the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

# Turbulent Flame Propagation Characteristics of High Hydrogen Content Fuels—Georgia Institute of Technology

## Background

A fundamental problem influencing combustor design and operation of gas turbines is flame propagation characteristics of high hydrogen content (HHC) fuels. In this project, Georgia Institute of Technology (Georgia Tech) will obtain data and develop models of the turbulent burning rate of HHC fuels at realistic conditions and in inhomogeneous conditions such as in premixer nozzle boundary layers and core flows.

This project was competitively selected under the University Turbine Systems Research (UTSR) program that permits academic research and student fellowships between participating universities and gas turbine manufacturers. Both are managed by the Department of Energy (DOE) National Energy Technology Laboratory (NETL). NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of these technologies to achieve power production from HHC fuels derived from coal that is clean, efficient, and cost-effective, minimizes carbon dioxide ($CO_2$) emissions; and will help maintain the nation's leadership in the export of gas turbine equipment.

## Project Description

This work will improve the state-of-the-art understanding of turbulent flame propagation characteristics of HHC fuels. The turbulent flame speed has a leading order influence on important combustor performance metrics such as flashback and blow-off propensities, emissions, life of hot section components, and combustion instabilities limits, including operating limits required to prevent harmful combustion dynamics. This research specifically addresses three of the combustion topic areas identified by DOE as of great importance for HHC systems: (1) turbulent burning velocities, (2) flashback, and (3) exhaust gas recirculation (EGR) impacts. The results of this effort will also enable advances in several other combustion topic areas; e.g., predicting combustion dynamics (which requires flame shape predictions) and improving large eddy simulation capabilities by providing turbulent burning rate sub-models for HHC fuels.

The project involves both experimental and modeling efforts. Prior work used optical flame emission in measurement of global turbulent consumption speeds of hydrogen ($H_2$)/carbon monoxide (CO) fuels. For this project, researchers will extend these previous efforts to a broader reactant class, including mixtures diluted with $CO_2$, water ($H_2O$),



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## PARTNERS

None

## PROJECT DURATION

| **Start Date** | **End Date** |
|---|---|
| 10/01/2010 | 09/30/2013 |

## COST

**Total Project Value**
$505,616

**DOE/Non-DOE Share**
$404,404/$101,212

## AWARD NUMBER

FE0004555

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and nitrogen ($N_2$). Depending upon the degree of dilution, these mixtures will simulate both gasified fuel blends and systems with EGR. This data will be used to further the development of physics-based, mixture-dependent models of turbulent burning rates and to guide selection of conditions for determining more localized measurements of turbulence/chemistry interactions. Specifically, high-repetition-rate particle image velocimetry and hydroxyl radical planar laser induced fluorescence systems will be used to determine local flame speeds under realistic turbulent conditions. This is necessary for developing an improved understanding of strained flame statistics, and for testing and refining propagation models based on leading point concepts. The work plan will initially focus on uniform, premixed reactant mixtures, and then expand in focus by investigating turbulent burning rates in inhomogeneous premixed flows. An example would be obtaining measurements of turbulent propagation speeds in mixtures with stratified fuel/air profiles.

## Goals and Objectives

The goal of this project is to improve the state-of-the-art understanding of turbulent flame propagation characteristics of HHC fuels. The current database of turbulent flame speed measurements will be extended to a broader reactant class that simulate both realistic HHC fuels as well as EGR situations at realistic gas turbine operating conditions. Models of turbulent burning rates in realistic flows will be developed through experimental and theoretical means. Turbulent propagation in spatially inhomogenous fuel/air mixtures will be characterized. Project objectives are as follows:

- Extend the existing data sets of turbulent flame speed measurements to a broader reactant class that is more representative of HHC fuels, such as mixtures diluted with $CO_2$, $H_2O$, and $N_2$, at realistic pressures, temperatures, and turbulence intensities. Depending upon the degree of dilution, these mixtures will simulate both gasified fuel blends and systems with extensive leels of EGR. The team will obtain measurements of global consumption speeds using the Bunsen burner and local displacement speeds using the low swirl burner (LSB) at realistic gas turbine conditions.

- Develop physics-based models of turbulent burning rates in realistic flows through both experimental and theoretical tasks. Experimentally, the team will obtain localized turbulence/chemistry interaction measurements using high-repetition-rate particle image velocimetry and hydroxyl radical planar laser induced fluorescence in the LSB configuration. This data will provide local characterization of instantaneous flame properties such as flame strain rate, flow fields, and burning rates, as well as time-averaged characteristics such as local turbulent displacement speed. These data can be used as both inputs to and validation of turbulent flame models. This work will be supported by parallel level set computations that will show how to relate the strained flame characteristics of the leading points of the turbulent flame brush to its turbulent burning rate.

- Characterize the turbulent burning rates in inhomogeneous flows. Specifically, the team will obtain measurements of turbulent propagation speeds in mixtures with stratified fuel/air profiles. Such data will be useful for extending turbulent flame speed data toward prediction of flashback in premixing nozzles, which have highly inhomogeneous flows and fuel/air ratio profiles.

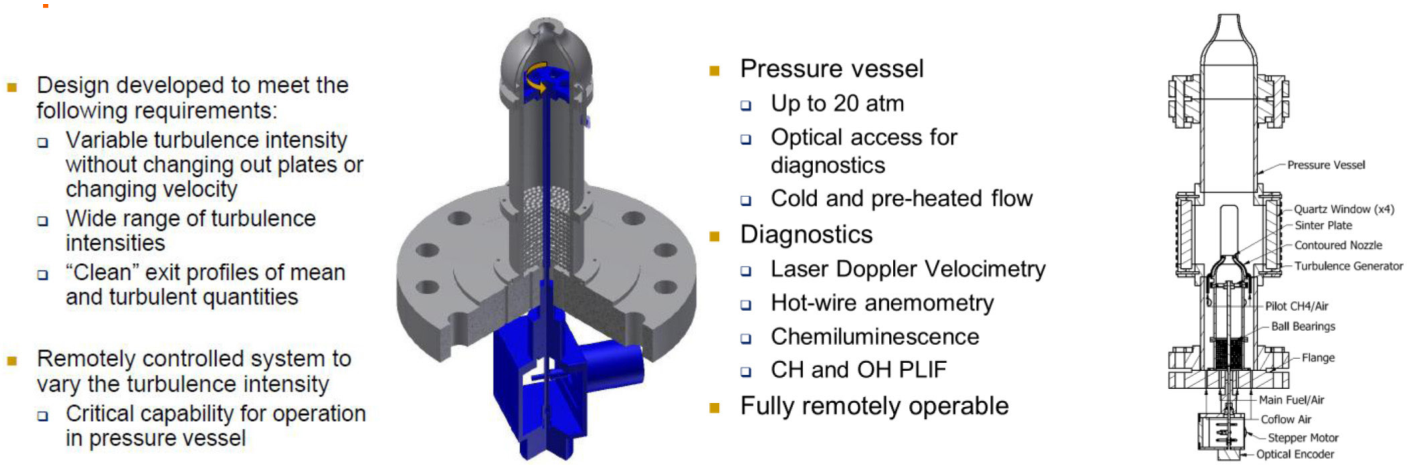


*Figure 1. Features of the Variable Turbulence Generator (left) and High Pressure Test Facility (right) showing the installation of the variable turbulence generator and advanced diagnostics.*

## Accomplishments

- Constructed a remotely operable high pressure test facility that will house the Bunsen burner and LSB nozzles.
- Installed a new fuel flow metering and control system, which allows for fuel compositions to be varied quickly during testing.
- Obtained global turbulent consumption speed data at 5 and 10 atmospheres (atm) for mean flow velocities ranging from 20–50 meters per second (m/s) and $H_2$/CO ratios of 30/70 to 90/10 by volume while investigating a wide range (5–30) of turbulence intensities.
- Performed cold flow velocity field characterization of the Bunsen burner for pressures and mean flow velocities of 1-20 atm and 10-50 m/s, respectively, using laser Doppler velocimetry (LDV).
- Performed extensive strain sensitivity calculations to investigate various parametric dependencies of key stretched flame quantities such as the maximum stretched laminar flame speed and the Markstein length.
- Acquired local displacement speed data at atmospheric conditions for mean flow velocities of 30 and 50 m/s and $H_2$/CO ratios from 50/50 to 100/0 by volume over a wide range of turbulence intensities using the LSB.
- Analyzed characteristics of the turbulent flame brush from flame images acquired in the Bunsen burner over a wide range of fuel compositions and pressures ranging from 1-10 atm. Investigated sensitivities of the flame brush thickness to turbulence intensity, pressure, and fuel composition.
- Calculated curvature statistics of LSB $H_2$/CO data from Mie scattering images obtained from high speed particle image velocimetry (PIV) experiments. Curvature measurements were also conditioned on the leading points of the turbulent flame front in order to better understand leading point characteristics with changing fuel composition and turbulence intensity.

## Benefits

This UTSR project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. This work will improve the reliability of gas turbines, decrease the cost of turbines, and develop predictive tools for utilizing HHC fuels. It will also advance the understanding of turbulent flame propagation characteristics of HHC fuels, including developing physics-based scaling and analyses to predict turbulent flame speed dependencies across broad fuel composition ranges that would be very useful to gas turbine designers.

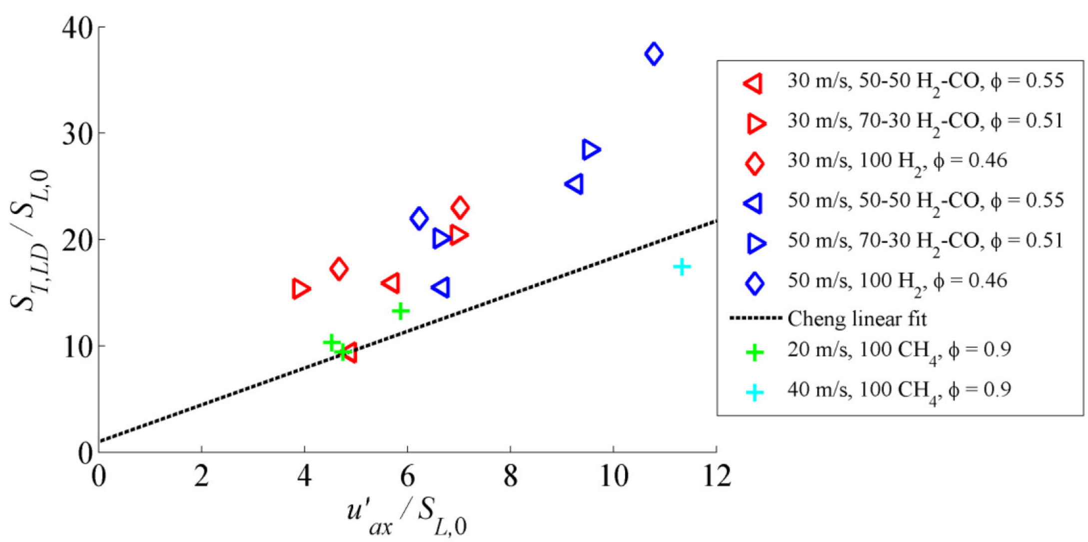


*Figure 2. Variations of the turbulent local displacement speed, $S_{T,LD}$, with axial turbulence intensity, $u'_{ax}$, normalized by $S_{L,0}$ for $CH_4$ and $H_2$/CO cases at STP. The plotted line is a previous correlation from the literature.*

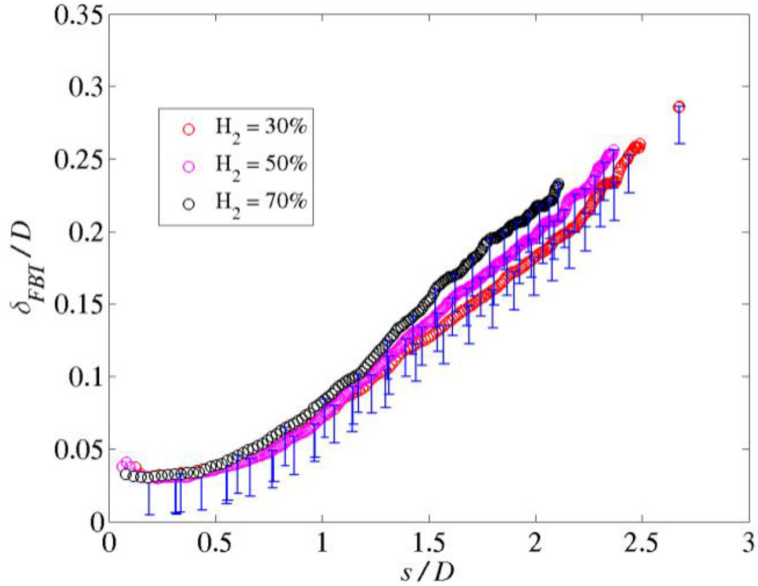


*Figure 3. Variation of flame brush thickness as a function of the flame coordinate for various $H_2$/CO ratios whose mixture $S_{L,0}$ has been held fixed. Measurements shown are for the 12 mm diameter burner at $u'_{rms}/S_{L,0}$ = 17.4*

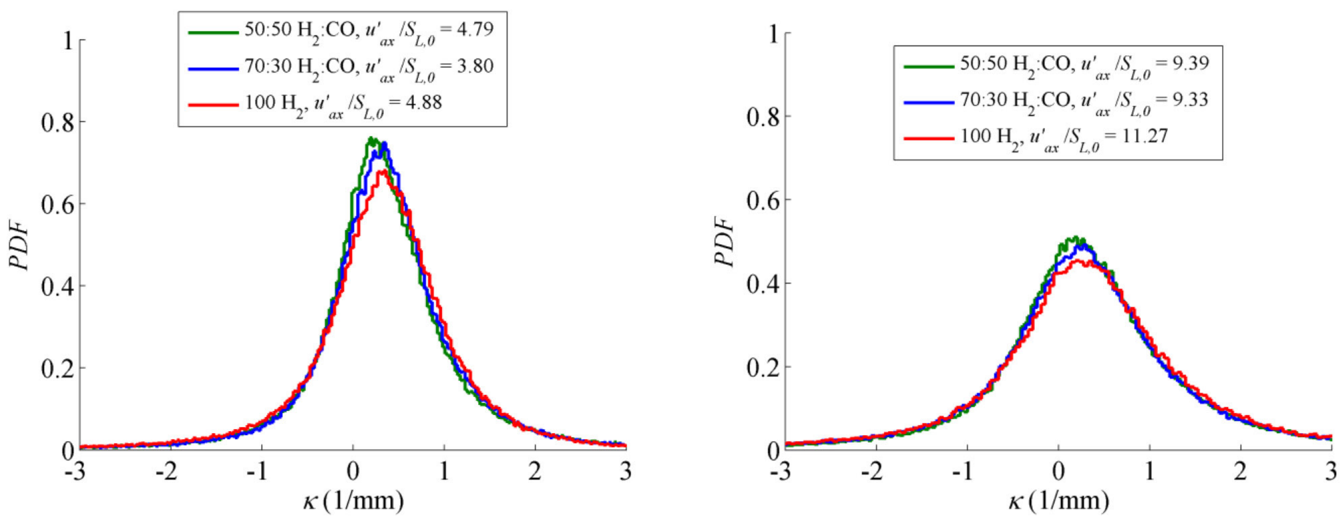


*Figure 4. Flame brush leading point ($0 \leq \langle c \rangle \leq 0.1$) curvature PDFs for varying fuel compositions at (left) $U_0$ = 30 m/s and (right) $U_0$ = 50 m/s.*