Combustion Instability and Blowout Characteristics of Fuel Flexible Gas Turbine Combustors

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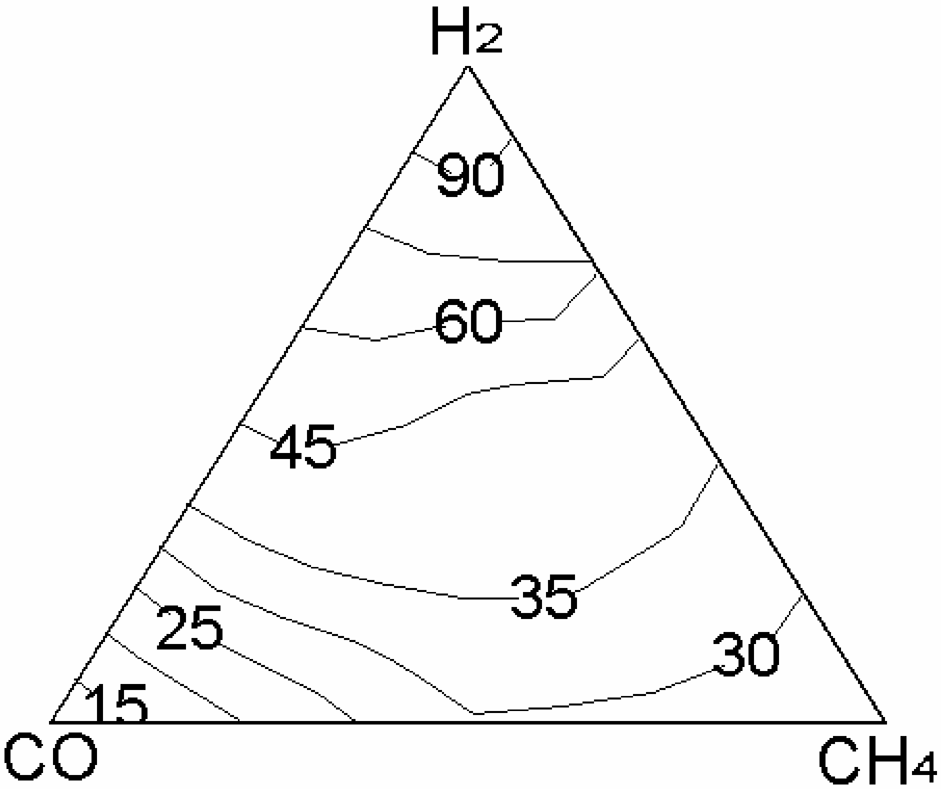
Gas Turbine Need

- ***Need:*** **Gas turbines with sufficient flexibility to cleanly and efficiently combust a wide range of fuels, particularly coal-derived gases**
  - *Problem:* Inherent variability in composition and heating value of coal-derived and other alternative fuels provides significant barriers towards their usage

- ***Need:*** **Combustion systems that can stably operate over a wide turndown range**
  - *Problem*: Combustion instabilities and blowout have been key problems encountered by gas turbines, severely limiting their turndown, restricting maximum power output, increasing unplanned outages, and increasing maintenance costs.

Example: Fuel Composition Effects on Flame Speed

(at Fixed Flame Temperature)



S_L (cm/s) at T_{ad}=2000 K

Project Objectives

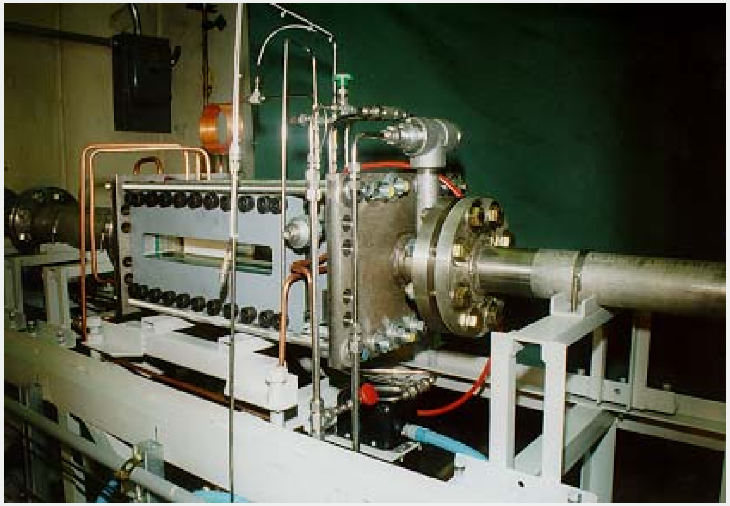
- **Analyze Static Stability Characteristics**
  - Objective: Reducing blowout events, thereby increasing turbine availability
  - Determine key variables that represent effects of fuel compositions and mechanisms that describe lean blowout
    - i.e., develop methodology such that for a given a combustor stability map for one fuel, results for arbitrary fuel compositions can be predicted

Project Approach

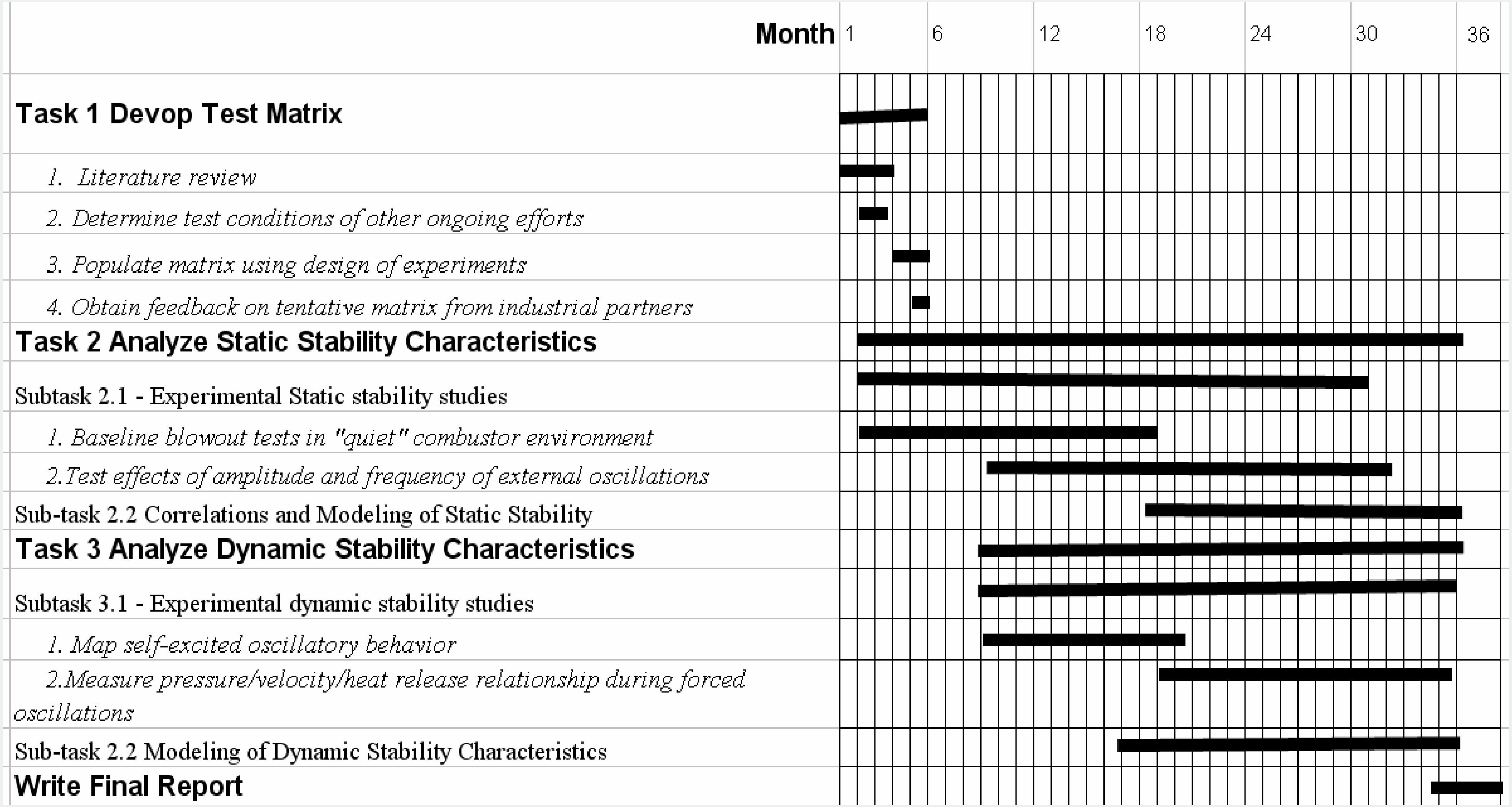
- **Task 1:**
  - Determine fuel compositions in various IGCC, landfill, process gas plants
  - Determine test conditions of other ongoing efforts
  - Statistical design of experiments
  - Obtain input from industry

- **Tasks 2 and 3**
  - Characterize fuel composition, dynamics effects upon blowout (Task 2) and pulsations amplitude (Task 3) conditions
  - Correlate results with chemical kinetics calculations
  - Communication with industrial partners

Combustor Testbed



Project Schedule



Task 1 Devop Test Matrix

1. *Literature review*
2. *Determine test conditions of other ongoing efforts*
3. *Populate matrix using design of experiments*
4. *Obtain feedback on tentative matrix from industrial partners*

Task 2 Analyze Static Stability Characteristics

Subtask 2.1 - Experimental Static stability studies

1. *Baseline blowout tests in "quiet" combustor environment*
2. *Test effects of amplitude and frequency of external oscillations*

Sub-task 2.2 Correlations and Modeling of Static Stability

Task 3 Analyze Dynamic Stability Characteristics

Subtask 3.1 - Experimental dynamic stability studies

1. *Map self-excited oscillatory behavior*
2. *Measure pressure/velocity/heat release relationship during forced oscillations*

Sub-task 2.2 Modeling of Dynamic Stability Characteristics

Write Final Report

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Accomplishments

- **High impact accomplishments to date:**
  - Determined key variables that capture fuel composition effects on lean blowout

- **Results are improving understanding of blowout in fuel flexible combustors**

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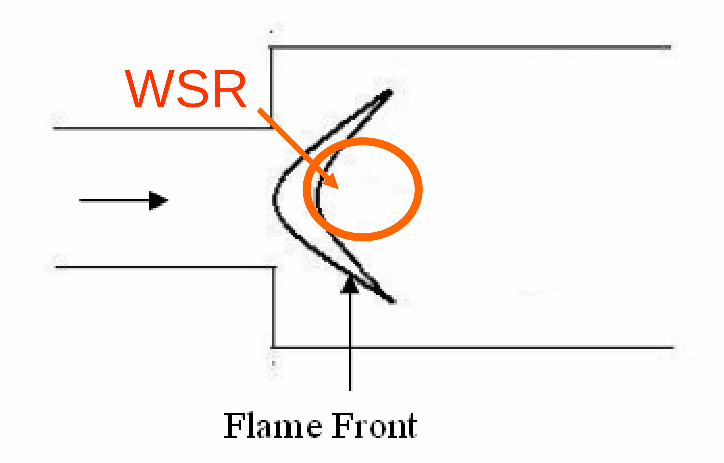
Blowout Studies

Well-Stirred Reactor Approaches

- **Blowoff occurs when chemical time is certain fraction of residence time**

$$\frac{\tau_{re}}{\tau_{chem}} = \frac{D/U_{ref}}{\tau_{chem}} = Da$$

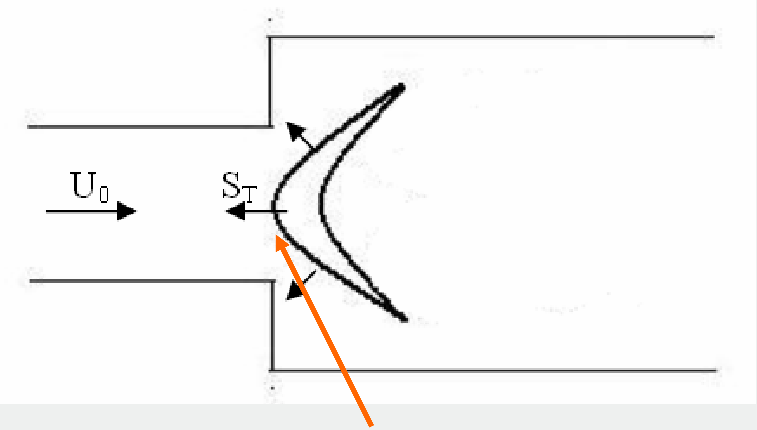


- **Chemical time**
  - Fuel composition
  - Flame temperature
- **Residence time**
  - Length scale?
  - Reference flow speed
  - U_0 or U_b are independent variables

Flamelet Propagation Model

- **Blowoff occurs when flame speed is every where less than flow speed**

$$\frac{S_T}{U_{ref}} = K_2$$



Flame Propagation

- **Turbulent Flame speed**
  - Fuel composition
  - Equivalence ratio, flame temperature
  - Turbulence intensity
- **Reference Velocity**
  - U_0 or U_b?

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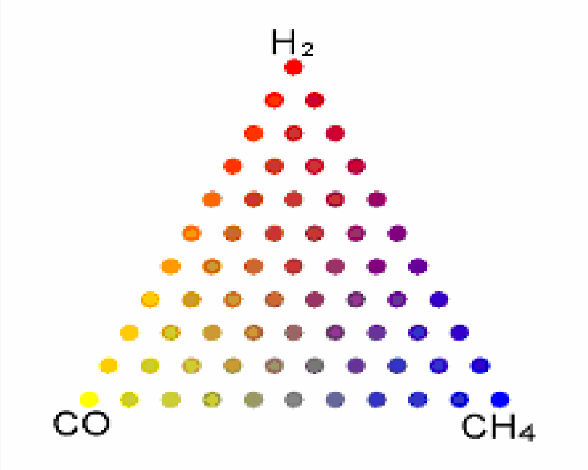
Experiment results

Test Matrix

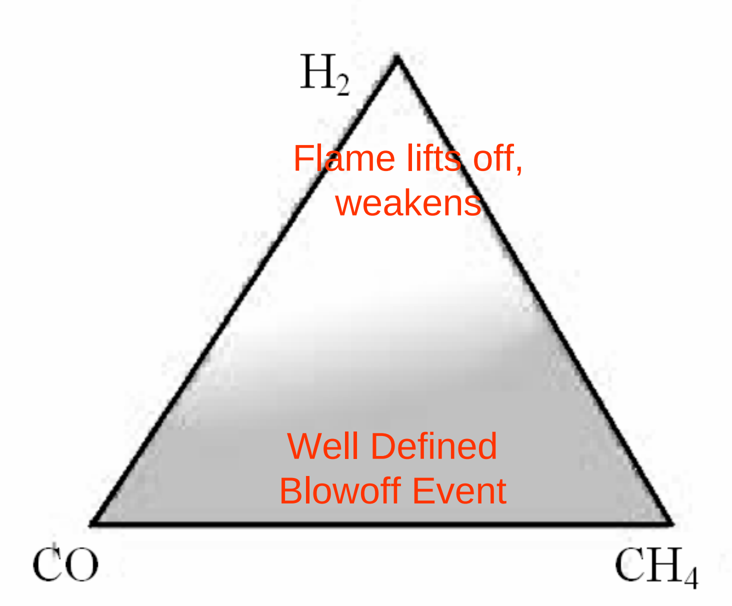
- **Three Fuels Used In Various Compositions:**
  - CH_4, H_2, and CO
- **Test Conditions:**
  - Premixer exit velocity~ 40-200 m/s (combustor unburned flow velocity: 4 - 20 m/s)
  - Pressure: 1 - 4.4 atm
  - Inlet Temperature: 70-390 °F (300 -390 K)
- **Test Procedure**
  - For each fuel composition, reduce mixture equivalence ratio (at constant U_0, T_i, and P) until the mixture blows off
  - Limited testing where T_{ad} or U_b were held constant

Color scheme

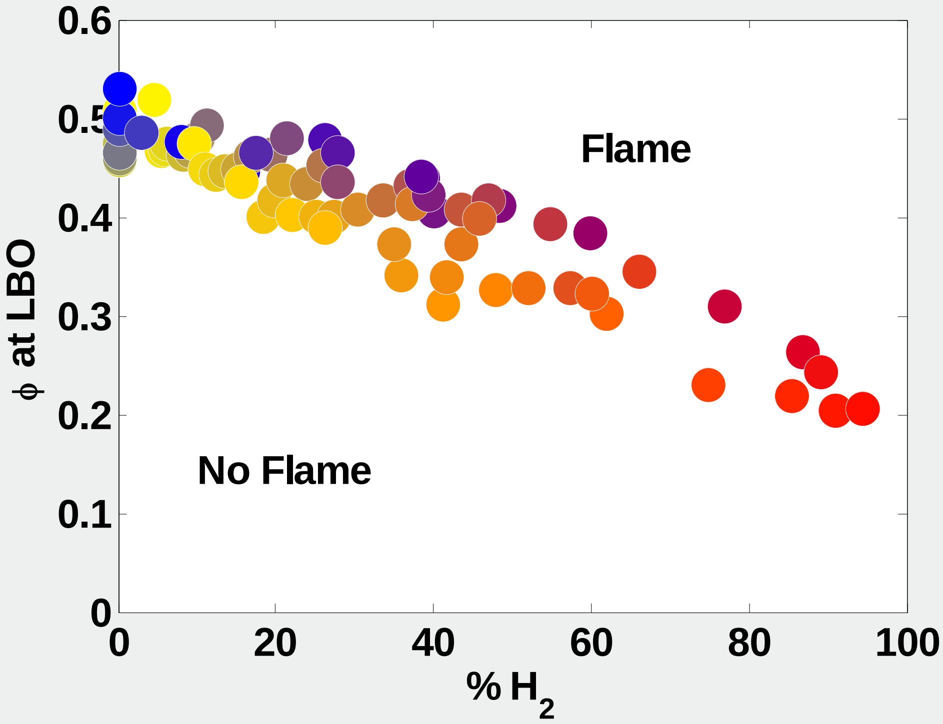


Blowoff Phenomenology

- **Well defined blowoff events occur at low H_2 mixtures**
- **At high H_2 mixtures, the flame would gradually liftoff and weaken; difficult to define specific "blowoff" point**
  - Blowoff defined in these cases as point where flame no longer visible in 4 inches test section

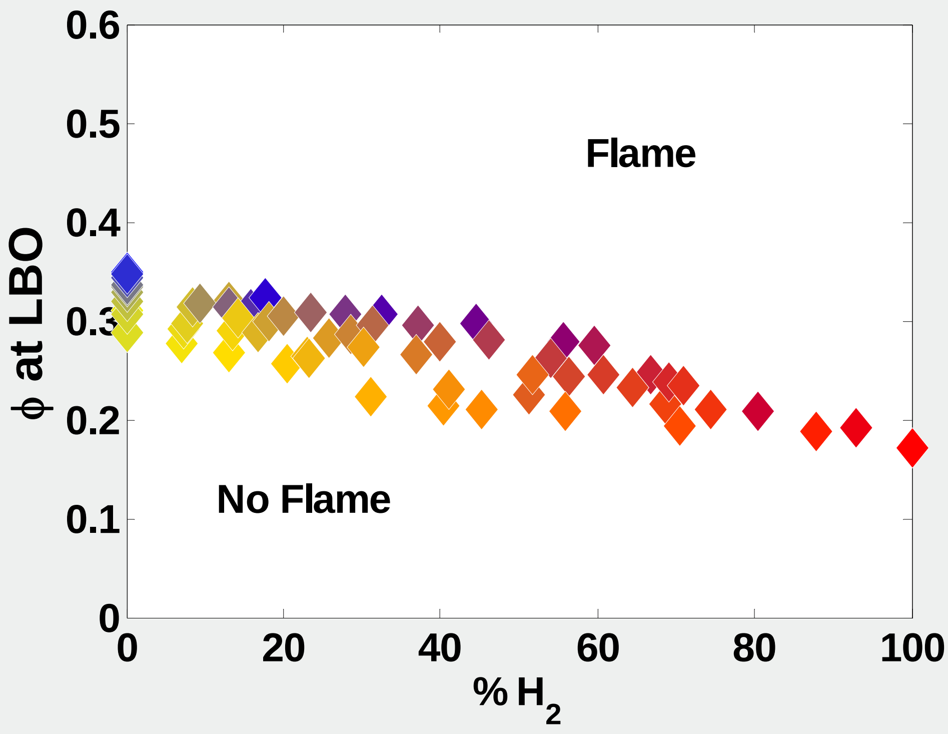


H_2 Addition Dominates Blowout Characteristics



- **Test conditions:**
  - U_0=6 m/s
  - T=300K
  - P=1.7atm
- **Monotonic reduction in blowoff equivalence ratio with increasing H_2 levels.**

H_2 Addition Dominates Blowout Characteristics



- **Conditions:**
  - U_0=6 m/s
  - T=460K
  - P=4.4atm,
- **In the same way, as H_2 levels increase, mixtures can be stabilized with lower**
  - Equivalence ratios
  - Flame temperatures
  - Flame speeds

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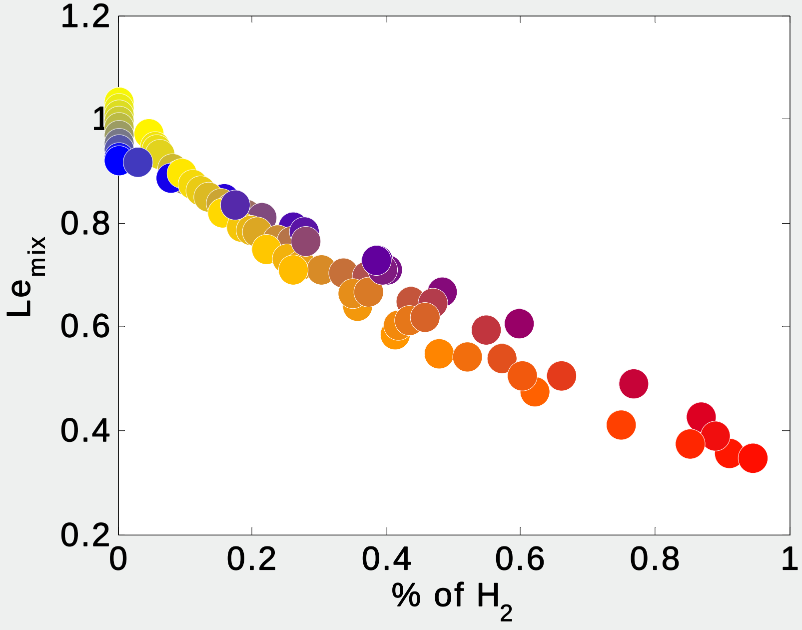
Need to be Careful in Correlating Data

- **Good correlations may not provide additional physics into blowout; e.g.,**
  - T_{ad} vs 2^*T_{ad}

- **Many meaningful parameters strongly correlated with H2 levels**
  - Le_{mix} at blowout vs $\%H_2$



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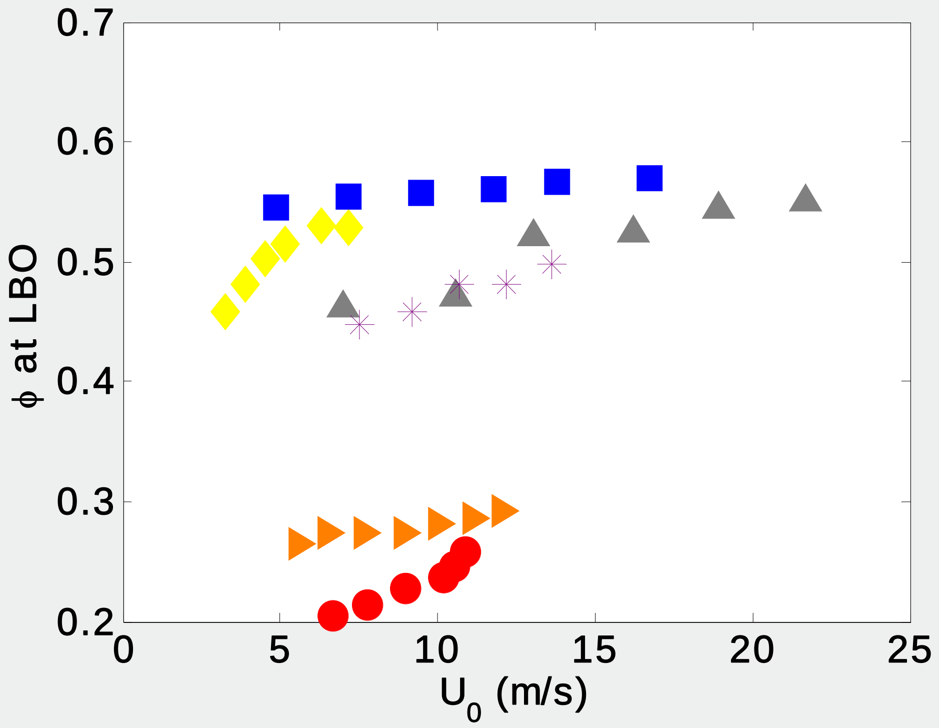
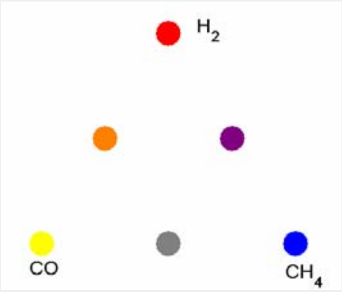
Flow Velocity Effects

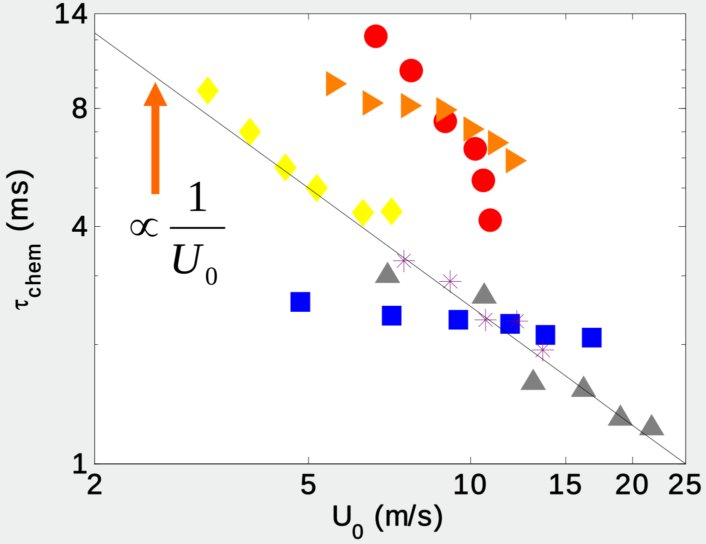


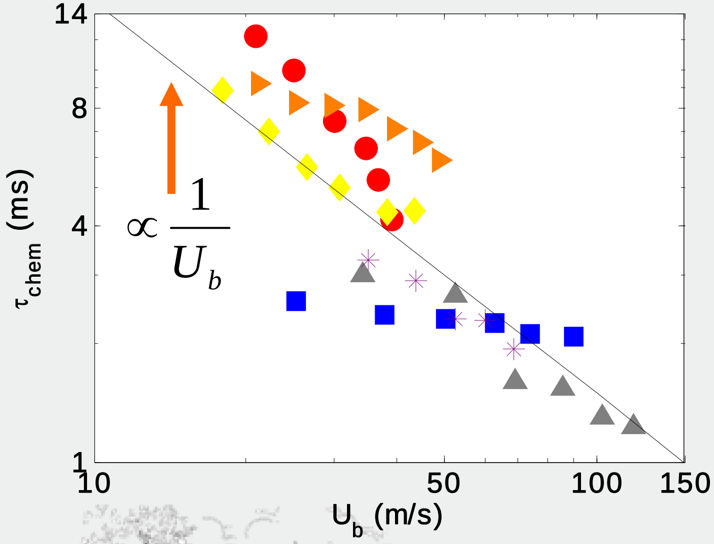
T= 300 K, P= 1.7 atm

- With a higher flow speed, flame blows off at higher equivalence ratio
- Different sensitivities to for speed



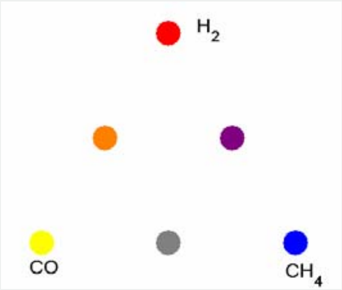
Reference Flow speed, U_0 or U_b ?



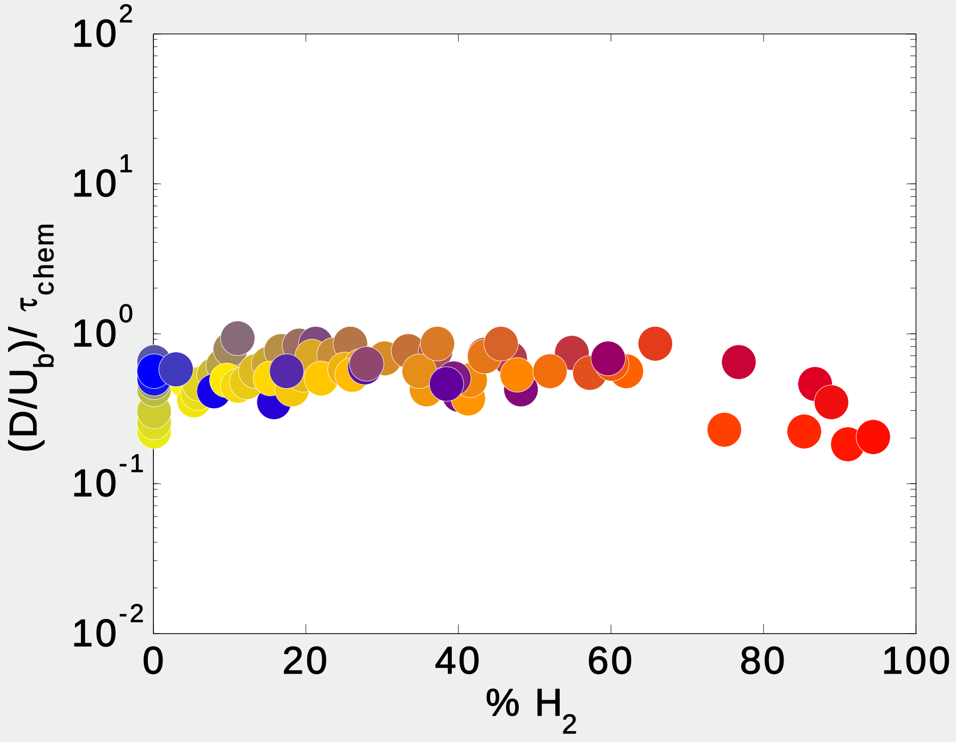


$$\frac{\tau_{re}}{\tau_{chem}} = \frac{D/U_{ref}}{\tau_{chem}} = Da$$

- **For each fuel, trends are reasonable**
  - Chemical time decreases with increasing flow speed
  - **U_b** provides a better correlation

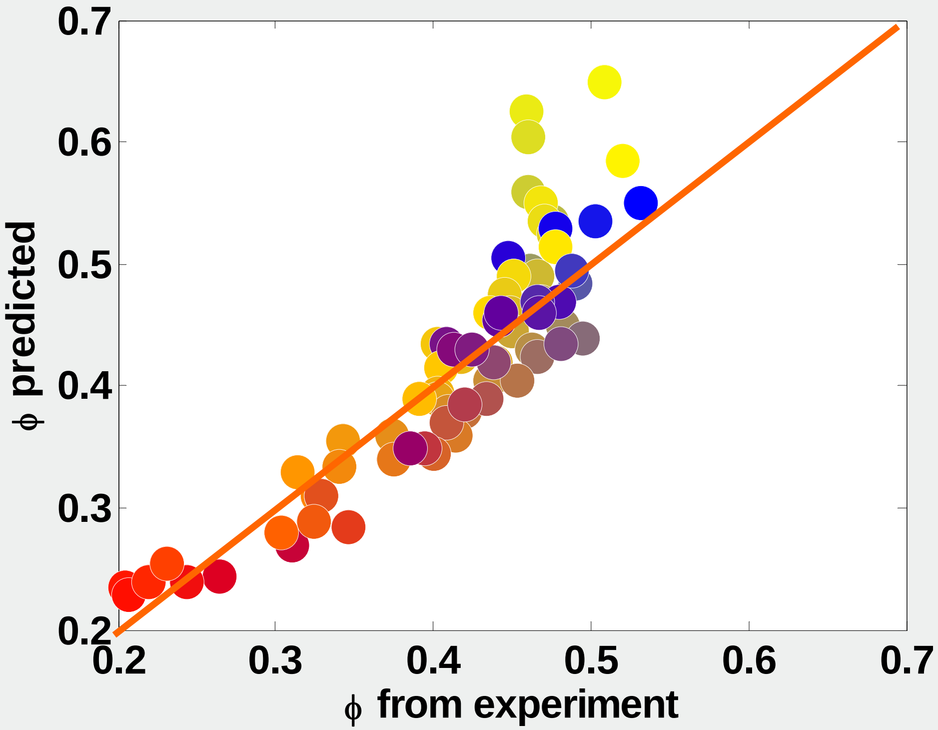


Damkohler # Correlation of LBO Data



- U_0=6 m/s, T=300K, P=1.7atm
- Blowoff occurs near Da=0.82.

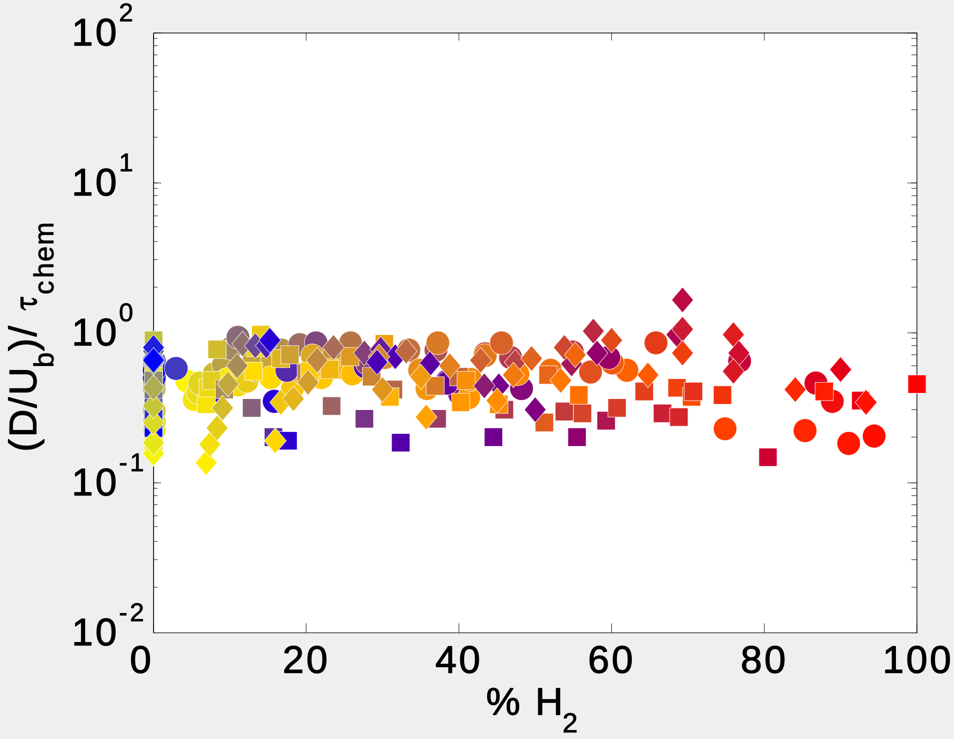
Accuracy of Blowout Prediction assuming Constant Damkohler # at LBO



$$Da = Da(\phi_{predict}) = 0.82$$

- **U_0=6 m/s, T=300K, P=1.7atm**

Damkohler # Correlation of all Data



- ● **Circle:**
  - U_0= 6 m/s,
  - T_i = 300 K
  - P= 1.7atm;
  - Da= 0.82
- ■ **Square:**
  - U_0= 6 m/s,
  - T_i = 460 K
  - P= 4.4atm;
  - Da= 0.39
- ◆ **Diamond:**
  - U_0= 4 m/s,
  - T_i = 300 K
  - P= 1.7atm;
  - Da= 0.56
- **Average Da at LBO**
  - Da=0.52 .

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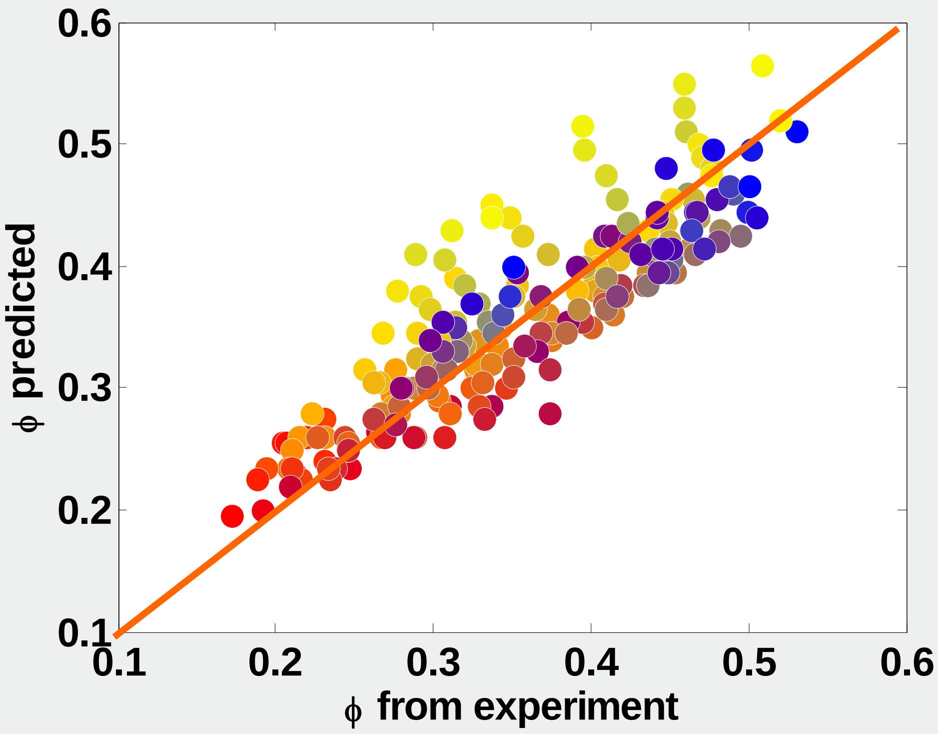
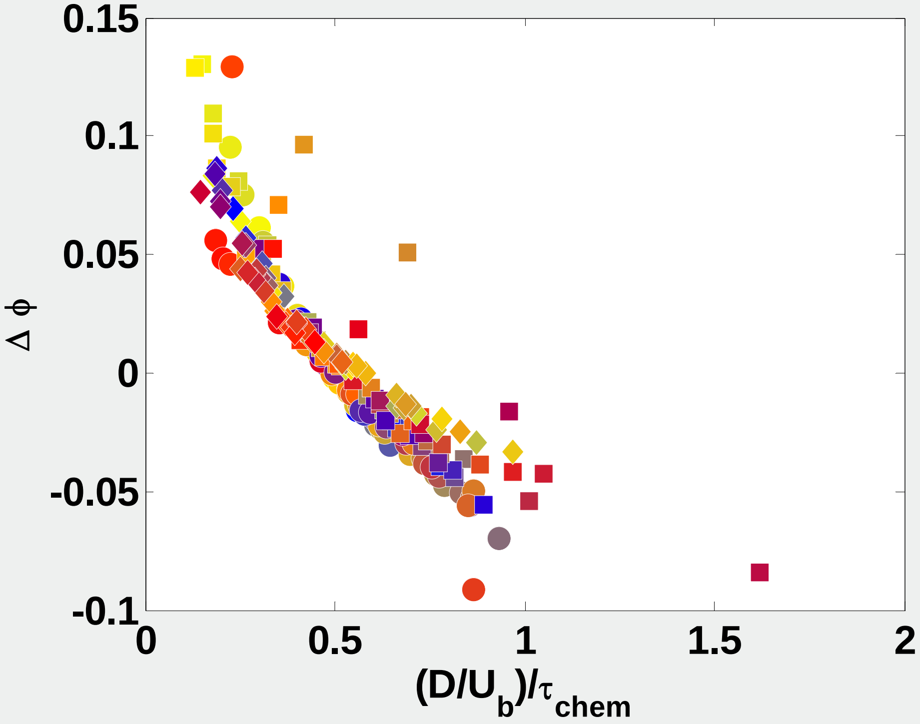
Accuracy of Blowout Prediction assuming Constant Damkohler # at LBO



$$Da = Da(\phi_{predict}) = 0.52$$

- **All data**
- **Assume blowoff at Da=0.52**

Correlation of “Error” with Damkohler



$$\Delta\phi = \phi_{actual} - \phi_{prediction}$$

$$\Delta\phi = f\,(Da)$$

- **All Data**
- **Is there physics in this correlation?**

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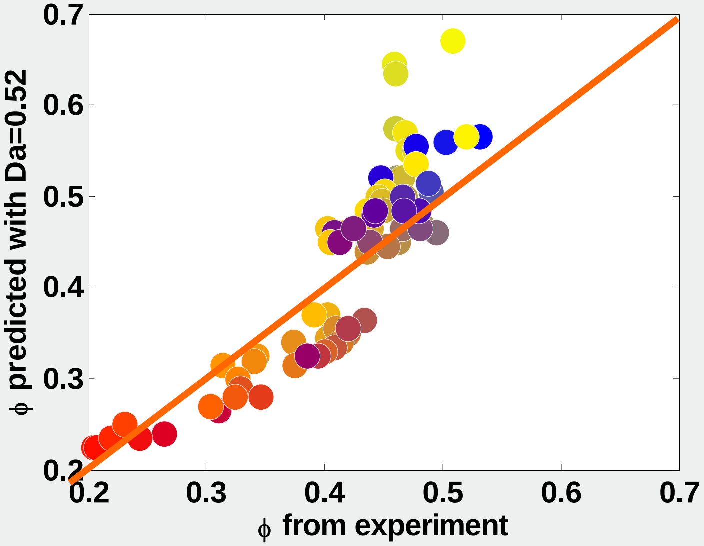
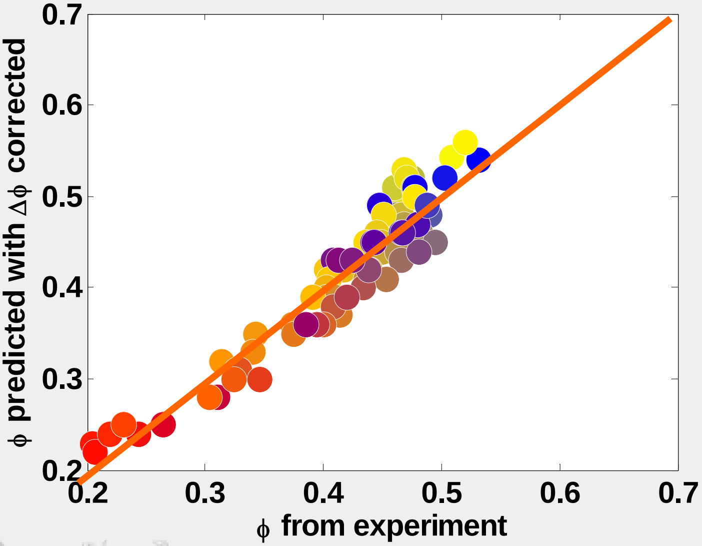
Answer: Yes, there is but we're still trying to understand it



$$Da = Da(\phi_{predict}) = 0.52$$

$$\Delta\phi_{RMS} = 0.059$$



$$Da\left[\ \phi + \Delta\phi(Da)\right] = 0.52$$

$$\Delta\phi_{RMS} = 0.026$$

Conclusions

- **H_2 percentage dominates lean blowout characteristics**
  - Higher H_2 level mixtures can be stabilized with lower equivalence ratios, flame temperatures, and flame speeds.
  - Simplest correlation of lean blowout data is just to use % H_2
- **Better correlation obtained with U_b than U_0**
  - Not significant point for narrow range of fuel compositions, but important effect for wide fuel range
- **Damkohler # scaling captures variability in blowout with fuel composition to within $\Delta\phi=\pm0.05$**
- **Future work:**
  - Detailed visualizations of dynamic blowoff process with several fuel compositions

Project Summary

- **Program benefits the gas turbine and energy industry by:**
  - removing barriers toward the usage of coal derived gaseous fuels through improved understanding of their combustion characteristics
  - improving modeling tools needed by OEM’s to design fuel-flexible combustion systems.

- **Benefits will improve air quality and increase the energy security of the USA, by allowing power plants to operate:**
  - efficiently
  - with minimal pollution
  - using a variety of domestic fuel sources

Questions?

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