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The Role of Reactant Unmixedness, Strain Rate, and Length Scale on Premixed Combustor Performance

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Introduction

Lean premixed combustion provides a means to reduce pollutant formation and increase combustion efficiency (Sattelmayer et al., 1990). However, fuel-air mixing is rarely uniform in space and time. This nonuniformity in concentration will lead to relative increases in pollutant formation and decreases in combustion efficiency. The nonuniformity of the concentration at the exit of the premixer has been defined by Lyons (1981) as the “unmixedness.” Although turbulence properties such as length scales and strain rate are known to effect unmixedness, the exact relationship is unknown. Evaluating this relationship and the effect of unmixedness in premixed combustion on pollutant formation and combustion efficiency are important parts of the overall goal of US Department of Energy’s Advanced Turbine Systems (ATS) program and are among the goals of the program described herein. The information obtained from ATS is intended to help to develop and commercialize gas turbines which have (1) a wide range of operation/stability, (2) a minimal amount of pollutant formation, and (3) high combustion efficiency. Specifically, with regard to pollutants, the goals are to reduce the NOx emissions by at least 10%, obtain less than 20 PPM of both CO and UHC, and increase the combustion efficiency by 5%.

Objectives

The contributions to the program which the University of California (Irvine) Combustion Lab (UCICL) will provide are: (1) establish the relationship of inlet unmixedness, length scales, and mean strain rate to performance, (2) determine the optimal levels of inlet unmixedness, length scales, and mean strain rates to maximize combustor performance, and (3) identify efficient premixing methods for achieving the necessary inlet conditions.

To understand unmixedness, the initial part of the program addresses the definition and measurement of unmixedness. The heart of the program is anchored on three experiments -- one to study premixing strategies; a second controlled study to address the effect of unmixedness, turbulent length scale, and turbulent strain rate on mixing and pollutant formation; and a third to
study the effect of premixing strategies on combustor performance.

Background

Oxides of nitrogen (NO\textsubscript{x}) refer to nitric oxide (NO) and nitrogen dioxide (NO\textsubscript{2}). Air quality is significantly impacted by NO\textsubscript{x} emissions since they directly or indirectly affect concentrations of nitrogen dioxide (NO\textsubscript{2}), inhalable particulate (PM10) and photochemical oxidant (including ozone and peroxyacylnitrates). Furthermore, the NO\textsubscript{2} and PM10 formed from the emission of NO\textsubscript{x} decrease visibility and lead to nitric acid deposition. Concerns have been expressed about the potential adverse health effects of other nitrogen compounds, such as nitrosamines, and nitrous oxide (N\textsubscript{2}O).

Several strategies are available for reducing NO\textsubscript{x} emissions from gas turbines. Most notable are selective catalytic reduction (SCR), exhaust gas recirculation (EGR), steam injection, and retrofitting with low-NO\textsubscript{x} combustors (LNC). The key to these low-NO\textsubscript{x} combustors is either a combination of staged combustion air and staged fuel or partially premixing the fuel and air. The level or degree of premixing required to effectively manage a low-NO\textsubscript{x} combustor is still to be determined. Specifically, the local fuel-air unmixedness inside the premixer and inside the combustor will affect the combustor's performance and, therefore, the effectiveness.

In a practical gas turbine, the fuel-air mixing is rarely uniform in time or space. Consequently, large deviations (i.e., fluctuations) about the mean local temperature can occur as packets of various mixtures of fuel and air pass through a point in space inside the combustor. These variations are not only observable as fluctuations in the flame luminosity; they also play a significant role in the generation of NO\textsubscript{x}. Decreasing the amplitude of the temperature has been shown in simulations to have a significant effect on NO\textsubscript{x} production. Understanding how to control the local turbulence to optimize the local unmixedness will aid in the design of more effective and less bulky fuel-air premixers.

Unmixedness is a quantity which is used to indicate, in a statistical sense, the degree of mixing of fuel and air at the molecular level. In a given system in which two or more streams of miscible fluids are mixing, a specific level of molecular unmixedness (grain size of fuel-and-rich parcels of fluid) depends on initial length scales, initial distribution of fuel-rich and air-rich parcels of fluid, the mean strain rate field, and the characteristics of the turbulent field (e.g., the intensity, the large structure, the degree of anisotropy, etc.). Two means are most frequently used to determine the statistical measure of unmixedness. Lyons (1981) introduces one which also requires the definition of the area averaged equivalence ratio, $\overline{\Phi}$, across the profile of the flow which in her case is a pipe of radius $r$. Thus:

$$\overline{\Phi} = \frac{\int_0^{r_{\text{int}}} \Phi_i r \, dr}{\int_0^{r_{\text{int}}} r \, dr}$$

where $\Phi_i$ is the equivalence ratio at a particular radial location. Using this value for the area averaged equivalence ratio, an area averaged measure of unmixedness, $S$, can be defined as the area averaged standard deviation. This standard deviation can be expressed as follows:

$$S = \sqrt{\frac{\int_0^{r_{\text{int}}} (\Phi_i - \overline{\Phi})^2 r \, dr}{\int_0^{r_{\text{int}}} r \, dr}}$$
The second measure of unmixedness (cited by Fric, 1992) is developed by considering temporal fluctuations in the fuel concentration. The level of unmixedness, \( U \), at a particular position in the flow can be defined as a function of the mean fuel concentration, \( \overline{C} \), at a location and the variance fluctuation about the mean, \( C^2 \), as:

\[
U = \frac{C^2}{\overline{C}(1-\overline{C})}
\]

This equation provides a statistical measure of the unmixedness due to temporal fluctuations while the preceding equation provides a measure of the unmixedness due to spatial variation. Both of these equations are representative of the unmixedness in a statistical sense. However, neither of these equations indicate the flow structure that leads to a particular value of unmixedness. For example, the same unmixedness could be obtained with a small number of large fuel- and air-rich eddies or a large number of smaller fuel- and air-rich eddies. Thus a complete determination of the unmixedness requires not only a statistical measure of the unmixedness but also a structural measure of the unmixedness, i.e., a measure of the statistical distribution of the length scales of fuel rich and air rich regions.

The structural measure of unmixedness can be obtained by first, forming indicator functions from the concentration signal and second determining the distribution of the length scales of fuel-rich and air-rich fluid parcels from those indicator functions. (Indicator functions are signals that have either zero or unity values depending on whether the concentration signals are, respectively, above or below a selected threshold.

Project Description

Although lean premixed combustion does lead to reduced production of NO\(_x\), and increased efficiency of gas turbine combustors, the minimal unmixedness required to achieve adequate combustor performance, or the point at which further mixing is ineffective are unknown. Thus, a relationship that describes combustor emissions and efficiency as a function of unmixedness is required. Specifically, since turbulence properties such as length scales, mean strain rate and other turbulent properties are known to effect unmixedness, the goals of this study are to determine this relationship and then use the results of this study to optimize the performance of gas turbine combustors.

Mixing devices and turbulence measurement techniques will be used to obtain spatial and temporal unmixedness, as defined in the background section, for a wide range of initial fuel and air length scales and mean strain rates and intensities. With unmixedness quantified with respect to the turbulence properties, these properties can be used within premixed systems to control unmixedness. The data obtained from experiments within these reacting systems will be used to determine a relationship between unmixedness and combustor performance (efficiency, pollutant formation, stability, lean blow-out).

Approach

The program has three objectives:

- Establish the relationship of inlet unmixedness (spatial and temporal), length scales, turbulent intensity, and mean strain rate to combustor performance (i.e. emissions and combustor efficiency).
- Determine the optimal levels of inlet unmixedness, length scales, turbulent intensity, and mean strain rates to maximize combustor performance.
• Identify efficient premixing methods for achieving the necessary inlet conditions.

These three objectives are directly related.

Previous Work

During the last reporting period, the UCI program focused on obtaining industrial input, constructing mixing and combustion test fixtures and obtaining stabilized reactions. Controllable premixers were designed for both reacting and non-reacting studies that allow adjustment in mixedness, length scales, turbulent intensity and mean strain rate. Test protocols and time lines were established to assure that the main goals of the project were met. Fundamental experiments were developed that provide basic isolated information on the mixing process. These experiments will act as "bridges" between the research oriented premixer and combustor tests and practical industrial designs.

Present Work

The program during this reporting period is focused on developing a means to measure and qualify different degrees of temporal and spatial unmixedness. Laser diagnostic methods for planar unmixedness measurements are being developed and preliminary results are presented herein. These results will be used to 1), aid in the design of experimental premixers, and 2), determine the unmixedness which will be correlated with the emissions of the combustor. This measure of unmixedness coupled with length scale, strain rate and intensity information is required to attain the UCI goals.

Premixer Description

For this development period, a single premixer design has been the focus. Its basic structure is a jet-grid tube array. Figure 1. shows the location of the premixer in the axial can combustor used in the present study. The premixer consists of 33 individually adjustable fuel tubes which are 0.085 in. and are positioned circumferentially on three different diameters. The air passes through 33 0.219 inch holes which are placed between the fuel tubes.

![Figure 1. Schematic of premixer](image)

Variable Premixing Length

Mesh Option

Fuel Injection tubes

Mixedness, with this premixer can be controlled by adjusting the length, and therefore time, between the point of gas injection and the point of measurement. Likewise, length scale can be changed by either adding nozzles of various sizes to the independent fuel jets or by added grid meshes to the outlet plane of the air flow passages. Finally, mean strain rate can be controlled by adjusting the fuel flow rate out of the jets to produce velocity gradients. In this manner, either strain rate in the radial direction or strain rate in a azimuthal direction can be induced. Figure 2 is a photograph of the premixer.
Diagnostic Development

As mentioned in the background section, a measure of mixedness is key to this project. The inherent non-intrusive nature of laser diagnostics coupled with the ability to obtain planer information makes Planer Laser Induced Fluorescence (PLIF) the most attractive candidate at this time. During this reporting period, UCI has been developing a PLIF capability. For these initial non-reacting studies, acetone was selected as the fluorescing seed. A schematic of the setup can be seen in Fig. 3. The laser used is a frequency quadrupled YAG that generates the required 266 nm wavelength necessary for acetone to fluoresce.

For the tests presented in this paper, a 200 μm by 20 mm laser sheet was generated using a cylindrical lens and placed at the exit of the premixer, just prior to the swirl vane location. The photograph shown in Fig. 4 shows the PLIF system in operation.

A CCD camera was used to collect the data images. For these initial mixing tests, the sheet was purposely sized to not cover the entire output plane so that the laser power would remain fairly high. Figure 5 is an example image. The fluorescing portion of the image shows a relatively
uniform output from the premixer. The laser sheet will be expanded for further tests such that overall fluid structures can be visualized and studied.

Figure 5. CCD Image of the PLIF Output

Fundamental Experiment

The purpose of this experiment was to access the strain effect of swirl vanes. To simplify the test conditions and to isolate the strain effects, straight vanes (plates) were used. A test facility was constructed to generate an initially low level of turbulence (RMS). A grid was then added to the system to generate a fixed, controlled RMS level at a specific test location. At this location, parallel plates were placed (Fig. 6).

Figure 6. Photograph of Parallel Vanes

Velocity and RMS profiles were measured at the exit of the vanes. The finding are shown in Fig. 7. As expected, the RMS levels are high near the plate boundaries. One key finding is the decrease in RMS in the center region of the flow. This shows that the structure of the flow is altered by these vanes even though no swirl has been added and even though they are very short in length (0.5 inches). The significant observation is that the swirl vanes have an influence on the entire flow.

Figure 7. Results of the Plate Experiment
Future Activities

Below is a brief description of the plans for the immediate future plans for the program.

Facility Design and Development

Premixer and Combustor Hardware will be fabricated as needed. Emphasis will be placed on the design of the model combustor hardware for the elevated pressure, and elevated temperature experiments.

Experimental Studies

For the premixer studies, experiments will be conducted using temperature as a scalar indicator and thermocouples/cold-wires as the measurement sensors. In addition, a specially designed concentration probe will be used as a measurement technique for mixedness. Substantial emphasis will be placed on the already initiated PLIF diagnostics (described in this report) for non-intrusive mixedness measurements. Overall, attention will address the effect of premixing mixedness length scale, and on the control of premixing to establish specified mixedness and length scale characteristics at the premixer exit plane. The effort will continue to “hand-shake” with the model combustor studies.

The model combustor studies will focus on the effect of inlet conditions (mixedness and length scale) on combustor performance. Air preheat will be provided in the atmospheric test facility to more effectively simulate the practical environment for NOx production. In-situ measurements of composition and temperature using physical probes will be complemented with laser anemometry measurements for velocity, CARS measurements for temperature and PLIF measurements for mixedness.

Data Analysis

A major diagnostic to be added will be FLUENT modeling of both the premixer and the combustor. This will complement the experimental measurements, and facilitate the development of the mechanistic understanding required to reach the goals of the project. Design of Experiments will be extensively employed to provide both direction in the design of the experiments, as well as to serve as a tool for the interpretation of results.

Industrial Interaction

The first stage this task was completed and an industrial questionnaire was generated. Further progress was made through visits to Allison, GE and Westinghouse. These groups were specifically chosen given their background in industrial gas turbines. Industrial interaction was stressed during these visits by presenting the groups with UCICL’s progress and inviting comments or suggestions to the work. Also a questionnaire was distributed for feedback to determine practical issues or concerns that the groups might have. This enabled further design and development of the program to be involved with immediate issues that the industrial gas turbine groups face today. The trips proved to be very productive and also helped establish a rapport with the groups, that will help in contributing to research.

Individual contacts made with each of these industrial participants provide good opportunity to maintain technical exchange and receive industrial input. At Allison contact was established with Dr. Mohan Razdan, Chief of Combustion Research. UCICL’s point contact was identified to be Dr. Rahul Puri. At Westinghouse Corporation contact was established with the research group headed by Rick Antos. Our point contact was established to be Graydon
Whidden. At GE we established contact with Dr. Hukum Mongia, head of advanced combustion technology. Dr. Narendra Joshi will serve as our point contact. Current goals are to maintain a rapport with these individuals, keep them apprised of our progress, acquire and utilize input and comments.

The ATS internship program provided the opportunity for more industrial interaction. Three students from the UCI Combustion Laboratory were placed at Allied Signal, Solar Turbines and Pratt & Whitney, respectively and provided the experience and opportunity to be involved with current state of the art work being conducted in industry.

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References


