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# Laser Ignition System over Spark Ignition

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*Abstract*— Energy demand in automobile and emission norms are forcing automotive researchers to develop new combustion technologies to comply with stringent emission norms being adopted worldwide and continue the quest for improving engine performance and reducing emission. Nowadays, combustion engines and other combustion processes play an overwhelming and important role in everyday life. Researcher and engineers discovered a new technology and powerful tool to investigate natural phenomena and improve technologically critical processes. The spark plug is widely used in various automobile engines as a source of ignition. But due to the increasing emission through the exhaust of vehicles emission norms are forcing automobile researchers & manufacturers to develop new technologies that can overcome this issue. So, to overcome this issue and improving the performance of engines in less emission the researchers are working on to develop the new alternate source of ignition by using laser pulses. Laser is a new technology and emerging source of ignition alternate to the spark ignition system. The flame propagation is fast as compared to the spark ignition system so in laser ignition system the air fuel mixture burns completely so there is no chance of unburnt gases it may helps to reduce emission. Laser is emerging as a strong concept for alternative ignition in spark ignition engine. Laser ignition has potential advantages over conventional spark plug ignition. Laser ignition system is free from spark electrodes hence there is no loss of spark energy to the electrodes, which are also free from erosion effect.

***Keywords:*** Spark Ignition, Laser Ignition, Emission Norms, Spark Plug, Laser Pulse, Combustion, Alternate Ignition, Spark Electrodes

## I. INTRODUCTION

With the development of industry and economy, energy short- age and environmental problems have been becoming more and more serious. The internal combustion engine and automotive industry are confronted with severe and realistic challenges. Current engines cannot be operated sufficiently lean due to ignition related problems such as the sluggish flame initiation and propagation along with potential misfiring. It is anticipated that the spark ignition engine of the future will operate with much higher compression ratios, faster compression rates, and much leaner fuel-to-air ratios. Due to market demands aimed at increasing the efficiency and the power density of IC engines, existing ignition systems are rapidly approaching their limits. To avoid this, IC engine manufacturers and researchers are seeking new technologies. The thermodynamic requirements of a high compression ratio and a high-power density are fulfilled well by laser ignition. the objective is to present the current state of the relevant knowledge on fuel ignition and discuss selected applications, advantages, in the context of combustion engines. Laser ignition can enhance the combustion process and minimize pollutant formation. This paper is on laser ignition of sustainable fuels for future internal combustion engines. Ignition is the process of starting radical reactions until a self-sustaining flame has developed. In technical appliances such as internal combustion engines, reliable ignition is necessary for adequate system performance. Ignition strongly affects the formation of pollutants and the extent of fuel conversion. Laser ignition system can be a reliable way to achieve this. 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, Non-resonant breakdown, Resonant breakdown, and Photochemical ignition. By far the most commonly used technique is the non-resonant initiation of combustion primarily because of its freedom in selecting the laser wavelength and ease of implementation [1]. To overcoming these challenges. Loss of engine power output can be compensated by boosting the charge density in the combustion chamber Increased charge density however requires higher secondary coil voltage to initiate combustion in a spark ignition engine which is using conventional spark ignition system. The voltage required to produce the spark depends on factors such as pressure inside the combustion chamber at the time of ignition, distance between the electrodes, and cylinder gas temperature. Providing the required voltage under these conditions would lead to spark electrode erosion. Since lean mixtures have relatively slower flame speed than stoichiometric mixtures, any technique which may provide increase in the air–fuel mixture burning rate, would be beneficial. Flame speed in the lean burn SI engine can be increased either by generating turbulence in the cylinder or by shortening the flame travel distance for the same mixture strength. Reduction in flame travel path can be realized by employing multiple spark plugs in each cylinder or by placing the ignition point at an optimum location inside the combustion chamber. It is rather challenging to install multiple spark plugs in multi-cylinder engines because of already overcrowded cylinder head. Optimum spark location inside the combustion chamber is also difficult in case of conventional spark ignition systems because spark location is always very close to the top of combustion chamber [2]. Ignition strongly affects the formation of pollutants and the extent of fuel conversion. Laser ignition system can be a reliable way to achieve this.

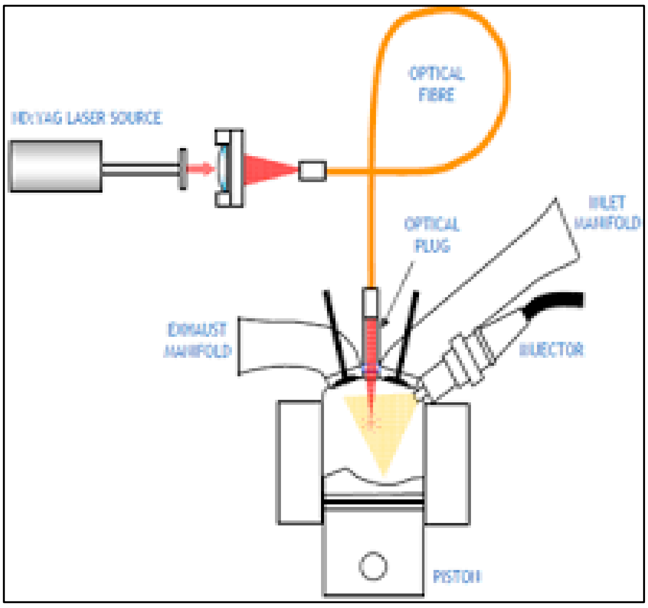

Figure 1: Laser ignition system.

### A. *Background Study of Ignition in IC Engine Ignition*

Ignition is the process of starting radical reactions until a self-sustaining flame has developed. One can distinguish between auto ignition, induced ignition and photo-ignition, the latter being caused by photolytic generation of radicals.

Types of Ignition

#### 1) *Compression Ignition (CI) or Auto Ignition*

At certain values of temperature and pressure a mixture will ignite spontaneously, this is known as the auto ignition or compression ignition.

#### 2) *Induced Ignition*

A process where a mixture, which would not ignite by it, is ignited locally by an ignition source (i.e. Electric spark plug, pulsed laser and microwave ignition source) is called induced ignition. In induced ignition, energy is deposited, leading to a temperature rise in a small volume of the mixture, where auto ignition takes place or the energy is used for the generation of radicals. In both cases subsequent flame propagation occurs and sets the mixture on fire.

#### 3) *Conventional Sparking Plug Ignition*

Conventional spark plug ignition has been used for many years. For ignition of a fuel-air mixture the fuel-air mixture is compressed and at the right moment a high voltage is applied to the electrodes of the spark plug.

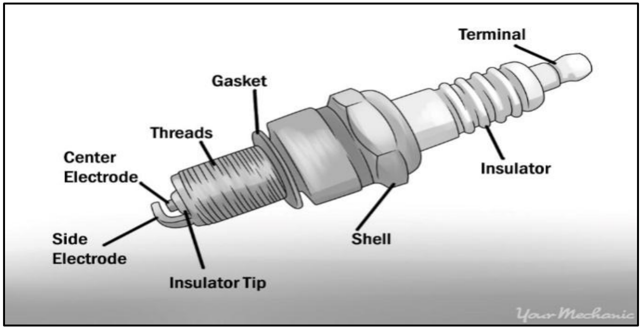

Fig. 2: Spark plug.

#### 4) *Alternative Ignition Systems*

Laser ignition as mentioned earlier, only laser ignition by optical breakdown fulfils the requirements on a well-defined ignition location and time. A powerful short pulse laser beam is focused by a lens into a combustion chamber and near the focal spot a hot and bright plasma is generated [1].

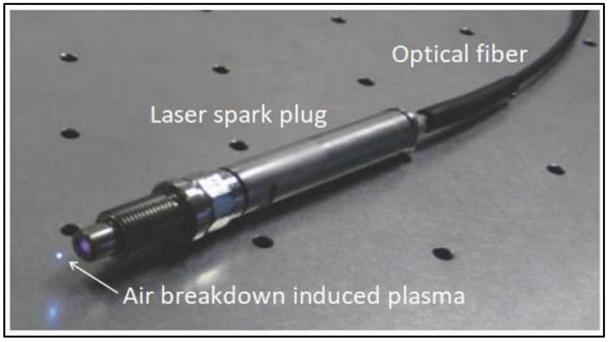

Fig. 3: Laser spark plug.

### B. *Types of Laser Ignition System:*

#### 1) *Thermal Initiation:*

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 translational, rotational, or vibration forms. Consequently, molecular bonds are broken and chemical reaction occur 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 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.

#### 2) *Non-Resonant Breakdown:*

In non-resonant breakdown ignition method, because typically the light photon energy is invisible or UV range of spectrum, multi photon processes are required for molecular ionization. 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. By far, the most commonly used technique is the non-resonant initiation of ignition primarily because of the freedom in selection of the laser wavelength and ease of implementation.

#### 3) *Resonant Breakdown:*

The resonant breakdown laser ignition process involves, first, a non-resonant multi photon dissociation of molecules resulting to freed atoms, followed by a resonant photo ionization of these atoms. This process generates sufficient electrons needed for gas breakdown. Theoretically, less input energy is required due to the resonant nature of this method.

#### 4) *Photochemical Mechanisms:*

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), 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.

## II. LITERATURE REVIEW

Swapnil S. Harel, Mohnish Khairnar, Vipul Sonawane studied on the thermodynamic requirements of a high compression ratio and a high- power density is fulfilled well by laser ignition. Through this paper, the objective is to present the current state of the relevant knowledge on fuel ignition and discuss selected applications, advantages, in the context of combustion engines. Sustainability with regard to internal combustion engines is strongly linked to the fuels burnt and the overall efficiency. Laser ignition can enhance the combustion process and minimize pollutant formation. This paper is on laser ignition of sustainable fuels for future internal combustion engines. Ignition is the process of starting radical reactions until a self-sustaining flame has developed. In technical appliances such as internal combustion engines, reliable ignition is necessary for adequate system performance. Ignition strongly affects the formation of pollutants and the extent of fuel conversion. Laser ignition system can be a reliable way to achieve this. 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 1. Thermal initiation, 2. Non-resonant breakdown, 3. Resonant breakdown, and 4. Photochemical ignition. By far the most commonly used technique is the non-resonant initiation of combustion primarily because of its freedom in selecting the laser wavelength and ease of implementation. Optical breakdown of a gas within the focal spot of a high-power laser allows a very distinct localization of the ignition spot in a combustible material. The hot plasma which forms during this breakdown initiates the following self-propagating combustion process [1].

R. Freeman, C. Anderson, J. M. Hill, J. King, the use of high-intensity lasers to cause ignition in inertial confinement fusion is presented, with emphasis on current experimental programs and physical concepts that are at the forefront of the field. In particular, we highlight the issues of fast electron transport through dense materials, an essential element of the “Fast Ignitor” concept [3].

M. Lackner, F. Winter presented Sustainability with regard to internal combustion engines is strongly linked to the fuels burnt and the overall efficiency. Laser ignition can enhance the combustion process and minimize pollutant formation. This paper is on laser ignition of sustainable fuels for future internal combustion engines. Ignition is the process of starting radical reactions until a self-sustaining flame has developed. In technical appliances such as internal combustion engines, reliable ignition is necessary for adequate system performance. Ignition strongly affects the formation of pollutants and the extent of fuel conversion. This paper presents experimental results on laser-induced ignition for technical applications. Laser ignition tests were performed with the fuels hydrogen and biogas in a static combustion cell and with gasoline in a spray-guided internal combustion engine. A Nd:YAG laser with 6 ns pulse duration, 1064 nm wavelength and 1-50 mJ pulse energy was used to ignite the fuel/air mixtures at initial pressures of 1-3 MPa. Schlieren photography was used for optical diagnostics of flame kernel development and shock wave propagation. Compared to a conventional spark plug, a laser ignition system should be a favourable ignition source in terms of lean burn characteristics and system flexibility. Yet several problems remain unsolved, e.g. cost issues and the stability of the optical window. The literature does not reveal much information on this crucial system part. Different window configurations in engine test runs are compared and discussed [4].

Jerald A. Caton (2000) analyzed complete version of thermodynamic engine cycle simulation for spark-ignition engine. The instructional version of cycle simulation used constant specific heats as compared to using variable properties and composition for the complete simulation. Mass fraction burned was calculated using Wiebe function. Woschni heat transfer coefficient model was used to calculate heat transfer to the cylinder gases. For the proper selection of constant properties, the global engine performance parameters and were obtained the instructional version of the simulation were in close agreement to the values obtained from using the complete version of the simulation [5].

Lawrence Mianzo and Huei Peng (2000) developed the cylinder by-cylinder model of a variable valve timing 4-cylinder engine. The model includes the cylinder and manifold mass, temperature, burned gas residual, and pressure dynamics, including combustion effects, as well as the valve actuator dynamics. The cylinder-by-cylinder model is used to obtain a cycle averaged mapping between torque at a given engine speed and intake valve timing, which is suitable for future control design implementations [6].

Jerald A. Caton (2001) developed a thermodynamic cycle simulation for a spark-ignition engine which included the use of multiple zones for the combustion process. This simulation was used for the complete analysis of a commercial, spark-ignition V-8 engine operating at part load condition. This simulation is limited to only in-cylinder processes. For simplicity, the combustion chamber was assumed to be cylindrical shape. In this work, all cylinders of a multiple-cylinder engine are assumed to be identical, and assumed to follow the same thermodynamic process, and to operate with identical conditions. Overall results for a multiple cylinder engine are obtained by multiplying the results from the single-cylinder analysis by the number of cylinders. The primary feature of this cycle simulation is the first law of thermodynamics which is utilized to derive expressions for the time (crank-angle) derivative of the pressure, gas temperature, and volume in terms of engine design variables, operating conditions, and sub-model parameters [7].

Pankaj Hatwar, Durgesh Verma Laser induced ignition of slow combustion processes has been examined. The feasibility of a laser-induced ignition system on a direct injected gasoline engine has been proven in long-term experiments. Main advantages are the almost free choice of the ignition location within the combustion chamber, even inside the fuel spray. Significant reductions in fuel consumption as well as reductions of exhaust gases show the potential of the laser ignition process. Results indicate that pollution of the beam entrance window is not critical as expected; even heavily polluted windows have had no influence on the ignition characteristics of the engine. Measurements show that the required pulse energy for successful ignition decreases with increasing pressure. Fast combustion processes (detonations) show a much more violent character than slow deflagrations. FEM simulations indicate that a well-designed beam entrance window can probably withstand pressures and temperatures during a detonation. Additional work is necessary to prove the results of the simulations by experiments [8].

## III. WHAT IS LASER IGNITION?

Laser is a device, which emits electromagnetic radiation through optical amplification based on simulation emission of photons. "LASER" means Light Amplification by Simulated Emission of Radiation. Laser ignition, or laser-induced ignition, is the process of starting combustion by the stimulus of a laser light source. caused by an intense laser pulse to ignite gas mixtures. The beam of a powerful short pulse laser is focused by a lens into a combustion chamber and near the focal spot and hot and bright plasma is generated.

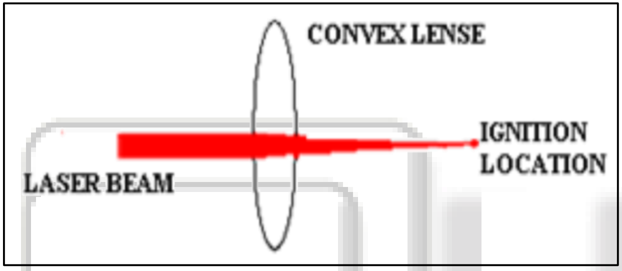

Fig. 4: Ignition in combustion chamber.

The process begins with multi-photon ionization of few gas molecules which releases electrons that readily absorb more photons via the inverse bremsstrahlung process to increase their kinetic energy. Electrons liberated by this means collide with other molecules and ionize them, leading to an electron avalanche, and breakdown of the gas. Multi photon absorption processes are usually essential for the initial stage of breakdown because the available photon energy at visible and near IR wavelengths is much smaller than the ionization energy. For very short pulse duration (few picoseconds) the multi photon processes alone must provide breakdown, since there is insufficient time for electron-molecule collision to occur. Thus, this avalanche of electrons and resultant ions collide with each other producing immense heat hence creating plasma which is sufficiently strong to ignite the fuel. The wavelength of laser depends upon the absorption properties of the laser and the minimum energy required depends upon the number of photons required for producing the electron avalanche [1].

## IV. WORKING OF LASER IGNITION SYSTEM

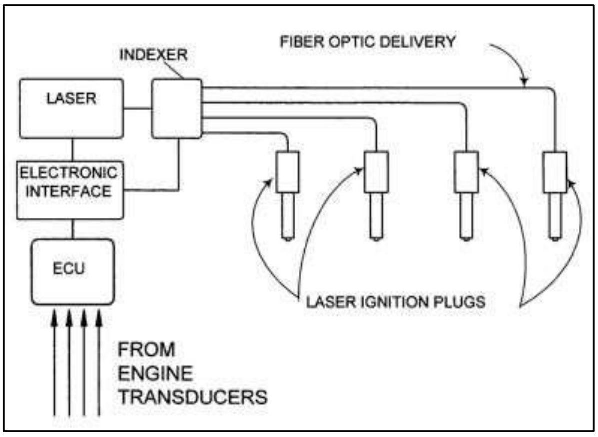

Fig. 5: Working of Laser ignition system.

Laser induced spark ignition begins with the initial seed electrons produced from impurities in the gas mixture (e.g. dust, aerosol soot particles). It is very unlikely that the initial electrons are produced by multi photon ionization because the intensities in the focus (1012 W/cm$^2$) are too low to ionize gas molecules via this process.

To provide appropriate ignition timing for combustion, igniters is in communication with an electronic control module (ECM) via power supply and fibre optics. Based on various input received by ECM like engine speed, engine load, emissions production or output, engine temperature, engine fuelling, and boost pressure, ECM may selectively direct a high-energy light beam from a laser energy generator to each igniter via fibre optics cable.ECM include components like memory, a secondary storage device, and a CPU.A battery of 12v to 24v gives power to either ECM or Laser generator or both. The ECM controls the laser energy generator to direct one or multiple laser beams into the combustion chamber. In the laser igniters, multi-photon ionization of few gas molecules takes place which releases electrons that readily absorb more photons via the inverse bremsstrahlung process to increase their kinetic energy. Electrons liberated by this means collide with other molecules and ionize them, leading to an electron avalanche, and breakdown of the gas. Multiphoton absorption processes are usually essential for the initial stage of breakdown because the available photon energy at visible and near IR wavelengths is much smaller than the ionization energy. For very short pulse duration (few picoseconds) the multiphoton processes alone must provide breakdown, since there is insufficient time for electron-molecule collision to occur. Thus, this avalanche of electrons and resultant ions collide with each other producing immense heat hence creating plasma which is sufficiently strong to ignite the fuel. The wavelength of laser depends upon the absorption properties of the laser and the minimum energy required depends upon the number of photons required for producing the electron avalanche.

### A. *Laser*

Lasers provide intense and unidirectional beam of light. Laser light is monochromatic (one specific wavelength). Wavelength of light is determined by amount of energy released when electron drops to lower orbit. Light is coherent and thus all the photons have same wave fronts that launch to unison. Laser light has tight beam and is strong and concentrated. To make these three properties occur something called “Stimulated Emission”, in which photon emission is organized is needed. The process begins with multi-photon ionization of few gas molecules which releases electrons that readily absorb more photons via the inverse bremsstrahlung process to increase their kinetic energy. Electrons liberated by this means collide with other molecules and ionize them, leading to an electron avalanche, and breakdown of the gas. Multiphoton absorption processes are usually essential for the initial stage of breakdown because the available photon energy at visible and near IR wavelengths is much smaller than the ionization energy. For very short pulse duration (few picoseconds) the multiphoton processes alone must provide breakdown, since there is insufficient time for electron-molecule collision to occur. Thus, this avalanche of electrons and resultant ions collide with each other producing immense heat hence creating plasma which is sufficiently strong to ignite the fuel. The wavelength of laser depends upon the absorption properties of the laser and the minimum energy required depends upon the number of photons required for producing the electron avalanche [9].

## V. COMPARISON BETWEEN SPARK IGNITION SYSTEM AND LASER IGNITION SYSTEMS:

Optimum spark location inside the combustion chamber is also difficult in case of conventional spark ignition systems because spark location is always very close to the top of combustion chamber. Less intense spark, Restrictions while choosing the ignition location, Leaner mixtures cannot be burned, Spark plug ignite the charge in a fixed position, so they can’t cope with a stratified charge, Flame propagation is slow, Multi point fuel ignition is not feasible, $NO_X$ emission-Ratio between fuel and air has to be within the correct range. It causes more NOx emission. In laser ignition a durable, high-energy, electrode-less ignition system with controlled energy deposition in the plasma, with flexibility to change the ignition location is a desirable option for overcoming these limitations faced in lean-burn SI engines. Laser ignition system meets most of these requirements and, offers several advantages for igniting lean mixtures. More intense spark, Free choice of the ignition location within the combustion chamber, Leaner fuel can burn effectively, Laser ignition system could cope with a stratified charge, Flame propagation is relatively fast resulting in shorter combustion time, Easier possibility of multipoint ignition, NOx emission-Engines would produce less NOx if they burnt more air and less fuel, but they would require the plugs to produce higher energy sparks in order to do so. Less NOx emission.

Absence of quenching effects by the spark plug electrodes, no erosion effects as in the case of the spark plugs - lifetime of a laser ignition, System expected to be significantly longer than that of a spark plug, High load/ignition pressures possible - increase in efficiency, Precise ignition timing possible, Exact regulation of the ignition energy deposited in the ignition plasma, Easier possibility of multipoint ignition, Shorter ignition delay time and shorter combustion time.

### *A. Disadvantages of Conventional Ignition System:*

- Location of spark plug is not flexible as it requires shielding of plug from immense heat and fuel.
- Spray and spark plug location cannot be chosen optimally.
- Spark plug electrodes can disturb the gas flow within the combustion chamber
- It is not possible to ignite inside the fuel spray.
- It requires frequent maintenance to remove carbon deposits.
- Leaner mixtures cannot be burned, Ratio between fuel and air has to be within the correct range.
- Degradation of electrodes at high pressure and Temperature
- Flame propagation is slow.
- Multi point fuel ignition is not feasible. Higher turbulence levels are required.
- Erosion of spark plug electrodesrequires frequent maintenance to remove carbon deposits.

### *B. Advantages of using Laser Ignition System:*

- The lifetime of laser ignitor is much more as compared to the conventional ignition system.
- Laser ignition system can burn leaner mixture more efficiently.
- Precise timing is possible in laser ignition system.
- Reduced fuel consumption rate.
- Free choice of the ignition location within the combustion chamber.
- As laser ignition system can ignite leaner mixture more effectively it will reduce the NOx emissions to a great level.
- Lasers can be focused and split into multiple beams to give multiple ignition points, which means it can give a far better chance of ignition.
- Optical wire and laser setup is much smaller than the current spark plug model, allowing for different design opportunities.
- Easier possibility of multipoint ignition.
- Quenching effects of spark plug electrodes are avoided.
- Erosion effects are avoided in laser ignition system.
- The laser also produces more stable combustion so you need to put less fuel into the cylinder, therefore increasing efficiency.
- The power required by laser ignition system is less as compared to conventional ignition system.
- Flame propagation is relatively fast combustion time is shorter.

## VI. CONCLUSION

Laser ignition system allows almost free choice of the ignition location within the combustion chamber, even inside the fuel spray. Main advantages are the almost free choice of the ignition location within the combustion chamber, significant reductions in fuel consumption as well as reductions of exhaust gases show the potential of the laser ignition process. Laser ignition system helps in significant reduction in consumption of fuel and also reduction in amount of CO and NOx emission in the exhaust gases in the engine. NOx is reduced up to half with respect to spark ignition system. LI engines improve stability of combustion with proper control, can run under leaner conditions and at lower speeds without increasing noise, vibration, and harshness. LI systems can also control misfiring under a high level of dilution. As Laser igniters will be able to combust the fuel with lean air-fuel mixture when compared to conventional spark plug, they lower down the NOx emission and give better fuel efficiency and cleaner environment. With the potential advantages over the conventional ignition systems, there is every possibility that LI systems would replace conventional spark plug based ignition systems in the near future.

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