PROJECT ACCOMPLISHMENTS SUMMARY

LA-CRADA -- 97-2

RECEIVED

CRADA Title: Advanced Aircraft Ignition

CRADA Number: LA95C10196

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DOE TTI Number: LDRD-95493

OSTI

Industrial Partner: Simmonds Precision Engine Systems, Inc./LaserFare, Inc.

BACKGROUND

Conventional commercial and military turbo-jet aircraft engines use capacitive discharge ignition systems to initiate fuel combustion. The fuel-rich conditions required to ensure engine re-ignition during flight yield less than optimal engine performance, which in turn reduces fuel economy and generates considerable pollution in the exhaust.

Los Alamos investigated two approaches to advanced ignition: laser based and microwave based. The laser based approach is fuel ignition via laser-spark breakdown and via photo-dissociation of fuel hydrocarbons and oxygen. The microwave approach involves modeling, and if necessary redesigning, a combustor shape to form a low-Q microwave cavity, which will ensure microwave breakdown of the air/fuel mixture just ahead of the nozzle with or without a catalyst coating. This approach will also conduct radio-frequency (RF) heating of ceramic elements that have large loss tangents.

Replacing conventional systems with either of these two new systems should yield combustion in leaner jet fuel/air mixtures. As a result, the aircraft would operate with (1) considerable less exhaust pollution, (2) lower engine maintenance, and (3) significantly higher fuel economy.

Los Alamos worked with B.F. Goodrich Aerospace and H.G.G. LaserFare on this project. B.F. Goodrich is pursuing this technology to maintain its lead as the manufacturer of ignition systems (it now manufactures 90% of all military systems).

DESCRIPTION

The goals of this R&D program were to develop and implement innovative fuel ignition technologies that would enable commercialization of a turbojet engine ignitor which would extend the operational envelope, reduce emissions and increase reliability.

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ECONOMIC IMPACT

B.F. Goodrich Aerospace is looking to maintain its lead in the market for ignitor systems for military aircraft. BFG predicts business of \$100 million per year. H.G.G. LaserFare anticipates business of approximately \$10 million per year.

BENEFITS TO DOE

In terms of energy benefits, this technology will enable safe flights at higher altitudes, thereby reducing the amount of fuel used. Present estimates predict fuel savings of approximately \$1 billion per year for aircraft operations.

Redirecting fuel from the existing spark plugs (located at the chamber wall) will also reduce CO emission, an environmental benefit of this technology. Another environmental benefit is that the ignition takes place in the optimum fuel flow region, which will result in hotter and more efficient burn with less No_x emission.

PROJECT STATUS

The work at LANL produced two new techniques for turbojet engine ignition (Laser and Microwave) both of which were successfully tested at LANL in pre-prototype form. However, the CRADA partner did not provide the technical information required for the design of a prototype. Without such information, we were unable to engineer the prototypes for field testing, and were forced to stop development.

DOE FACILITY POINT OF CONTACT FOR PROJECT INFORMATION

LANL Contact: Albert Migliori (Microwave)/Jim Early (Laser)
Telephone: 667-2515/667-9896

COMPANY SIZE AND POINT OF CONTACT

Simmonds Precision Engines (B.F. Goodrich) is located in Norwich, NY. The contact person for B.F. Goodrich is David Eddy, phone number 607-335-5213 and fax number 607-335-5198. LaserFare, Inc. is located in Providence, RI. The contact person is Terry Feeley, phone number 401-783-9559.

PROJECT EXAMPLES

None

FINAL ABSTRACT

We have developed unique and effective schemes for advanced ignition systems for jet turbine engines. The schemes are based on laser technology

and microwave technology. The microwave approach uses a microwave-generated free-standing plasma to provide superior ignition performance throughout the flight envelope. The laser-based fuel ignition concepts deliver laser energy to the fuel medium in an efficient and effective manner providing consistent and reliable ignition of fuel aerosols over a broad range of fuel composition and fuel/air temperature. Both systems have been successfully tested in pre-prototype form at LANL.

FINAL TECHNICAL REPORT

The goals of this R&D program were to develop and implement innovative fuel ignition technologies that would enable commercialization of a turbojet engine ignitor which would extend the operational envelope, reduce emissions and increase reliability. The work at LANL produced two new techniques for turbojet engine ignition (Laser and Microwave) both of which were successfully tested at LANL in pre-prototype form.

Advanced Ignition CRADA Final Report

James W. Early
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I) Introduction

Los Alamos has investigated the potential use of laser light to efficiently and reliably ignite both gaseous and aerosol fuel/air mixtures within an LDRD funded, CRADA based R&D program with B.F. Goodrich Aerospace and Laser Fare Inc., known as the Advanced Ignition Program. The primary goal of this collaboration between industry and government is to develop an advanced ignition system for aircraft turbo-jet engines which would replace the currently used capacitive discharge ignitors. Los Alamos investigated two technology paths to this goal incorporating both laser-driven and microwave-based ignition approaches. The results of basic studies supporting the development and implementation of an advanced, laser-based fuel ignition system are described within this report.

All commercial and military turbojet aircraft currently use capacitive discharge fuel ignition systems. These spark-plug-like ignitors, residing at the wall of the turbojet engine's combustion chamber, require fuel spray to be diverted away from the primary combustion zone at the combustor's center to the combustor wall in order to establish a fuel condition for reliable ignition. This non-optimal mode of engine operation, due to the initiation of fuel combustion at the combustor wall, results in reduced fuel economy, increased generation of unburned hydrocarbon pollutants within the exhaust, and increased thermally induced engine maintenance. Furthermore, the fuel condition which must be maintained to ensure engine re-light, limits the maximum altitude to which turbojet aircraft can be operated.

The use of focused laser light to initiate fuel combustion within a turbojet combustion chamber has several distinct advantages over spark-plug-like ignitors which would significantly improve turbojet engine performance. The

primary attraction is the ability to generate an ignition spark within the optimal location via the laser light breakdown of air. This is accomplished in a manner which is unobtrusive to combustor flow dynamics, i.e. - no ignitor components need to be inserted directly within the combustion chamber which may alter combustor operation and stability. The need to purposely direct fuel to the combustion chamber wall is thus eliminated, potentially enhancing engine performance by permitting leaner fuel/air mixtures to be burned at the wall reducing thermal induced engine maintenance, while increasing fuel economy.

Despite the great promise afforded by the application of a laser-based ignitor, the development and implementation of a laser-based ignition system has progressed slowly despite considerable industrial and governmental effort. The reasons for this are many-fold, but are primarily due to issues of ignitor reliability (fuel ignition performance), ignitor cost and implementation difficulties (size and complexity of laser required, laser light transport and insertion into the hostile engine environment, etc.). The laser-induced fuel ignition program described in this report addresses several of these implementation problems.

The Advanced Ignition Program focuses primarily upon the laser induced fuel ignition reliability problem and the cleaning of combustion residues from the laser window surfaces. Two novel laser-induced, fuel-ignition concepts were developed and evaluated within this R&D program which demonstrate the ignition of Jet A aerosols produced by an actual turbojet fuel atomizer. The first of these novel concepts, the dual laser pulse ignition method, utilizes the laser light pumping of a previously established laser spark to actively heat the fuel medium for durations of time much longer than that readily obtainable by the laser spark ignition method alone. A second ignition concept, called the laser pre-heat ignition method, utilizes the light absorptive property of the fuel at a specific IR wavelength to vaporize aerosol fuel droplets prior to gas phase ignition via a laser induced spark. The ignition performance obtained for each of these advanced fuel ignition concepts is described in the following sections of this report. Direct comparison of ignition performance relative to that obtained using conventional laser spark fuel ignition is made. Benefits to the realization of a commercial laser-based fuel ignitor by adoption of these ignition methods are described.

II) Laser-Breakdown-Spark Induced Ignition

The first phase of the Advanced Ignition Program characterized the fuel ignition performance of a laser spark breakdown method to initiate both gaseous and aerosol fuels. This ignition method employs short duration, high peak power laser pulses of laser light to first generate a light absorbing plasma via non-resonant multiphoton ionization of hydrocarbon fuel and air components, followed by the coupling of laser energy to the induced plasma (through electron cascade) to provide sufficient thermal energy for ignition kernel growth. A study to evaluate and compare the various laser approaches for igniting both gaseous and aerosol fuels was conducted.

A Q-switched Nd:YAG laser was used to provide near IR (1064 nm) light pulses with a short temporal width of 12 ns. Both single transverse mode (TEM₀₀) and multiple transverse mode light in the output of the Nd:YAG laser were utilized in these studies, providing maximum pulse energies of 40 and 150 mJ respectively. The primary ignition parameters evaluated were ignition threshold energy, threshold energy for the breakdown of the fuel/air medium and fuel ignition probability as a function laser pulse energy and fuel composition. The results of these experiments are summarized in this report.

a) Laser Induced Ignition of Gaseous Fuels

Primarily, the laser spark ignition of two gaseous fuels, methane and propane, were investigated. A couple of single point ignition test were also performed for butane/air and Jet A/air mixtures to demonstrate the ability of the laser ignitor to initiate these fuels. Mixtures of fuel and air were prepared by flowing the constituent gases at known flow rates through a baffled mixing chamber to a combustion tube, where the free flowing mixture at near atmospheric pressure was ignited by focused laser light. The apparatus used for this investigation is shown in Figure 1. A 5-cm focal length, convex-convex lens was used to focus TEM₀₀, Nd:YAG light to a tight focal spot size diameter of 32 micron (FWHM) at the center of the combustion tube.

Laser pulse energy was increased until the threshold for ignition of the mixture was obtained. Ignition threshold is defined here as that laser pulse energy required to ignite the gas mixture with a > 50 % probability, based

upon 20 ignition attempts for a given laser pulse energy setting. The Nd:YAG laser was operated in a single-shot mode. Following each ignition, the fuel flow was momentarily interrupted to extinguish the burning gases. Fuel was then permitted to flow for a period of at least 10 seconds before the next ignition attempt in order to purge combustion product gases from the combustion tube. The ignition threshold energy was obtained as a function of fuel/air composition for both methane and propane fuels. A typical result is shown in Figure 2 for propane/air mixtures. Also shown on the same plot is the laser pulse energy required to produce a breakdown plasma within the fuel/air medium. A minimum in the ignition threshold energy of about 17 mJ is observed at a fuel/air mass ratio of about 0.12. This mass ratio corresponds to an equivalence ratio of about 1.7. For fuel mixtures near this value, the laser energy thresholds for both spark breakdown and fuel ignition were virtually identical. This was not the case for fuel-lean and fuel-rich conditions, as observed in the ignition profile, where additional laser energy must be supplied for ignition to occur once a breakdown plasma has been established. A similar ignition profile (see Figure 3) was obtained for methane in which minimum laser energy required for ignition was somewhat higher, about 23 mJ. The minimum within the ignition threshold energy curve occurred at a stoichiometric fuel/air mass flow ratio of 0.048.

b) Laser Induced Ignition of Jet A Fuel Aerosols

To evaluate the performance of the conventional laser spark ignition method to initiate Jet A aerosols, an apparatus was used which consisted basically of a Q-switched, Nd:YAG laser, a focusing lens and a combustor rig which generated the fuel spray. The combustor rig, provided by BFG Aerospace, consisted of a forced-air, fuel-atomization nozzle of a type commonly used in commercial turbojet aircraft, and two pumps which provided fuel and air flows to the spray nozzle. Fuel and air flows to the nozzle were controlled by throttling valves and monitored by analog differential pressures gauges. The fuel atomization nozzle was operated in open-air with no combustion-chamber-like enclosure containing the fuel flow. To prevent modification to fuel aerosol parameters by air movement, the nozzle was operated within a large enclosure which minimized air turbulence. This enclosure also provided the means to collect and recover unburned fuel for disposal. No provision for the temperature regulation of fuel and air flows was incorporated within the combustor rig. All ignition

investigations described here were performed under ambient conditions, typically in the temperature range of 70 to 85 degrees F. An exception to this mode of operation is described in section (IIIId) where a dual pulse investigation outside of this temperature range was performed.

The Q-switched, Nd:YAG laser used was operated with a multiple transverse mode output to provide laser pulses with a temporal pulse length of 12 ns (FWHM) and peak powers as large as 12 MW. A 10-cm focal length, plano-convex lens was used to focus the laser's output. This focal length lens provided a small laser spot size of about 63 microns diameter (FWHM) at the focal plane and provides sufficient separation between the focusing lens and the fuel aerosol to prevent lens fouling by peripheral contact with the aerosol cloud. A pulsed shutter, opened for several milliseconds to allow the passage of laser pulse, was also used after the lens to inhibit lens fouling by drifting fuel mists.

The experimental approach used to evaluate the laser induced ignition of fuel aerosols differed substantially from that used previously to characterize gas phase ignition performance due to the spatially in-homogeneous composition of the fuel aerosol produced. To determine ignition performance, laser spark breakdown at some constant laser pulse energy was initiated at sequential positions within the plume, forming a grid pattern of ignition sites confined to a horizontal plane intercepting the nozzle axis. The laser light was directed horizontally into the fuel plume at orthogonal incidence to the nozzle axis. To vary the distance of the laser initiation site from the nozzle axis, the lens used to focus laser light into the fuel medium was translated laterally. To access sites at different distances from the nozzle, the nozzle was translated along the direction of the nozzle axis. The ignition probability was recorded for each of these sites thus forming an ignition profile for a specific laser pulse energy. The criterion used to define a successful, sustained ignition event in the ignition probability analysis was the generation of a long-lived ignition flamelet which propagated at least 1 cm from the laser initiation site.

A summary of these measurements over a range of laser pulse energy is summarized in Figure 4, where ignition probability is given as a function of radial focal point position within the aerosol cloud. Positive numbers indicate radial distances from the nozzle axis to the ignition site in the direction toward the focusing lens. This ignition scan was generated at a 1.0

cm distance from the nozzle, which was operated at fuel and air pressures of 25 psig and 1.0 inch H₂O respectively. Some additional ignition scans were also performed at a higher air flow condition of 2.0 inch H₂O, although these data have not been analyzed.

In general, the fuel aerosol ignition performance achieved using conventional laser spark ignition was marginal at best with respect to consistency of laser initiation and sensitivity of fuel ignition to variations in both laser peak power and location of laser initiation within the fuel cloud. As seen in Figure 4, the maximum ignition probability (100 %) occurred for a single value of laser pulse energy of 120 mJ (320 GW/cm²) and at a single initiation site located within the periphery of the aerosol cloud.

The roll-off in ignition probability at higher pulse energy or laser peak power, as shown by the ignition profile obtained at a laser pulse energy of 144 mJ, is unexpected. This may be due to the formation of shock waves within the fuel medium with sufficient intensity to extinguish any flamelets formed. Similar results were obtained at a pulse energy of 133 mJ (not included in Figure 4).

Similar ignition performance to that described above was obtained for focal points at longitudinal distances from the nozzle face between 0.5 and 2.0 cm. At increasing distances from the nozzle face exceeding 2.0 cm, a steady decrease in the maximum ignition probability was observed for fixed laser pulse energy.

III) Dual Laser Pulse Ignition Method

This laser based fuel ignition method was the first of the advanced ignition concepts to be investigated within our LDRD funded fuel ignition program. The dual laser pulse ignition concept is fundamentally different with respect to the conventional, laser spark ignition method and provides several distinct advantages. Of primary importance is the effective decoupling of breakdown plasma generation from the laser heating of the fuel medium. Initially, a short duration, high peak-power laser pulse is applied to the fuel medium to initiate a laser light absorptive breakdown plasma. This is then followed by the application of a second laser light pulse with a longer duration and lower peak power which efficiently couples laser light energy into the previously established breakdown plasma and sustains the plasma

over time durations typically exceeding the temporal length of the second laser pulse. By employing two laser pulses with differing temporal pulse length and peak power, the rate of energy delivery to the fuel/oxidizer medium is reduced while the duration over which the fuel medium is actively heated by the laser light is substantially increased. Both of these factors greatly influence the growth of laser-induced flame kernels to stable, self-sustaining combustion as demonstrated in the experimental study described below.

a) Dual Pulse Sustenance of an Air-Breakdown Plasma

Initial dual laser pulse experiments defined the ability to efficiently transfer laser light energy to a previously established air breakdown plasma and ability to sustain the plasma over long durations of time. A short duration (12 ns FWHM) light pulse from a Q-switched, Nd:YAG laser was used to generate the laser breakdown spark. The generated plasma was then pumped by a longer duration (81 ns FWHM) laser pulse obtained from a Q-switched, Cr:LiSAF (chromium doped; lithium-strontium-aluminum-fluoride) laser operated at a wavelength of 900 nm. Pulse energies of 24 and 29 mJ were provided by the Nd:YAG and Cr:LiSAF lasers respectively. A dichromatic, beam combiner was used to spatially overlap and coaxially propagate the TEM₀₀ output of the lasers to a 5-cm focal length lens. Laser spot sizes (diameter) at the focal point of the lens were 35 and 29 micron (FWHM) for the Nd:YAG and Cr:LiSAF light respectively.

The ability of the dual pulse method to sustain an air-breakdown plasma was determined by measurement of the duration of plasma white light emission obtained with and without application of the long pulse length laser light. A large aperture light collection lens (2-inch diameter), a low-pass optical filter and a 900 nm highly reflecting flat mirror which block the scattered 1064 nm and 900 nm laser light and a fast photodiode were used to monitor white light emission. A plot of the duration of the plasma light emission detected by this photodiode is given in Figure 5 as a function of temporal delay between the two laser pulses. This delay was measured as the temporal spacing between the intensity maxima for the two pulses. These measurements demonstrated that an air breakdown plasma produced by a high peak power laser pulse could be sustained over extended time intervals (~350 ns), significantly exceeding the lifetime of the Nd:YAG generated breakdown plasma (40 ns). The short pulse laser was operated at

a the lowest peak power required to generate a breakdown plasma within the lens focal plane ($\sim 2.0 \times 10^6$ W). The peak power of the long duration pulse was about 1/14 of that value. Measurements of light transmission through the air-breakdown plasma show a 70 % coupling of long pulse light to the plasma. In addition, profiler measurements of the spatial distribution of white light emission from the breakdown plasma showed a 25% increase in both plasma cloud length and radius under conditions in which laser light was efficiently coupled to the plasma.

b) The Dual Laser Pulse Method for Inducing Fuel Aerosol Ignition

An experimental procedure similar to that described for the conventional laser spark ignition studies was adopted to characterize the fuel ignition performance of the dual pulse concept. The fuel atomizer was operated during these studies at fuel and air pressures of 25 psig and 1.0 inch H₂O respectively. Low and high peak power laser light pulses were spatially overlapped and coaxially propagated to a 10-cm focal length lens. This lens was used to bring both laser pulses to a common focus within the fuel aerosol cloud. During these experiments, the lasers were operated at a 1 Hz repetition rate and with a multiple transverse mode at the laser's output. The Cr:LiSAF laser was operated at a wavelength of 900 nm. The temporal lengths of the 1064 and 900 nm were 12 and 81 ns (FWHM) respectively.

The mean beam waist diameters of the Nd:YAG and Cr:LiSAF laser light at the focal plane of the 10-cm focal length lens were measured to be 60 and 75 microns (FWHM) respectively. These were measured by a profiling method which utilizes a scanning, 5-micron core optical fiber and photodetector to monitor the fiber's light output. The Nd:YAG and Cr:LiSAF lasers provided pulse energies of 90 and 55 mJ respectively during these measurements. The output of these lasers was attenuated using a multiple, first-surface-reflection technique prior to focusing and beam waist measurement. Both laser spots exhibited some astigmatism and mean values are quoted resulting from vertical and horizontal profile measurements. A slightly larger mean value for the Nd:YAG spot size of 63 micron (FWHM) diameter was obtained using a CCD camera-based instrument, although both measurements agree to within the precision of the instrumentation.

Timing between the sequential application of the laser pulses was monitored by a fast silicon photodetector. A temporal delay of 100 ns was selected, which had provided the maximum extension of breakdown plasma lifetime within the previous experiment. The delay was characterized as the temporal separation between intensity maxima within the temporal profiles of the Nd:YAG and Cr:LiSAF pulses. Shot-to-shot variation in the temporal spacing of lasers pulses was less than 20 ns.

The effectiveness of the dual pulse method to reliably and consistently ignite a Jet A fuel aerosol is demonstrated by the ignition profiles of Figure 6. Ignition probability is plotted as a function of radial distance of the laser light focal point from the fuel cloud center and for a distance from the spray nozzle of 1.0 cm. Curve A of this figure shows the ignition profile obtained for a total laser energy contained within the short and long duration laser pulses of about 145 mJ. 100% reliable ignition was obtained over an expanded cross-section of the fuel cloud compared to the single, 144 mJ laser pulse. The ignition performance obtained by the dual pulse method was superior to that obtained via the conventional laser spark method. This is demonstrated by the ignition profile of Curve B in which only the short duration laser pulse was applied to the fuel aerosol but containing approximately the same laser light energy (144 mJ). For this case, a maximum ignition probability of 80% was achieved at a single ignition site within the fuel cloud.

When the dual pulse laser energy was increased to 174 mJ by increasing the peak power of the long duration pulse, the ignition profile of curve C resulted. In this case, 100% reliable ignition was obtained over a broader region of the fuel plume and 80% or better ignition probability was obtained across nearly the full width of the fuel cloud. Ignition performance does not appear to degrade at higher total laser energies, as was observed with the single pulse method. Also, the ability to ignite over wide range of locations within the fuel cloud suggests a relative insensitivity of the dual pulse ignition method to local variations in fuel parameters. Unity ignition probability was obtained over regions in which the fuel volume flux varied by a factor of 3.

c) Dependence upon Temporal Delay between Laser Pulses

An experiment was performed to determine the dependence of the dual pulse ignition process to the temporal delay between the application of laser pulses. The same experimental configuration was used in this investigation as that described above. The energy of the Nd:YAG pulse was set at a value (74 mJ) which provided sufficient peak power to consistently breakdown air at the focal plane of the 10-cm lens. The pulse energy of the Cr:LiSAF laser was set to 100 mJ. The temporal lengths of the Nd:YAG and Cr:LiSAF pulses were 14 and 84 ns respectively. The Jet A aerosol was initiated at a single location within the fuel cloud - 1.0 cm from the nozzle and 3.75 mm from the nozzle axis in the radial direction towards the laser light focusing lens. Ignition frequency was determined as a function of timing delay between the application of short and long duration pulses ranging from -150 to +450 ns. Negative values designate pulse sequencing conditions in which the long duration pulse preceded the application of the spark breakdown pulse. The temporal separation between the intensity maxima of the two pulses was monitored by a digitizing oscilloscope.

The result of this experiment is shown in Figure 7, where ignition frequency is plotted versus temporal delay. Maximum ignition probability was achieved for temporal delays in the range of 0 to 150 ns. As the inter-pulse delay was increased beyond 150 ns, a significant decrease in ignition probability was observed. A similar behavior was also observed with respect to the prolongation of a breakdown plasma by laser pumping, as indicated within Figure 5, where the white emission from the plasma falls below a detectable intensity. In both cases, a significant decrease in the coupling efficiency of laser light energy to the air breakdown plasma is indicated for inter-pulse delays exceeding 150 ns.

d) Dependence upon Fuel Temperature

In addition, the ability of the dual pulse method to ignite the Jet A fuel aerosol over a broad range of fuel temperature was investigated. Heat exchangers were installed within the fuel and air feed lines to the nozzle to permit the attainment of fuel and air temperatures over a range of 35 to 105

degree F. In this experiment, the fuel temperature was varied over this temperature range, while the air flow through the nozzle was maintained at a temperature of 85 degree F. The entrained air temperature during this portion of the tests was about 45 degree F. Differential pressures for fuel and air flows of 25 psig and 1.0 inch H₂O respectively were used. The results of these experiments are summarized in Figure 8. The experimental configuration used in these studies is identical to that described in the preceding section. To induce a breakdown plasma, pulses from the Nd:YAG laser were maintained at an energy of 100 mJ and a temporal length of 12 ns (FWHM) during the course of the experiment. The temporal length of the 900 nm light pulses from the Cr:LiSAF laser varied from 100 to 60 ns as laser pulse energy was increased to maintain 100% ignition probability as fuel temperature was decreased from an initial temperature of 105 degree F. A constant delay of 100 ns between the application of the laser pulses was used. As fuel temperature was decreased from 105 degree F to 35 degree F., a 280% increase in the energy of the second laser pulse was required in order to maintain unity ignition probability.

IV) Laser Induced Preheating and Vaporization of Fuel Droplets

This novel ignition method utilizes two laser pulses to ignite Jet A fuel aerosols. The first laser pulse applied to the fuel aerosol heats and vaporizes the fuel droplets by the absorption and thermalization of laser energy. The resultant cloud of vaporized fuel is then allowed to turbulently mix with surrounding air to produce a flammable fuel/air mixture within the region of the focused laser light. A second laser pulse with sufficient peak power to induce a spark breakdown is then applied to the fuel vapor/air mixture to induce ignition. Combustion of the gas phase mixture induces the initiation of fuel droplets outside the laser light interaction region, promoting a general ignition of the aerosol cloud. In this manner, the laser induced ignition of an in-homogeneous fuel aerosols is transformed to that for the ignition of gas phase fuel/air mixtures.

For the experimental demonstration, an Er:YAG laser operating at a wavelength of 2.94 micron was utilized to induce fuel droplet vaporization. Light of this wavelength was shown to be moderately absorbed within Jet A fuel. An absorption coefficient of 6.5 cm⁻¹ was measured for the 2.94 micron laser light. The Er:YAG laser was operated in the free-running mode, providing laser pulses with a long temporal length of 120

microseconds (FWHM). Initial experiments conducted demonstrated the ability of this technique to heat and vaporize fuel droplets contained within the focal volume of the laser light using modest laser peak powers (<1.2 kW). Light from the preheating laser was directed into the fuel aerosol at a right angle to the fuel spray nozzle axis and focused using a 10 cm focal length lens to a ~ 170 micron beam waist diameter (FWHM) within the densest portion of the fuel cloud. Evidence of fuel droplet vaporization was observed during the experiment by the formation of a small cloud of a fine mist, consisting presumably of re-condensed fuel, appearing several centimeters downstream from the location where the 2.94 micron light was focused within the fuel spray.

Ignition of vaporized fuel was accomplished by applying Q-switched, Nd:YAG laser light with a peak power sufficient to induce spark breakdown within the fuel/air medium (typically about 8 MW). The light output of this laser was focused into the fuel plume using the same lens used to focus the preheating laser light. Both lasers were operated at a 1 Hz repetition frequency. Optimal performance was attained when the application of the igniting laser pulse was delayed by 20 microseconds relative to the application of the igniting pulse. This delay was defined as the temporal separation between intensity maxima for the two pulses. The enhanced ignition performance achieved using this method is demonstrated in Figure 9, where ignition probability is plotted as a function radial focal position within the Jet A fuel aerosol for two cases; (1) with and (2) without application of the preheating laser light. For both cases, the energy of the Nd:YAG laser pulse was set to 91 mJ, which provided the minimal peak power to produce the fuel igniting breakdown spark. As shown in this figure, consistent ignition was attained over an extended region within the fuel cloud when the preheating of fuel droplets was introduced..

V) Laser Light Window Contamination Issues

Although a couple of laser-induced fuel ignition methods have resulted from this R&D effort that facilitates the realization of a commercial, laser-based fuel ignitor, little practical use can be made of this technology if ignitor light cannot be introduced efficiently into an engine combustion chamber due to the accumulation of opaque fuel combustion residues upon the light insertion window. To address this issue, an experimental study was

initiated at LANL to develop a practical method to remove window contaminants.

Two potential forms of window contamination were simulated in these investigations; 1) a thin but optically opaque, soot-like deposit containing elemental carbon and other hydrocarbon combustion residues which results from the direct exposure of optical surfaces to burning fuel and 2) a low volatility, varnish-like coating resulting from the fractional distillation of the fuel which forms a semi-transparent, amber-brown colored deposit.

To facilitate the implementation of a method to remove window residues, a laser-based approach was adopted which utilizes the same high peak power laser light employed within the advanced laser ignitor concepts. The optically opaque, sooty residues were determined to be readily removed by the strong absorption of 1064nm light and subsequent ablation of coating material. An experiment was conducted in which the soot coated window was placed at various distances from a 10 cm focal length lens used to focus ignitor laser light in order to determine the minimum laser light power density and number of laser shots required to remove this type of coating. Optimal performance was obtained at a distance of 4-cm from the focusing lens. At this distance from the lens, minimal laser peak power density required to remove window contaminants is utilized and damage to the window surfaces is avoided. The result is illustrated in Figure 10, where window transmission is plotted versus number of successive laser shots. At an incident laser power density of about 1.3 MW/cm^2 , virtually complete removal of the window contaminant was achieved within 20 laser shots. The incomplete recovery of window transmission (95%) was due to vignetting of laser light in the low intensity wings of the laser's spatial mode, where the local light intensity is too low to ablate residue material.

Unlike the sooty residue, the varnish-like coating is semi-transparent to 1064 nm Nd:YAG light (~65% transmission) and is not readily removed from the optical surface by laser ablation. To adequately remove this material, the window must first be heated to temperature of 350 degree C at which the high molecular weight hydrocarbon is rapidly decomposed to a black, optically opaque product. Window cleaning performance identical to that given in Figure 10 was obtained for the decomposed varnish coating. In the application of this residue removal method, the laser light transport window will require operation at elevated temperatures to ensure complete

conversion and removal of residue varnishes. Temperatures of this magnitude normally exist at the wall of the turbojet engine combustor where the laser window would most likely be placed.

VI) Conclusion

The results of this R&D effort provide an extensive ignition technology base facilitating the development of a commercial laser-based advanced ignitor for turbojet aircraft engines as well as application to other areas of gas turbine operation. Two innovative ignition concepts have been conceived and developed within this program which surpass the fuel ignition performance provided by a more conventional, single-laser-pulse induced ignition method in both reliability and efficiency, facilitating the development of a viable alternative to currently used capacitive discharge ignitors. In addition, a practical laser-based method for the maintenance of clean laser window surfaces required for the transport of laser light into the hostile environment of a turbojet combustor was realized. Three patent applications have been filed to date which document the innovations resulting from this research program.

MICROWAVE IGNITION RESULTS

LANL Initiative On Advanced Microwave Ignition Systems For Turbine And Other Engines

Principal Investigators: A. Migliori, Microwave Project Leader
T.W. Darling
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Summary

All ignition systems for military and commercial jet turbine engines used in aircraft today rely on a capacitive discharge source firing a spark plug placed in the cool wall of the engine combustor. The technology is 30 years old and is unsatisfactory because plug placement, designed to protect the plug from combustion heat, is far from optimum for engine operation. Rich mixtures must be used to ensure ignition, leaving fuel unburned, and the difficulty with high altitude relight, completely limited by present ignition systems, determines the maximum altitude at which commercial aircraft fly. The higher they can fly, the less fuel they burn, and so dangerous high altitude emissions are reduced, while efficiency improves. Emissions are also reduced directly if more robust ignition systems could ignite leaner mixtures, also reducing fuel consumption, fuel weight, aircraft weight and therefore emissions indirectly as well.

At present, the U.S. is the world leader in researching new ignitor technology, but other countries, notably Japan, are poised to jump in. Simmonds Precision, together with Laser Fare, and Allied Signal compose the basic industry groups that lead in present technology. Both of these groups have concentrated on laser ignition systems.

LANL has initiated work on an alternative approach to laser based systems that has the potential to outperform any other advanced ignition scheme. This work has been in response to needs expressed by Simmonds Precision and Laser Fare, with whom we have negotiated a CRADA. The principle is based on the use of microwave plasmas as the ignition source, either as a stand-alone system or in conjunction with laser based technology. Microwaves can produce robust plasmas in advantageous regions of the engine combustor without the requirement for either optical or other windows, and, in principle, without contact with the walls of the combustor.

We describe here initial experiments that demonstrate the ability to generate plasmas in air at equivalent altitudes from sea level to 150,000 ft. This work will show that a microwave system can be as inexpensive as present capacitive discharge systems, requires absolutely no materials other than simple inconel structures be introduced into the combustor (even insulators, as used in present ignitors, are not required), is potentially more reliable, and can be easily modularized and integrated with present engine designs and laser schemes if appropriate.

No measurements have been performed with ignitable mixtures however, and, although very non-restrictive design requirements have been established, our industrial partners, Simmonds Precision and Laser Fare, have not yet supplied the jet engine design information adequate to design a pre-prototype system because a suitable initial platform for such a design is still under discussion. Because of the success of initial experiments, no further preliminary work is planned. The next step is to design a microwave ignitor compatible with at least one actual jet engine.

Initial Concepts

The initial concept was to utilize the combustor of a jet turbine engine as a microwave resonator. A microwave resonator is characterized by a resonant frequency f and a Q . f is determined by geometry and is the frequency at which the amplitude of microwave energy in the resonator builds up to a level such that the total microwave energy level $W = QP / 2Bf$ where P is the input power. The electric field present is proportional to $W^{1/2}$ and this is the quantity that determines the level at which the energy in the resonator (or cavity as we shall call it) can electrically ionize the air to form a plasma. The plasma then ignites the mixture.

Experiments were designed to implement this concept. A J79 combustor was supplied by Simmonds Precision. This was instrumented at very low power to determine its efficacy as a microwave cavity using a Hewlett-Packard 6GHz network analyzer. We found that the Q ranged from about 100 to about 1000, entirely satisfactory, and that resonances existed near 2.45GHz, a very desirable range because the FCC allows essentially unrestricted high power usage of this frequency (it is the frequency of kitchen microwave ovens).

The J79 combustor was then inserted into a high-altitude chamber. The chamber was irradiated with microwaves from a laboratory (Amperex Electronics) 6kW, 2.45 Ghz source. Initially, microwaves were coupled to the chamber using coaxial cable. Repeated arcing caused destruction of the connectors so we quickly switched to waveguide, eliminating arcover problems. At pressures corresponding to 150,000 ft (0.5mm Hg) a large (10cm) plasma ball was easily introduced into the central region of the combustor. The power source was capable of measuring the forward and reflected power

into the chamber. Such measurements established that about 450 Watts was being consumed, and we estimate that at least 2/3 of this was in the walls of the pressure chamber, leaving about 150 Watts to light the combustor.

This experiment, though encouraging, proved that the use of the combustor as cavity was unsatisfactory because; 1) the combustor needs to be resonant at 2.45 Ghz. Though the J79 was, it is not expected that other combustors would be. 2) The combustor is large, requiring excessive power levels. 3) The size of the combustor was such that the needed power levels, though acceptable at 150,000 ft. are prohibitive at sea level. 4) the microwave source must be tuned to each individual combustor because it is anticipated that manufacturing variations would not allow a universal microwave source to be used. Such tuning adds complexity and an order of magnitude to the cost of a practical system.

The Compact Resonator

To circumvent these difficulties, we initiated a second set of experiments on a compact resonator, shown schematically in Figure 1. This cavity design is essentially a small can whose shape is almost unrestricted, but must be designed to resonate at 2.45 Ghz. Such a task is particularly simple and can be done with either the 2 1/2D Superfish or the 3D Mafia and Hewlett Packard microwave design codes, available at LANL and used for this project. Using these codes, a broad range of designs is possible, enabling the microwave ignitor (MI) to: 1) be incorporated into the air jacket around any present combustor, or 2) be designed much like a spark plug, easily retrofittable to existing engines, or 3) incorporated into the fuel nozzles or combined with a laser ignitor. Either way, the MI can be compact and have electrical and tuning requirements independent of engine design.

With the compact resonator, we easily produced a 2.45GHz plasma at less than 150 Watts input and at altitudes from sea-level to 150,000 ft. Note that for microwaves, the Paschen curve (Figure 2) indicates that it is more difficult to generate a plasma at LOW altitudes. We also checked to see if this resonator detuned when the plasma formed. That is, when the plasma lights, it acts as if it were a conducting (metallic) object. This should shift the cavity away from resonance, extinguishing the plasma. When the plasma goes out, the cavity shifts back to resonance, the microwave field builds up (the time scale is Q/f or about a microsecond), the plasma relights and so forth. Such an effect would be interesting, and perhaps useful because it would provide an ignition cycle that was inherently pulsed, a desirable effect, though it is unlikely that this natural pulsing would be of the right frequency to match ignition requirements. The effect was not observed, primarily due to the very high power level available from the laboratory microwave source. A weaker source would undoubtedly show detuning.

The ease of plasma generation and the power levels observed, lead us to the following conclusions. 1) the compact resonator is the right approach. 2) Broader operating ranges are easily achievable than if the combustor were used as the cavity. 3) very inexpensive microwave magnetrons are adequate (the cost here could approach \$5.00! 4) Very simple electronics are needed to power the magnetron. i.e., a simple rectifier and filter, combined with a two transistor pulser operating directly off the aircraft main power bus (\$60.00) might be all you need. 5) flexible or semi-rigid stainless steel or inconel hollow pipe is all that is needed to get microwaves into the combustor. 6) by using simple fixed frequency magnetrons, the magnetron can survive very high temperatures (250C).

Future directions

At this point, we have achieved all our original feasibility goals, essentially on budget. To proceed with either a microwave or laser/microwave hybrid (a cost comparison is shown in Figure 3) pre-prototype will require 1) detailed coordination with designers of a jet turbine engine to lock in a design for a useful compact resonator. 2) Coordination and design work by BF Goodrich engineers appropriate to the aircraft environment 3) Ignition tests of actual fuel-air mixtures under pressure/flow conditions found in a turbine.

To achieve these goals will require very substantial funding in the near future, especially in light of the fact that the LANL internal funding contribution to this project was well under the requested amount so that our success to date was fortuitous. Had any difficulties arisen, we could not have gotten this far.

Figure 1:
Gas Ignition Set-up

Figure 2:

Methane/Air Mixture Ignition

Figure 3:

Summary of Single Pulse Ignition Results

Figure 4:

Figure 5:

Plasma Sustainance vs Interpulse Delay

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More reliable ignition can be achieved using dual pulse format

Ignition Profiles

A - Conventional, single laser pulse ignition

B - Dual pulse ignition with same laser energy

C - Dual pulse ignition with 20% more laser energy

Proprietary to Los Alamos

Figure 6:

Dual Pulse Ignition Probability with Temporal Delay

Figure 7:

Figure 8:

3 micron Preheating of Fuel Aerosol

Figure 9:

Laser Ablative Window Cleaning

Figure 10:

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Figure 1 Shown is a schematic of a generic compact resonator. retrofittable to existing engines, or 3) incorporated into the fuel nozzles or combined with a laser ignitor. Either way, the MI can be compact and have electrical and tuning requirements independent of engine design.

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Figure 2 The Paschen curve illustrates how lower altitudes place greater demands on a microwave ignitor. Plotted is the variation in breakdown voltage with altitude.

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Magnetron	\$5.00
Magnetron pulsed power supply	\$60.00
Waveguide	SS pipe
Cavity	May be integral with engine

Nd-YAG Laser	\$200.00
Electronics package	\$500.00
Optics	\$Maybe fiber optics

Figure 3 The cost of adding a microwave boost to current laser ignition schemes is minimal.

Microwave Ignition