Laser Ignition For Combustion Engines

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ABSTRACT

With the advent of lasers in the 1960s, researcher and engineers discovered a new and powerful tool to investigate natural phenomena and improve technologically critical processes. Nowadays, applications of different lasers span quite broadly from diagnostics tools in science and engineering to biological and medical uses. In this article basic principles and applications of lasers for ignition of fuels are concisely reviewed from the engineering perspective. The objective is to present the current state of the relevant knowledge on fuel ignition and discuss select applications, advantages and disadvantages, in the context of combustion engines. Fundamentally, there are four different ways in which laser light can interact with a combustible mixture to initiate an ignition event. They are referred to as thermal initiation, nonresonant breakdown, resonant breakdown, and photochemical ignition. By far the most commonly used technique is the nonresonant initiation of combustion primarily because of its freedom in selecting the laser wavelength and ease of implementation. Recent progress in the area of high power fiber optics allowed convenient shielding and transmission of the laser light to the combustion chamber. However, issues related to immediate interfacing between the light and the chamber such as selection of appropriate window material and its possible fouling during the operation, shaping of the laser focus volume, and selection of spatially optimum ignition point remain amongst the important engineering design challenges. One of the potential advantages of the lasers lies in its flexibility to change the ignition location. Also, multiple ignition points can be achieved rather comfortably as compared to conventional electric ignition systems using spark plugs. Although the cost and packaging complexities of the laser ignition systems have dramatically reduced to an affordable level for many applications, they are still prohibitive for important and high-volume applications such as automotive engines. However, their penetration in some niche markets, such as large stationary powerplants and military applications, are imminent.

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14. ABSTRACT

With the advent of lasers in the 1960s, researcher and engineers discovered a new and powerful tool to investigate natural phenomena and improve technologically critical processes. Nowadays, applications of different lasers span quite broadly from diagnostics tools in science and engineering to biological and medical uses. In this article basic principles and applications of lasers for ignition of fuels are concisely reviewed from the engineering perspective. The objective is to present the current state of the relevant knowledge on fuel ignition and discuss select applications, advantages and disadvantages, in the context of combustion engines. Fundamentally, there are four different ways in which laser light can interact with a combustible mixture to initiate an ignition event. They are referred to as thermal initiation, nonresonant breakdown, resonant breakdown, and photochemical ignition. By far the most commonly used technique is the nonresonant initiation of combustion primarily because of its freedom in selecting the laser wavelength and ease of implementation. Recent progress in the area of high power fiber optics allowed convenient shielding and transmission of the laser light to the combustion chamber. However, issues related to immediate interfacing between the light and the chamber such as selection of appropriate window material and its possible fouling during the operation, shaping of the laser focus volume, and selection of spatially optimum ignition point remain amongst the important engineering design challenges. One of the potential advantages of the lasers lies in its flexibility to change the ignition location. Also, multiple ignition points can be achieved rather comfortably as compared to conventional electric ignition systems using spark plugs. Although the cost and packaging complexities of the laser ignition systems have dramatically reduced to an affordable level for many applications, they are still prohibitive for important and high-volume applications such as automotive engines. However, their penetration in some niche markets, such as large stationary powerplants and military applications, are imminent.

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INTRODUCTION

In order to ignite a mixture of gaseous fuel and air and initiate a flame, a localized input energy in a form of heat or active chemical species (radicals) must be added. The magnitude of this energy should be higher than a critical value called minimum ignition energy (Emin). The physics of combustion initiation guides us to a requirement of a minimum flame embryo (flame kernel) size or radius of, say L_k, see Ronny (1994). The L_k can be approximated by the thickness of a flame front (L_f) consuming the charge in a homogeneous fuel-air mixture. Hence, the simplest physical picture of the ignition process can be formed as an injection of a certain minimum amount of energy (Emin) to raise the temperature of a spherical zone of fuel-air mixture with size of L_f to a distinct temperature referred to as "adiabatic flame temperature". The term "adiabatic flame temperature" defines a terminal temperature of a fuel-air mixture when its combustion occurs under adiabatic condition (i.e., no heat losses from the combustion chamber). For example, experimentally speaking, the Emin of about 0.02 mJ energy is needed to ignite a stoichiometric mixture of hydrogen in air, whereas 0.4 mJ is required for methane and air mixture.

Fundamentally, there are four different methods in which laser light can interact with a combustible gaseous mixture for ignition, see Ronny (1994). They are referred to as thermal initiation, nonresonant breakdown, resonant breakdown, and photochemical ignition. In *thermal initiation* of ignition, there is no electrical breakdown of the gas and a laser beam is used to raise the kinetic energy of target molecules in either translational, rotational, or vibrational forms. Consequently, molecular bonds are broken and chemical reaction occurs leading to ignition with typically long ignition delay times. This method is suitable for fuel/oxidizer mixtures with strong absorption at the laser wavelength. However, if localized ignition in a gaseous or liquid mixtures is an objective, thermal ignition is unlikely a preferred choice due to energy absorption along the laser propagation direction. Conversely, this is an ideal method for homogeneous or distributed ignition of combustible gases or liquids. Thermal ignition method has been used successfully for solid fuels due to their absorption ability at infrared wavelengths.

In *nonresonant breakdown* ignition method, because typically the light photon energy is in visible or UV range of spectrum, multiphoton processes are required for molecular ionization, see Fig. 1a. This is due to the lower photon energy in this range of wavelengths in comparison to the molecular ionization energy. The electrons thus freed will absorb more energy to boost their kinetic energy (KE), facilitating further molecular ionization through collision with other molecules. This process shortly leads to an electron avalanche and ends with gas breakdown and ignition. The multiphoton absorption occurs in presence of losses (electron diffusion outside the focused volume, radiation, collisional quenching of excited states, etc.), thus demanding very high input beam intensities (through tightly-focused high-energy short-duration laser beam pulses) for a successful ignition process. To assist the breakdown process, in some studies a metal needle is inserted just behind the beam focused volume as an additional source of electrons. By far, the most commonly used technique is the nonresonant initiation of ignition primarily because of the freedom in selection of the laser wavelength and ease of implementation.

The *resonant breakdown* laser ignition process involves, first, a nonresonant multiphoton dissociation of molecules resulting to freed atoms, followed by a resonant photoionization of these atoms, see Fig. 1b. This process generates sufficient electrons needed for gas breakdown. Theoretically, less input energy is required due to the resonant nature of this method.

In *photochemical* ignition approach, very little direct heating takes place and the laser beam brings about molecular dissociation leading to formation of radicals (i.e., highly reactive chemical species), see Fig. 1c. If the production rate of the radicals produced by this approach is higher than the recombination rate (i.e., neutralizing the radicals), then the number of these highly active species will reach a threshold value, leading to an ignition event. This (radical) number augmentation scenario is named as chain-branching in chemical terms.

MINIMUM IGNITION ENERGY MEASUREMENTS

As mentioned earlier, the most widely used approach for the laser ignition is based on the nonresonant mechanism. Therefore, some results of the minimum ignition energy for this case are presented here. Figure 2 from Syage et al. (1988) shows a plot of the required minimum ignition energy to ignite a mixture of hydrogen and air as a function of the fuel volume fraction. The dashed curve in this plot indicates the minimum ignition energy measured by Lewis and von Elbe (1951) using electric spark energy. Both fundamental (1064 nm) and harmonics (532 & 355 nm) of the Nd:YAG laser gave similar results. Also, Q-switched (12 ns pulse) and pulse-mode locked operation (25 to 50 ps) showed similar minimum ignition values for the hydrogen. The minimum ignition energies by the laser are higher by about an order of magnitude near the stoichiometric fuel/air ratio and approach those of the electric spark values for the rich and lean mixtures.

Figure 3 shows the Emin for the gaseous methane fuel with values of about one order of magnitude larger than the hydrogen. It is seen that the minimum ignition energy for the laser is higher than the values by electric spark systems, similar to the hydrogen trends. Note that under the lean mixture, the minimum ignition energy by the laser becomes independent of the pulse duration and matches or goes lower than that of the electric spark case. However, near the stoichiometric mixture (about 9.5% by volume), effects of the pulse duration is strongly felt. To explain the higher Emin values for the laser ignition, it was considered possible that different minimum ignition energies by the ps versus ns sparks may be due to the dependence of the ignition energy on the spark kernel size, see Ronney (1994). As an example, one may imagine that if the size of the laser-initiated spark exceeds the critical energy deposition radius (L_k), the ignition process may be less efficient. As a reference, this radius is about 300 microns in size for the stoichiometric methane in air mixture at 1 atm. Figure 4 shows the size of the laser focused volume as a function of the laser energy for two pulse durations tested. This size was measured using the visible emission of the sparks. Near the lean and stoichiometric values, estimates for the L_k are about 1000 and 400 μm, respectively. Hence, considering the measurements in Fig. 4, the size of the energy deposition by laser is smaller than the L_k and the reverse trend exists for the near-stoichimetric case. This is proposed by Lim et al. (1996) to partly explain the fact that higher minimum ignition energies are needed around the stoichimetric mixture ratios whereas towards the lean limit this requirement is relaxed.

More recently, Phuoc and White (2002), using a Q-switched Nd:YAG laser at 1064 nm with a 5.5 ns pulse duration, showed that the shock wave propagation and radiation energy losses can be a significant portion of the input energy. In fact, with spark energies in between 15 to 50 mJ, they estimated 51 to 70% and 22 to 34% losses attributed to shock and radiation energy, respectively. Considering these energy loss mechanisms, they reported comparable Emin for the eclectic spark and laser ignition.

LASER IGNITION IN FLOWS

The concept of the minimum ignition energy discussed above was in the context of an ideal, well-mixed, and quiescent fuel/air system. However, in most industrial applications there is a flow of fuel/air mixture combined with a certain degree of charge stratification. For example, even in a conventional spark-ignited gasoline engine there is a certain level of cyclic variability of the charge motion and mixing between the fresh charge and residual burned gases (or even EGR) at the time of the ignition and at the location where it occurs. Hence, from the practical point of view, controlled studies simulating these effects are important and very useful. Figure 5 shows results from a study by Phuoc et al. (2002) investigating the laser ignition behavior in a gaseous diffusion-flame jet arrangement where the fuel is injected into the ambient air. Note that due to variabilities mentioned earlier, and in order to have a meaningful data set, the concept of the ignition probability is introduced and this quantity was measured as shown in Fig. 5. Ignition probability indicates the fraction of a successful ignition leading to an established flame. A laser energy of 4 mJ was used for all the tests and considered high enough for the ignition probability to be independent of the laser energy. The laser focused-volume was traversed both radially and axially to produce the results shown in Fig. 5. Near the jet exit plane the probability values are generally low, due to poor fuel/air mixing, and increases at larger distances away from this area, see Fig. 5. Radial profiles exhibit a very low probability near the jet symmetry axis area, which is dramatically improved at larger distances from the jet exit plane. Effects of the increased flow velocity are also shown to be detrimental to the ignition quality.

LASER IGNITION OF LIQUID SPRAYS

In many industrial applications, liquid fuels are used and as such one must consider liquid jet breakup and atomization processes. In these cases, the ignition system sees an ensemble of liquid fuel droplets fluidized with a mixture of vaporized fuel and oxidizer at the ignition point. There have been a few studies to elevate our understanding on special requirements of such systems, see Gajdeczko et al. (1999) and Liou (1994). As an example, a reference is made here to the work of Liou (1994) at NASA Lewis Research Center in the context of the liquid-fueled rocket engines. In his study, both gaseous and liquid fuels were used to offer a comparison between the two cases in a simulated rocket reactor. In rockets, separate fuel and oxidizer channels are required to bring them to the injector plate of the combustion chamber. In this study, gaseous oxygen and gaseous hydrogen (GOX/GH_2), and GOX/CH_4(gas) pairs were used as propellants, and GOX/RP-1(liquid) was used for liquid spray ignition studies.

The laser was Nd:YAG and fired at 1064 nm with a pulse width of 9 ns. It was found that the laser ignition was highly feasible for the ignition of the GOX/GH_2 and GOX/CH_4 and moderately compatible with the GOX/RP-1 propellant pair. Liou reported that the flow speed in the combustion chamber did not have an effect on the ignition limit and ignition delay of the GOX/GH_2. However, when GOX/CH_4 was used, the flow speed affected both the ignition limit and the delay time. This can be attributed to the high activation threshold and slow chemical kinetics of the GOX/CH_4 and that under turbulent conditions the heat losses from the ignition spark becomes significant to affect the ignition outcome.

Figure 6 shows results of the ignition by a laser as compared to those when an electric spark system is employed. Note that for the GOX/GH_2 pair, the two ignition systems are comparable in terms of establishing the lean and rich limits. Differences are seen when GOX/CH_4 pair was used. The big contrast is observed when the liquid fuel (RP-1) is injected with GOX. It appears that as the Oxidizer/Fuel mass ratio (i.e., O/F) is increased, the liquid spray becomes less dense and consequently less interference for the laser induced-breakdown is experienced (for example, it was reported that increasing laser energy did produce successful ignition contrary to the gaseous propellant cases).

In an attempt to investigate ignition of a liquid ethanol with nitrogen-diluted oxygen gas, Gajdeczko et al. (1999) used an Nd:YAG laser at 532 nm. They found that when the liquid spray had an SMD of 63 μm, 100 % ignition probability was measured under the overall equivalence ratio somewhere in between 0.2 and 0.5 when laser pulse energy was larger than 22 mJ. However, with the SMD of 80 μm, 100% ignition probability was obtained for all equivalence ratios as long as the laser pulse energy was greater than 36 mJ. The most favorable overall equivalence ratio region was found to be on the stoichiometric and rich sides.

LASER-INDUCED CAVITY IGNITION

One of the known disadvantages of the laser ignition is the fact that a large fraction of the energy of the laser beam is lost because it passes through the mixture relatively unabsorbed before gas breakdown occurs. To use all the beam energy, a conical cavity was proposed to confine the laser beam in order to test the ignition of methane with air in a constant volume chamber, see Morsey et al. (1999). The most interesting feature of this method is the ejection of the hot gaseous products from the cavity a few milliseconds after the laser is fired. When tested inside a chamber with the cavity positioned near the wall versus when the charge was ignited at the center, pressure traces rose more quickly and the total combustion times were shorter. The reduction in total combustion time was reported and attributed to the observed ejection of the hot gaseous jet from the cavity into the chamber. Figure 7 shows preliminary results from this work. Multipoint ignition of up to three points were also investigated showing an enhanced rate of pressure rise with the number of ignition sites.

LASER IGNITION APPLICATIONS

An observed advantage of the laser ignition over the electric spark ignition method is the reduction of the Emin as the charge pressure is increased. For example, a nine-fold decrease in Emin was observed as pressure was raised from 1 to 10 bars for methane/air mixture, see Fig. 8. Kopecek et al. (2000) showed that the use of optimized optics and laser systems can reduce the required minimum laser pulse energy for the ignition to where the application of the laser becomes reasonable. A minimum useful focal spot size of 20 μm was found to be independent of the laser wavelength.

Use of lasers for ignition purposes at three different wavelengths in a constant volume bomb was demonstrated by Ma et al. (1998) and results were compared with those obtained by an electric spark system. Lower combustion times and higher early flame speeds were measured for the laser ignition system. Figure 9 shows a comparison of the pressure traces when combustion is initiated by different ignition methods. They also showed that equivalence ratio, initial temperature, initial pressure, and ignition location were all significant in determining the combustion duration, peak heat release, peak pressure, and flame speed, whereas ignition energy was not. Finally, laser ignition exhibited smaller cycle-to-cycle variations during the early combustion phase than those with the electric spark plug.

One of the earliest application of the laser ignition in a gasoline engine was demonstrated by Dale et al. (1978). They reported that the laser ignition was able to ignite a leaner mixture and that the pressure rise time was shorter compared to an electric ignition unit. However, the smaller pressure rise time led to a higher emission of the nitric oxide (NO). In particular, the use of laser increased the peak cylinder pressure by 5% and 15%, without the exhaust gas recirculation (EGR) and with 16% EGR, respectively. Additionally, they found that the CO and HC emissions were comparable for the two ignition systems. Figure 10 shows samples of their reported results.

Figure 11 indicates the so-called tradeoff between the specific fuel consumption and NO emissions for the two ignition systems. It is clear that for a given level of NO emission, the laser ignition system offers a superior fuel economy than the spark plug system. Regarding the window fouling, the authors reported that carbon deposit build-up made it necessary to remove the window for cleaning every 30 to 75 minutes of operation.

One of the most promising near-term applications of the laser ignition is for large lean-burn natural gas engines. Regulations on NOx emissions have continued to force operation of natural gas engines to leaner air/fuel ratios. Engine operation under the lean fuel/air mixtures using a spark plug ignition is limited because of the misfire and unstable operation. Additionally, ignition of the lean mixture is difficult and conventional systems require high ignition energies. High energies are usually achieved through an increased ignition coil energy. However, this measure tends to rapidly burn out even the precious metal spark plugs utilized in stationary engines for power generation. Also, natural gas is more difficult to ignite than gasoline due to the strong C-H bond energy. Considering the foregoing, and the recent availability of small-sized high-power solid-state rugged lasers, the near-future use of the laser ignition in this application is promising.

Figure 12 shows the coefficient of variation (COV) of the indicated mean effective pressure (IMEP) from a single-cylinder lean-burn natural gas engine using two ignition, systems (electric and laser) for power generation, see McMillan et al. (2003). A much lower COV values are seen with the laser especially when the ignition timing is retarded to 15 degrees before top dead center (BTDC). Similarly, 0-to-10% mass burn duration was also reduced with laser ignition indicating accelerated combustion in the early development phase. In this study, a Q-switched Nd;YAG laser with 10 ns pulse is used at 1064 nm with 60 to 180 mJ/pulse of energy. They reported no issues with vibration or with combustion products fouling the sapphire window installed on the engine for the laser beam.

SUMMARY AND CONCLUSIONS

Although photochemical (resonant) ignition may be more energetically efficient (less energy needed) than laser induced plasma ignition, the requirement of a spectral match imposes limitations. Practical laser induced plasma ignition systems, being less spectrally sensitive, can be made transferable across different fuel/oxidizer mixtures. There are many technical advantages of the laser ignition over conventional electric spark ignition system. Laser ignition is nonintrusive in nature, high energy can be rapidly deposited, has limited heat losses, and is capable of multipoint ignition of combustible charges. More importantly, it shows better minimum ignition energy requirement than electric spark systems with lean and rich fuel/air mixtures. It possesses potentials for combustion enhancement and better immunity to spurious signals that may accidentally trigger electric igniters. One of the potential advantages of the lasers lies in its flexibility to change the ignition location. Also, multiple ignition points can be achieved rather comfortably as compared to the conventional electric ignition systems using spark plugs. Although the cost of the lasers has dramatically reduced to an affordable level for many applications, it is still prohibitive for technologically important applications such as automotive engines. However, their penetration in some niche markets, for example large stationary powerplants and military, are imminent.

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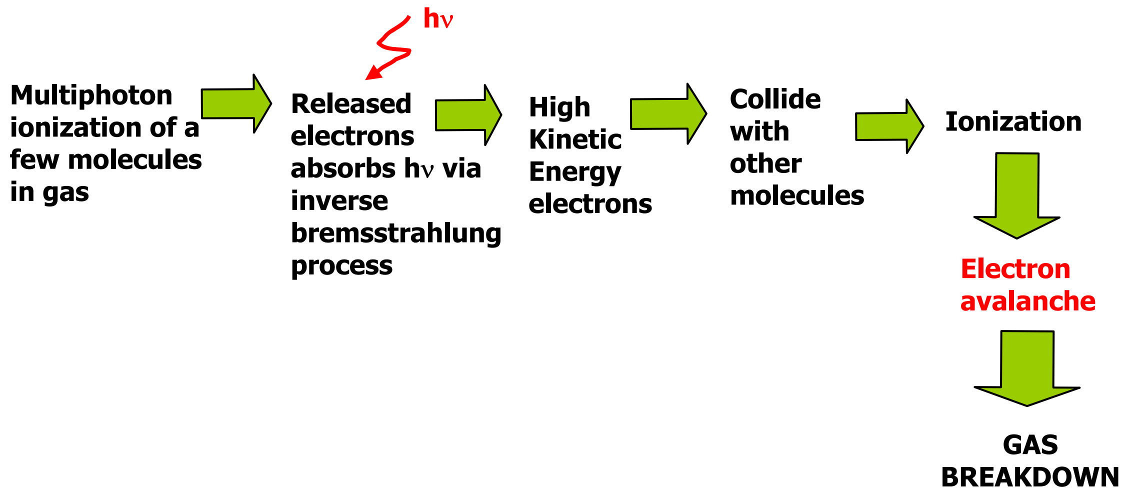


Figure 1a. Nonresonant laser-induced ignition

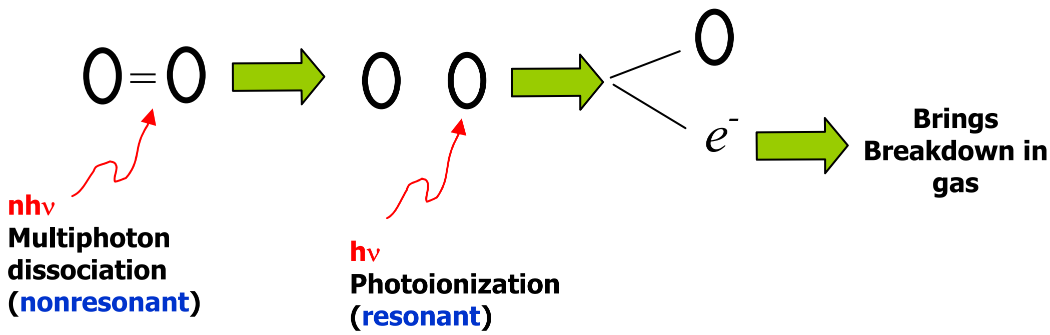


Figure 1b. Resonant laser-induced ignition

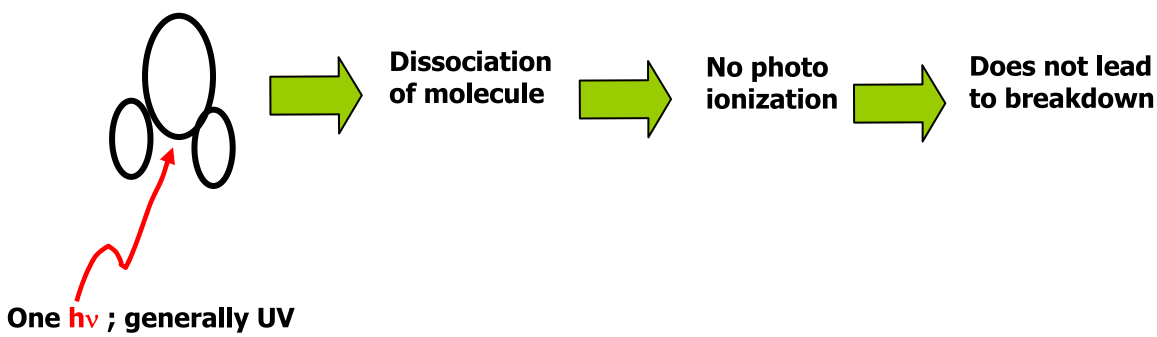


Figure 1c. Photochemical laser-induced ignition

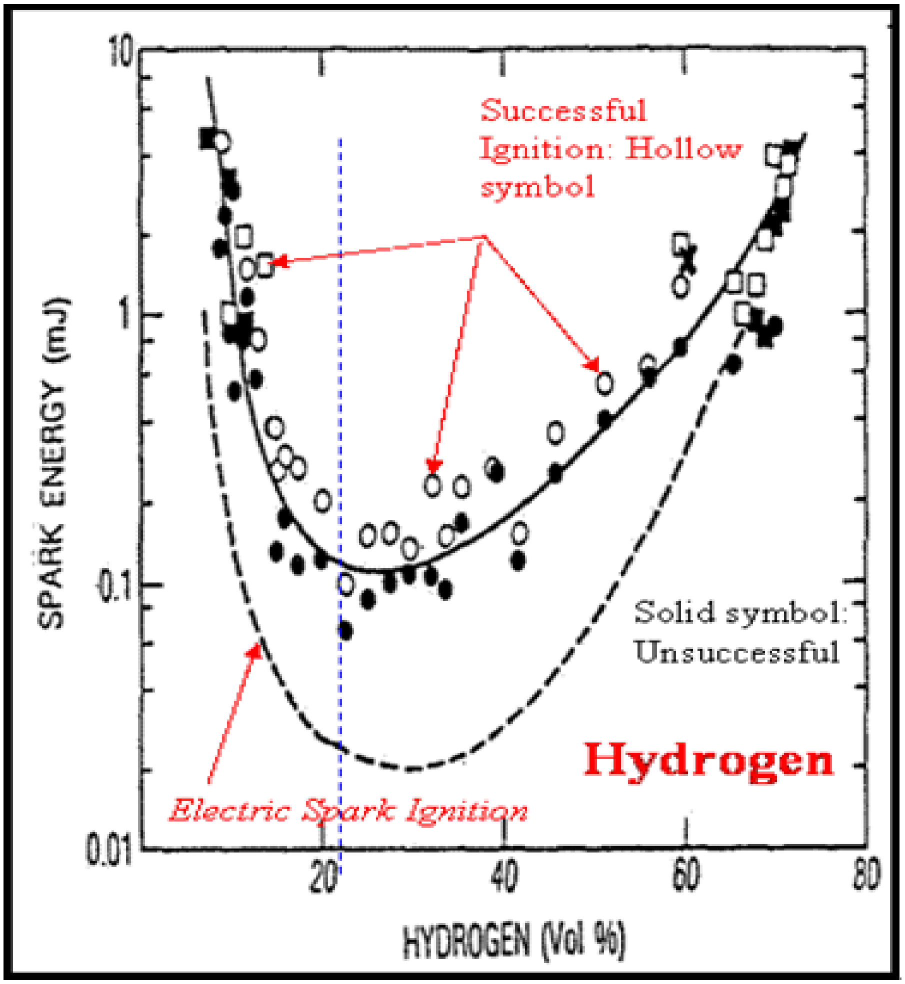


Figure 2. Shows a plot of the required minimum ignition energy to ignite a mixture of hydrogen and air as a function of fuel volume fraction. Ronny (1994) [or Syage et al. (1988)].

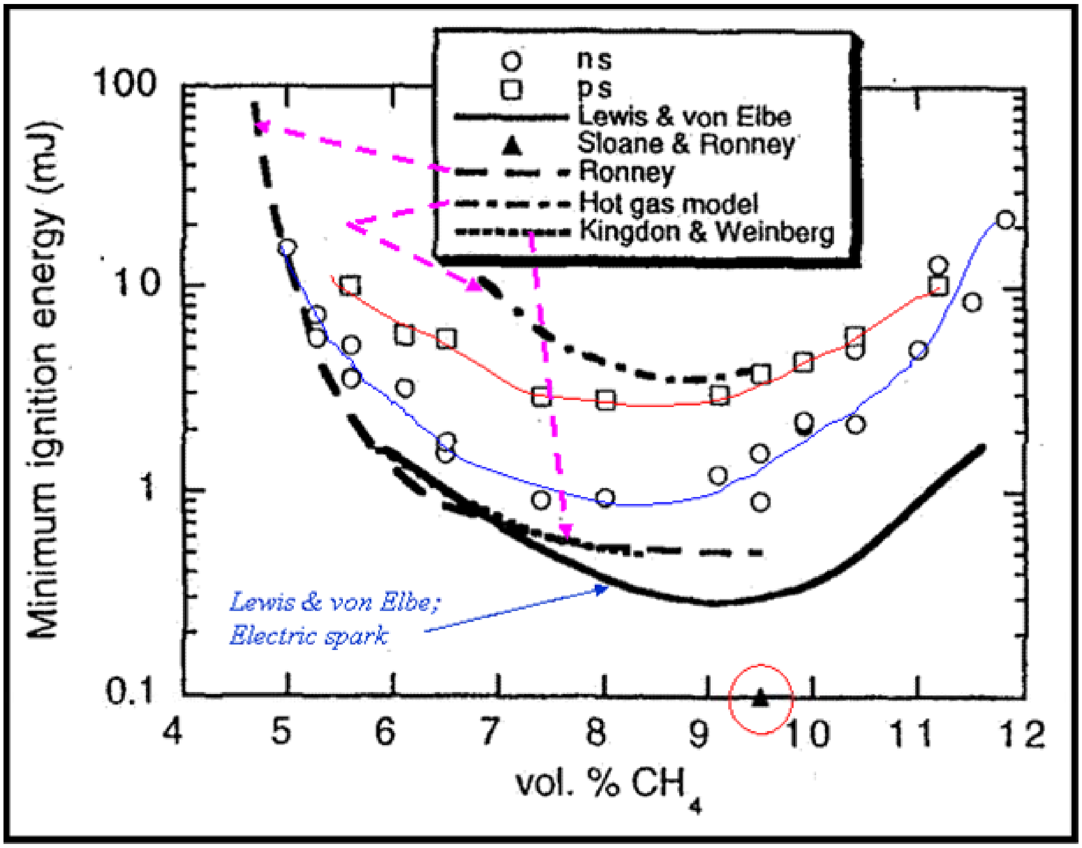


Figure 3. Shows results of the required minimum ignition energies to ignite a mixture of methane and air as a function of fuel volume fraction using laser at two different pulse durations (ns: nanosecond; ps: picosecond). Experimental and theoretical/computational results are shown for comparison purposes. Ronny (1994).

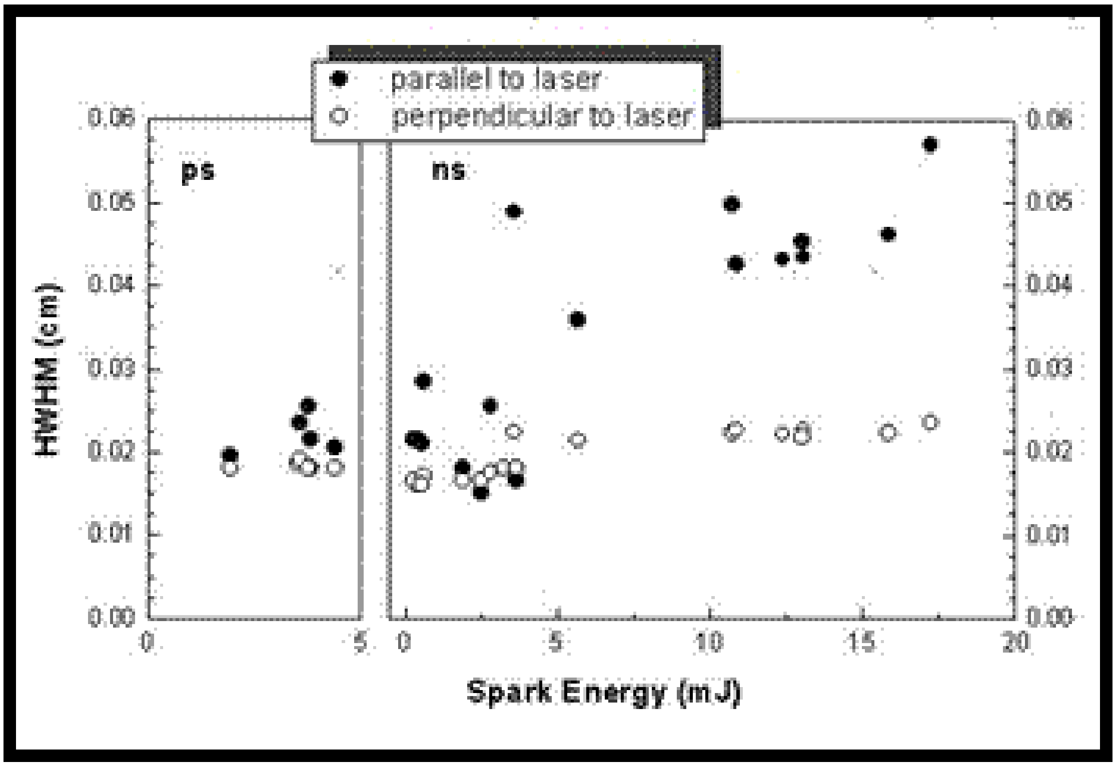


Figure 4. Measurements of the geometrical size of the laser focused volume in two perpendicular directions at the location where ignition occurs. HWHM: half width half maximum. Lim et al. (1996).

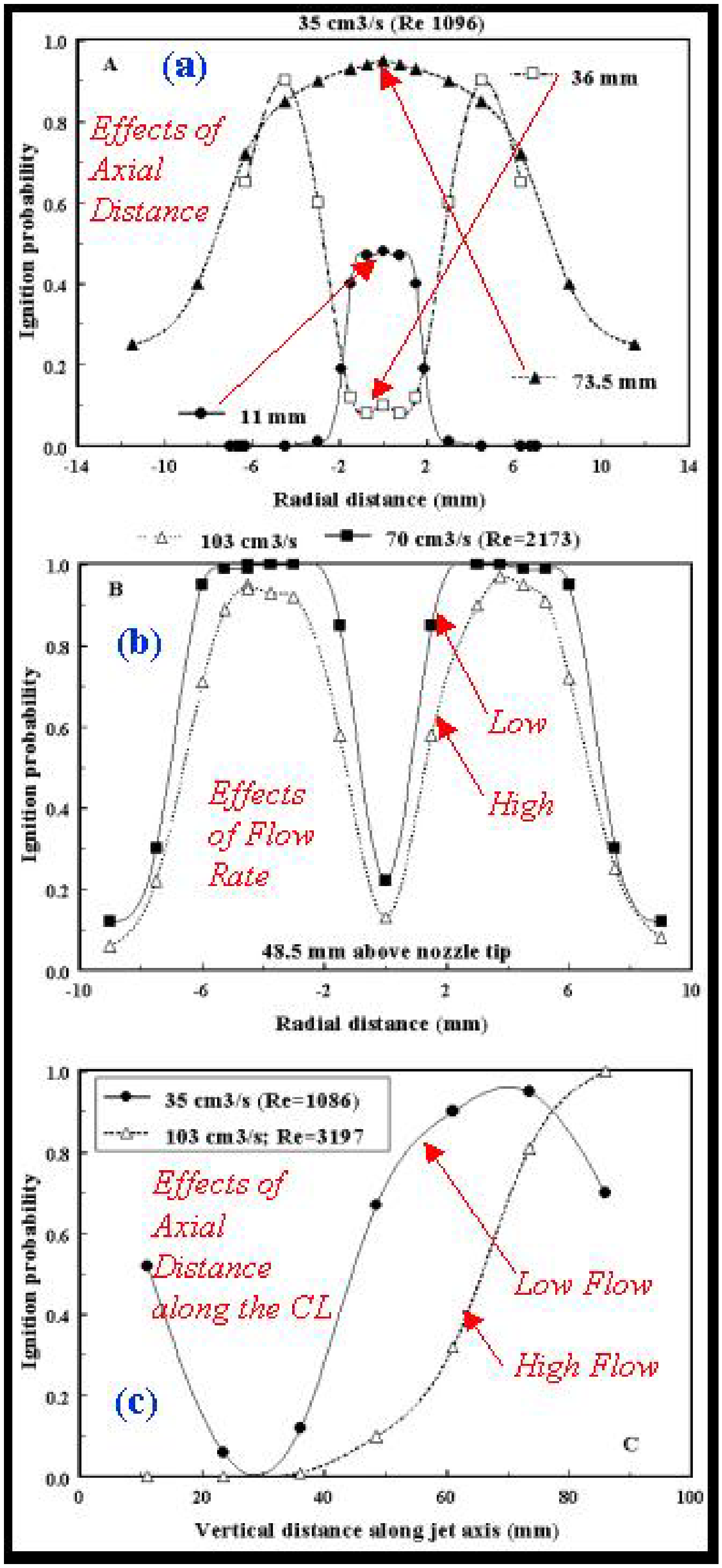
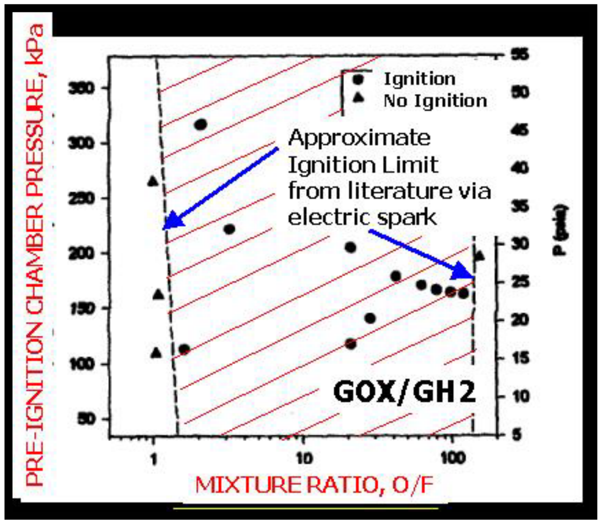


Figure 5. Shows ignition probability as a function of the axial and radial distances and jet velocity. Phuoc et al. (2002).



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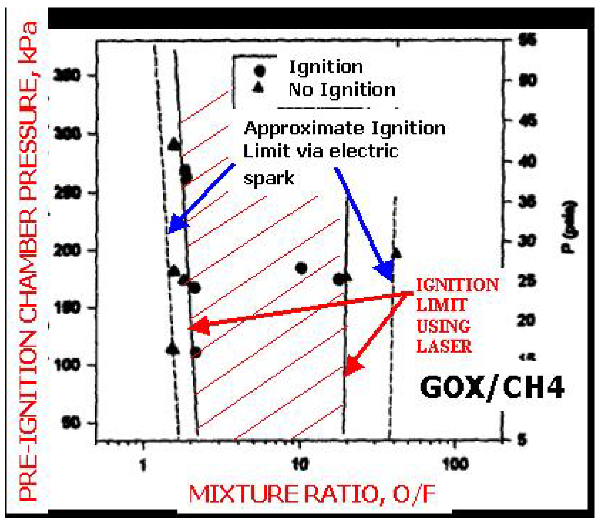
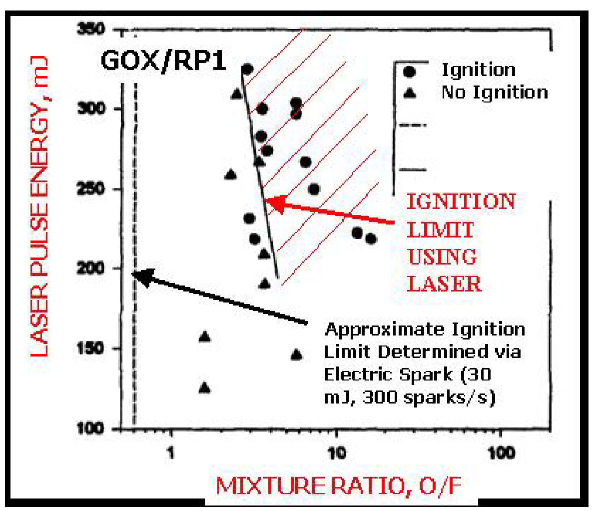


6(b)



6 (c)

Figure 6. Shows results of the ignition limits by a laser for a simulated rocket engine fueled with both gaseous and liquid fuels as compared to those when electric spark is employed. Liou (1994).

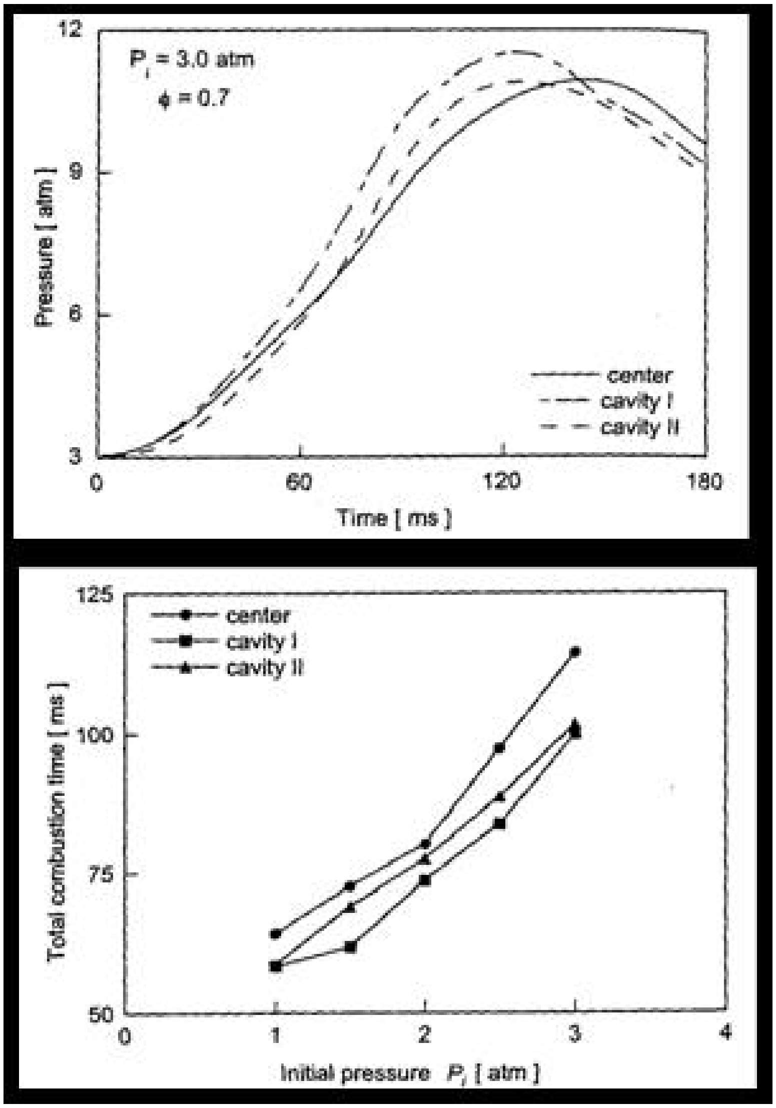


Figure 7. Pressure traces and total combustion times as functions of time and initial pressure, respectively. Results for two different cavity dimensions are shown. Morsey et al. (1999).

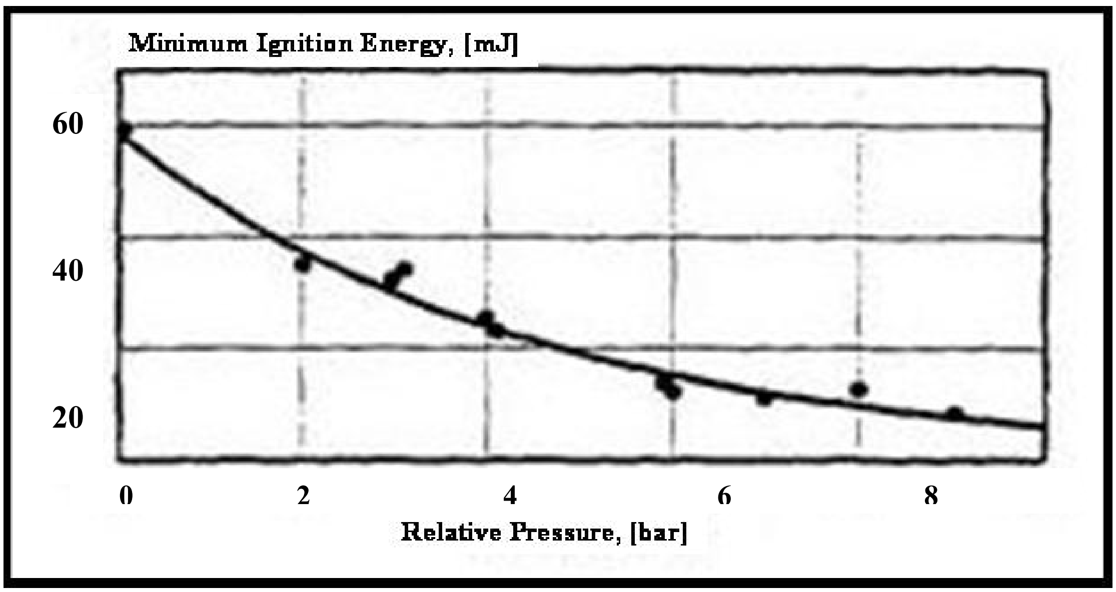
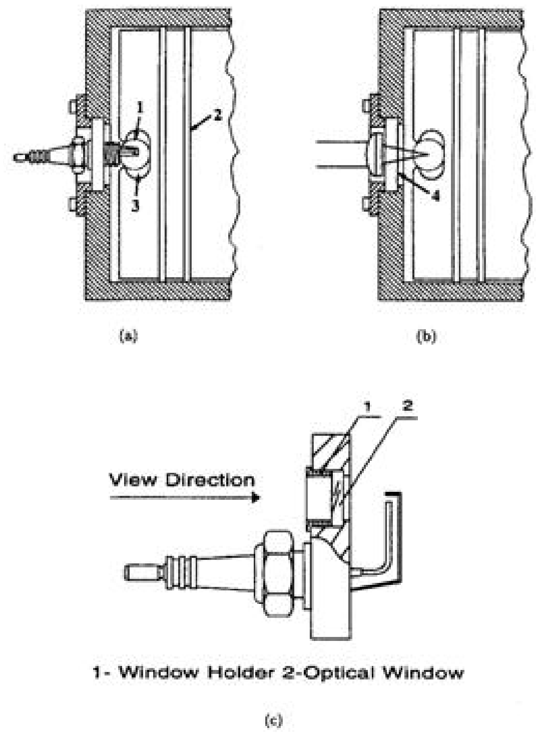
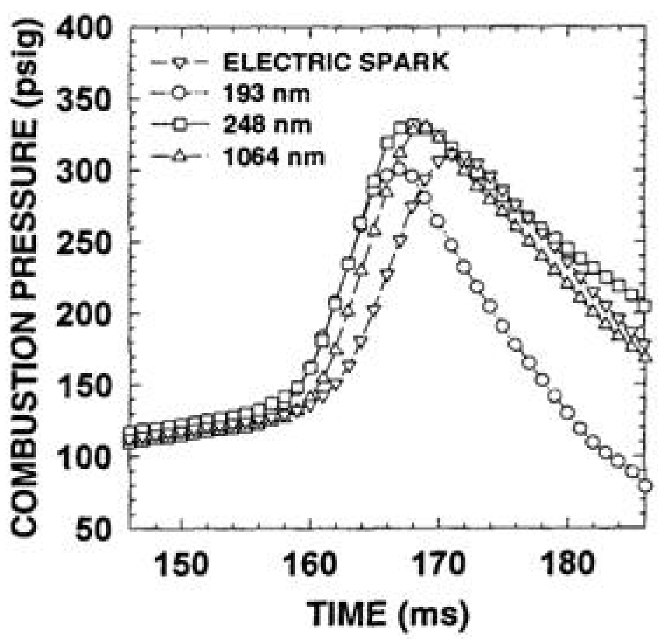


Figure 8. Effects of chamber pressure on Emin for laser ignition. Kopecek et al. (2000).



9(a)



9(b)

Figure 9. (a) shows details of the laser and electric spark ignition system arrangements. (b) pressure traces after the combustion initiation by laser (three wavelengths) and electric discharge with spark plug. Ma et al. (1998).

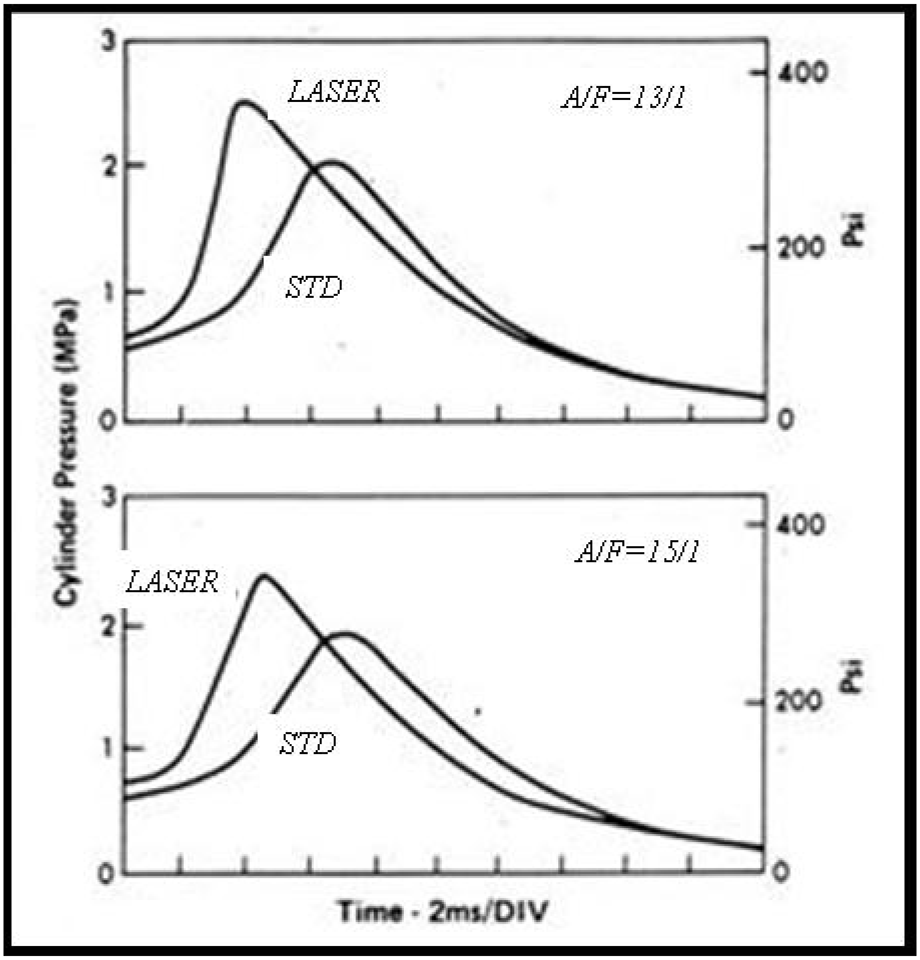


Figure 10. Cylinder pressure traces at two different air/fuel (A/F) mass ratios for laser and standard (STD) ignition systems. Dale et al. (1978).

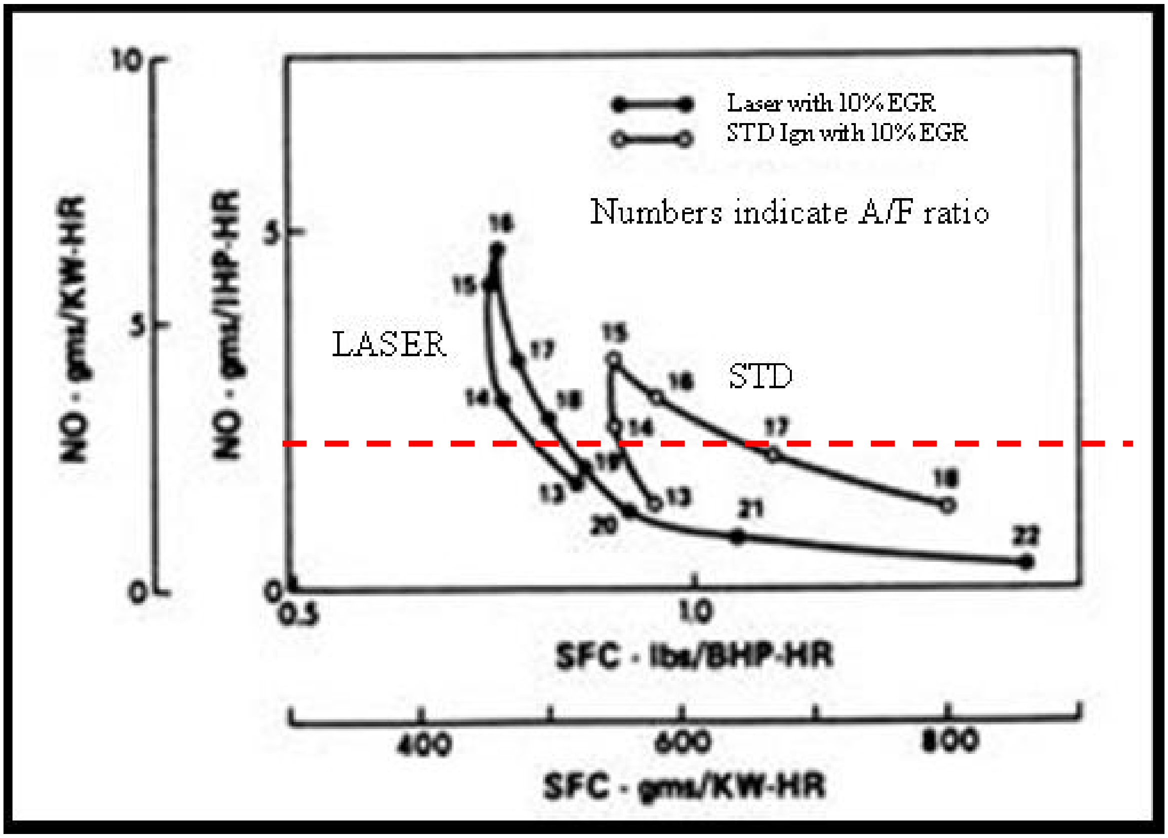


Figure 11. Plots of NO emissions versus specific fuel consumption (SFC), the trade-off curves, for laser and standard (STD) electric ignition systems. Dale et al. (1978).

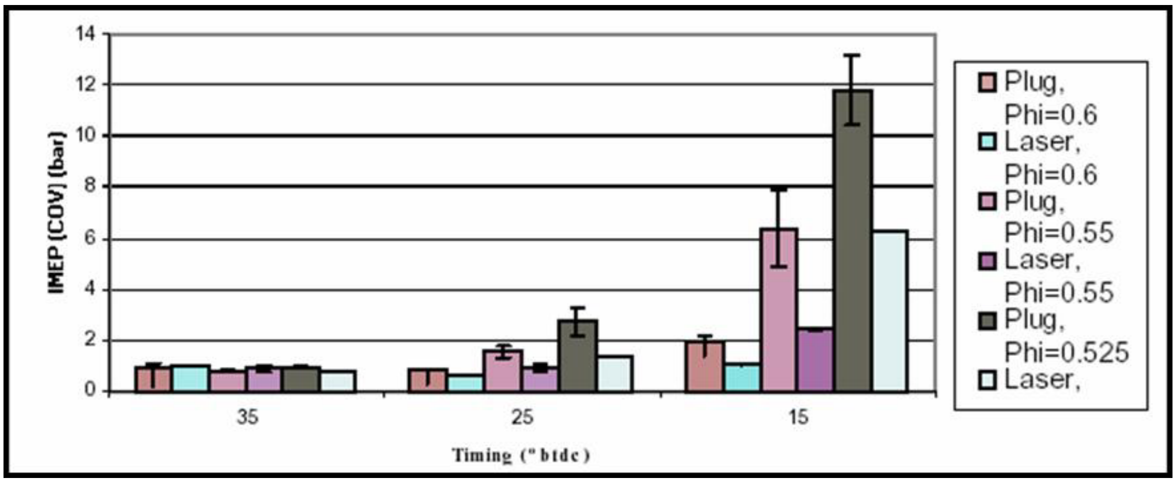


Figure 12. Coefficient of variation of the IMEP at three different ignition timing. Results are shown for three different equivalence ratios (phi). McMillan et al. (2003).