeling, a 25 MW gas turbine was investigated using a partially premixed lean gas-air mixture. The generated 3D computational model for a basic gas turbine yielded several interesting results. The computational model generated for a modified, plasma assisted gas turbine combustor, gave significant improvements of the combustor's temperature distributions and ecological characteristics. Maximum temperature levels of the products in combustion decreased by 190 degrees, resulting in decrease in $NO_x$ emissions from 16 to 1 ppm. Secondary flow rate increases allowed deeper penetration into the flame tube, and tangential variation in the outlet cross section decreased. The total pressure loss also decreased from 6.11% in the unmodified case to 5.72% in the improved design. The CFD results are shown and compared in Figure 6 and Figure 7.

## 2.2. *Supersonic and hypersonic flow systems*

High-speed airbreathing engines are key to future supersonic and hypersonic transportation vehicles. Two predominant strategies for tackling the challenges of designing these future craft include conventional and laser plasma-assisted ignition. Plasma-assisted ignition shows promise with both ignition methodologies, but further research is needed, especially in the laser ignition field. The following sections discuss experiments conducted in the past two decades regarding advanced ignition studies related to supersonic and hypersonic aerospace applications.

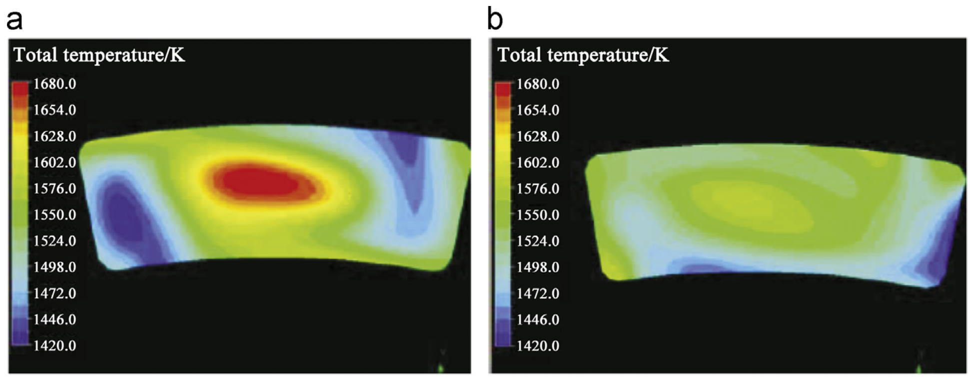
### 2.2.1. *Plasma-assisted ignition*

Ultra-lean mixtures are desired for use at high initial and average pressures ($P \sim 15$–$40$ atm and $V \sim 10$–$70$ m/s) in internal combustion engines, while hypersonic aircraft engines operate at low pressures with high flow velocities




Basic case Modified

**Figure 6** Temperature field in the combustor. (a) Basic case and (b) modified [36] (reprinted with permission).




Basic gas turbine case Modified gas turbine

**Figure 7** Temperature field of the combustor outlet cross section. (a) Basic gas turbine case and (b) modified gas turbine with plasma assisted combustion [36] (reprinted with permission).

in combustion regions ($P \sim 100$ Torr and $M \sim 2$) [12]. In the case of a lean-burn gas engine, the operational window is restricted by conventional ignition methods. The aforementioned limits can be increased through the use of plasma assisted ignition technologies, described in detail in this section.

Using nonequilibrium plasma for flame stabilization in subsonic and supersonic flows has been growing in interest, as nonequilibrium plasma discharges have a high propensity to produce reactive radical species. These radical species facilitate combustion reactions and reduce ignition delay times. Do et al. [37,38] and Leonov et al. [39,40] recently introduced a two-stage mechanism which can describe conventional plasma-assisted combustion flame stabilization (by electric discharge). In the case of hydrocarbon fueling and low temperature, flame stabilization can occur by using nonequilibrium plasma. In the first stage, the plasma induces active radical production and preflame (also known as fuel reforming), which can be simplified as a production of $H_2$, $CH_2O$, and CO. The zone does not experience a significant temperature and pressure increase. The preflame/cool flame appears as a source of active chemical species that initiates the second stage of normal combustion, characterized by high temperature and pressure rise.

One of the following two conditions must exist for sustained deflagrative combustion in a supersonic stream: a continual source of ignition must exist, or conditions for autoignition should be maintained. Ignition behavior of laser-induced plasma in thermal equilibrium applied to sonic, underexpanded jets injected into a hypersonic crossflow, during which deflagrative combustion takes place, was investigated by Brieschenk, O'Byrne, and Kleine [41]. $H_2$ fuel was ionized before being injected into the crossflow, without autoigniting the hypersonic flow. Previous studies by the same authors [42] where laser-induced plasma was generated in shear-layers showed that this method could promote the formation of hydroxyl and ignite a supersonic flow (these works are discussed in more detail later). Latest work focuses on whether or not fuel-jet laser-induced plasma ignition can outperform shear-layer ignition, in terms of laser energy requirements and ignition effectiveness. $H_2$ fuel was diluted with Ar (serving as a plasma buffer gas, which extends plasma lifetimes), which serves as the plasma buffer gas. It was discovered that fuel-jet laser-induced plasma ignition is less effective unless a plasma buffer gas is used to extend the lifetime of the plasma. Hydroxyl signals were increased with increased laser pulse energies, as fuel diluted with Ar was found to increase the OH signal being observed. The hydroxyl radicals are consumed during combustion, thus making the plasma buffer gas useful as it increased hydroxyl formation. Enthalpy of the crossflow and the fuel plenum pressure did not significantly impact ignition effectiveness. The fuel-jet ignition technique was concluded to allow for lower laser energies to be used when compared to the shear-layer technique, but could only achieve similar OH densities with a plasma buffer gas.

Brieschenk, Kleine, and O'Byrne [43] continued their work on laser-induced ignition in hypersonic regimes with air-hydrogen fuel flow. Work was carried out at the T-ADFA hypersonic tunnel with a specific total enthalpy of 2.5 MJ/kg and a freestream velocity of 2 km/s. Using a compression-ramp model with a port-hole injector, the authors further investigated how laser-induced ignition can effectively produce hydroxyl. Time-resolved luminosity imaging indicated that laser-induced plasma rapidly grew within the first microsecond after initiation of the laser due to a laser-driven shock wave. The luminosity separated into two regions, traveling along the shear layer behind the injector bow shock. Turbulence of the flow at the injection region did not seem to affect the early evolution of the luminosity cloud. A calculated 54% of the laser energy was absorbed by the plasma, but was of secondary concern as techniques exist which decrease the energy requirement (such as using a plasma buffer gas in a fuel-jet ignition, as stated earlier). Blast wave theory was used in conjunction with an expansion wave model which yielded enthalpies on the same order of magnitude as those predicted by NASA CEA code.

Further studies conducted on laser-induced plasma ignition were characterized by Tsuchiya et al. [8]. The effectiveness of laser irradiation focused at near fuel-jet boundary and recirculation regions were investigated in supersonic airstreams. Other efforts included providing insight into ignition augmentation, wave propagation processes, and interactions of the waves with a supersonic flow region. Propagation phenomena (such as wave interactions and plasma formation) of plasma-waves, flame-waves, and shock waves and associated recirculation zone formations are also studied. Using a numerical simulation, positions of the plasma kernels induced by laser irradiation affected ignition and flame stabilization characteristics and also the induction process of local turbulence augmenting local mixing. The authors were able to characterize the laser ignition process into a five stage time scale: 1 ($10^{-9} \sim 10^{-8}$ s): Incident laser pulse is absorbed. 2 ($10^{-8} \sim 10^{-7}$ s): Plasma formation process. 3 ($10^{-6} \sim 10^{-4}$ s): Ignition. 4 ($10^{-5}$): Shock flow interaction. 5 ($10^{-5}$): Convection/diffusion.

In a follow-up study by Horisawa and Tsuchiya et al. [44], additional CFD simulations, utilizing time-dependent Navier-Stokes equations, were conducted in supersonic airstreams with transverse hydrogen-fuel injection, in order to study phenomena outlined earlier [8], for two specific cases. In the first case, where laser plasma was induced near the fuel injection port, it was observed that the initial phase (20–30 μs after laser pulse) proved effective, whereas an upstream part of the flame region, developed from the plasma kernel, was blocked by an oblique shock brought upon from fuel injection. For the second case, in which a plasma kernel was induced downstream of the fuel injection port, plasma effects became significant only after 40 μs, where the flame region expanded in both upstream and downstream areas. In high pulse energy cases, a flame nucleus propagated with a shock wave. The propagating shock wave induced recirculation zones and enhanced local mixing, particularly at near-wall regions with associated flamelets. Active species from the flame nucleus were supplied in a hydrogen/air mixing region via recirculating zones formed by the shock wave. At each recirculation zone in the simulations tested, the flame region stabilized in supersonic regimes. In lower pulse energy cases, no shock wave structures induced by the plasma kernel could be observed in the flow field. The propagating combustion was induced weak recirculation zones, but were smaller in size compared to the ones formed by the higher pulse energy.

A study conducted over the course of five years by Leonov [40], in conjunction with the Air Force Research Laboratory, sought to further study the phenomena of plasma-induced ignition of air-fuel mixture at direct fuel injection into separation zone downstream backwise wall-step and wall cavity by multi-electrode quasi-DC electrical discharge at highs-speed flow. Both computational and experimental data were developed for comparison and verification. The two-step mechanism for plasma assisted combustion, mentioned previously [37,39], was analyzed as well. The effect of transversal discharge on flameholding was conducted at Mach 2 in a cavity behind a backwise wall step, along a plane wall. Temperature was varied from 300 to 750 K.

As can be seen in Table 1, the energetic threshold measured for ignition and flameholding can be compared amongst ignition in a cavity behind a wallstep, threshold of flameholding in shear layer over a wallstep, and threshold of flameholding over a plane wall. Comparable power levels are observed for flameholding with the wallstep or on the plane wall. Contrary to what is expected, the threshold for flameholding does not decrease (improve) with a rise in static temperature. The author states that a hypothesis for this phenomena is that an increase in temperature leads to intensification of gas circulation in the separation zone, thus a gas exchange between the separated zone and the core flow. From the experimental data, two factors are considered for successful fuel ignition and flameholding: discharge power and length of discharge filaments. Nonequilibrium power deposition into the gas lead to the creation of species which possess higher reactivity, when compared to those found at equilibrium. It was demonstrated that plasma should be generated in situ, at the exact location of fuel-oxidizer interaction. This diminishes fast relaxation and mixing with the surrounding air.

Uniform mixing of injected fuel in high-speed flows becomes difficult with increasing Mach number, and the problem of adequately spreading flame across the combustion chamber is not realized. Self-ignition delay time for hydrocarbon fuels exceed 10 ms at 1 atm and temperatures of 600–1200 K, translating into a long ignition region. Several ideas are explored in a study by Macheret et al. [45] to help analyze energy and power requirements to shorten the ignition delay time in hydrocarbon-fueled scramjets using nonequilibrium plasma generation. The first concept is a multi-point, repetitively pulsed plasma ignition scheme, which is purposed to reduce the power budget by multiple orders of magnitude (from $\sim 100$ MW/m$^2$ to several MW/m$^2$). This idea involves planting multiple ignition spots several centimeters apart in the combustion chamber so that flames being ignited by these spots will overlap in time.

**Table 1** Energetic thresholds at various conditions according to Ref. [40].

| Energetic threshold | $H_2$ $T_0 = 300$ K | $C_2H_4$ $T_0 = 300$ K | $C_2H_4$ $T_0 = 500$ K | $C_2H_4$ $T_0 = 650$ K |
|---|---|---|---|---|
| Threshold of ignition in cavity and behind wallstep/kW | 1 | 2.5 | 4 | $\sim 5$ |
| Threshold of flameholding in shear layer over wallstep/kW | $< 3$ | 3.5 | $\sim 5$ | $\sim 10$ |
| Threshold of flameholding over plane wall/kW | $< 3$ | $> 4.5$ | $> 5$ | $> 8$ |

This is less costly energetically compared to volumetric ignition. This concept relies on high flame propagation speed; the higher the flame spreading speed is, the lower the energy requirements on the igniters are. The second concept explored is electron-beam assisted fuel injection and atomization. Efficiency of high-speed systems, such as ramjets and scramjets, depends strongly on how fuel and air are mixed before the ignition process. Fuel entering as a vapor, in the form of microdroplets, would not penetrate into dense, high-speed flow, and efficiency of ignition would be limited. A form of injection is proposed in which fuel is injected into the core flow as a liquid jet, and low-power electron beams are used to electrostatically charge the droplets, thus controlling droplet break-up, atomization, and mixing. This would allow the injection of fuel into a scramjet engine as a powerful liquid jet, allowing adequate penetration into the flow, while simultaneously breaking up into droplets, facilitated by Coulomb repulsion due to the negative charge from high-energy electron beams. The final proposed concept is multi-spot combustion ignition by subcritical microwave discharge at the surface of fuel droplets. The subcritical microwave discharges, brought on by a local enhancement of electric field strength at the surface of the droplets, would initiate combustion in multiple spots. This would assist in spreading the flame ignition across the combustor. Several advantages could be realized from this concept; it would eliminate protruding metallic objects in the airflow, be characterized by multi-spot ignition across the combustor (equivalent to volumetric ignition, solving the flame spread problem), save energy, and easily ignite in fuel-air mixtures that are lean in average (since combustion would occur easily at the droplet surface, where the local equivalence ratio is high).

Do, Cappelli, and Mungal [38] explored the concept of igniting supersonic and sonic hydrogen jet flames in supersonic pure-oxygen crossflows, without the aid of geometric variances (such as cavities and wall steps). Nonequilibrium plasma was produced by 7 kV peak voltage, 20 ns pulsewidth, 50 kHz repetitive pulses. Upstream subsonic jets produced an oxygen-hydrogen mixture that convected toward the downstream main sonic jet when activated by the plasma. Interaction with the bow shock, formed by the jet, forms a combustion region that controls the formation of a jet flame. Ignition was observed to be considerably easier at higher Mach numbers as post-shock conditions played an important role in the autoignition process.

Do, Cappelli, and Mungal [46] continued their work on plasma assisted combustion in another study focused on cavity flame ignition in supersonic airflow, with the geometric variance being absent in their previous study. Using the same nonequilibrium plasma characteristics from their previous study, the nanosecond pulsed plasma discharge, located within a wall cavity, was used to ignite hydrogen and ethylene jet flames in a crossflow. The use of the cavity resulted in flame ignition in the leeward side of the oblique hydrogen jet, and the cavity flame auto-ignited when the enthalpy of the free-stream rose higher than 2 MJ/kg. A reduction in the ignition delay of the mixture within the cavity was observed. A parametric study indicated that even higher pulse energy could lead to a higher reduction in ignition delay. These benefits are seen as well in the ethylene jet, suggesting that the combustion process in this experiment may be applicable to other hydrocarbons. It should be noted that the experiment in this particular study was limited by the discharge power available for their pulse discharge source.

Research was continued in a follow-up study in the same year by Do et al. [37], in which the authors used the same plasma discharge source to ignite jet flames in supersonic crossflows over the specific case of a flat wall, without the use of a cavity. Low power nonequilibrium nanosecond pulsed discharges for the stabilization of supersonic combustion has not been widely studied due to the low discharge energy per pulse, in comparison with the flow enthalpy over time between successive pulses. Hence a dual fuel jet injection configuration was utilized to overcome these limitations by channeling plasma energy into activation of a subsonic fuel/oxygen mixture that serves as a pilot flame. Two stages were found to represent this plasma-enhanced supersonic combustion; the first stage diverts fuel towards an oblique subsonic injector, while in the second stage, increased radical production (more than what would be achieved by plan discharge alone) ignites and sustains the combustion in a majority of the fuel. This experimental setup was easily integrated into a flat wall and did not require any geometrical variations to induce flow recirculation.

### 2.2.2. *Ramjet and scramjet applications*

Although the concept and configuration of scramjets is relatively simple, there are many complicated physical phenomena behind the operation of such an engine. The scramjet engine utilizes forward motion to compress the incoming air (as opposed to a rotary compressor). An inlet at the front end converges to the area of combustion (where fuel is injected, mixed, and combusted), then diverges into the nozzle. Thrust is produced by the expansion of the products of combustion through this nozzle. As opposed to ramjets, scramjets contain a supersonic combustor, while ramjets contain subsonic flow in their combustion chambers. The difficulty in designing scramjets come from the physical characteristics experienced during high-speed flight, and should allow for sufficient air compression, fuel-air mixing, combustion, and gas expansion. In Mach 4–8, with a dynamic pressure of 1000–2000 psf (0.5–1 atm), combustor entrance conditions can be characterized as follows: static pressure is 0.5–2 atm, static temperature is 400–1000 K, and flow velocity is 1200–2400 m/s [45]. The following section details laser ignition applications in ramjets and scramjets, but is not complete with several additional studies on fuels and geometric variances.

Due to the high speeds at which airbreathing scramjet engines travel (Figure 8), the time available for fuel injection, fuel-air mixing, and combustion is very short, on the order of 1 ms. Flame holding, an important factor in the design of an injection system, has the primary objective of reducing ignition delay time and to provide a continuous source of radicals for chemical reaction to be established in the shortest time possible. This can be achieved by three techniques. The first is by creating a recirculation area where the fuel and air can mix at decreased velocities. The second is via interaction of a shock wave with partially or fully mixed fuel and oxidizer. The final method is by formation of coherent structures containing unmixed fuel and air, in which a diffusion flame occurs as the gases are convected downstream. Several geometric surface alterations have been tested in order to help with the characteristics mentioned above, such as cavities [46–48], ramp injectors [49,50], wall steps, and angled combustor walls.

The simplest approach to geometric variances is the transverse injection of fuel from a wall orifice. As a fuel jet interacts with a supersonic crossflow, a bow shock is formed. The upstream wall boundary layer thus separates, providing a region where the boundary layer and jet fluids mix upstream at a subsonic velocity. Though there are considerable flame holding capabilities, there are stagnation pressure losses due to the strong three-dimensional bow shock formed by the jet penetration, which is increasingly evident at higher velocities, such as in a scramjet. A step, followed by transverse injection, is another method of achieving flame stabilization. The step creates a large recirculation area with hot gases serving as a continuous ignition source, but suffers the same disadvantage of stagnation pressure losses and an increase in drag due to the step. It is possible to angle the injection process at 30° or 60°, thus providing a weaker bow shock and reducing pressure losses. Due to the fuel jet's angle, the axial momentum can actually contribute to the net thrust of the engine. Based on observations from various works [51,52], angled injection is likely to reduce autoignition and stabilization at flight speeds lower than Mach 10. Cavity flame holders, another type of geometric variance, has been shown to significantly improve hydrocarbon combustion efficiency in a supersonic flow when placed after a ramp injector. Ben-Yakar and Hanson [47] provide an overview of research (up until 2001) into cavity flame-holders. Some studies [53] indicated autoignition within the cavity at Mach 6.5, even without the use of spark ignition plugs. Small injector dimension and low combustor operation pressure reveals that without the cavity, ignition is unlikely. Similar studies [54] also revealed that cavity length $L$ and step height $D$ significantly influence combustion sustainment.

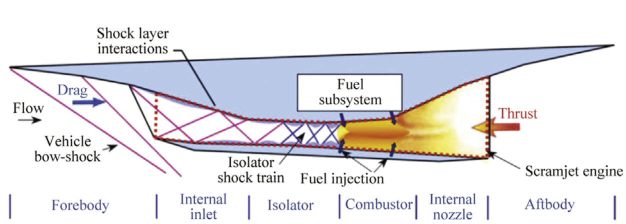



**Figure 8** Diagram of air-breathing scramjet system [12] (reprinted with permission).

Ultimately, a cavity length to depth ratio between $1.7 < L/D < 2$ showed sustained combustion in supersonic combustors utilizing solid fuels. Figure 9 details some of the traditional injection methods described above.

An aeronautical injection system has been considered by Zimmer, George, and Orain [55], which utilizes a staged liquid fueled injector, injecting fuel through a central pressurized atomizer while air is swirled. Laser ignition was used with dual Nd:YAG lasers with a 105 mJ maximum pulse. There are two recirculation zones: the inner and outer zones. In the inner recirculation zones, all sparks lead to a complete ignition of the chamber, regardless of temperature variation. The probability of plasma formation was strongly correlated with the temperature, however, and overall ignition probability was low for temperatures below 150 °C. In the outer recirculation zone, not all plasma led to ignition of the chamber. The researchers determined that almost all sparks led to complete ignition above 170 °C, where the probability of getting any spark was almost zero below 135 °C. Future work will include studies on the transition of success from the inner recirculation zone to the zone where spray hits the wall, which is of strong interest in aerospace applications.

Autoignition, an aforementioned characteristic of scramjet flow, is the rapid spontaneous ignition and reaction of the fuel-air mixture, and is required to achieve efficient combustion. A difficulty in developing scramjets includes the slightly long ignition delay times of hydrocarbons relative to hydrogen. In addition to this, heat release rates are affected by autoignition, and if these rates are too rapid, dynamic instabilities or choking may occur. Shock-tube experiments were conducted by Colket and Spadaccini [56] in 2001 to study and compare the ignition delay times of several scramjet propulsion fuel candidates. Ethylene, heptane, and JP-10 were measured at specified conditions (1100–1500 K, pressures of 3–8 atm, and equivalence ratios of 0.5–1.5). Using previous results published for heptane and ethylene, new correlations were found from the two experimental data sets. Studies on hydrogen and methane ignition-delay times were also compared. A summary of the results from the study can be seen in Table 2.

The ignition delay times from Table 2 can be expressed in descending order, with the longest ignition delay time listed first: methane, JP-10, heptane, reformed fuel, ethylene, and hydrogen. The delays for the simulated reformed fuel in the experiment were calculated to be 50% to 70% of heptane's delay time (heptane being the parent hydrocarbon), supporting the argument that endothermic reaction products will ignite more readily. It was also found that the addition of heptane to the simulated reformed fuel increased ignition delay, while hydrogen decreased the ignition delay; however small changes in concentrations of individual component species are not usually likely to make dramatic changes in the delay times. Moreover, the autoignition of the endothermic reaction product mixture was found to be not entirely driven by the individual constituent with the lowest ignition delay, such as ethylene and hydrogen.

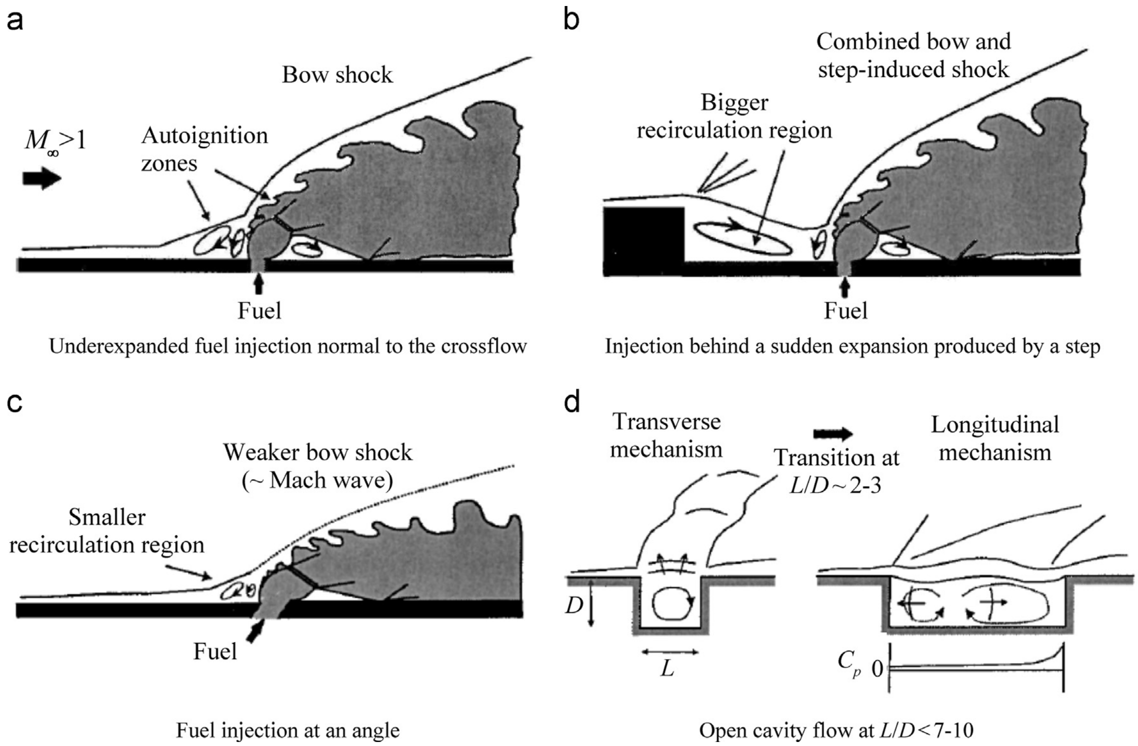



**Figure 9** Flowfield schematics of various injection/flame-holding schemes in supersonic combustors [47] (reprinted with permission). (a) Underexpanded fuel injection normal to the crossflow, (b) injection behind a sudden expansion produced by a step, (c) fuel injection at an angle, and (d) open cavity flow at $L/D<7$-10.

**Table 2** Ignition delay time comparison between fuels @ 7 atm (times in ms) [56]. Baseline fuel is a mixture of $0.3CH_4/0.6C_2H_2/0.1H_2$.

| **Relative ignition delay times** | | | | |
|---|---|---|---|---|
| Eq. ratio | $\varphi=0.5$ | | $\varphi=1.0$ | |
| Fuel | 1300 K | 1400 K | 1300 K | 1400 K |
| Methane | 16.8 | 14.6 | 15.1 | 13.1 |
| JP-10 | 1.33 | 1.2 | 1.33 | 1.2 |
| Heptane | 1 | 1 | 1 | 1 |
| 80%heptane/20%baseline | 0.96 | 0.72 | 0.86 | 0.73 |
| Baseline fuel | 0.64 | 0.6 | 0.77 | 0.7 |
| 10%$H_2$/90%baseline | 0.58 | 0.49 | 0.66 | 0.51 |
| Ethylene | 0.33 | 0.39 | 0.33 | 0.39 |
| Hydrogen | 0.04 | 0.07 | 0.03 | 0.06 |

As stated earlier, the USAF has expressed interest in scramjet propulsion and its corresponding ignition processes. The Air Force plasma ignition program, introduced in a 2003 study by Jacobsen et al. [57], aims to assess the possibility of utilizing a plasma generating device for main-fuel ignition in supersonic flow regimes. Employing computational and experimental methods, two plasma torch devices (one AC, one DC) were investigated, in addition to establishing baseline conditions of operation (such as required time to initiation a combustion shock train). Results indicated that the plasma igniters produced hot pockets of excited gas with a 2 kW total input power and peak temperatures up to around 5000 K. In Mach 2 supersonic flow, ethylene and JP-7 flames (with substantial levels of OH) were produced at a total temperature of 590 K and pressure of 5.4 atm. Further work conducted in 2008 by Jacobsen et al. [58] with the Air Force Research Laboratory continues upon the studies conducted earlier in the decade. The purpose of the work was to further expand knowledge in the understanding of the ignition process in a small-scale scramjet duct. The flow physics of each igniter/fuel-injector/combustor system was studied to understand and compare the potential of each plasma torch concept, and several plasma igniter locations and duct configurations were analyzed. A cavity flame holder was incorporated into the flow path, as previous studies had recently discovered their importance in aiding the ignition process [47,48]. CFD simulations completed by the team indicated that ignition can be accomplished in a few milliseconds, and the energy required for 10 ms of torch operation is roughly 10's of Joules, which is a reasonably small amount of energy compared to that of a battery. Further work is being conducted to continue research into the design and development of new igniter concepts. Additionally, a more fundamental understanding of alternate starting methods (such as silane based or a gas generator) is being pursued, as these methods do not involve the use of toxic chemicals and allows for restart attempts.

In 2011 and 2012, two plasma ignition methodologies were investigated by Brieschenk, O'Byrne, and Kleine [42,43,59] (before their 2014 study mentioned earlier [41]): shear-layer laser induced plasma ignition and fuel-jet laser induced plasma ignition in the case of a 2D scramjet inlet. Tests were conducted in the T-ADFA free piston shock tunnel, with a specific total enthalpy of 2.7 MJ/kg and a Mach 9 freestream. For shear-layer tests, laser induced plasma was formed immediately downstream of four transverse injector ports, while the fuel-jet plasma was formed inside the sonic throat of a single fuel injector for its respective runs. Diluting fuel with a plasma buffer gas, in this case 8% Ar and 92% $H_2$, was also investigated to extend the life of the plasma. A schlieren image of flow features in the experiment is shown in Figure 10, representing the difference in intensity between an image taken before the experiment and an image taken with actual flow (local features are labeled as well).

It is proposed that in the case of the shear-layer tests, most hydroxyl is generated in an explosive fashion up to 5 μs, and is then consumed by combustion thereafter, generating more heat. The recompression shock slightly increases hydroxyl concentration when laser induced plasma regions pass through. For ignition of an entire flow field, laser pulse frequencies of 100 kHz are recommended, but is stated as a possible overestimation. Relatively high laser energies are needed (around 750 mJ) due to the high threshold energy at lower gas densities, as a considerable portion of this energy is transmitted through the focal region, and is unable to partake in the course of plasma formation. In the fuel-jet tests, hydroxyl is produced at a significantly lower rate when compared to shear-layer experiments. This is due to rapid recombination of the hydrogen plasma at high pressures. No hydroxyl is found to be generated in the boundary layer of the walls, instead being located between the center and upper boundary of the jet. When diluted with argon, hydroxyl formation increases by an order of magnitude. However, an 8% dilution of argon results in a specific impulse loss in a scramjet by a factor of 2.5 when compared with pure, $H_2$ fuel. Though both techniques are found to be effective, they each come with a set of disadvantages. Shear-layer ignition, though producing high amounts of hydroxyl, requires high laser energies when gas densities are low. Fuel-jet ignition allows for lower laser energies to be utilized, but requires a plasma buffer gas in order to achieve the same hydroxyl concentrations, thus reducing a scramjet's overall specific impulse. Utilizing OH-PLIF (Planar laser induced fluorescence), the OH radical can be seen in different delay timings in Figure 11 for the shear-layer experiment.

Scramjet operational efficiency can be defined by the efficiency and extensiveness of the combustion process. Tests conducted on the 14-X scramjet engine in the T3 Shock Tunnel, utilizing electric spark igniters, have proven that electrical igniters are impractical in terms of the overall performance and efficiency of the test model [9]. This is due to the fact that the igniters are installed on the inner walls of the combustor, restricting combustion reactions to the boundary layer established on the adjacent wall. This limits the igniters influence on the flow. In addition, the electrical power used to produce stable conditions for combustion, such as a continuous electric-arc or plasma torches, have similar orders of magnitude as the produced scramjet engine thrust power, making the electric igniters impractical. Laser ignition, as researched at Universidade Federal do ABC in Brazil (in conjunction with IEAv) [9] offers to circumvent these issues and may offer a way to manipulate shock waves by using laser beams to virtually shape the geometry of the combustion chamber. Nascimento et al. [9] have shown that through the Vaschy-Buckingham π Theorem of dimensional analysis, a preliminary mathematical relationship can be developed which represents the theoretical scramjet laser-induced supersonic combustion efficiency, or $\eta_{cs}$, shown below in Eq. (3).

$$\eta_{cs} = \varphi\left(f_p \Delta t_p, \frac{h_f}{E_p}, \frac{k_f \Delta t_p \lambda}{T_f E_p}, \frac{\rho_f \lambda^5}{E_p \Delta t_p^2}\right) \tag{3}$$

Laser parameters that influence supersonic combustion efficiency include $E_p$, which represents energy per pulse, $\lambda$, representing wavelength, $\Delta t_p$, representing pulse duration, and $f_p$, the repetition rate. Fluid parameters that influence supersonic combustion efficiency include flow enthalpy, $h_f$, flow density, $\rho_f$, flow temperature, $T_f$, and flow thermal conductivity, $k_f$. Refinement of Eq. (3) is still required through experimental analyses.

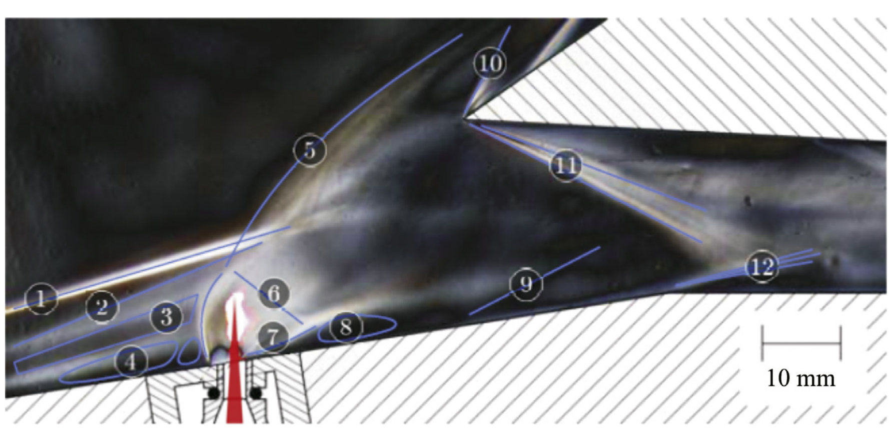



**Figure 10** Flow field features on compression ramp [42] (reprinted with permission).

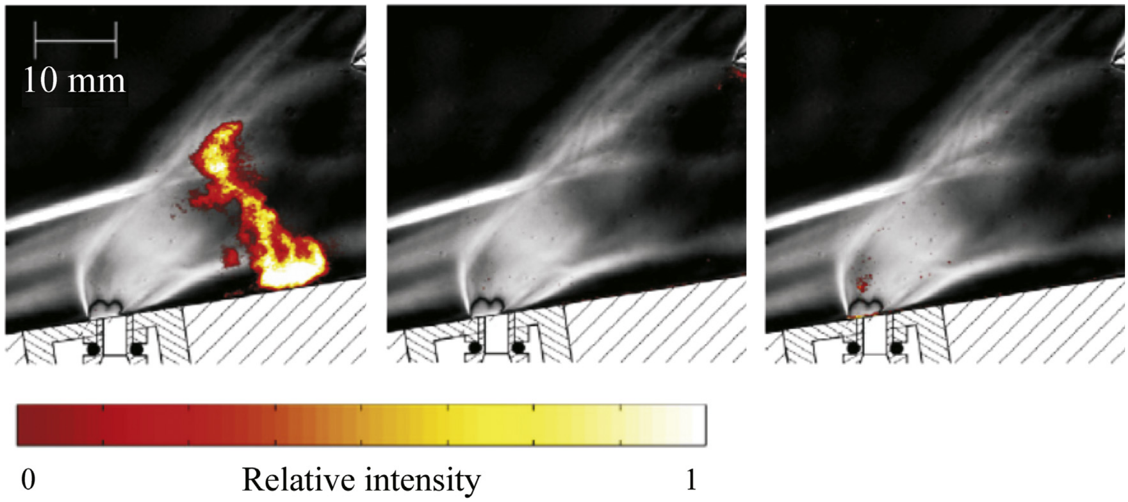



**Figure 11** Fluorescence of OH radical the in shear-layer ignition experiment [42] (reprinted with permission).

Preliminary results achieved from the analysis of a new laser igniter for the 14-X scramjet have offered several possible interpretations as to the influence of laser parameters on supersonic combustion. Shorter pulse durations correlated with higher pulse power, due to increases in photon's temporal density on the pulse. This results in a possibly higher temperature reached by the fuel mixture. There is a greater probability of the formation of free radicals, working as catalyzers for combustion. Laser repetition rate was also found to influence the constant maintenance of radicals formed after laser ignition, in order to achieve stable and complete supersonic combustion. It was found that the repetition rate is essential to enabling manipulation of virtual geometry in the scramjet combustor. Finally, laser wavelength influences the energy transfer process and consequent generation of reactive radicals on the supersonic flow [9].

### 2.3. *Rocketry, satellites, & space*

Progress has been made in the development of laser ignition systems at NASA Marshall Space Flight Center. Past studies initially encountered issues with depositing laser sparks inside a rocket chamber, thus limiting laser ignition's potential utilization. Recent advances in fiber optic technologies and multi-pulse laser formats have renewed interest in using lasers for future rocket designs. In the study prepared by Osborne et al. [60], single and dual pulse laser sparks are characterized and analyzed for use in rocket ignition applications. Dual-pulse laser-induced spark, or DPLIS, ignition is performed using the following process: a very short-duration, high-power pulse is fixated at the combustible medium, which starts plasma formation that preconditions the gas volume by maximizing absorption of the second laser pulse. The second pulse provides additional photon energy, extending plasma lifetime and augmenting ignition conditions. Dual pulse laser sparks are found to produce plasmas that absorb laser energy just as efficiently as a single pulse format, with the added benefit of longer plasma lifetime. Using the same amount of energy as a single pulse system, a dual pulse laser format also produced a spark that provided better ignition characteristics and sustained combustion of fuel-lean $H_2$/air propellants. It is unclear in the study whether the benefits provided by the dual pulse format is correlated to longer plasma lifetimes, better coupling of the laser energy into the plasma, or longer spatial profile of the dual-pulse spark.

In order to stay in space, satellites must perform many small-scale maneuvers using small rocket engines. These engines are constantly being turned on and off as needed. Engines such as the Orbital and Maneuvering System for the Hershel/Planck Satellites described by Manfletti and Kroupa can have as many as 93, 130 engine cycles [61]. Currently, the types of engines used for these low thrust operations are liquid bipropellant engines using hypergolic fuels. Hypergolic fuels have the benefit of autoignition upon contact with the oxidizer and can be stored for long periods of time at room temperature. Unfortunately, these types of fuels are toxic and highly destructive to the environment. As more people push towards greener and more efficient energy the need for new methods for small-scale re-ignitable engines is being re-examined. The concept of controlling satellite maneuvers with non-hypergolic fuels poses other problems. Fuel such as cryogenic liquid oxygen possess their own issues involving storage of the fuel and feeding the system. However, these are engineering challenges that can be overcome. As lasers move to being smaller and more powerful, ignition through lasers becomes a more feasible concept for satellites.

The development of small scale laser systems for these applications is one method for incorporating alternative fuels. Manfletti and Kroupa used a small-scale laser (Nd:YAG Laser), approximately the size of a computer mouse, as the ignition source. The experiments were focused on determining the minimum incident energy needed to ignite mixtures of liquid oxygen and gaseous hydrogen. The set-up described, which provided 30 mJ of energy, was successful in igniting the fuel mixtures between 17% and 33% of the time depending on the focal point. Another test of the set-up was reported later, adding data on liquid oxygen and gaseous methane mixtures [62]. The results show that the methane mixtures require more energy to unite, making such a combination less feasible with current lasers.

As traveling to deep space and other planets becomes more realistic, new technology is currently being developed for faster space travel. One method currently being considered is nuclear propulsion. Nuclear propulsion using lasers to ignite the reaction has become a widely researched topic as of late. Similar to the concept of laser ablation, nuclear propulsion is possible by creating fusion reactions through lasers. One research group has studied the fast ignition of nuclear fuels using a picosecond terawatt laser [63,64]. Currently such studies are in their infancy with much more information needed but the concept shows potential for high thrust applications and minimal radiation allowing for implementation in space.

#### 2.3.1. *Laser ablation systems & solid propellant applications*

Laser ablation propulsion has found numerous uses with spacecraft and other objects associated with space. Laser ablation involves a concentrated, intense laser beam striking a condensed-matter surface, producing a jet of vapor or plasma. Thrust is produced from the resulting reaction thrust force, similar to chemical rockets. Only a few applications utilizing laser ablation are beyond the research stage of development, but there are a wide array of conditions that can benefit from this sort of propulsion. These include, but are not limited to, milliwatt-average-power satellite attitude-correction thrusters, kilowatt-average-power systems for reentering near-Earth space debris, and megawatt/gigawatt systems for ground launch into low earth orbit (LEO). An extremely thorough literature review, much more in depth than what is presented here, can be found by Phipps et al. [65].

Various benefits can be realized from the use of a laser ablation system. Variable specific impulse ($I_{sp}$) is possible by adjusting laser intensity on a target surface, changing the focal-spot area, and switching the laser-pulse duration. This causes the exhaust velocity to vary across ranges of chemical reactions ( $500\,s < I_{sp} < 5000\,s$). Thrust can also be controlled independently of the specific impulse through variations in the laser-pulse repetition rate. Efficiency of energy consumption is strongly improved by constant-momentum exhaust-velocity profiles, which require a variable $I_{sp}$, and is difficult to obtain through conventional chemical rockets. In a self-contained laser propulsion system, cryogenic or high-pressure fuel tanks, gas-driven turbopumps, and nozzle cooling structures, as well as other systems, are merely replaced by lightweight diode or diode-pumped fiber lasers. The laser itself does not require complicated cooling systems up to the kilowatt level, due to large surface-to-volume ratios. Though chemical rockets still outperform laser ablation propulsion in terms of thrust, spacecraft using laser engines experience more agile feedback. Laser ablation propulsion systems have also demonstrated thrust densities with a value of 800 $kN/m^2$ [66], due to the thrust originating from a spot with an area equal to that of the laser focus. This is particularly important for satellite applications as ion engines have a much larger throat-area-to-thrust ratio. In systems intended to launch satellites and other spacecraft into LEO (with a launch frequency of five per day), the cost of operations is reduced to as little as $300/kg [67]. Many of the benefits stated above arise from conceptual ideas, and many remain to be demonstrated. However, the vast amount of potential benefits arising from this source of laser ignition is too great to be ignored.

A recent development in the field of laser ablation propulsion is the research into a laser-electrostatic hybrid acceleration thruster, studied by Osamura, Sakai, and Horisawa [68,69]. In these hybrid acceleration thrusters, there are three different acceleration regimes: electrostatic acceleration, electromagnetic acceleration, and electrothermal acceleration. Optimization of a thruster which can adapt to all acceleration regimes is proposed through the use of an augmented electrode configuration. In earlier studies by the authors, laser-electromagnetic acceleration was the area of focus. Delays in phase changes were observed due to a difficulty in completing simultaneous phase change and electromagnetic acceleration after the pulse discharge initiation. In order to improve thrust efficiency and reduce delayed ablation, laser-pulse irradiation was utilized. It was found that this irradiation induced a conductive plasma in short durations, allowing for shorter pulse switching or discharge. Higher peak currents and improvements in thrust performance can be expected due to shorter-pulsed plasma. In the current study, the laser-electrostatic hybrid acceleration thruster employs laser ablation plasma accelerated through an electrostatic field. The process starts as an irradiated laser pulse is focused on a target surface, creating laser-induced plasma at the target region. Typically, in laser ablation systems, electrons are emitted from the surface first, followed by ions, accelerated through ambipolar diffusion. The ions are accelerated further by using an additional acceleration electrode. A high specific-impulse is expected as the plasma is further accelerated through the electrostatic field. Using a Faraday cup, the speed and number of ions in the electrostatic hybrid thruster is estimated to determine an optimum electrode geometry. For 10 mm diameter electrodes placed 20 mm away from the laser target surface, the speed of ions was observed to increase with voltage. As the electrode gap increased, the number of ions decreased. Ion speeds, measured 80 mm away from the target, were observed at 16 km/s and 32 km/s for voltages of 0 and 500 V, respectively, at an electrode gap of 20 mm.

Recent attention has been given to microthrusters for small satellites and spacecraft weighing less than 100 kg, which are believed to be more economical from a development and launching perspective [70,71]. The use of diode lasers have also been proposed for ignition of pyrotechnic materials and ablation of polymers in microthrusters. Other researchers have also proposed the use of diode lasers in microthrusters for maneuvering [72,73]. Diode lasers have the advantages of being lightweight, requiring low voltages typically lower than 5 V, and having convergent efficiencies over 40%, but suffer from lens fouling from jet plumes and require an advanced feeding system to deliver solid propellants to the laser. In studies done by Koizumi et al. [71], a dual propulsive mode microthurster used a 1 W multi-mode diode laser for both laser ablation of polymers and laser ignition of pyrotechnics. The two modes, laser ablation mode and laser ignition mode, were investigated. In laser ablation mode (no chemical reaction), the diode laser irradiates the surface of the polymer propellant, generating low thrust. In laser ignition mode (energy release with chemical reaction), the laser irradiates and ignites the pyrotechnic (solid propellant) material, which is pre-loaded in small craters, resulting in higher thrust. These two modes are interchangeable by simply switching the surface being irradiated by the laser beam. The advantage seen here by using the dual mode microthruster is the fact that there is a wider allowable thrust range. Impulses of 1–40 μN · s (achievable with varying pulse width) were observed in laser ablation mode and 10 mN · s in laser ignition mode. This is a thrust range that spans over four orders of magnitude and can be installed in a 1–10 kg spacecraft.

In other studies done by Koizumi et al. [74], the following propellants were examined for laser ablation using a diode laser: polyvinylchloride, acrylonitrile butadiene styrene polymer, polyoxy methylene, natural rubber, and polymethylmethacrylate. Using polyvinylchloride as the ablative material yielded the best performance and thrust. More heavily carbon doped polyvinylchloride yielded even better performance, leading to the conclusion that absorption length had a large effect on performance. Intensity of the laser was varied during the experiments, and had little effect on thrust capability. Urech et al. [75,76] also investigated the use of 3 polymers for the application of micro-laser plasma thrusters (utilizing laser ablation): polyvinylchloride, glycidyl azide polymer and polyvinyl nitrate. Absorbers in the form of carbon nanoparticles and IR-dye were added to the polymers to promote IR absorption at wavelengths of 1064 nm. Glycidyl azide polymer doped with carbon was the most efficient (368%, or 3.68 times thrust energy over deposited laser pulse) material in their experiment and generated the highest specific impulse, followed closely by the glycidyl azide polymer doped with IR-dye (198%). Polyvinylchloride yielded a lower ablation efficiency (50%) as only a small amount of energy was gained from the decomposition of this polymer. Polyvinyl nitrate contained the lowest efficiency (21%) and is most likely cause by the ejection of the molten polymer away from the ablation area.

Advanced ignition systems for solid propellants are required in order to increase the safety and effectiveness of the ignition process. Solid propellants and energetic particles are usually ignited by heating a pyrotechnic igniter, which in many cases comes from electrical driven systems. Laser ignition systems offer increased stability over electrically heated systems by negating the possibility of electrical errors in the heating circuit and chemical instability of the pyrotechnics [77]. Lasers also offer the possible advantage of multipoint ignition in solid propellants, which can be utilized for combating low ignition probability in solid rockets [78,70].

The use of lasers for solid propellant ignition has been studied for over 10 years. Between 1993 and 1999 the United States Army Research Laboratory did extensive research on laser ignition of solid propellants for the application of advanced munitions. The research done in this time frame was a part of the Laser Ignition in Guns, Howitzers and Tanks (LIGHT) Program which focused on the creation of laser ignition systems to replace the igniters in guns and artillery. The main motivation of this research was the efficiency of laser ignition systems if properly tuned to the absorption of the propellant [79]. The LIGHT Program was stimulated by the potential for reducing the vulnerability inherent of primers and igniters in the ignition train and allowing for ignition of insensitive munitions [79]. The LIGHT Program used Nd:glass lasers based on their small size, low cost, and reliability to ignite a variety of propellants such as Black Power, JA2, M30, LKL, XM43, HELP2 and HMX1 [78–81].Continuous wave $CO_2$ lasers have been used in studies of JA2 ignition [78]. Research done by Ulas and Kuo investigated the ignitability of 6 different solid propellants using a 50 W $CO_2$ laser as the ignition source; trials were done with 3 different laser heat fluxes, 30, 50 and 100 W/cm$^2$ as well as 2 different chamber pressures, 1 and 69 atm [82].

Aluminum and boron are popular energetic metallic fuels used in explosives and propellants. Energetic particles of aluminum, boron, and magnesium samples have been ignited via $CO_2$ laser in previous works [83–85]. Researchers at the New Jersey Institute of Technology have used a $CO_2$ laser to ignite aluminum particles of diameter ranging from 1 to 14 μm in attempts to determine particle burn times and flame temperature from aluminum combustion [86,83]. Experiments conducted by Arkhipov and Korotkikh have addressed the influence of aluminum powder dispersity on the ignition time and burning surface temperature of composite solid propellants using a multimode $CO_2$ laser with a wavelength of 10.6 μm and maximum power capacity of 100 W as the ignition source [87]. Studies by Zhou et al. employed a $CO_2$ laser to ignite boron powered particles of diameter between 50 and 60 μm with oxide layer of thickness between 0 and 1.384 μm to study the effects of the initial oxide layer thickness on the combustion of boron [84]. Magnesium has also been researched as an additive in aluminum and boron based powders to promote ignition via $CO_2$ laser [85,88]. In cases of high fluences acting on aluminum and molybdenum trioxide ablation from thermal stress has been observed following the ignition of the mixture [89].

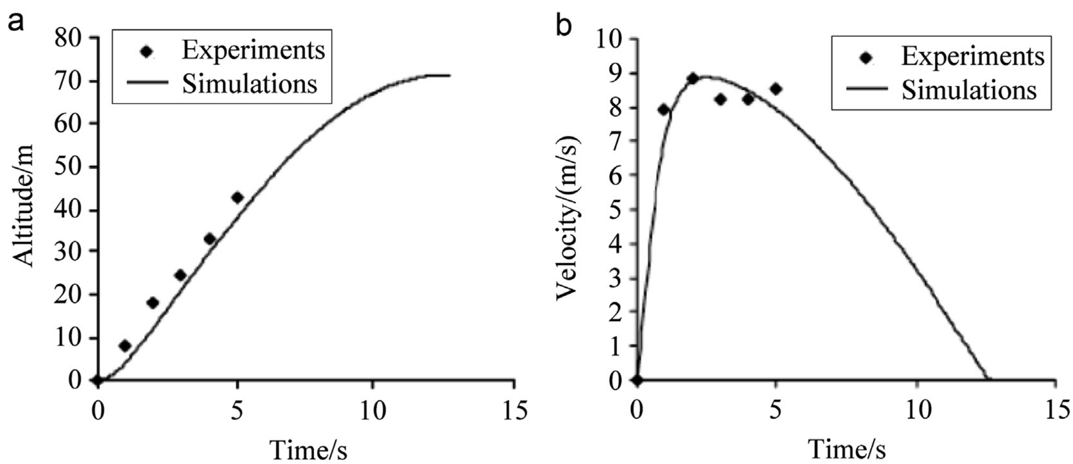



**Figure 12** Laser-propelled flight experimental [91] vs. simulated data [90] (diamonds represent experimental data). (a) Altitude vs. time and (b) velocity vs. time.

Laser propulsion may also be applied to rocket applications, allowing for the possibility of a higher specific impulse, higher thrust, and a lower propulsion weight, among other advantages. A simple propulsion system that can accomplish this task is through the use of a solid propellant, where the surface is continuously vaporized by laser irradiation. Thermal laser propulsive concepts are based on absorption in two mechanisms: laser-supported combustion (LSC) waves or laser-supported detonation (LSD) waves. Based on thermodynamic constraints, only a subsonic LSC wave can be used efficiently in a converging-diverging nozzle section, while a supersonic LSD wave can only be made efficient in a diverging nozzle configuration. Numerical simulations are performed by Resendes et al. [90] to study the flight mechanics of ascent trajectories controlled by a laser propulsion system. COLVET, a launch vehicle simulation software program, is used to simulate the motion of vehicles propelled by laser. Experimental data, obtained from an earlier laser-propelled flight by Myrabo [91], is used to reproduce the experiment using COLVET. A comparison of the two data sets is seen below in Figure 12. A lack of published data on the vehicle developed by Myrabo led the authors to estimate several parameters, but data seems to have correlated nicely with the flight test results.

Based on other results, the researchers concluded that the most promising form of thermal laser propulsion is the LSD wave mechanism, using either an air breathing or rocket mode. A combination of short pulses ($\sim 10^{-9}$ s) and high repetition rates ($10^4$–$10^5$ Hz) for pulse formatting is proposed to improve thruster performance. Uniform ignition is required in systems utilizing the LSD concept, and can be achieved by using laser focusing or by using low temperature ionization. Due to ballistic considerations, there is a required minimum laser power to launch a given mass. Preliminary simulations with COLVET suggest that the minimal size of the vehicle is 3 kg with an onboard 3 MW laser. It is also suggested that with current laser power levels, on the order of 100 kW, a craft of 200 g mass should theoretically launch to above 10 km in height. It is proposed for future experiments to launch smaller scale vehicles to several kilometers in altitude, since a vertical ascent trajectory is used to reach this height, and the present study can be used to analyze such a case.

## 3. Summary and conclusions

Presented here is a review of laser ignition and its application to both aero and space vehicles. With respect to gas turbines, research performed on microwave-enhanced laser ignition yielded significantly evident kernel growth rates, with reductions in ignition delay times and larger ignition volumes. MIE values and how they are affected in differing circumstances were also investigated, indicating that MIE's decrease with increasing pressure at a given turbulence but increase with increasing turbulence at a fixed pressure. The development of a laser ignition system is reviewed in both a single- and multi-cylinder system, with possible benefits including a 60% reduction in $NO_x$ emissions and a 0.8% increase in thermal efficiency in the case of a 6 cylinder preliminary study. Plasma assisted combustion in gas turbines was also detailed in the manuscript, using CFD modeling to demonstrate potentially cooler temperatures in the combustion chamber, as well as lower $NO_x$ emissions.

Advanced ignition systems were examined in supersonic and hypersonic systems. An area of great interest is through the use of plasma-assisted technologies, using both conventional and laser ignition methods. Using conventional ignition methods, a two-stage mechanism was developed to describe plasma-assisted combustion flame stabilization for hydrocarbon fueling and low temperature by nonequilibrium plasma. This includes active radical production and preflame, followed by high temperature and pressure rise. Several studies are also reviewed regarding advanced ignition in supersonic crossflows, which can lead to reductions in ignition delay time and may contribute to the autoignition process. In terms of scramjet applications, several different geometric fuel injection variances were analyzed, including the advantages and disadvantages of cavities, ramp injectors, wall steps, and angled combustor walls. Several laser-induced plasma ignition methodologies were studied as well, such as shear-layer and fuel-jet ignition. Laser ignition in the 14-X scramjet engine is also reported with respect to its efficiency.

Advanced ignition, particularly laser ablation, also has its place among future rocket and space designs. Laser ablation, especially with the advent of such technologies as fiber optics, could allow for applications ranging from milliwatt-powered satellite correction thrusters to gigawatt systems for ground launch into orbit. Benefits from this type of system include adjustable specific impulse, variable thrust by differing laser-pulse repetition rate, and a reduced cost of operation. From an economical standpoint, microthrusters on satellites which utilize diode lasers are proving to be much more efficient, not to mention lighter in weight and more efficient. The aforementioned characteristics of laser ignition and diagnostics are promising, and future research on the subject may yield systems with a significant aerospace applications.

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