ME – PhD Thesis Colloquium

Studies on the application of plasma-assisted ignition for lean combustion

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ABSTRACT

Non-thermal or non-equilibrium plasma is an emerging field in combustion science. Stable ignition of lean fuel-air mixtures continues to remain a challenge. The present work explores the potential of non-thermal plasma for igniting lean mixtures using both fundamental studies in a constant volume chamber and applied studies in an internal combustion engine. The first part of the study focused on evaluation of non-thermal plasma as an effective combustion enhancement tool by initially conducting experiments in a constant-volume combustion Chamber (CVCC) with optical access. A high-voltage nanosecond pulse discharge (NPD) generator that can operate at a maximum frequency of 3.5 kHz is used to generate non-thermal plasma. The improvement in combustion was confirmed by comparing the Flame Development Time (FDT), lean limit and flame kernel size between the conventional and NPD plasma ignition systems. The configuration of the sparkplug for NPD plasma ignition is decided based on the experiments carried out in the CVCC. With suitable modifications to the spark plugs, the FDT is observed to reduce significantly. With the NPD system, a modified, conventional J-shaped spark plug (MJ) and a modified surface plug (MS) performed better than their conventional counterparts. With MJ and MS spark plugs, a 12% and 15% decrease in FDT is achieved, respectively, even with a single pulse of NPD as compared to a conventional ignition system. Similarly, a two-fold increase in flame kernel size is seen with a single pulse of NPD plasma ignition. The improvement in combustion shown with NPD plasma is also confirmed by OH chemiluminescence measurements.

In the second part of the study, Optical Emission Spectroscopy (OES) is used to calculate the post-discharge gas temperature. The plasma system is characterized based on the reduced electric field (E/N) and electron temperature calculated using the BOLSIG+ software. Zero-dimensional plasma simulations are carried out using the Chemical Workbench and CHEMKIN software to simulate the discharge and ignition phase of NPD plasma combustion, respectively. The electron-impact reactions in the discharge phase are observed to generate excited nitrogen and oxygen molecules, which in turn produce chain-carrying radicals such as O, H and OH. Among these radicals, the O radical generated by NPD plasma affects combustion the most, as observed in the sensitivity analysis of ignition delay and quantitative reaction path diagrams (QRPD). These calculations are conducted to establish the initial chemical kinetics in the flame kernel, which are then used initiating three-dimensional simulations of the flame propagation. The simulations are observed to successfully capture the trends of the lower FDT with NPD plasma ignition observed in the CVCC.

In the third and final part of the study, the efficacy of the plasma-assisted ignition is assessed in an internal combustion (IC) engine. Experiments are carried out in a single-cylinder Port Fuel Injection (PFI) based four-stroke spark ignition (SI) engine. The results were very encouraging as it was found that the engine could run leaner with the NPD plasma system, reducing HC and CO emissions by 25.7% and 62%, respectively, in cold start tests using gasoline fuel. Steady-state engine experiments are also carried out at two load points, and at engine speeds of 2500 rpm and 4000 rpm. The lean operating condition of the engine is represented by the lambda (λ) value, which is defined as the ratio of the actual air-fuel ratio to the stoichiometric air-fuel ratio. Thus, as lambda increases beyond 1, the mixture become leaner, resulting in lower fuel consumption and higher efficiency. With NPD plasma-assisted ignition, the stable operating limit of the engine could be extended from $\lambda = 1.2$ to $\lambda = 1.4$ at an engine speed of 2500 rpm and from $\lambda = 1.25$ to $\lambda = 1.3$ at 4000 rpm. The engine torque and thermal efficiency have improved in the extended lean operation zone with NPD ignition. Similarly, the NPD plasma ignition system at these lean operating points shows a considerable decrease in fuel consumption, ignition delay, combustion duration, HC, and CO emissions. Operating on methane fuel, a similar enhancement of lean limit is noticed. At an engine speed of 3000 rpm and 8% throttle, the lean limit of operation increased from $\lambda = 1.1$ to $\lambda = 1.3$ with a two-pulse NPD plasma-assisted ignition. The NPD plasma-assisted ignition could achieve the same power output as the conventional system with 9.4% lesser fuel consumption. Overall, the above results show that using an NPD plasma ignition system has great potential to achieve higher efficiency and lower emissions under lean conditions in IC Engines, particularly those operating on clean fuels such as natural gas and hydrogen.

ABOUT THE SPEAKER

Avaneesh Athreya V is a PhD student in the Department of Mechanical Engineering at IISc Bengaluru. He completed his B.Tech. in Mechanical Engineering from Vasavi College, Osmani University, Hyderabad, in 2019. He joined IISc as a direct PhD student in August 2019. His research interests include combustion, alternate fuels, IC Engines, and heat transfer.