Flameholding Tendencies of Natural gas and Hydrogen Fuel at Gas Turbine Premixer Conditions

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UCI COMBUSTION LABORATORY

UNIVERSITY of CALIFORNIA• IRVINE

UTSR Research Workshop

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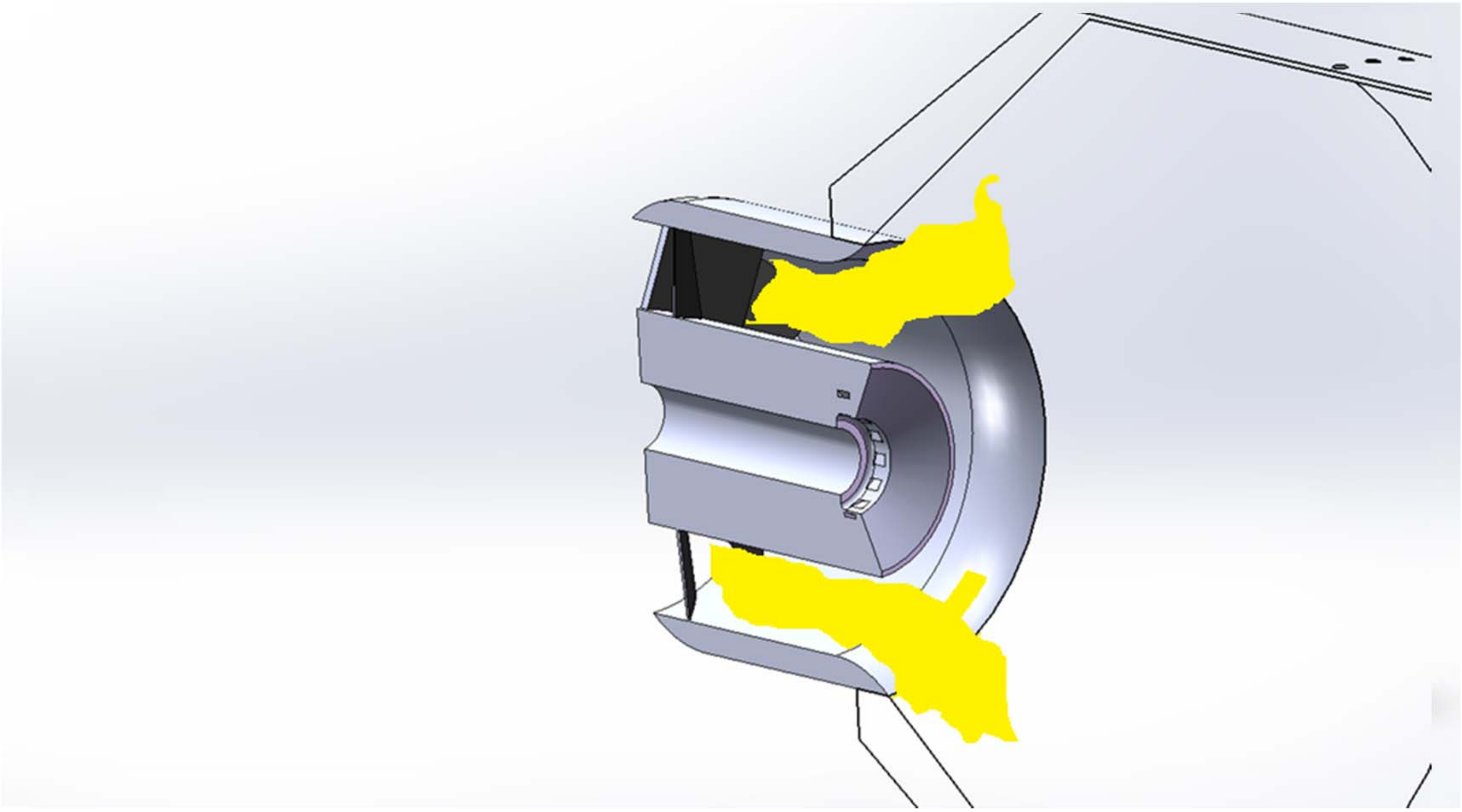
Motivation



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Motivation

Premixer/Injector

Before Flashback

After Flashback

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Sources of Flashback

There two broad classes of flashback:

- **Steady state flashback- the flame propagates upstream from the combustion chamber during steady operation.**

- **Transient flashback - the flame is forced upstream into the premixing zone by a transient event.**

Research Questions

How to avoid flashback damage:

• ~~**Develop flashback resistant combustors**~~

• **Determine how to prevent flames from holding in the premixer if flashback does occur.**

How to avoid premixer flameholding:

• **Determine the limits of flameholding**

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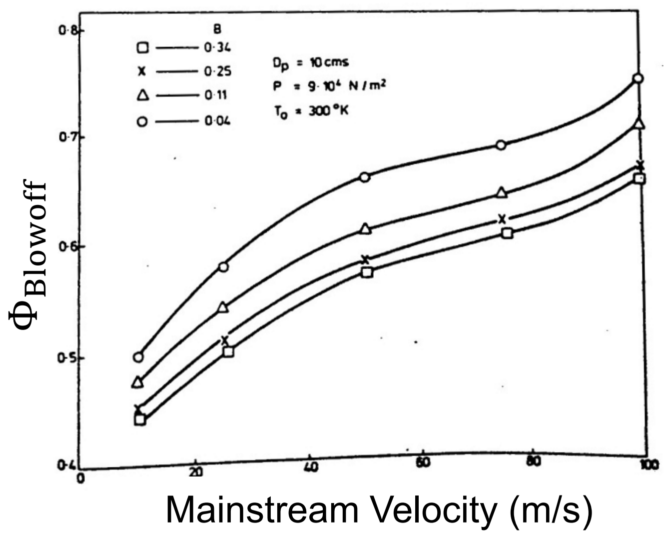
Timeline

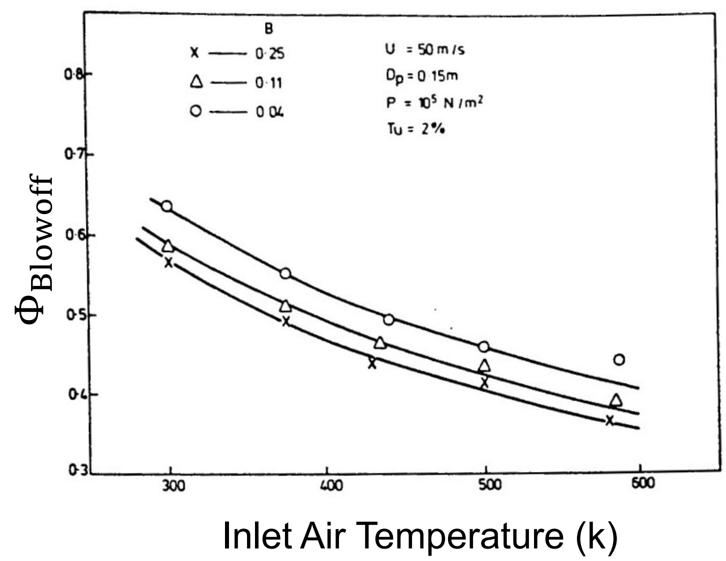
Milestone Title	Planned Completion Date	Actual Completion Date	Verification Method	Comments
Project Management	6/2014	6/2014		
Fuel/Module Selection	5/2012	5/2012	Consensus from OEMs and DOE on plan	Input from industry for test conditions and hardware configurations. Initial fuels will be pure H2 and natural gas
Fabrication	6/2012	6/2012	Photos of completed installation and test hardware	Completed short of specific wall feature modules which are easily fabricated in house.
Diagnostics/Rig Setup	9/2012	2/2013		Complete. Test rig has been operational as of February 2013 and commissioning tests have been performed
Commissioning	9/2012	3/2013	Comparison of commissioning data with literature data	Complete. Blowoff of a rod stabilized flame evaluated at several pressures for natural gas fuel. Trends show good agreement with literature.
Experimental Studies	6/2014	9/2014	High speed imaging with external. Pressure, temperature measurements. LDV velocity field mapping.	Complete LDV velocity field and turbulence intensities measured. Turbulence data along with reacting experiment data used for model development.
Analysis and Model Development	6/2014	10/2014		Complete

Background

Ballal and Lefebvre (1979) developed correlations for $\Phi_{Blowoff}$ in terms of standard variables (Temperature, Pressure, Velocity, Blockage ratio, and Diameter)

$$\Phi_{Blowoff} \propto \left[\frac{U}{P^{0.25}T_0\exp(T_0/150)D(1-B)}\right]^{0.16}$$

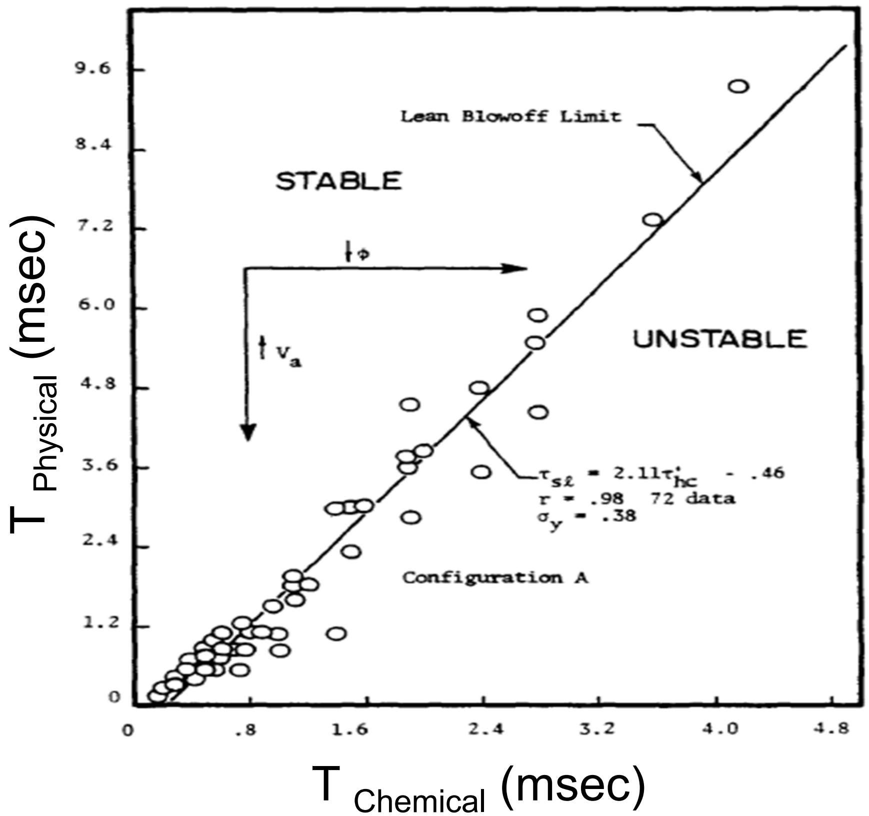




Ballal, D.R., Lefebvre, 1979, Weak Exitinction Limits of Turbulent Flowing Mixtures, ASME Journal of Engineering for Power, pp. 343-348

Background

Plee and Mellor (1979) used the data from Ballal and Lefebvre (1979) but suggest that controlling factors are chemical time scales and physical timescales



Plee, S.L., Mellor, A.M., 1979, Characteristic Time Correlation for Lean Blowoff of Bluff-Body-Stabilized Flames, Combustion and Flame, Vol. 35, pp. 61-90

Background

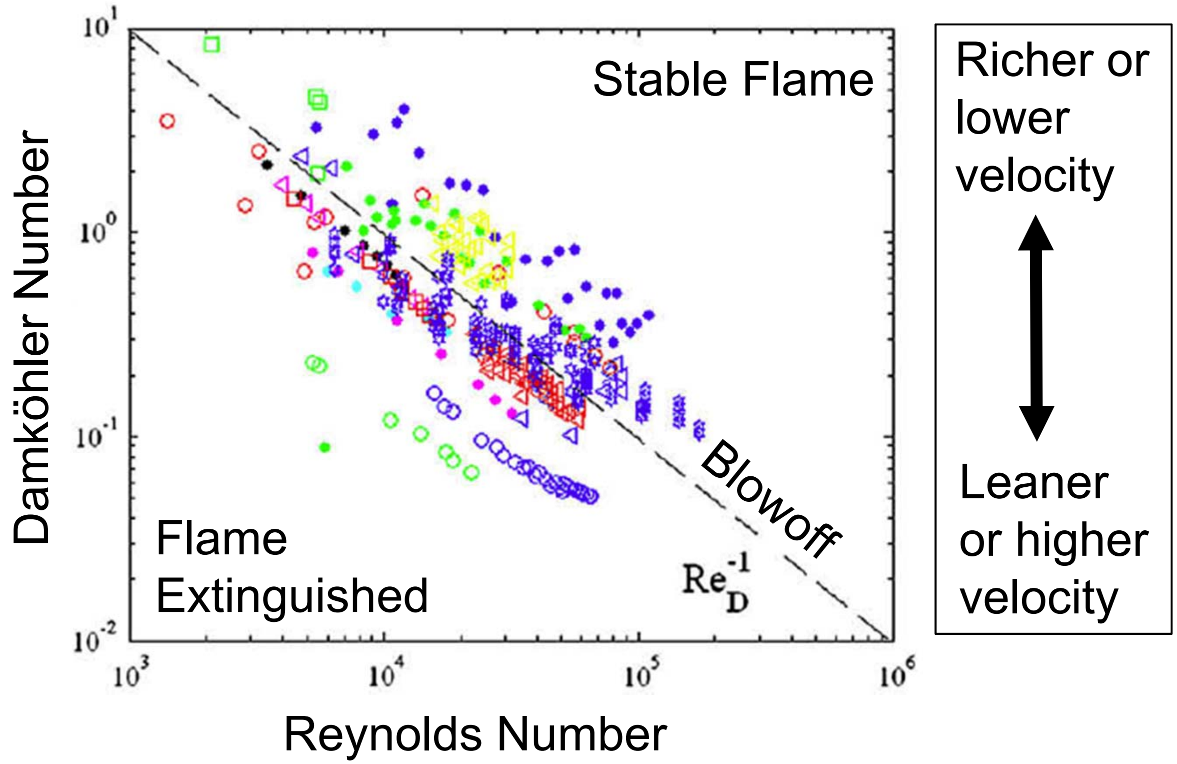
Shanbhogue, et al. (2009) conducted a review study that collected data from many other studies on flameholding and attempted to describe all the data with a single equation.

Damköhler Number:

$$Da = \frac{T_{Phys}}{T_{Chem}} = \frac{D/U}{t_{PSR}}$$

Reynolds Number:

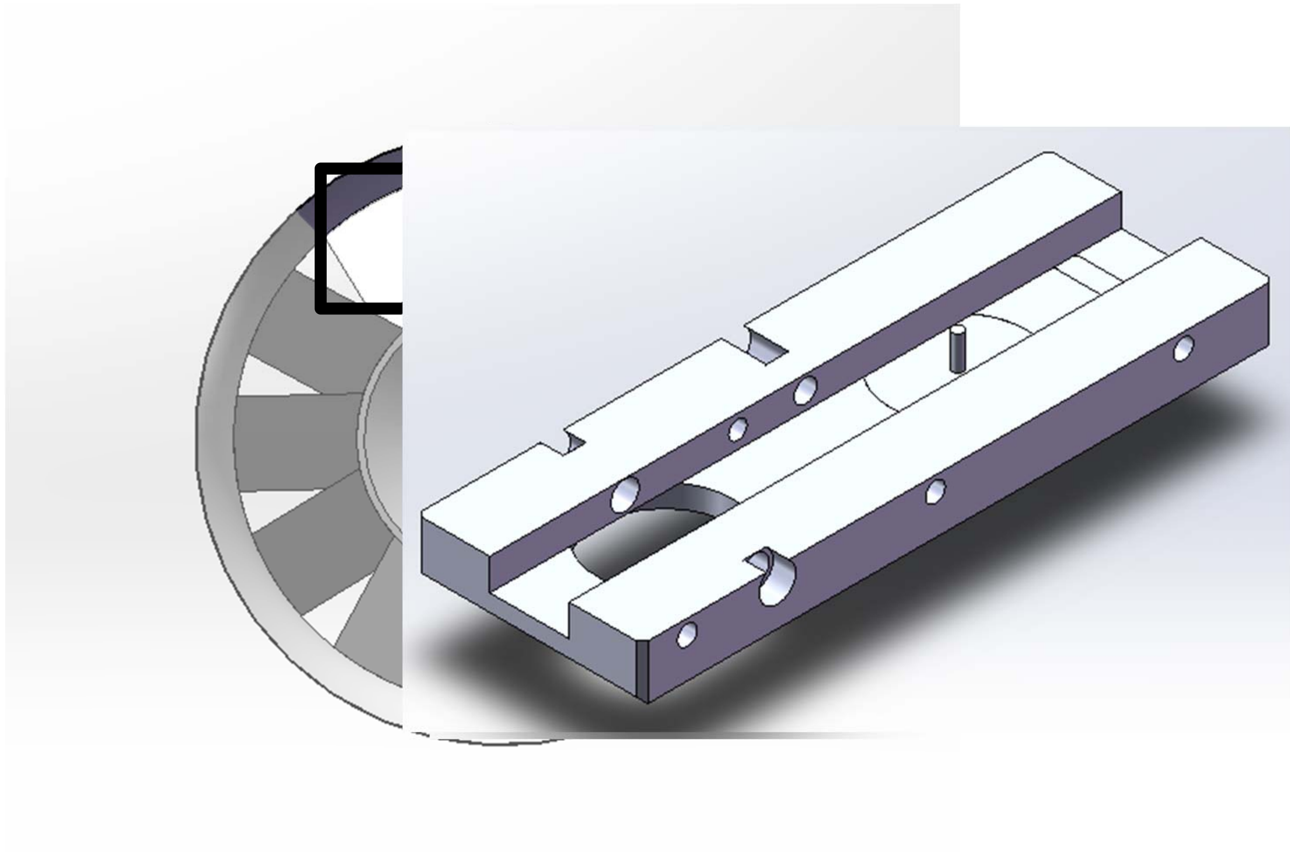
$$Re = \frac{\rho U D}{\mu}$$



Shanbhogue, S.J., Husain, S., Lieuwen, T., 2009, Lean Blowoff of Bluff Body Stabilized Flames: Scaling and Dynamics, Progress in Energy and Combustion Science, 98-120

Experiment

Motivation



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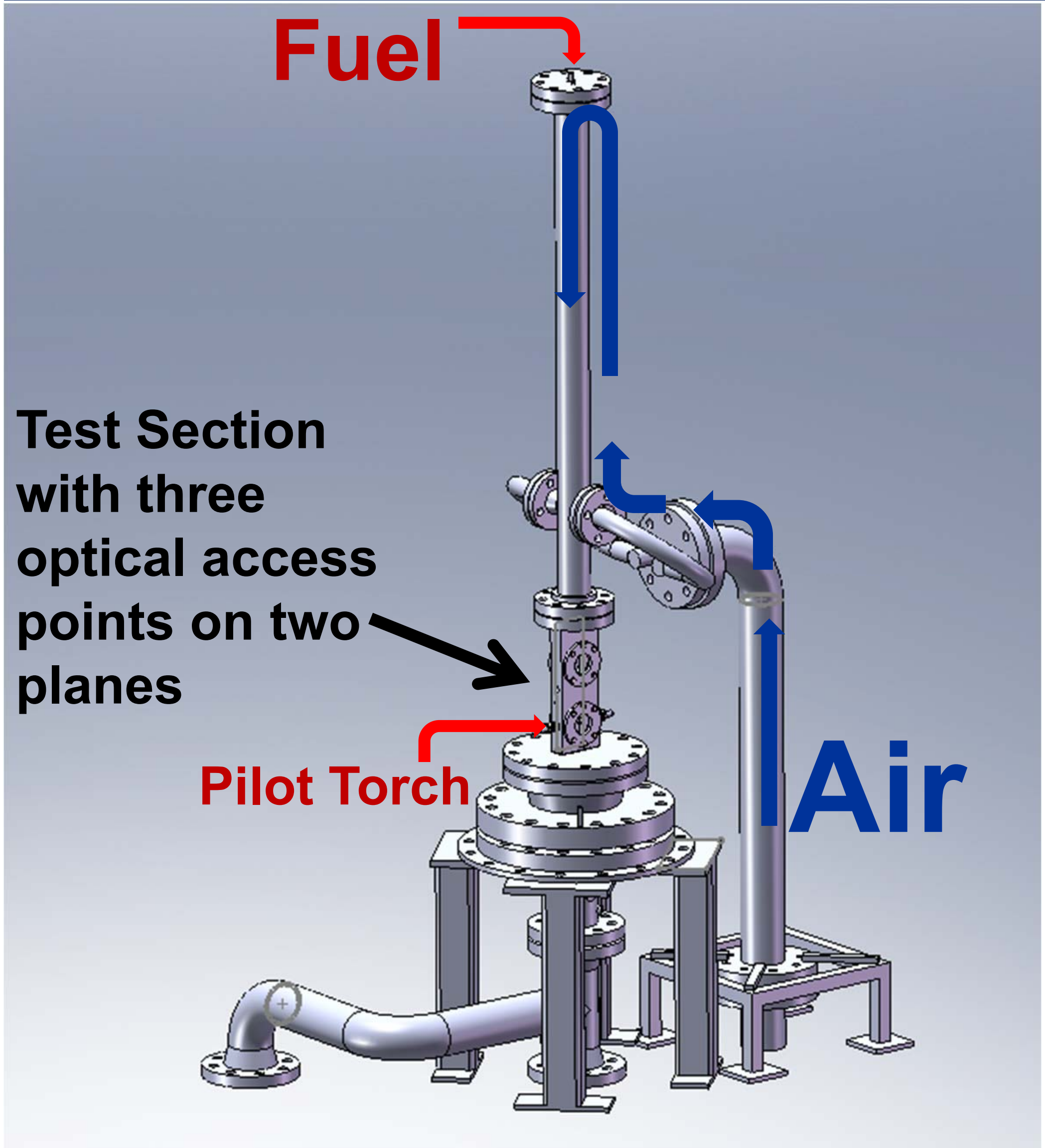
Test Rig Assembly



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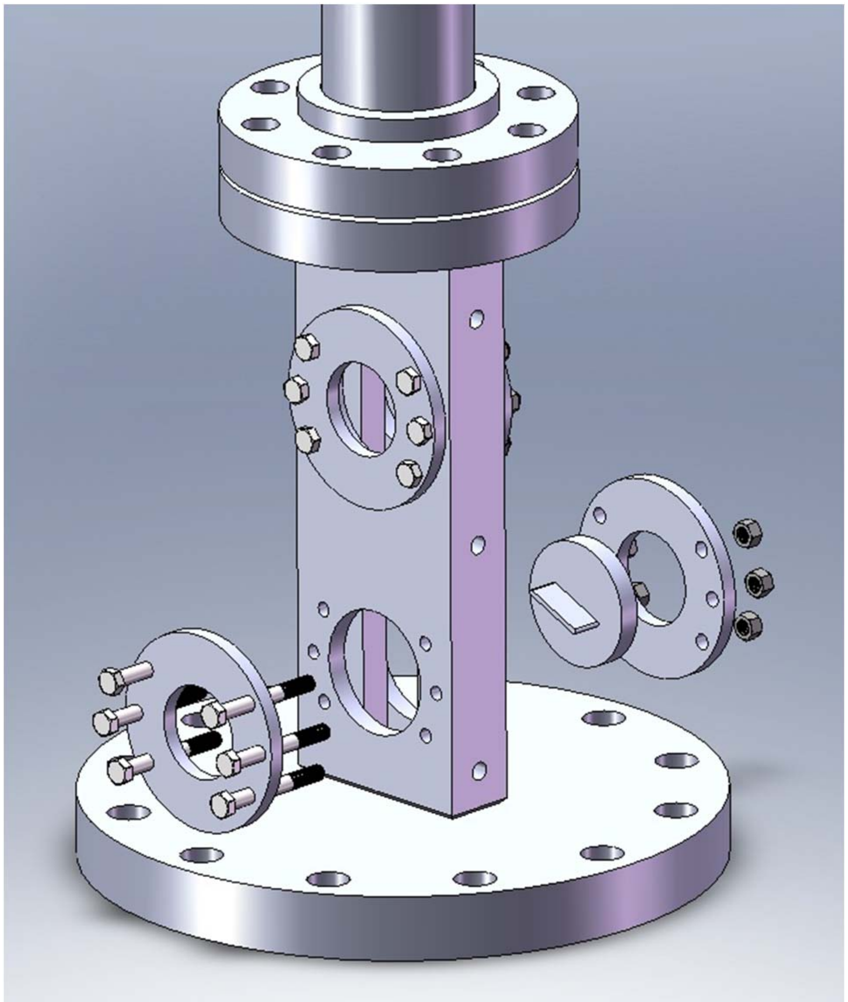
Test Section



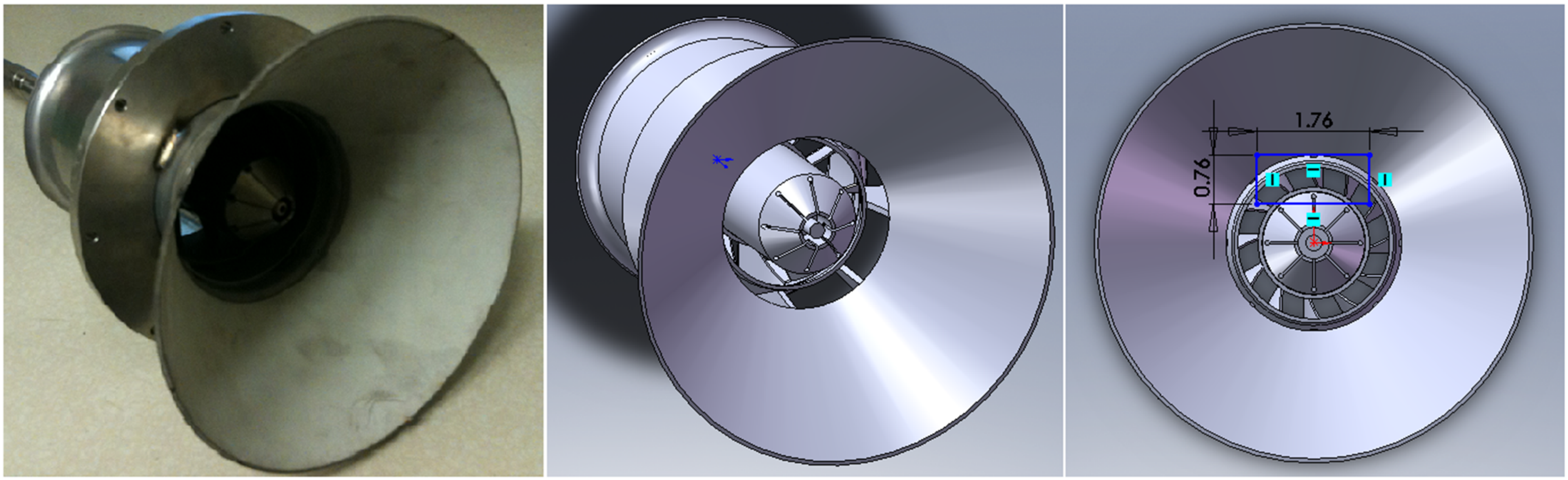
Optical windows and test feature have same base so that the test feature can be moved upstream or downstream of ignition source

Round base of test feature insert allows test feature to be rotated

Test Section Sizing

Test section with cross section of 1.76” x 0.76” is representative of current engine premixing sections

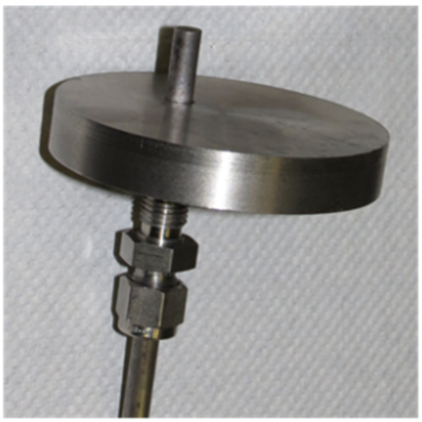
Siemens Gas Injector/Premixer



Test Section Sizing

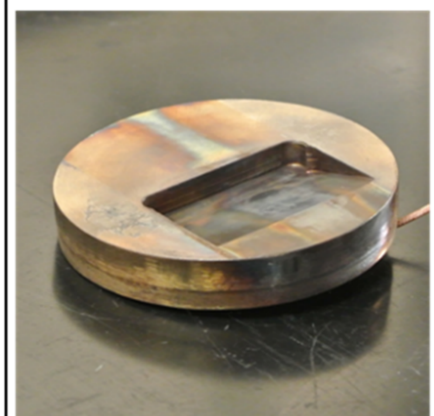
Test section with cross section of 1.76” x 0.76” is representative of current engine premixing sections

0.25″ Cylinder

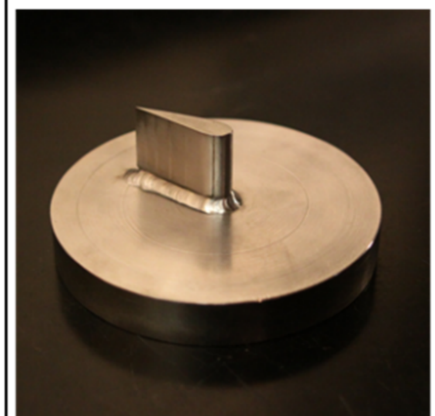


0.50″ Cylinder

Reverse Step



Airfoil



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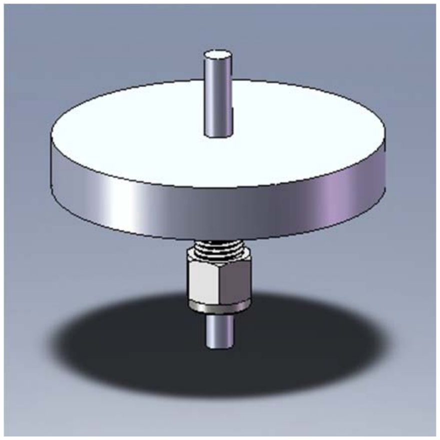
Testing

Testing

Cylindrical Flameholder



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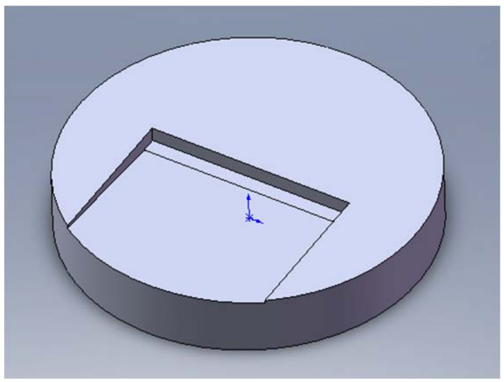
Testing

Reverse Step Flameholder



1/4" Height Reverse Step Flameholder

5 ATM

500F Inlet Temperature

40 m/s bulk Velocity

Natural Gas Fuel, 0.9->0.85 Equivalence Ratio

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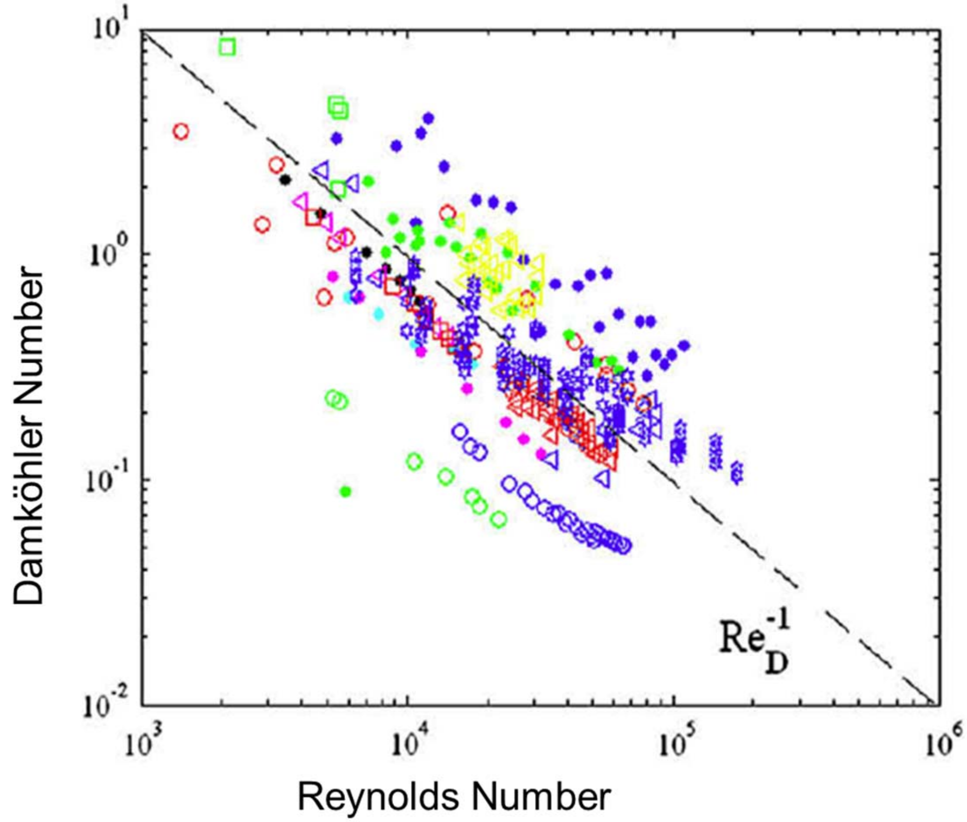
Results

Results

How does this data compare to the Re-Da correlations developed by Shanbhogue (2009)?



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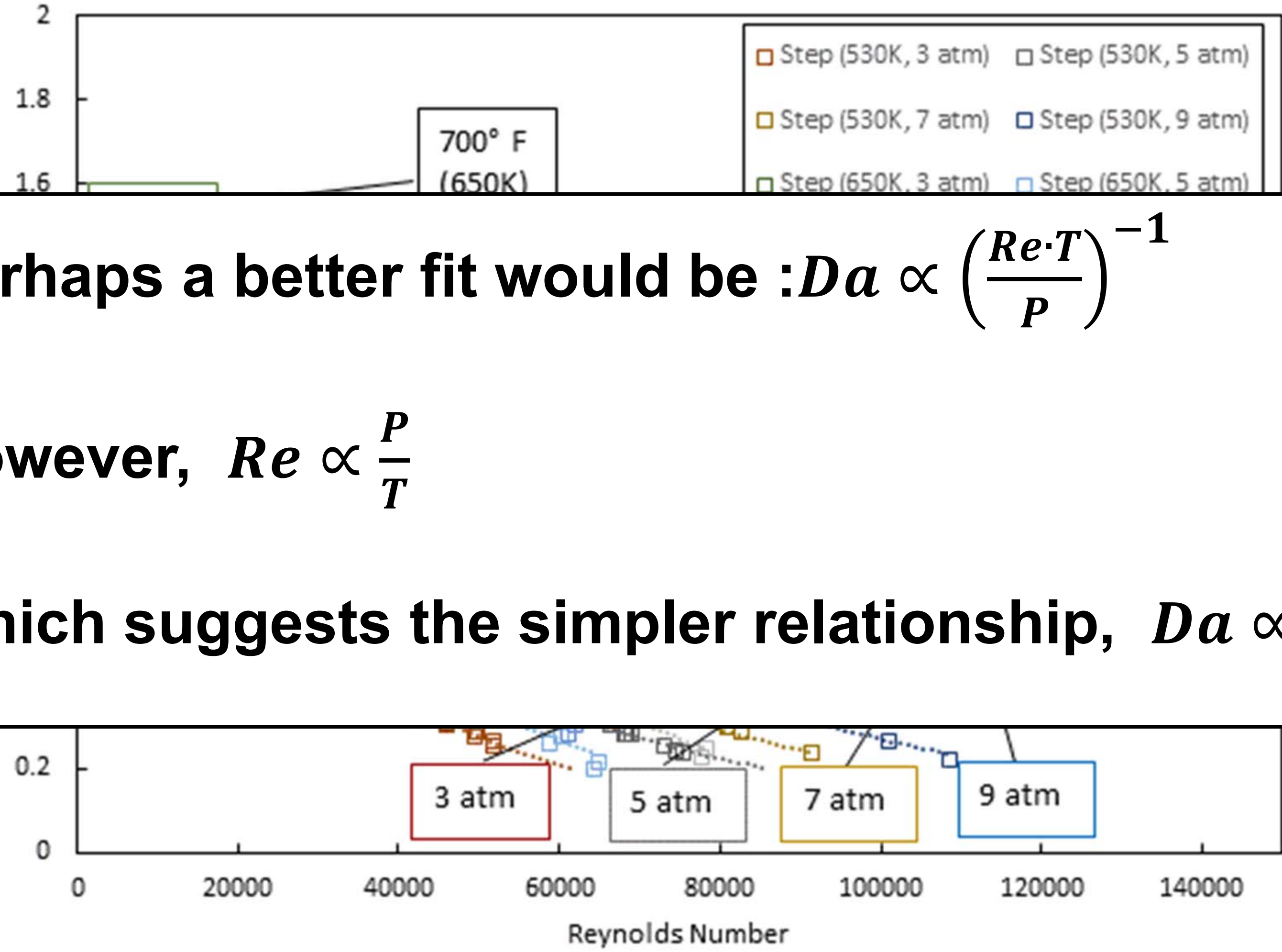
Results



Perhaps a better fit would be : $\boldsymbol{Da \propto \left(\frac{Re \cdot T}{P}\right)^{-1}}$

However, $\boldsymbol{Re \propto \frac{P}{T}}$

Which suggests the simpler relationship, $\boldsymbol{Da \propto V^{-1}}$

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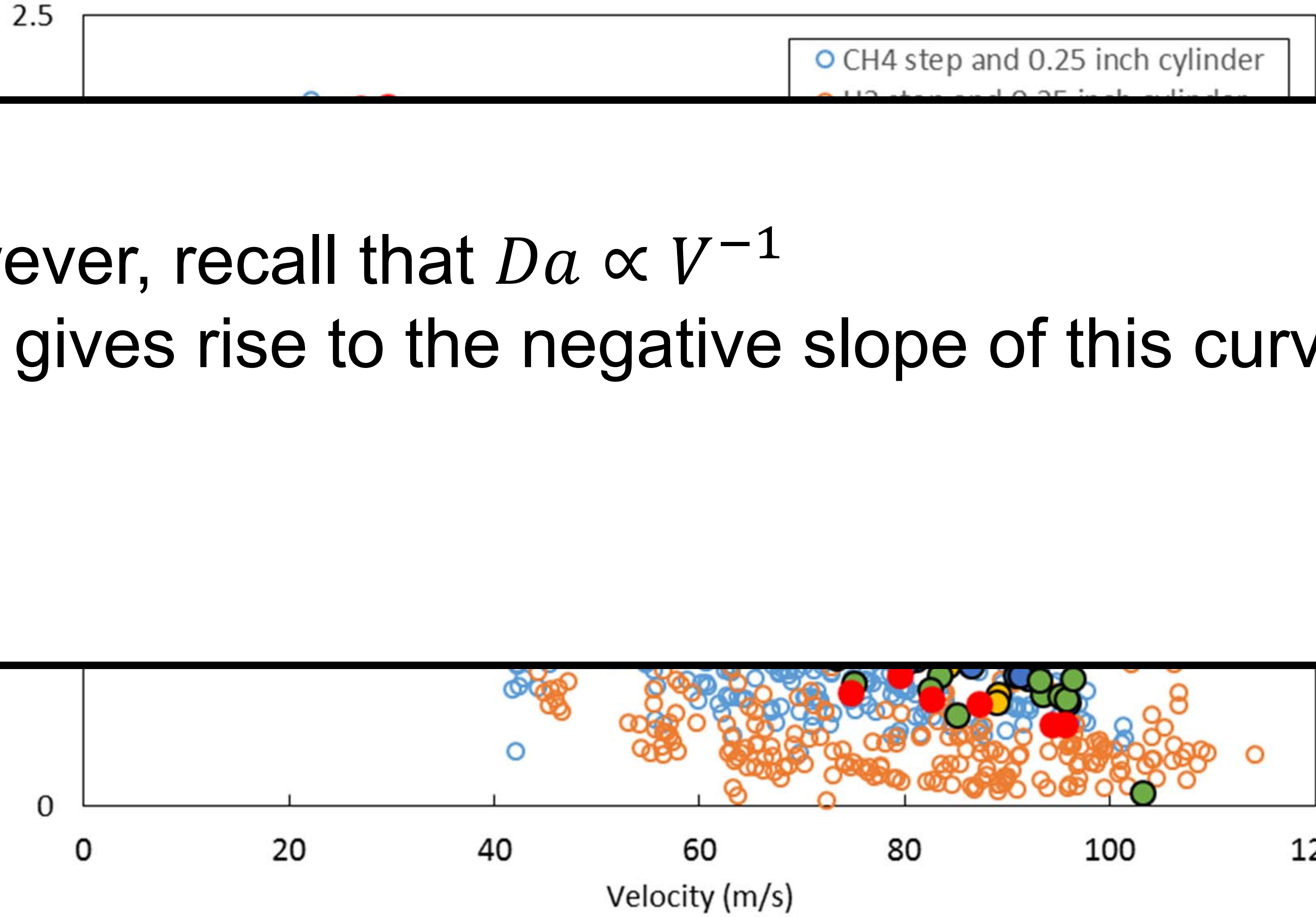
Results

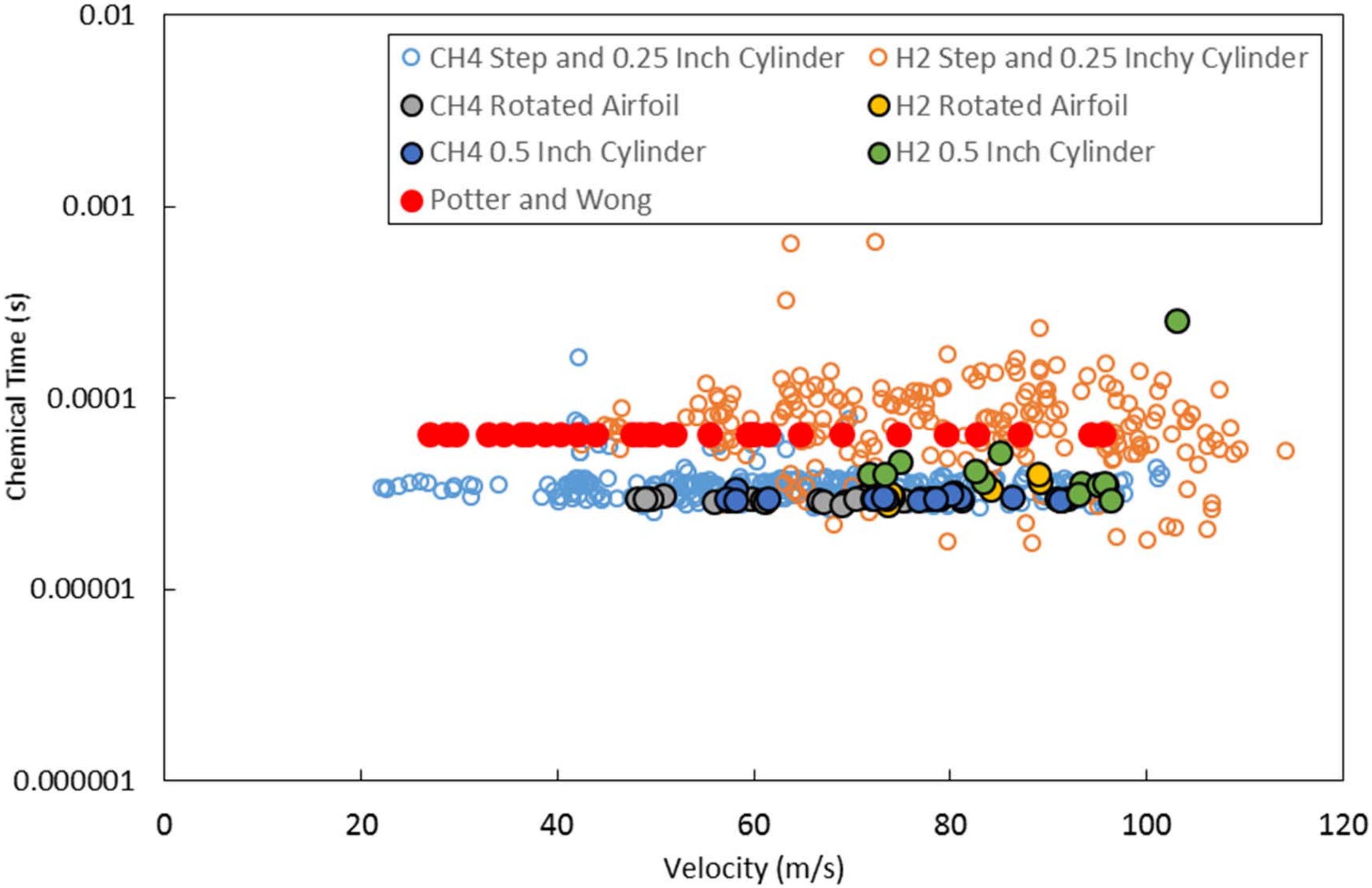


However, recall that $Da \propto V^{-1}$

This gives rise to the negative slope of this curve

Potter, A., Wong, E., 1958 Effect of Pressure and Duct Geometry on Bluff-Body Flame Stabilization, NACA TN 4381, National Advisory Committee for Aeronautics

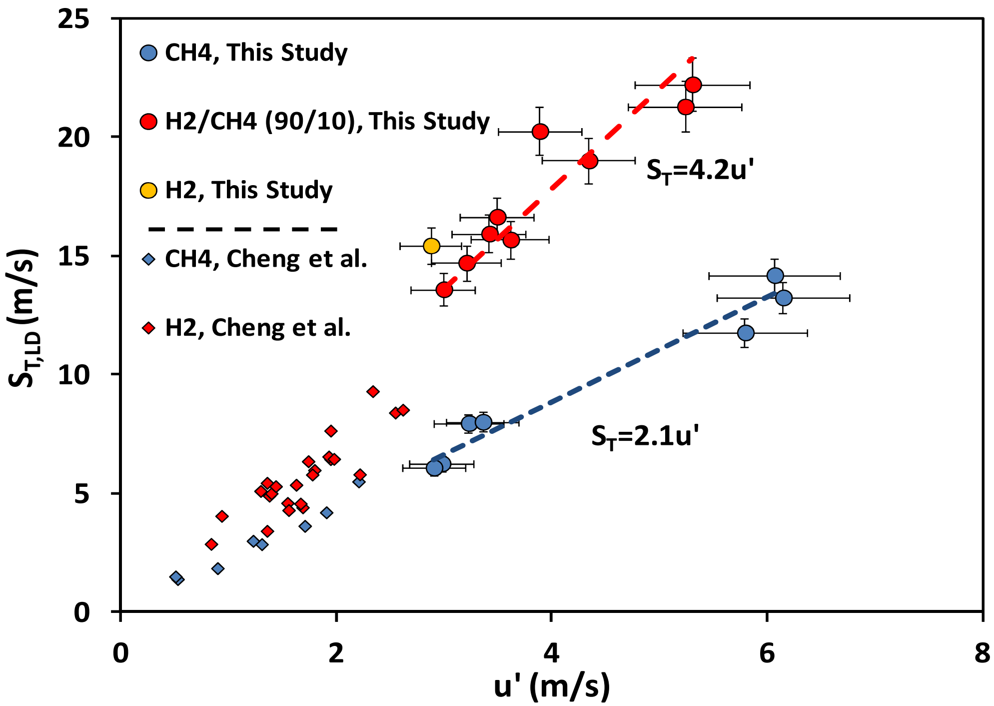
Results



Potter, A., Wong, E., 1958 Effect of Pressure and Duct Geometry on Bluff-Body Flame Stabilization, NACA TN 4381, National Advisory Committee for Aeronautics

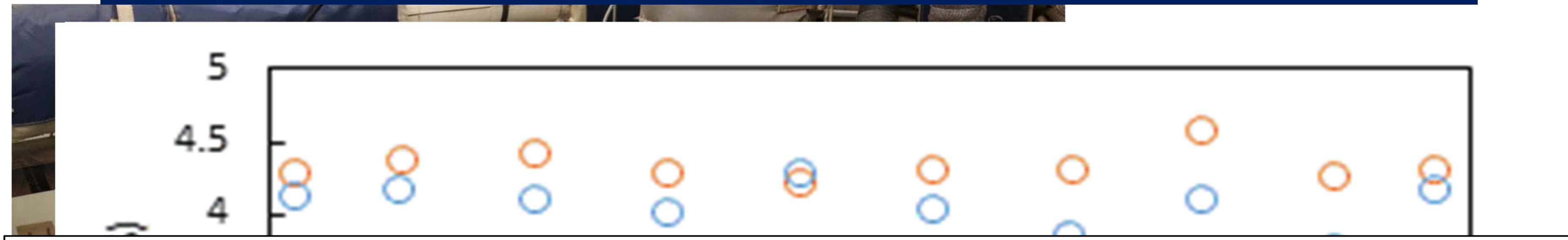
Results

- **Why isn't the T_{Chem} decreasing as velocity increases?**
  - **Turbulent flame speed increases linearly with turbulent fluctuation magnitude.**
  - **If turbulent magnitude remains approximately constant then turbulent flame speed also increases linearly with velocity**



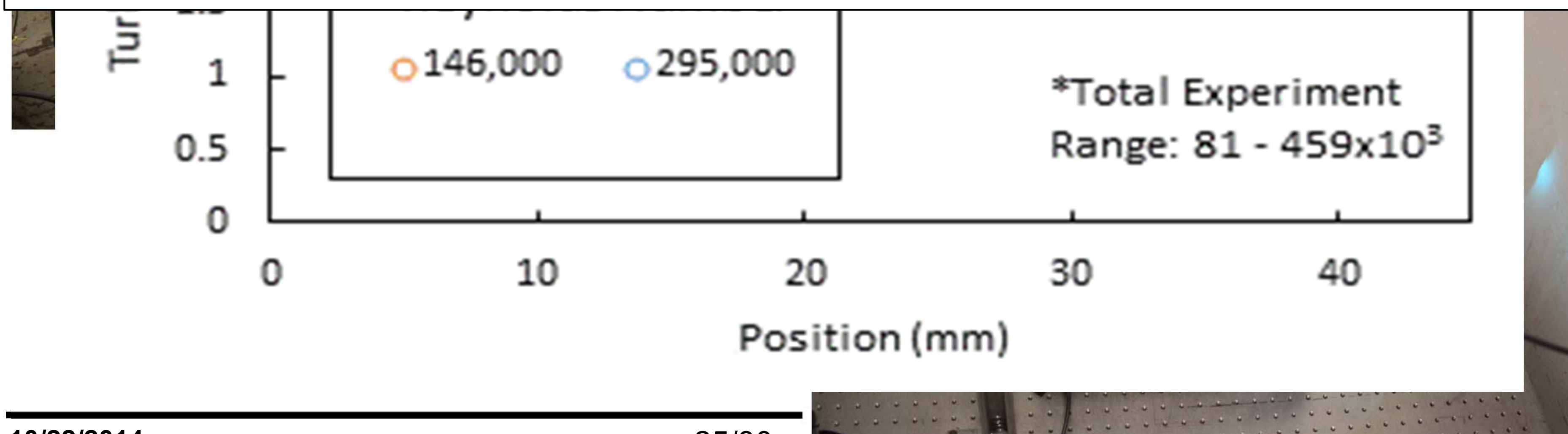
Beerer, D., McDonell, V., Therkelsen, P., Cheng, R., 2013, Flashback and Turbulent Flame Speed Measurements in Hydrogen Flames Stabilized by a Low-Swirl Injector at Elevated Pressures and Temperatures, J. Eng. Gas Turbines Power, 031501 (1-9)

LDV measurements



Results are both 20% higher than predicted for fully developed pipe flow:

$$I = 0.16 \cdot Re_{Dh}^{-0.125}$$



Results

Flame speed alone does not address the influence of the bluff body or flame temperatures.

Higher blockage ratio increases edge velocity, reducing contact time between reactants and hot products.

Higher combustion temperatures increase heat transfer to reactants.

Empirical correlation term was developed:

$$U \propto S_T \left(\frac{T_{Burned}}{T_{Unburned}} \right) (1 - B)$$

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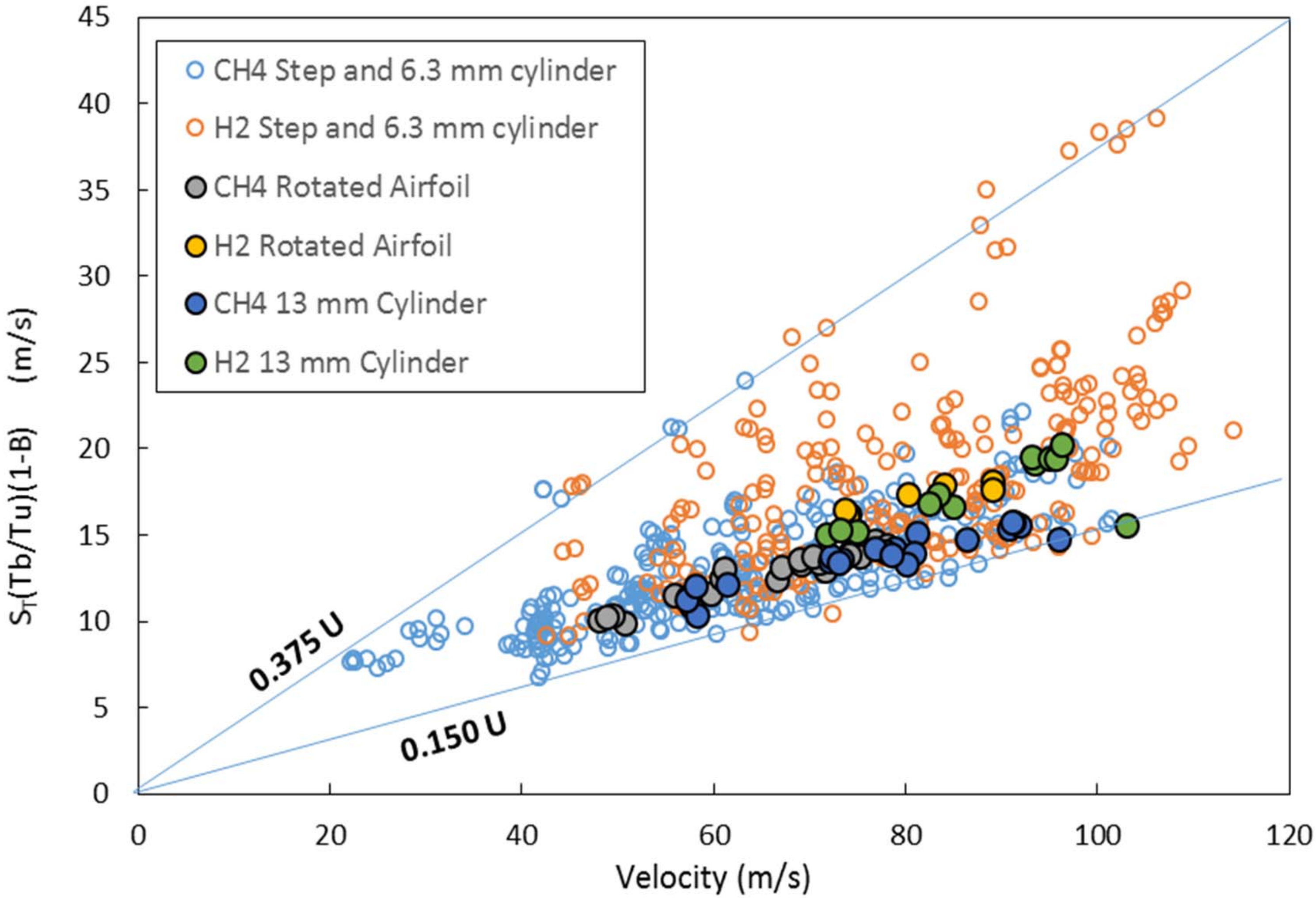
Results



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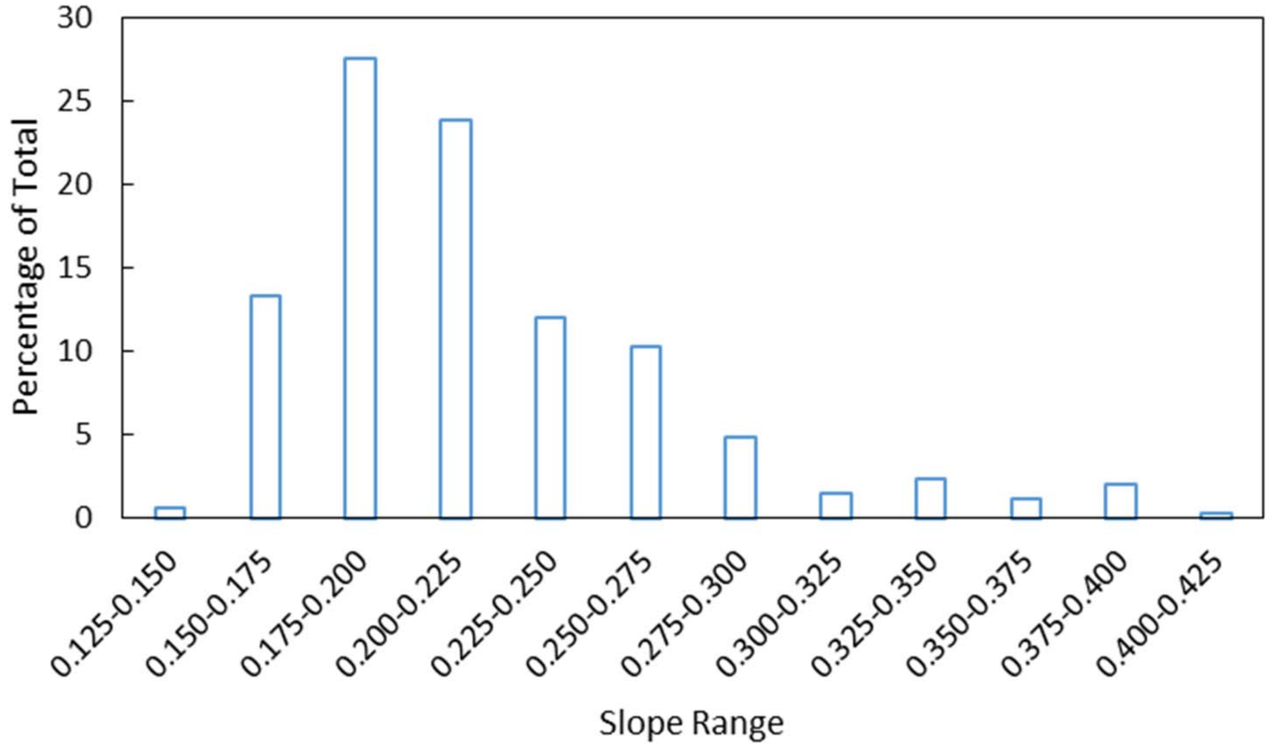
Results

Blow off probability follows a Rayleigh Distribution



Probability Density Function

$$P(s) \propto (s - 0.15) exp\left(\frac{-(s-0.15)^2}{650}\right)$$

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Example

A premixer has a blockage ratio of 0.7 and turbulence intensity of 5%
Reactants: Hydrogen and Air at 600K and an equivalence ratio of 0.3

Determine the minimum average velocity that will avoid flame holding.

Based on the reactant mixture: T_{Burned} = 1467 K, S_L = 0.9 m/s

$$\frac{T_{Burned}}{T_{Unburned}} = \frac{1467\ K}{600\ K} = 2.445$$

$$S_T = S_L + 3.73U' = 0.09\frac{m}{s} + 3.73(0.05)(U)$$

$$\left(0.09\frac{m}{s} + 0.1865U\right)(2.445)(1-0.7) = 0.15U$$

$$.1320\frac{m}{s} = 0.0132U$$

$$\boxed{10\frac{m}{s} = U}$$

Summary

- Experiments have been carried out on four flameholder geometries with both natural gas and hydrogen
- Temperature and fuel type were found to affect flameholding propensity more than any other parameter.
- Adiabatic flame temperature can be used as the characteristic temperature
- Chemical timescale does a reasonable job of predicting the point of blow off but does not take into account bluff body effects
- The product of turbulent flame speed, dilation ratio and (1-B) correlates well bulk velocity at blow off and captures the stochastic nature of blow off

Analysis

- **Scaling parameters investigated:**
  - Velocity
  - Equivalence Ratio
  - Adiabatic flame temperature
  - Mach Number
  - Lewis Number
  - Peclet Number
  - Reynolds Number
  - Damköhler Number
  - Turbulent flame speed (local displacement)
  - Chemical time
    - PSR time
    - Ignition Delay time at AFT
    - Flame thickness/laminar flame speed