Laser Stabilization for Near Zero NO_x Gas Turbine Combustion Systems

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Abstract

Historically, the development of new industrial gas turbines has been primarily driven by the intent to achieve higher efficiency, lower operating costs and lower emissions. Higher efficiency and lower cost is obtained through higher turbine operating temperatures, while reduction in emissions is obtained by extending the lean operating limit of the combustor. However reduction in the lean stability limit of operation is limited greatly by the chemistry of the combustion process and by the occurrence of thermo-acoustic instabilities.

Solar Turbines, CFD Research Corporation, and Los Alamos National Laboratory have teamed to advance the technology associated with laser-assisted ignition and flame stabilization, to a level where it could be incorporated onto a gas turbine combustor. The system being developed is expected to enhance the lean stability limit of the swirl stabilized combustion process and assist in reducing combustion oscillations. Such a system has the potential to allow operation at the ultra-lean conditions needed to achieve NO_x emissions below 5 ppm without the need of exhaust treatment or catalytic technologies.

The research effort was focused on analytically modeling laser-assisted flame stabilization using advanced CFD techniques, and experimentally demonstrating the technology, using a solid-state laser and low-cost durable optics. A pulsed laser beam was used to generate a plasma pool at strategic locations within the combustor flow field such that the energy from the plasma became an ignition source and helped maintain a flame at ultra lean operating conditions. The periodic plasma generation and decay was used to nullify the fluctuations in the heat release from the flame itself, thus decoupling the heat release from the combustor acoustics and effectively reducing the combustion oscillations. The program was built on an existing technology base and includes: extending LANL's existing laser stabilization experience to a sub-scale combustor rig, performing and validating CFD predictions, and ultimately conducting a full system demonstration in a multi-injector combustion system at Solar Turbines.

Executive Summary

Introduction

The need to improve efficiency, lower operating costs and lower emissions is the primary driver for the development of new industrial gas turbines. Higher efficiency and lower cost is obtained through higher turbine operating temperatures, while reduction in emissions is obtained by extending the lean operating limit of the combustor. However reduction in the lean stability limit of operation is limited greatly by the chemistry of the combustion process and by the occurrence of thermo-acoustic instabilities.

Solar Turbines, CFD Research Corporation, and Los Alamos National Laboratory have teamed up to develop the technology associated with laser-assisted ignition and flame stabilization, with an aim to enhance the lean stability limit of the swirl stabilized combustion process and assist in reducing combustion oscillations. Such a system is expected to allow operation at the ultra-lean conditions needed to achieve NO_x emissions below 5 ppm without the need of exhaust treatment or catalytic technologies.

The program aimed at using a pulsed laser beam to generate a plasma pool at strategic locations within the combustor flow field such that the energy from the plasma became an ignition source and helped maintain a flame at ultra lean operating conditions. The periodic plasma generation and decay was used to nullify the fluctuations in the heat release from the combustion process thereby reducing the combustion oscillations.

Goals and Objectives

This research effort aimed at developing a lean premixed combustion system that could achieve the following

- Provide a gas turbine system that generates less than 5 ppm NO_x at 15% O₂, without the use of any costly exhaust treatment.
- Provide an active control system that could be used to effectively eliminate the occurrence of the combustion driven oscillations

Status

The program was awarded in October of 2001. Since then Solar Turbines, Incorporated. built and assembled an atmospheric rig at no cost to DOE. This was used to conduct the initial tests defined in task 2. Simultaneously CFD Research had initiated the CFD modeling of a Taurus 60 injector in both the single injector atmospheric rig and the single injector high-pressure rig. CFDRC had also initiated the process of determining the best possible way to simulate the laser induced plasma generation process. The proper selection of this simulation process was determined to be crucial to the success of the CFD endeavor. The development of the laser system that LANL was responsible was initiated only in March 2002 as LANL received the clearance from DOE to work on this project only in March 2002.

In the second quarter of this year, atmospheric tests were conducted to evaluate the viability of the laser stabilized combustion process for gas turbines. The results indicated that it was not feasible to reduce the flammability limit of swirl stabilized flames under gas turbine operating conditions using the laser assisted flame stabilization process. Further the pulsing of the laser sparks failed to control combustion induced pressure oscillations. Similar conclusions were also derived from the CFD analysis conducted by CFD Research.

In view of the experimental results, Solar concluded that a significant amount of fundamental research was required in the areas of laser spark generation, plasma generation, and plasma decay before this concept could be implemented onto a gas turbine. The activities related to such a fundamental study were beyond the scope of this program. Therefore Solar has requested DOE for an early termination of the program. DOE has accepted the request, and the program has been officially closed.

Conferences and Publications

1. A Kick-off Meeting with DOE was held in Pittsburgh, PA on January 24, 2002. Solar, LANL and CFDRRC were represented at the meeting. During the meeting the potential of this technology along with the program details were presented to DOE. The progress to date was accessed and found satisfactory by the DOE personnel. Suggestions by DOE personnel with regard to making the initial atmospheric tests more detailed and using them as a critical platform for proving the merit of laser stabilized combustion technology were well received and have been incorporated in the program.
2. Solar and LANL attended the “Next Generation Turbine and Condition Monitoring Conference” held at Galveston Texas on February 25- 27, 2002. Solar presented a program summary at this conference. Suggestions made by DOE personnel with regard to the program objectives and the testing process, were well received and have been incorporated into the program.
3. Solar attended the “HEET-UTSR Combustion Workshop IX” held at State College PA on August 26-28, 2002. Solar presented a program summary and the final results at this conference.

1. Approach

1.1 Introduction

Historically, the development of new industrial gas turbines has been primarily driven by the intent to achieve higher efficiency, lower operating costs and lower emissions. Higher efficiency and lower cost is obtained through higher turbine operating temperatures, while reduction in emissions is obtained by extending the lean operating limit of the combustor. However reduction in the lean stability limit of operation is limited greatly by the chemistry of the combustion process and by the occurrence of thermo-acoustic instabilities.

Solar Turbines, CFD Research Corporation, and Los Alamos National Laboratory have teamed to advance the technology associated with laser-assisted ignition and flame stabilization, to a level where it could be incorporated onto a gas turbine combustor. The system being developed is expected to enhance the lean stability limit of the swirl stabilized combustion process and assist in reducing combustion oscillations. Such a system has the potential to allow operation at the ultra-lean conditions needed to achieve NO_x emissions below 5 ppm without the need of exhaust treatment or catalytic technologies.

The research effort was focused on analytically modeling laser-assisted flame stabilization using advanced CFD techniques, and experimentally demonstrating the technology, using a solid-state laser and low-cost durable optics. A pulsed laser beam was used to generate a plasma pool at strategic locations within the combustor flow field such that the energy from the plasma became an ignition source and helped maintain a flame at ultra lean operating conditions. The periodic plasma generation and decay was used to nullify the fluctuations in the heat release from the flame itself, thus decoupling the heat release from the combustor acoustics and effectively reducing the combustion oscillations.

The program was built on an existing technology base and includes: extending LANL's existing laser stabilization experience to a sub-scale combustor rig, performing and validating CFD predictions, and ultimately conducting a full system demonstration in a multi-injector combustion system at Solar Turbines. The technology was targeted towards natural gas fired lean premixed gas turbine systems using Solar's Taurus 60 combustor as a platform. Initially a series of proof of concept type experiments were conducted on a single fuel injector rig at atmospheric pressure conditions. These tests were conducted at inlet boundary conditions that were scaled from those of the Taurus 60 gas turbine. Beyond the atmospheric rig tests the program aimed at performing system optimization in a single injector high-pressure rig that would have simulated the flow temperature and pressure conditions experienced in a Taurus 60 gas turbine system. The effort would then have advanced to full annular rig tests of a Taurus 60 combustor (12 injectors; annular liner) and eventually an engine test at Solar.

1.2 Goals and Objectives

This research effort aimed at developing a lean premixed combustion system that will achieve the following

- Provide a gas turbine system that generates less than 5 ppm NO_x at 15% O₂, without the use of any costly exhaust treatment.

- Improve the durability of the gas turbine combustor hardware by lowering the primary zone temperature at which the combustor operates and by eliminating the occurrence of any unstable combustion.
- Reduce the maintenance required by eliminating the need for actuation/modulation of fuel or air flow, to prevent combustion induced pressure oscillations.

1.3 Technical Approach

The Project Network Diagram (*Figure 1.1*) summarizes the approach the project team used and illustrates the flow and interrelations of activities and tasks. Solar was responsible for providing the combustion system development and production engine test hardware, as well as design and test expertise. LANL was responsible for procurement and assembly of the prototype laser system. CFDRC was signed up to conduct numerical simulations of the various test conditions and will help in optimizing the laser assisted combustion process.

Figure 1.1 Project network diagram

1.4 Technology Overview

This section discusses the various technical aspects of the program and the tools that were expected to be used to achieve the goals of the program.

1.4.1 Combustion Modeling

Understanding the aerodynamics and chemical kinetics involved in the combustion process is critical to the optimization of the gas turbine combustion system. To achieve this understanding numerous time-accurate Large Eddy Simulations (LES) were scheduled to be performed using CFD-ACE code. Of critical importance was the demonstration that CFDRC's LES code can accurately model the combustion process and be used to guide the design and optimization process of the laser system.

LES methods involve direct solution of the general conservation equations for mass, momentum, energy, and chemical species for the large, energy containing scales in a combustion environment. The proposed LES methodology has been tested in the CFD-ACE+ code. The turbulence models for LES compute an eddy viscosity that is a function of the grid (or filter) size. The turbulent viscosity is computed from the magnitude of the resolved strain tensor, the grid cell volume and the filter width. This approach allows LES calculations with arbitrary grid types, including hybrid grid schemes and permit the simulation of geometries that are as complex as the Taurus 60 combustor. In addition to sub grid turbulence, a sub grid chemistry model were utilized to assess the interaction between the laser induced plasma with small-scale turbulent fluctuations. In the current version of the LES code, the filtered reaction rate source term is obtained from a one-step, finite-rate to equilibrium expression. For lean premixed CH₄-air combustion, appropriate reaction rates previously derived by matching numerical results with laminar flame speed and lean and rich flammability limit experimental data were utilized.

LES modeling is very essential to accurately capture time dependent characteristics of the laser assisted combustion process, which is not be possible using the present 3D RANS technology. This requirement is clearly demonstrated by comparing the fuel iso-surface predicted at the maximum pressure using the 3D unsteady RANS approach and LES (*Figure 1.2*). The LES results show the expected non-axisymmetric and irregular combustion features, which are smeared out in the unsteady RANS computation. The accurate prediction of similar unsteady combustion process in the presence of laser induced plasma was considered to be very essential for the success of this program.

Figure 1.2 Predicted fuel mass fraction iso-surface 3D unsteady RANS 3D LES

Using LES, the time dependent reacting flow field can be predicted for flow conditions under which experimental data is acquired. The experimental data was acquired for both stable combustion, and unsteady combustion in the presence of pressure oscillations. Upon comparing and anchoring the predicted flow field with the experimental data, the next step was to utilize the knowledge gained from the predicted flow field to optimize the strength and location of the laser pulse that was required to lower the lean blow off limit and control the combustion induced pressure oscillations.

1.4.2 Laser Pulse Format Specification

The primary laser pulse characteristic explored in this project was a variation of the laser induced spark (LIS) fuel ignition method. LIS incorporates a dual pulse format. The first pulse is, a very short duration, high power laser pulse that is applied directly to the combustion medium to breakdown the mixture and create a light absorptive plasma. This is followed by a longer duration, low power laser pulse that is used to sustain the previously generated plasma. This process is schematically summarized in *Figure 1.3*. The peak power of this second laser pulse is normally an order of magnitude lower, and its temporal length is an order of magnitude longer than that of the plasma-inducing high power pulse. Apart from the LIS method, the conventional single pulse format was also studied for its effectiveness in achieving the goals of the project. For comparative purposes the conventional single pulse format is also shown in *Figure 1.3*.

Figure 1.3 Typical laser pulse formats

The advantages of using the proposed dual pulse format are:

- The mode of laser energy delivery can be instantaneously optimized to provide ongoing reliable combustion dynamics damping over an extremely wide range of combustion systems and operating parameters.
- The physical location where the energy is delivered can be manipulated to accommodate different systems and/or power levels.
- By utilizing a second long duration laser pulse and inserting a temporal delay between the two laser pulses, the potential to sustain plasma pool over a desired interval of time is significantly greater than the combined temporal lengths of independent laser pulses. Previous work in this area has shown that the measured lifetime of the generated plasma using the dual pulse format was 8 times greater than that for a single pulse format.

1.4.3 Laser System Development

The initial investigation using the single injector combustion rig was conducted utilizing both dual laser pulse and single laser pulse spark breakdown initiation methods. Laser pulse energy, spark location in the injector's fuel/air flow, inter-pulse delay (for dual pulse) and pulse repetition rate were varied to determine laser operating conditions for optimal flame stabilization and pressure oscillation dampening. Comparison of results for single and dual laser pulse methods were made to determine the advantages of utilizing the dual pulse method. A Nd:YAG laser with a repetition rate of 30Hz was used to determine if there is any improvement in the lean blow-off limit and if the combustion oscillations could be controlled. The next stage of experiments would have then required thin film polarizers, that would be used to mix the output beams of the multiple lasers. *Figure 1.4* shows a sketch of how this would be accomplished.

Figure 1.4 Combining multiple laser outputs

After determining the optimal laser pulse format and repetition rate for single injector operation, the next step would have been design a laser system suitable for implementation into an annular combustor with multiple injectors. It was expected that more than one injector in the multi-injector annular combustor would require laser assisted stabilization to achieve the goals of low NO_x. One possible alternative to achieve this objective will be to time share a single laser in a manner so that one excitation laser is used to provide pump light to more than one stabilizing laser spark. This multiplexing approach and the elements required for such a laser system are described below:

Multiplexing

Multiplexing of the laser output to various fiber-coupled output ports can be accomplished using an electro-optic controlled laser light switching device that utilizes no moving mechanical parts. Control of the optical distributor is accomplished with an electronic module containing output port sequencing, timing and high voltage electro-optic driver circuitry. Since the proposed electro-optic switch contains no moving parts, the device is expected to be fairly insensitive to the mechanical shocks and vibrations. *Figure 1.5* shows a schematic of such a setup.

Figure 1.5 Prototype 7-output port light distributor

Fiber Optic Transport

Regardless of pulse format required, direct transport of laser light to the combustor is not practical due to the constrained workspace and complex spatial orientation of the injectors in the combustion chamber. The use of optical fiber to transport laser light is required to resolve the transport issue. A short focal length lens located at each output of the optical distributor is expected to be used to focus and inject the laser pulse into the selected optical transport fiber. Silica multi-mode optical fibers with core diameters of 400 microns will initially be employed to transport the laser light. Unfortunately, laser light output from the fiber is not immediately useful in producing a laser breakdown spark because light at the output of a transport fiber becomes unpolarized. Unpolarized light is not diffraction limited and suffers substantial pulse energy reduction. Also, the pulse shape may be altered depending on the peak power of the light transported and the diameter and length of the fiber used. All of these are detrimental to the laser spark formation process. Therefore, rather than using optical fiber to transport the laser light directly, the optical fiber can be used to conduct low peak power light, which is used to energize a small laser rod capable of delivering near-diffraction limited laser energy to induce a laser spark breakdown. This packaged laser rod is located at the combustor.

1.5 Facilities and Equipment

Each organization brings facilities and equipment that complement one another to fulfill the analytical and experimental needs of this program. Brief summaries of the facilities and equipment available for the program are provided below.

1.5.1 Solar Facilities and Equipment

Rigs available for this project include:

- A high-pressure single-injector test rig with a 9 pps, 300 psi air flow capability, and an indirect heater that can provide inlet temperature control up to 1000F (*Figure 1.6*).
- A full-scale, multi-injector atmospheric pressure rig with a 10 pps air flow capability.
- A full-scale, multi-injector high pressure rig that operates at C50 conditions (*Figure 1.7*).
- Development gas turbines maintained in-house for component testing.

The facilities include instrumentation to monitor fuel and air flows, system pressures (static and dynamic), temperatures, and emissions (NO_x, CO, CO₂, O₂, UHC).

Figure 1.6 *Solar's high-pressure single injector test rig*

Figure 1.7 *Solar's high-pressure multi-injector test rig*

1.5.2 LANL Facilities and Equipment

Laser systems, optics, pulse generators, signal attenuation equipment, and other related instrumentation available at LANL is unparalleled. In addition, their alliances with other institutes and industries facilitates help them leverage highly sophisticated systems that complement their present facilities and equipment. LANL shall procure/provide all systems instrumentation and hardware required to successfully deliver a laser pulse into the combustion chamber.

Lasers currently available at LANL, that will be used for the single injector rig tests are summarized in *Table 1.1*

Table 1.1 Los Alamos multi-pulse lasers utilized in present program

Laser	Operating Mode	Wave Length [nm]	Pulse Energy [m joules]	Pulse Width [ns]	Repetition Rate [Hz]	Pump Source
Cr:LiSAF	Q Switched Narrow Line	800-950 400-475 200-237	60	0.030- 0.060	5	Flash Lamp Xenon or Diode
Nd:YAG	Q Switched Single mode	1064 532 355 266	850 360 160 125	9 7 6 4	30	Flash Lamp or Diode

1.5.3 CFDRC Facilities and Equipment

CFDRC's computer facility has over 110 engineering workstations and computer servers from SGI, DEC, HP, IBM and SUN. In addition, CFDRC has many MacIntosh's, IBM PC's, X-terminals, an image scanner, and a (computer graphics) video recording facility. In addition, CFDRC has personnel qualified to plan and conduct experiments for validation of new design concepts, codes and/or physical models.

2. Discussions

2.1 LES as a Computational Tool

Large Eddy Simulation (LES) was used to model the effect of laser pulsing on combustion instability and flame stabilization in lean premixed combustors. For simulations of reacting flows LES is more accurate than steady-state RANS (Reynolds Averaged Navier Stokes) since the large scales are resolved and models are needed only for the sub-grid processes. The turbulence and chemistry sub-grid models used in LES are quite generic and are widely applicable because they simulate phenomena that are common to all swirl stabilized flows. Therefore these sub-grid models are fairly independent of geometry being simulated when compared to the models being used in steady-state RANS based simulations. However LES requires more computational time than RANS and thus needs parallel processing.

2.1.1 Model Description

The general conservation equations for mass, momentum, energy, and chemical species are filtered to obtain equations for the large-scale (energy containing) variables needed for LES. The filtered equations contain unknown terms such as a sub-grid turbulent stress tensor and a

sub-grid reaction rate that must be modeled. Unlike typical steady-state turbulence models, the sub-grid models for LES are a function of the local grid (or filter) size.

The subgrid turbulence was approximated with the Localized Dynamic Kinetic Energy Model (LDKM - Kim and Menon, 1997). Within the LDKM, the eddy viscosity is computed as a function of the local grid size ($\bar{\Delta}$) and the subgrid turbulent kinetic energy (k_{sgs}): $\nu_T = C_r \bar{\Delta} k_{sgs}^{1/2}$. A transport equation for the k_{sgs} is solved and requires terms that are obtained from velocity gradients at a test filter level. The test filter width is taken to be ~ 2 times the grid filter width. The LDKM has no adjustable constants and is widely applicable to a large range of turbulent flow conditions. Recent studies by McDaniel et al (2002) show good comparisons of experimental data and LES predictions with the LDKM for a lid driven cavity.

The subgrid chemistry was described with a 1-step finite rate chemical mechanism. The 1-step methane oxidation mechanism has been tuned to match laminar flame speeds over a range of equivalence ratio, inlet temperature, and pressure. The effect of subgrid turbulent fluctuations on the chemical reaction was ignored.

The laser spark was implemented during the transient calculation by modifying the source term in the LES energy transport equation. Variations in the laser power, spark location, radius, duration, and the duty cycle for laser pulsing can be specified. The laser pulse was typically applied over 5-6 computational cells for 10 time-steps (50 microseconds). This relatively coarse laser spark model allowed for practical computational times and did not require detailed treatment of ionization effects at high plasma temperatures (> 5000 K). Professor Ivan Dors, from the University of New Hampshire, reviewed the simplistic CFDRC laser model and indicated that it would be appropriate for the LES calculations performed in this DOE study. Professor Dors' review of laser pulse modeling is detailed in *Section 2.2*

The CFD-ACE+ code was used for the LES calculations performed under this program. The code features a co-located, fully implicit and strongly conservative finite-volume formulation, pressure-based solution algorithm (SIMPLEC), second-order Crank-Nicholson temporal differencing, and second-order central spatial differencing. The CFD-ACE+ flow solver has been parallelized for distributed and SMP architectures using the MPI message passing library and domain decomposition. A parallel cluster of Linux-based PC's (up to 24) were used for the 2D and 3D LES computations. Each PC includes a 1400 Mhz AMD Athlon chip, 1 Gbyte of DDR-PC2100 RAM and 100-Base-T networking.

2.2 Modeling of the Laser induced Plasma Generation

2.2.1 Overview

The decay of a laser spark is a complex process with interesting phenomena occurring on time scales ranging from femtoseconds to milliseconds, many of which are inter-related. Fortunately, not all of the induced phenomena need to be specifically modeled for the combustion instability stabilization application. Thus only a small set of induced phenomena that significantly interact with the combustion instability, need to be addressed. The main

requirement of the laser spark ignition model needed for this DOE program is that it must be computationally inexpensive while still producing the desired results. This requirement stems from the additional complexity of the combustion instability model over which the laser spark ignition model is to be superimposed, and the limitation of the computational power and resources currently available. Thus the computational model of the laser spark that is required for this investigation should sufficiently simulate the necessary phenomena with minimal complexity and computational requirements. In order to develop such a model, numerous simplifying approximations must be applied without adversely affecting the dynamics of the interaction.

To find the model with the optimum balance between computational expense and performance, one can start with a simplified model that maximizes efficiency while still remaining marginally realistic. Complexity should be added to the model only if the comparison between experimental measurements and computational results shows necessity to do so.

With these goals in mind CFDRC developed a simplified model to simulate the plasma generation and decay, which has been evaluated by Dr. Ivan G. Dors. This section details the current spark simulation model and the suggestions of Dr. Dors that would help in improving the model.

2.2.2 *Current Laser Ignition Model*

The current CFDRC model simulates the laser spark by super-imposing a spherical ignition kernel on to the ambient field of a combustor that exhibits acoustic instabilities. This ignition kernel is added to the simulation by the application of an energy source term over 10 consecutive, 5- μ s time steps. The resulting temperature profile of the kernel has a top-hat distribution a maximum value of 2500 K. The diameter of the distribution is set by the absorbed laser energy that is being modeled. A single-step finite-rate chemical kinetics mechanism is used to model the $\text{CH}_4\text{-O}_2$ reaction. The species concentrations, bulk velocity and pressure fields of the initial condition are taken to be that of the ambient field in the combustor prior to the laser pulse.

The current model inherently assumes that the explicit modeling of the laser spark prior to the time of the initial condition, τ_{ic} , is not necessary for the simulation of later-times. Such an approach is valid, however it requires a detailed knowledge of the fluid property fields at time τ_{ic} . Ideally, the initial condition is a snapshot of the fields at the selected time delay, and therefore contains the development of important effects up to this time. This snapshot does not need to be perfect since some early-time effects get damped out and become inconsequential as the energy of the reaction dominates the energy of the flow-field. The magnitude and timing of this damping effect, which is characterized by the onset of a steady-state self-propagating flame-front, is directly related to the ignition delay (τ_{id}). The value of the ignition delay depends on the ambient pressure, fuel, equivalence ratio, and laser spark energy.

The relationships between τ_{id} , τ_{ic} , and the time scales of the acoustic instability (τ_{ai}) are all important in this study. These relationships define the appropriate value of τ_{ic} , which is the key parameter that determines how rigorous the laser spark model must be for proper

simulation. For example, if the $\tau_{id} \ll \tau_{ai}$ then τ_{ic} should be set to a value on the order of τ_{id} and a simple model of the initial profiles may be used to model the steady state condition. However, if $\tau_{ai} \ll \tau_{id}$ then τ_{ic} should be set to a value on the order of τ_{ai} and a more complex laser spark model will be required to model early-time dynamics. Such a model would have to include plasma kinetics with the corresponding thermodynamic and transport properties.

The combustion instabilities studied in this investigation have frequencies on the order of 100 Hz, which corresponds to a τ_{ai} value of 10 ms. The complexity of the laser spark model is now to be determined by the time that it takes for the laser spark to induce ignition and cause a steady state combustion (τ_{id}). The value of τ_{id} is best determined through analysis of experimental results, which are currently unavailable. Using $\text{NH}_3\text{-O}_2$ laser ignition results as an estimate, τ_{id} is on the order of 100 μs . These values indicate that t_{ic} should be given a value of around 100 μs , which is ideal since it allows the initial condition to be a simple snapshot of the steady-state (reaction-dominated) condition. Additionally, the nominal transport and thermodynamic properties from the old JANNAF tables can be effectively utilized in this case.

2.2.3 Improved Laser Ignition Model

Due to the characteristics times of the acoustic instability and laser ignition processes, an initial condition that corresponds to the flowfield 100 μs after the laser pulse has been selected for the modeling. The dependence of the 100- μs profile on the laser spark asymmetry is a complicated function involving the laser pulse, focusing optics, ambient pressure, energy of the reaction, and the equivalence ratio. The asymmetry in the laser spark ignition can be initially considered as inconsequential, but should be added later if the experimental results indicate that it is necessary. Since experimental results have not yet been produced for the particular laser-optical system and fuel-air mixture in question, the model improvements formulated below are based on $\text{NH}_3\text{-O}_2$ laser ignition studies. The results of such studies may be viewed at <http://cla.utsi.edu/html/research/fluids/13.htm#>.

Ignition Kernel Energy Profile

The energy deposition modeled by the energy source term in the initial condition should only be a fraction of the actual absorbed laser energy. This discrepancy in the energy deposition is caused by the disregard of plasma and blast wave effects. For example: If 70% of the laser pulse energy gets deposited in the plasma, and 20% of deposited energy remains in the kernel region, then the energy of the initial condition should only contain about 14% of the total laser pulse energy. The exact percentages for the particular apparatus can be experimentally determined, or computationally adjusted for the best results.

To initialize the simulation process, a sphere with an 8-mm diameter can be used to approximate the source term geometry. Another source geometry that may result in a more realistic simulation is a cylinder (8-mm in diameter, and 5-mm long), which is aligned coaxially with the optic axis. Simple improvements on the source term geometry should be made when experimental data taken at a 100-microsecond delay becomes available. Experimental measurements such as shadowgraphs will become especially important for the tailoring of the initial geometries to compensate for pulses of different energies focused in

combustors with different ambient pressures. This is important because the size and geometry of the ignition kernel is not simply scaled by the laser pulse energy or ambient pressure. In fact it is note worthy that the kernel induced by increased pulse energy is not necessarily larger at later times. The reason relates to the increased energy in the generated blast wave and differing geometry of the subsequent collapse. This collapse of gas, starting at around a delay of 5- μ s, tends to non-uniformly stress the weak flame front. Increasing the laser energy well above breakdown threshold can actually extinguish the young flame kernel, resulting in the blowing out of the flame. This effect can be partially overcome by the two-pulse technique, if the second pulse has an adequately long duration.

The energy source term describing the deposition of the laser pulse energy should be applied as quickly as possible, ideally in a single time step. Spreading the energy source over several time steps will allow dissipation mechanisms to take energy away from the ignition process. If multiple time steps are required for better convergence behavior, then the insertion of several short (sub-microsecond) time-steps is advantageous.

Species Concentration Profile and Kinetics Model

The initial species concentration profiles should be taken as those present in the combustor prior to the laser spark. The single-step chemical kinetics model limits the number of species and the accuracy of the corresponding concentrations. A more accurate kinetics model will allow for the calculation of intermediate combustion species as well as the species concentrations in regions with temperatures greater than the flame temperature. The single-step chemical kinetics mechanism will produce good results only if it is able to accurately mock its more advanced multi-step counterparts, and if the temperatures considered remain below the flame temperature. The ability to accurately model the speed of the reaction is critical for properly timing the heat release for the stabilization of the acoustic instabilities. *Figure 2.1* shows the peak temperature of laser spark decay in air to be adequately below the flame temperature of 2500 K at the delay of 100 μ s, thereby partially validating the use of the current kinetics model. The magnitude of the energy source term should be designed to realistically keep the temperature at or below the flame temperature. A more complex chemical kinetics model should be adopted only if absolutely necessary as these complex models would require additional computational resources and generate new convergence problems.

Figure 2.1. Temporal plot of the maximum kernel temperature predicted during laser spark decay in air. Temperature values are in units of Kelvin. Temporal values are in units of seconds[1].

Pressure Profile

Figure 2.2 shows the time-history of the pressure at a point located within a laser spark during the decay process. The laser spark contained 25 mJ of energy and was simulated for laboratory air. After 100 μ s the pressure field has decayed significantly. Due to this fast relaxation of the pressure gradients, the initial pressure profile can be taken to be that of the ambient profile in the combustor. This profile will serve as a good approximation. To promote the growth of the flame front, a slight increase in the pressure field can be applied to the high-temperature region.

Figure 2.2. The pressure at a point located in the region of the laser plasma and ignition kernel. Pressure values are in units of Pascal. Temporal values are in units of seconds [1].

Velocity Profile

The modeling of the initial velocity profile should take into account both the kernel and the blast wave. *Figure 2.3* shows the H_2O concentration and velocity field at a steady-state expansion during $\text{NH}_3\text{-O}_2$ combustion. At the 1-ms time delay there exists an outward pointing velocity field that is helping the growth of the flame. The initial velocity profile can be set up to consist of the that which is ambient in the combustor plus an additional outward-pointing component that will serve to promote the expansion of the flame front.

Figure 2.3 The molar concentration profile of H_2O at 1.0 ms. The velocity direction field is represented by arrows. The bottom graph depicts the temperature along the x-axis in units of Kelvin. The distances on the x-axis and the y-axis are in units of meters [1].

Blast Wave Model

The blast wave induced by the laser spark may cause interference with acoustic instabilities and the spokes of the fuel injector. If this is the case, then a blast wave model should be included in the initial conditions of the laser spark. *Figure 2.4* shows the experimental and computational behavior of a blast wave induced by a laser spark of ~ 25 mJ. These data sets are in good agreement with the Sedov model for weak blast waves [3]. If modeling of the blast wave is desired, the Sedov model should be used to modify the pressure, temperature, and velocity profiles of the initial laser spark.

Figure 2.4 Comparison of the predicted blast wave radius (black line) with experimental measurements (circles with error bars). The red lines represent a one-cell-width deviation from the predicted blast wave radius. Blast wave radii are in units of meters. Temporal values are in units of seconds [1,2].

2.2.4 Conclusions

The initial CFDRC laser spark model offers a great starting point for this investigation. The modifications suggested in this section should produce a stable simulation that satisfies the computational and model requirements. However, additional tailoring of the model will be necessary to match the experimental data. To ensure proper modeling of the interaction between the laser spark ignition and the acoustic instability, a proper orthogonal decomposition (POD) analysis is suggested. Such an analysis could be performed separately on the acoustic instability and laser spark ignition for both the experimental and computational data. The result of the analysis will include the fundamental eigenmodes of the processes, and comparisons will show if

- 1) The acoustic instabilities are being properly modeled
- 2) The laser spark ignition is being properly modeled
- 3) The coupling between the two processes is being accurately modeled
- 4) The coupling between the two processes is strong enough for the desired stabilization
- 5) The location, geometry, and timing of the laser spark optimized for stabilization

A POD analysis will also help to quantify the effects of the various simplifying assumptions on the simulation results, as well as ensure proper use of the laser-induced heat release during the combustion instability.

2.3 CFD Simulations of Combustion Under Atmospheric Conditions

2.3.1 Steady State 3-D Simulations

Figure 2.5 Velocity vectors for orifices 2, 4, and 6. The bottom orifice has a much higher effective flow area.

Steady-state calculations were first performed of the Taurus 60 injector to obtain both mean flow-field patterns and flow distributions at each orifice in the fuel spoke. The predicted steady-state fuel flow distribution was then set as a boundary condition in the full combustion LES calculations to avoid the extra grid generation and computational time needed to resolve the internal fuel spoke flow-field.

The steady-state Taurus 60 injector modeling showed the highest fuel flow rate was experienced at orifice locations nearest the inner premix barrel. The velocity vectors in-line with three orifice locations are shown in Figure 2.5. From these simulations, it is concluded that the lowest orifice has a larger effective flow area than the upper ports. This fuel distribution thus provides a richer region along the inner premix barrel that persists downstream at the dump-plane.

Initial 2D steady-state modeling of the reacting flow using the injector and combustor were performed. The fuel spokes were modeled as three axisymmetric rings that had the same radial fuel distribution as predicted in the steady state Taurus 60 injector model. Baseline conditions for these 2D simulations included the following:

PHI = 0.85	$T_{in} = 300 \text{ K}$
P = 1 atm	$U_{noz} = 45 \text{ m/s}$
Swirl Angle = 42 deg	

The location of maximum heat release, along with steady-state fluid traces are shown in Figure 2.6. The fluid traces start at the fuel injection location and end at the heat release

zone. The the fluid trace time provides an indication of the fuel time-lag and the potential instability frequency (~ 303 Hz) for equivalence ratio modulation. However, the actual instability frequency would be dependent on a number of parameters including the fuel flow boundary (choked vs. unchoked), swirl air pressure drop, mixing and reaction times, acoustic time (from heat release zone to fuel injection location), as well as unsteady flow paths.

Figure 2.6 Steady-state fluid traces for the baseline Taurus 60 atmospheric simulation.

2.3.2 Transient 2D Simulations – Instability Dampening

Initial 2D axisymmetric transient CFD modeling was performed using unsteady RANS. The steady-state solution was used as the starting point for the transient calculation. The computational domain along with steady-state temperature prediction is shown in *Figure 2.7*. No artificial forcing was used in these unsteady calculations, thus allowing the thermo-acoustic instabilities to develop solely by the interaction between the unsteady heat release and the natural acoustic frequency or bulk mode of the system.

Figure 2.7 Computational domain and steady-state temperature prediction for the 2D axisymmetric Taurus 60 (baseline case).

Figure 2.8 Predicted time series and Fourier Transform of combustor dome pressure for baseline Taurus 60 atmospheric case.

Figure 2.9 Predicted instantaneous equivalence ratio, reaction rate, and axial velocity at maximum and minimum pressure during instability cycle.

At the baseline conditions, described in *Section 2.3.1*, the unsteady simulation predicted an instability near 364 Hz, that has a peak-to-peak amplitude of about 4% of the mean combustor pressure. Another oscillation of a smaller magnitude is predicted at 675 Hz. The time domain and frequency domain results of this simulation are shown in *Figure 2.8*. The predicted oscillation at 364 Hz is nearest to the convective time-lag of the fuel. *Figure 2.9* shows equivalence ratio, reaction rate, and axial velocity contours during the maximum and

minimum pressure conditions that are predicted for the 364 Hz instability. The fixed mass boundary condition used in this simulation, prevented any significant level of equivalence ratio modulation. Simulation of the non-reacting flow with the same boundary conditions showed that the vortex shedding along the inner shear layer occurred at ~1375 Hz. Since the vortex shedding frequency is about 4 times larger than the observed thermo-acoustic instability, it is highly unlikely that vortex shedding is the driving mechanism for the combustion instability. The simulation however seems to indicate that a variation in feed-rate of reactants to the flame zone is the driving mechanism and this corresponds closely to the steady-state fluid trace (see *Figure 2.6*).

To get a better understanding of the combustion dynamics of the system, several unsteady RANS cases were studied with variations in combustor/premix barrel lengths and boundary conditions. The aim of the exercise was to simulate a low frequency oscillation (60-100 Hz) that could be affected by a 30 Hz laser pulse format. *Table 2.1* shows a number of the cases that were run by CFDRC to try and achieve a low frequency oscillation.

Table 2.1 CFD cases of Taurus60 with predicted instability frequency and amplitude

CFD Case	Premix L (in) & U (ft/s)		Comb & Ext L (in)		Comb & Ext D (in)		Air (F)	Inlet BC	Freq (Hz)	Amp (%)
0	1.73	148	17.67	120.6	8.23	10	80	Fixed Mass Flow	364	4
6	11.73	148	17.67	120.6	8.23	10	80	Fixed Mass Flow	174	2.6
7	11.73	148	17.67	120.6	8.23	10	80	Fixed Total Pressure	170,369,578	3.4
8	11.73	148	29.5	29.5	8.23	3.54	260	Fixed Mass Flow	1000,2000	0.12
9	11.73	148	29.5	29.5	8.23	3.54	260	Fixed Total Pressure	84, 560, 646	2.5
10	11.73	88	29.5	29.5	8.23	3.54	260	Fixed Mass Flow	456,609,1137	0.45
11	11.73	88	141.24	--	8.23	--	260	Fixed Mass Flow	48,140	5.0
12	11.73	88	141.24	--	8.23	--	260	Fixed Total Pressure	55,145	4.9
13	11.73	88	141.24	--	8.23	--	260	Upstream Plenum	158,486	1.15
15	11.73	88	141.24	--	8.23	--	260 Case 13 (phi=0.75 vs 0.85)		--	Quiet

The results of the simulation showed that the predicted combustion instability is very sensitive to the length of the pre-mixer, velocity of the reactants in the pre-mixer, geometry of the combustor, and inlet air boundary conditions. Cases 0-7 utilized the baseline combustor/extension geometry, while cases 8-10 utilized a Helmholtz combustor/neck geometry and cases 11-15 utilized quarter-wave length combustor geometry. The Helmholtz and quarter-wave geometries were sized to give an approximate 60 Hz natural frequency. Case 12 showed the most promise as it utilized a quarter-wave combustor length and a long pre-mixer and resulted in a strong 55 Hz oscillation. Unfortunately, significant negative flow occurred at the fixed total pressure inlet air boundary and the case diverged after several cycles of instability. To prevent the numerical error that occurs at the fixed total pressure boundary during negative flow, the computational domain was extended further upstream and swirl source terms were used at the swirler location (case 13). A fixed mass was then used at the inlet to the upstream plenum. Results of this simulation exhibited a thermo-acoustic instability at a frequency of 158 Hz, instead of the 55 Hz instability observed earlier.

Case 13 was selected to study the effect of laser pulsing on the 158 Hz instability, and its predicted instantaneous temperature and pressure signal are detailed in *Figure 2.10*.

Figure 2.10 Case 13, predicted instantaneous temperature and dome pressure signal.

Figure 2.11 Instantaneous temperature contours after laser pulse was simulated in reactant stream (0.25 millisecond spacing).

Unsteady reacting flow simulations, with the presence of a 30 Hz laser pulse, were performed using the geometry and boundary conditions defined in case 13. The laser pulse was simulated at a location 0.55 inches downstream of the premixer exit and at a radial location that was in the main swirling stream of cold unburned reactants. *Figure 2.11* shows instantaneous temperature contours near the combustor inlet, where the laser pulse was applied. Peak temperatures reached 3900 K immediately after the pulse was turned off

(Time 1). The high temperatures are due both to the laser pulse energy and the completed reaction of premixed methane-air to products. At 250 microseconds later (Time 2) the high temperature burned gas envelope elongates slightly and then seems to collapse or extinguish at later times (Times 3-6). From these results it was concluded that the high strain rates in the reactant flow stream may have been responsible for extinguishing the flame kernel.

Simulation of the unsteady reacting flow without the presence of a laser pulse, using the geometry and boundary conditions described by Case 13 exhibited a combustion driven pressure oscillation at 155 Hz. These pressure oscillations had an amplitude of $\sim 3.1\%$ of the mean pressure. Simulation of the same case, but with the presence of a 30 Hz laser pulse was achieved by applying a short duration (15 microseconds) source term to the energy equation at periodic intervals of approximately every 6.45 msec. For the results shown here, a laser pulse was applied after a large amplitude oscillation has been reached. The addition of laser pulse energy occurred at approximately the same time the combustor pressure reached a minimum. *Figure 2.12* shows the time history of combustor dome pressure for simulation with and without the presence of the laser pulse. Comparing the two results it is noted that the presence of the laser pulse reduced the pressure oscillations by $\sim 30\%$.

Figure 2.12 Predicted combustor pressure history for the baseline (no laser pulses) case and the case with the presence of laser pulses. Presence of laser pulses damps instability by $\sim 30\%$.

Figure 2.13 Instantaneous temperature snapshots immediately after laser pulse event

From simulations described by *Figure 2.11*, it was concluded that the laser spark, with energy levels commensurate to commercial hardware, were extinguished within 1 millisecond. In contrast, the amount of energy applied to the source term, for the results reported in *Figure 2.12*, was nearly ten times the amount expected in the actual laser pulse obtained from commercially available lasers. Thus the spark was able to sustain itself in the flow field. Simulation of this extra high intensity spark is shown in *Figure 2.13*. The high temperature region from the spark is much larger than the results shown in *Figure 2.11* and the flame kernel from the laser spark does not extinguish, but instead propagates outward as desired. Based on these results it can be concluded that instability damping can be obtained if the laser spark is large enough to sustain a flame kernel without extinguishing. Also, the addition of laser energy must occur when the combustor pressure is near its low point. 3D modeling is needed to predict the circumferential propagation of the laser-induced flame kernel.

2.3.3 Transient Simulations – Laser Stabilization

Time-accurate CFD methods, including 2D and 3D LES, were used to study the effect of laser pulses on flame stabilization. Initial studies started with a laser spark being initiated in the central re-circulation zone with the expectation that the low velocities, low turbulence levels and strain rates present in the re-circulation zone would aid in the initiation and sustenance of the flame. LES calculations were initiated on a converged non-reacting flow-field with the simulation of a laser pulse. The computations were performed with time steps of 5E-6 seconds. A small 8.5 mm diameter region was activated to simulate the absorption of the pulsed laser energy ($3880 \text{ W} = 618 \text{ W/rad}$) for the first 10 time steps. Thus providing total laser energy of 194 mJ. The peak temperatures, after simulation of the absorption of laser energy, reached levels of $\sim 3000 \text{ K}$. A smaller energy absorption volume would have shown much higher plasma-type temperatures, but would have complicated the use of JANNAF thermodynamic property data and thus was not attempted. Simulations were performed for the baseline Taurus 60 injector geometry for combustor pressures of 1 atmosphere and 17 atmospheres, equivalence ratio of 0.48, air mass flow rate of 0.155 lbm/sec (0.0703 kg/sec), and inlet temperature of 640 F (611 K).

Figure 2.14 shows the predicted instantaneous flame shape at various points in time. A smaller kernel (3 mm diameter) simulating the absorption of laser energy was required for the high-pressure case compared to the 8.5 mm diameter kernel required for the atmospheric case. As can be seen from *Figure 2.14*, the laser pulse was successful in igniting a non-reacted mixture.

Similar calculations were also performed at an equivalence ratio of 0.4, the results of which are shown in *Figure 2.15*. The results indicate that under both pressure conditions of one atmosphere and seventeen atmospheres, the laser energy and subsequent local ignition was not sufficient to sustain a flame for more than 0.02 seconds.

Figure 2.14 Instantaneous LES predictions of flame shape after laser pulse of initial non-reacting flowfield ($\phi=0.48$).

Figure 2.15 Instantaneous LES predictions of flame shape after laser pulse of initial non-reacting flowfield ($\phi=0.4$).

The effect of pulse location and a modification to add a low-speed LP (lean premixed) pilot flow were also studied at the condition of $\text{PHI}=0.4$. The pulse location was moved further downstream and away from the centerline compared to previous simulations. The idea for the 'LP pilot (also $\text{PHI}=0.4$) was to provide a small flow of reactants that would not contribute to NOx production and that would not extinguish the initial flame growth. Previous calculations seemed to indicate that the flame would extinguish completely once it was entrained into the main high-speed reactant stream. The low-speed pilot flow was expected to help maintain a steady source of heat release without high strain rates that can extinguish flames.

Figure 2.16 shows the locations in the flowfield where the laser pulse was simulated. These locations were within the central re-circulation zone and about 7.4" downstream of the combustor dome. The outboard laser pulse location was ~ 1.7 " from the combustor centerline (~ 2.9 " radially inward from the combustor wall). The LP pilot that was modeled here included a uniform axial velocity of 4.8 m/s entering the combustor. The diameter of the pilot was 0.88 inches and utilized $\sim 1.5\%$ of the main injector flow.

Figure 2.16 Steady-state axial velocity flow field and laser pulse locations for baseline Taurus 60 injector and low-speed LP pilot injector.

Figure 2.17 Instantaneous LES predictions of flame shape after laser pulse of initial non-reacting flow field (No Pilot Case & Low-Speed LP Pilot Case; $T_{air} = 611$ K; $\phi = 0.4$).

Instantaneous LES snapshots of temperature for simulation of the reacting flow in the presence of the laser spark, with and without the LP pilot are shown in Figure 2.17. From the results it is clear that the low-speed pilot prevents the initial strong recirculation of laser-generated combustion products towards the combustor dome. At 20 milliseconds, the LP pilot case shows a larger flame kernel and the flame has not quite yet reached the dome. At 30 milliseconds the non-pilot case seems to have been nearly blown out, while the LP pilot case shows a much larger flame. The improved laser assisted flame stability seen in conditions that had a LP pilot can be explained by the following two reasons

- Lower centerline velocities for the LP pilot case allows the laser-generated flame to grow before being entrained into the high-speed reactant stream.
- The LP pilot provides a continuous source of heat release without a high strain rate.

Figure 2.18 *Instantaneous LES predictions of flame shape after laser pulse of initial non-reacting flow field (Centerline pulsing and outboard pulsing; low-speed LP Pilot; $T_{air} = 611$ K; $\Phi = 0.4$).*

The placement of the laser pulse away from the centerline in presence of a low-speed LP pilot flow was also investigated. The laser energy was increased for the outboard laser

pulsing until ignition was achieved since the model assumes axisymmetric flow conditions. The actual axial-radial cross-sectional area of the initial burning plasma was similar to that used in the simulation the laser spark along the centerline. *Figure 2.18* shows instantaneous snapshots of the flow field temperature for simulation of the reacting flow in the presence of the laser spark, along and away from the centerline. As shown, the case with the outboard laser pulsing shows much better flame propagation than the centerline pulsed case. The centerline negative axial velocity was $\sim 40\%$ higher than the negative axial velocity at 1.7" from the centerline. The outboard pulsing case does not exhibit a fast propagation of products towards the combustor dome, but instead allows sufficient flame spread and growth towards the combustor dome and the combustor outer wall. The flame is much larger at 30 milliseconds for the outboard pulsing case. The idea of applying a laser pulse at a location away from the combustor centerline seems to hold promise at this point. Further 3D simulations need to be performed to examine the possibility of sustained combustion with a more realistic plasma volume that is not an axisymmetric ring.

Figure 2.19 Instantaneous temperature contours for 3D LES case. (Outboard pulsing; $T_{air} = 611$ K; $\Phi = 0.4$).

Preliminary 3D LES simulations with presence of a laser spark at an off center-line location was conducted. Instantaneous snapshots of the combustor temperature are shown in *Figure 2.19*. Unfortunately, the initial plasma kernel could not sustain a reacting flow. The 3D grid was required to be coarser than the 2D simulations and may have excessively diffused out the temperature so that ignition could not take place.

2.4 CFD Simulations of Combustion Under Pressurized Conditions

2.4.1 Steady State 3-D Simulations

Figure 2.20 Computational domain for Taurus 60 injector and combustor

A 3D steady-state simulation has been performed of the Taurus 60 injector at high pressure conditions. The simulation includes a small upstream plenum that feeds the premix annulus. The premix annulus contains the 16-vane axial swirler, and fuel spokes. The premixed

swirling flow then dumps into the combustor can. As a preliminary case the boundary conditions chosen included a fixed mass air flow at the upstream plenum inlet, a fixed mass fuel flow at each fuel orifice and a fixed static pressure at the combustor. *Figure 2.20* shows the computational domain of the 3D Taurus 60 configuration. A total of 1.75 million structured hexahedral cells were used in the model. A relatively coarse grid around the fuel spokes was used, with only 2x2 cells used to represent each orifice face. A butterfly grid was used to represent the combustor in order to avoid the infinitely small cells at the centerline.

The computational domain was decomposed in the axial direction into 23 pieces and initial calculations were performed on CFDRC's Linux cluster of PC's. Partially converged solution after 1000 iterations was obtained. Despite the partially converged solution, important features of the 3D predicted flow can be observed. Flow conditions for the baseline 3D case were: $P = 20$ atm, $\text{PHI} = 0.6$, $T_{\text{inlet}} = 589$ K (600 F), and $m_{\text{air}} = 0.78$ kg/sec (1.72 lbm/sec). Steady-state predictions of the fuel mass fraction iso-surface are shown in *Figure 2.21*. This iso-surface shows the mixing interface just downstream of the spokes and the reaction zone in the combustor. Central and outer recirculation zones form in the combustor for stabilizing the flame. It seems likely that the flow will open up further once full convergence is obtained. These initial predictions also showed hot product recirculation along the injector ID and extending approximately 0.5" upstream of the injector exit. Further computational work was terminated as the program being curtailed.

Figure 2.21 Steady-state fuel (0.015) iso-surface for initial 3D Taurus 60 prediction

2.5 Atmospheric Single Injector Tests

Solar decided to run the initial Task 2 laser stabilization experiments on an atmospheric pressure test rig. The rig allows visual access to the combustion process, as the containment vessel is a cylindrical quartz tube. The testing used a single Taurus 60 injector. The experimentation was aimed at generating dynamic stability and lean blow off data both with and without laser pulses. The lasers used for this experiment were provided by LANL. The experimental data was used to evaluate the viability of the laser stabilized combustion process for gas turbines, establish the operating envelope for the future single combustor, high-pressure rig tests and validate the CFD simulations generated by CFD Research.

For the purpose of the atmospheric tests Solar modified an existing rig and built all the interfacing hardware. The rig and the related hardware were assembled at Energy Research Corporation, Irvine, CA. (ERC) where the atmospheric tests were conducted. The combustor section of the rig consists of an 8" diameter quartz tube and stainless steel extension tubes. The stainless steel extension tubes are used to vary the length of the combustor with an aim to excite different acoustic frequencies.

The lasers used in these atmospheric experiments were supplied by LANL and were capable of outputs of 1.064um wavelength light with a pulse width of about 10ns, pulse energies of up to 2 joules and repetition rates up to 30 Hz.

2.5.1 Sizing of the Combustor

Preliminary tests were conducted to ascertain the length of the combustor that would exhibit the desired acoustic characteristics. Based on these tests it was decided that two combustor lengths detailed in *Table 2.2* would be used.

Table 2.2 The combustor lengths used in the experiments

Test Type	Combustor Length	Excited Acoustic Frequency
Lean Stability Enhancement	10 inches	Stable
Control of Combustion Induced Oscillations	60 inches	105 Hz.

The 60" combustor length was chosen for the tests aimed at determining the capability of the laser pulse to control combustion driven oscillations because, this was the most practical combustor length that provided the lowest excitable acoustic frequency. The need for the lowest excitable acoustic frequency arose from the limitation of the pulse rate of the lasers provided by LANL for the atmospheric tests.

Based on the above results the two combustors were built and assembled. *Figure 2.22* shows the photographs of the atmospheric test rig with the 10" quartz combustor and the 60" combustor that consists of a 40" stainless steel pipe and a 20" quartz viewing section.

10 inch Combustor Liner Length

60 inch Combustor Liner Length

Figure 2.22 Atmospheric test rig with the two combustors.

2.5.2 Laser System Setup

Several important laser-based efforts were conducted at LANL on the two lasers that were selected for the experiments. These lasers were used to provide the duel pulse formats required during the experiments. The pulse energy and duration of the 30Hz lasers selected for use in the combustion stabilization experiments were characterized by Los Alamos National Laboratory, with respect to adjustments in flash lamp current and pulse repetition frequency. The lasers were then commissioned at ERC (Energy Research Consultants) in Irvine, California, by members of the LANL laser team.

2.5.3 Baseline Experiments – Without Laser Sparks

Experimental Conditions

Using the two combustors, experiments were conducted to record the baseline results for tests without laser excitation. The flow conditions under which the experiments were conducted are detailed in Table 2.3. The equivalence ratio for which the data was collected varied upward in Φ from lean blowoff to $\Phi = 0.66$ in increments of 0.025, for experiments using the 10" quartz combustor and was limited to three equivalence ratios between lean blow off and $\Phi = 0.484$, for experiments with the 60" long combustor.

Table 2.3 Experimental flow conditions

Air Flow Item	Value
DP/P	2.89 – 3.03 %
M_{air}	0.133 – 0.141 lbs/sec
Inlet Air Temperature (F)	635 – 645 F
ACd	1.545 – 1.628 in ²
% Pilot Fuel	0%, 2.5%, 5%

The emissions at the exit of the combustor, the dynamic pressure trace and a photograph capturing the flame structure, were recorded at each of the test conditions.

The composition of the natural gas fuel used during the experimentation is detailed in *Table 2.4*.

Table 2.4 Fuel composition

Fuel	Percent by Volume
CH ₄	94.9
C ₂ H ₆	1.90
C ₃ H ₈	0.03
CO ₂	1.20
N ₂	1.00

Experimental Results

Flow Visualization

Photographs were taken using a 35 mm camera adjusted to an exposure of 1 sec and f-stop of 3.3. These photographs were aimed at documenting the flame structure and are shown in *Figure 2.23* through *Figure 2.28*. Note that no conclusions should be drawn from variations in the brightness of the photos, since the prints were not necessarily printed with the same settings. The purpose of the photographs is solely to detail the flame structure.

Maximum $\Phi = 0.658$

Unstable, $\Phi = 0.467$

LBO, $\Phi = 0.451$

Figure 2.23 0% Pilot using a 10" long combustor

Maximum $\Phi = 0.658$

Unstable, $\Phi = 0.465$

LBO, $\Phi = 0.451$

Figure 2.24 2.5% Pilot using a 10" long combustor

Maximum $\Phi = 0.658$

Unstable, $\Phi = 0.465$

LBO, $\Phi = 0.404$

Figure 2.25 5% Pilot using a 10" long combustor

Maximum $\Phi = 0.484$

Unstable, $\Phi = 0.465$

LBO, $\Phi = 0.442$

Figure 2.26 0% Pilot using a 60" long combustor

Maximum $\Phi = 0.484$ Unstable, $\Phi = 0.47$ LBO, $\Phi = 0.447$ *Figure 2.27 2.5% Pilot using a 60" long combustor* Maximum $\Phi = 0.484$ Unstable, $\Phi = 0.447$ LBO, $\Phi = 0.423$ *Figure 2.28 5% Pilot using a 60" long combustor*

Emissions

Emissions measurement was made at five radial locations in the exit plane of the combustor using a water-cooled sample probe that had an outer diameter of 0.375 inches. The extracted sample was dried and fed to three analyzers for measurement of total hydrocarbons and oxygen (Horiba model FMA-220), carbon monoxide and carbon dioxide (Horiba model AIA-220), and oxides of nitrogen, NO_x , (Horiba model CLA-220). The results obtained at the 5 radial location were averaged using an area weighted scheme and then corrected to 15% excess O_2 . These averaged emissions results (15% O_2) are shown in *Figure 2.29* and *Figure 2.30*.

Figure 2.29 CO for all cases

Figure 2.30 NO_x for all cases

Dynamic Pressure Measurements

Dynamic pressure measurements were made using a microphone-amplifier system (Audio Technia ATM63HE with a Mackie Micro Series 1202-VLZ amplifier). The results of the dynamic pressure measurements are shown in *Figure 2.31* through *Figure 2.35*.

Figure 2.31 10% Pilot $\Phi = 0.658$ using a 10" Liner

Figure 2.32 0% Pilot $\Phi = 0.494$ using a 10" Liner

Figure 2.33 5% Pilot $\Phi = 0.658$ using a 10" Liner

Figure 2.34 0% Pilot $\Phi = 0.484$ using a 60" Liner

Figure 2.35 0% Pilot $\Phi = 0.442$ using a 60" Liner

2.5.4 Laser Assisted Flame Stabilization

Table 2.5 Location and various Laser setups

Axial Distance	Min. Radial Distance	Max Radial Distance	Laser Setup
13 mm	0 mm	90 mm	New Wave
13 mm	0 mm	90 mm	DCR3
48 mm	24 mm	90 mm	Duel Pulse
19 mm	24 mm	90 mm	Duel Pulse
89 mm	10 mm	90 mm	Duel Pulse

Laser assisted flame stabilization experiments were performed with the assistance of LANL personnel. Initial testing involved the attempt to lower lean flammability limit of the combustion process with an aim to lower the NO_x production when compared to combustion without the assistance of a laser pulse. Experiments without the assistance of the laser pulse showed a lean blow off at $\Phi = 0.43$. Experiments aimed at determining the equivalence ratio at which the laser would be able to ignite a mixture of methane and air were done using three laser setups as described in Table 2.5. The laser beam was focused at various locations within the combustor and it was noted that the shear layer between the outer re-circulation zone and the inner re-circulation zone was the most effective location to ignite the fuel-air mixture. The first series of experiments used the output from a single laser operating at energy levels of 170 mJ and a pulse rate of 20 Hz. These experiments resulted in ignition of fuel-air mixture only at $\Phi \geq 0.48$. At lower equivalence ratios the laser was unable to sustain a flame. The next series of tests were conducted with a higher powered DCR3 laser that had a power of 500mJ. The increase in power did not show any improvement on the effectiveness of the laser pulse to ignite a methane–air mixture. Finally the dual pulse format was applied. Here the two pulses were separated by 100 ns. The second pulse was varied from 10 ns duration to 80 ns duration. Regardless of the second laser pulse width, a substantially longer (1 cm) laser breakdown spark was obtained using the dual pulse method. Energies of the first and second laser pulses used were 100mJ and up to 500mJ, respectively. The result of this effort provided no improvements in flameout mixture limit or pulling of the flame back to the injector top.

2.5.5 Laser Assisted Combustion Instability Control

LabVIEW Phase Delay System

An effective phase delay system was designed using LabVIEW Real-Time and the equipment required to build the system, was acquired. This system was needed to ensure that the phase difference between the oscillatory energy release due to combustion driven pressure oscillation, and the energy addition due the generation of the laser assisted plasma is about 180 degrees.

The phase delay system was designed to implement the following controls logic.

- Step 1: Measure the width of the positive half of the pressure oscillation period.

- Step2: Scale the time measured in step 1 by a constant percentage to obtain the desired phase delay.
- Step3: Wait the appropriate amount of time (as determined in step 2) in the second half of the period corresponding to the desired phase delay.
- Step4: Fourth, send a narrow TTL pulse to the laser trigger circuitry.

Figure 2.36 Phase relationship

The methodology described above is graphically shown in *Figure 2.36*, where the controls sequence is as follows

- Step 1: Count the number of clock cycles for which the signal is positive.
In this example count = 10.
- Step 2: Scale the count in Step 1 by a scaling factor.
For this example: $SF = 0.5$.
- Step 3: Wait the appropriate number of clock cycles calculated in Step 2.
 $Delay = 10 \times 0.5 = 5$
- Step 4: Generate a narrow TTL pulse after the delay from Step 3.

This system has a special computer dedicated to data acquisition, with minimal operating system overhead requirements. Performance tests indicated that the maximum sampling rate of the system was 40 KHz and the phase delay was accurate to about 0.9 degrees, for a 100 Hz signal. This accuracy is expected to be linear, thus translating into an accuracy of 2.7 degrees for 300 Hz.

Figure 2.37a shows a trace of the functioning phase delay system running under the LabVIEW environment. Channel 1 simulates the acoustic signal acquired by the microphone. Channel 2 shows the trigger pulse output and phase relationship to the input signal. In this case, the input signal is 106 Hz and the phase delay of the trigger is 90 degrees with respect to the zero crossing, as viewed from the negative side of the sine wave or 270 degrees with respect to the zero crossing as viewed from the positive side of the sine wave. At this phase delay the trigger pulses should coincide with the negative peak of the sine wave.

Figure 2.37a

Figure 2.37b

Figure 2.37 Oscilloscope Trace of LabVIEW Real-Time System

Figure 2.37b shows the LabVIEW system functioning with a higher frequency input signal of approximately 425 Hz and the same phase delay as applied to the 106 Hz signal seen in Figure 2.37a. The system's ability to maintain phase delay relationships with various frequencies is a key aspect of the system. The system was capable of controlling a phase delay to a required value between 0 and 180 degrees with respect to the zero crossing of a signal.

While the sine wave input as shown in Figure 2.37 is an idealization of the acoustic signal, some preliminary testing was carried out with intentionally noisy sine waves to determine system performance for a more realistic signal. While the system seemed to perform satisfactorily under relatively low broadband noise (<10% of sine wave amplitude), tests with

higher noise cases indicated that a dead band trigger or antibounce switch was worth investigating to prevent premature triggers. However it was determined that the system specifications and test results obtained met the needs of this preliminary set of experiments conducted under atmospheric conditions.

Laser Assisted Combustion Instability Control

Experiments to assess of the ability of laser pulses to dampen combustion oscillations were initiated after testing and proving the proper performance of the phase delay system. The combustor used was 60" long and exhibited a combustion driven pressure oscillation at a frequency of ~105Hz. The flow conditions under which the tests were conducted are detailed in *Table 2.6*, while the laser setup and the laser pulse locations used for the control of the pressure oscillation are detailed in *Table 2.7*.

Table 2.6. Air flow data

Air Flow Item	Value
DP/P	2.89 – 3.03 %
Mair	0.133 – 0.141 lbs/sec
T	635 – 645 F
Phi	0.465, 0.475, 0.5

Table 2.7. Test locations and laser setup (60" Liner)

Axial Distance	Radial Range	Phase Delay Range	Laser Setup
34 mm	0-30mm	0-180 degrees	Dual Pulse

At each operating condition, acoustics data was collected using the microphone and the pressure transducer. Each data set consisted of discrete data points collected at a sampling rate of 4096 Hz for 16 seconds. This allowed the averaging of 16 blocks of data (each block consisting of one second worth of data). Additionally, a 4th order low pass Butter worth filter (Krohn-Hite 3200) with a cutoff frequency of 1kHz was installed on the microphone channel to minimize high frequency aliasing of the frequency spectrum. Finally, the data were digitally filtered at 60, 180, and 300 Hz using 12th order, band stop filters to remove 60 Hz noise components. This conditioned time series data was then processed through a FFT analysis to generate a power spectrum.

The Experimental procedure insured that at every operating condition back to back comparisons could be made between the acoustic signature of the combustor with and without the presence of the laser pulse. For each operating conditions tested the phase of the laser pulse was varied between 0 and 180 degrees and the location of the laser spark was varied radially outward from the center line of the combustor to a radius of 30 mm.

The analysis of the collected data showed that under all operating conditions, the laser pulse was not able to control the combustion driven pressure oscillation. There was some variation in the amplitude of the oscillation between the data set without the laser pulse and the one with the laser pulse but this variation was attributed to a very low frequency thermal

interaction between the combustor and its environment. This low frequency oscillation of the pressure amplitude at ~ 105 Hz is seen in *Figure 2.38*. Here the flow condition was fixed to maintain $\Phi = 0.465$ and no pilot fuel flow. After giving the rig about 45 minutes to stabilize the data was collected in batches of 16 seconds with the laser spark turned on during every other batch. Upon processing the data, the magnitude of the pressure oscillation peak around 105Hz was picked for each data set (16 seconds worth of data) and plotted as a function of time in *Figure 2.38*. Here it can be clearly seen that the amplitude of the pressure oscillation varies with time in an almost sinusoidal manner and there is little or no effect of the laser pulse on its behavior.

Figure 2.38 Magnitude of the pressure oscillation at ~ 105 Hz as a function of time for $\Phi = 0.465$ (alternating data set with and without the laser pulse)

To ascertain if the amplitude of the pressure oscillation stabilized over a long period of time, the rig was run at a $\Phi = 0.475$ with no pilot fuel flow, and data was collected every half hour. *Figure 2.39* shows the power spectrum of the pressure signal after operating the rig for one hour. The power spectrum exhibits a distinct oscillation of amplitude 0.53 V^2 at a frequency of 106 Hz. This amplitude decays completely within the next half hour as is seen in *Figure 2.40*.

The decay of the amplitude of the pressure oscillation discussed above is attributed to the thermal interaction of the rig with its environment and can be prevented with making modifications to the rig. However since the data acquired to date is compelling enough to conclude that the laser pulse has little or no effect on the pressure oscillations it was decided not to proceed with the rig modifications.

Figure 2.39 Power spectrum of the pressure signal for $\Phi = 0.475$ and no pilot after running the rig for one hour

Figure 2.40 Power spectrum of the pressure signal for $\Phi = 0.475$ and no pilot after running the rig for one and a half hour

3. Combustor Integration Issues

Apart from the technical feasibility of the laser assisted flame stabilization concept, the implementation of the concept in a typical industrial gas turbine combustor involves a number of hardware and system integration issues. These include

- Modifying combustor liners and housings to accommodate optical windows and focusing optics to ensure proper delivery of the laser pulse to the desired location(s) within the combustor.
- Development of a robust version of the miniaturized ignitor laser seen in *Figure 3.1*. This laser is used to produce a collimated beam that carries the laser pulse energy.

(a) Exciter Laser

(b) Operational Flexibility

(c) Ignitor Laser with JTAGG Rig Adapter

Figure 3.1 CFDRC/LANL prototype dual pulse laser ignition system with adapter

3.1 Windows

It will be necessary to provide windows in the combustor liner and depending on the laser beam delivery system, it may also be required to provide windows in the combustor casing.

The windows in the combustor liner are expected to experience temperatures of the order of 2500 F on the inner side of the liner and temperatures of the order of 700 F on the outer side of the liner. The pressure differential across these windows is expected to be negligible. The windows on the combustor housing need to be designed to sustain a temperature gradient of about 700 F and a pressure gradient of 17 atmospheres

In addition to the mechanical design constraints, the windows should provide minimal loss of laser power. Typically using quartz windows results in at least a 4% loss of laser power. However in a combustion environment, the windows will be subjected to increased fouling that could significantly increase the loss in power of the transmitted laser pulse. Under extreme circumstances the fouling could completely block the optical access. Therefore, proper window purging designs need to be developed that would keep the windows clean.

3.2 Optical Focusing

Figure 3.2 Impact of lens focal length on the initial spark energy density

Since the miniaturized laser being developed by LANL does not include the focusing lens, suitable focusing lenses must be designed to fit in the combustor housing. In some applications, the focusing lens can additionally serve as the window. Important considerations for the lens include the diameter and focal length. As the lens diameter decreases, the power per unit area (power density) seen by the lens increases and, there is a maximum laser power density level that the lens can safely sustain. Increases in spark energy density beyond this limit typically results in pitting and destruction of the lens coating, rendering the lens unusable. Focal length is also an important consideration. With longer focal length lenses, the initial breakdown of the air becomes increasingly difficult because longer focal lengths result in increase of the effective volume of the focal area. This is illustrated in Figure 3.2. Very small focal lengths require very thick lenses. Increase in lens thickness, increases the transmission losses. However, there is typically a broad range

of focal lengths between the two extremes where excellent laser generated sparks have been generated. For the Taurus 60 combustor application considered in this program lens focal lengths in the range of 1.5" to 5.3" are expected to produce reasonable results.

3.3 Laser Combustor Plenum Adapter Design

Figure 3.3 The JTAGG III rig laser ignitor installation (comparable in complexity to Taurus)

Figure 3.4 Adapters with Corresponding Sparks

Figure 3.3 shows the design of an adapter that has been used to attach a laser ignitor to a typical combustor rig. The adapter is designed to hold the laser tube over the plenum installation boss. Implementation of this system into either a can or annular combustion rig at Solar was planned for next year. *Figure 3.3* also provides a schematic description of how this would be achieved in a combustor rig that is as complex as the Taurus 60 engine.

In previous development programs LANL had developed four different adapters that accommodated a range of focal lengths. The range of focal lengths was selected to provide the capability to place the spark in the combustor at locations from near the inner liner wall to the outer liner wall. Focal lengths of the lenses (corresponding to the distance of the spark from the outer liner wall) were 1.4, 2.9, 3.8, and 5.1 in. An image of each adapter and the corresponding spark projection is shown in *Figure 3.4*.

4. Conclusions

LES combustor calculations were performed to determine the effect of laser pulsing on combustion oscillation damping and flame stabilization. The predicted laser pulsing did damp instabilities by 30 %, but the simulated laser energy source required

- Laser energy levels that were ten times greater than commercially available lasers
- The assumption that all the laser pulse energy coupled with the plasma generation process.

In reality only 10 % to 17% of the laser energy gets utilized for plasma generation. Pulsing in the high-speed reactant stream with the actual laser energy did not allow ignition and propagation of the plasma kernel and thus did not damp instabilities. LES of laser pulsing was shown to be effective at igniting ultra-lean ($\text{PHI}=0.4$) mixtures when used with proper plasma placement and a LP pilot injector only if all the energy from commercially available lasers was utilized in the plasma generation process.

Atmospheric tests were conducted to evaluate the viability of the laser stabilized combustion process for gas turbines. The results indicated that it was not feasible to reduce the flammability limit of swirl stabilized flames under gas turbine operating conditions using the laser assisted flame stabilization process. Further the pulsing of the laser sparks failed to control combustion induced pressure oscillations.

Based on the experimental and computational work done during this program it is concluded that given the present state of understanding of the plasma generation and decay process and the capability of commercially available lasers it is not possible to enhance the lean stability of swirl stabilized flames seen in industrial gas turbines. It is hoped that with advancement of the laser technology and better understanding of the plasma generation and decay process it will be possible in the future to successfully implement this concept in industrial gas turbines.

5. References

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