Development of Criteria for Flashback Propensity in Jet Flames for High Hydrogen Content and Natural Gas Type Fuels

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Outline

- Motivation
- Background
- Project Goals
- Experiment
- Test Procedures
- Results
- Summary

Motivation

Motivation

- Integrated Gasification Combined Cycle (IGCC)
- Steam reforming of natural gas or liquid hydrocarbons
- Waste Treatment – Digester Gas
- Biomass
- “Power to Gas”

Source	H_2	CO	CH_4	CO_2	N_2	C_2	C_3
High H_2	90-100	0-10					
Process and refinery gas	25-55	0-10	30-65	0-5		0-25	0-25
Gasified coal/petcoke (O_2 Blown)	35-40	45-50	0-1	10-15	0-2		
Gasified biomass	15-25	15-35	0-5	5-15	30-50		
Digester gas	0-1		50-75	25-50	0-10		
Power to Gas	0-20?		75-80			0-5	0-1

High hydrogen content fuels

Motivation

- **Impact of Alternative Fuels on gas turbine combustion**
  - **Emissions**
  - **Operability issues**
    - **Lean Blow Off (Static stability)**
    - **Flashback**
    - **Combustion Dynamic (Dynamic stability)**

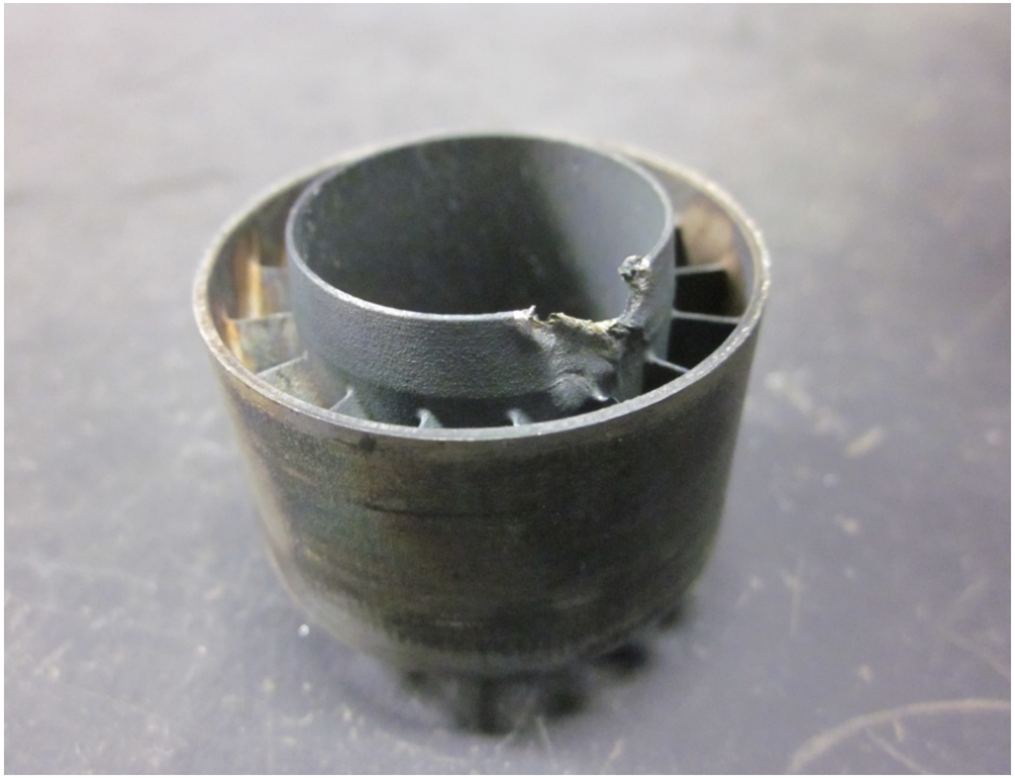
High hydrogen content fuels

Motivation

Premixer/Injector: 90/10 H2/NG

Before Flashback

After Flashback



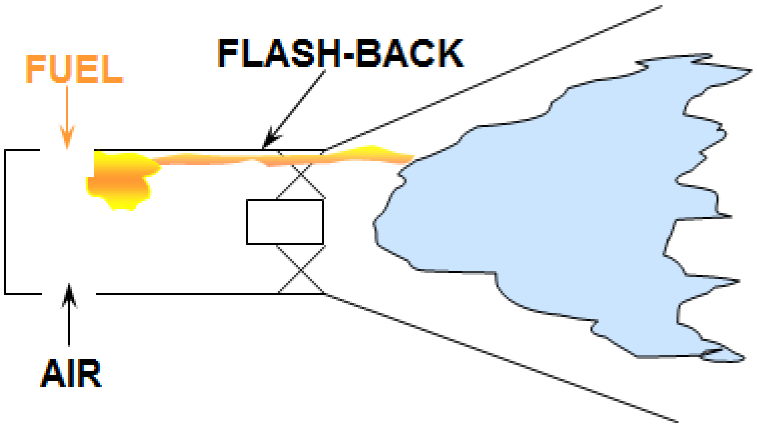
Background

Flashback

- **Flame propagation from the combustion zone into premixing section of combustors[/1]**
  - ➢ **Flashback in the core flow**
  - ➢ **Combustion induced vortex breakdown (CIVB)**
  - ➢ **Flashback due to combustion instabilities**
  - ➢ **Flashback in the wall boundary layer**

    Propagation of flame upstream of the flow inside the boundary layer

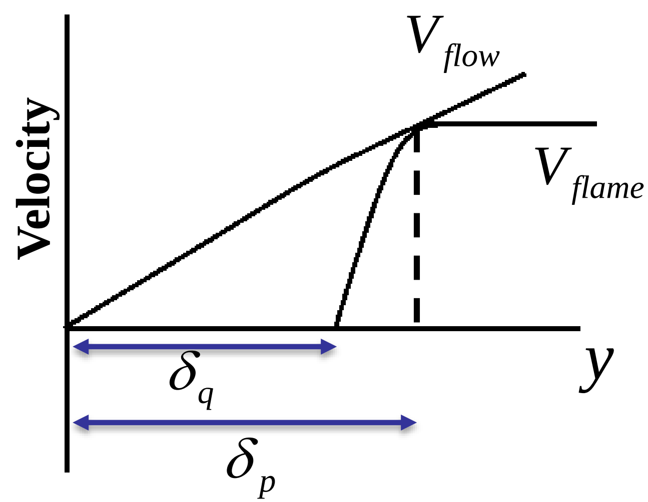
Jet flame



/1 T. Lieuwen, V. McDonell, D. Santavicca, and T. Sattelmayer, Combust. Sci. and Tech. 180 (6) (2008)1169–1192.

Structure of Burner Flames

Lewis, B., & Von Elbe, G.	Stability and structure of burner flames	1943
Von Elbe, G., & Mentser, M.	Further Studies of the Structure and Stability of Burner Flames	1945
Putnam, A. A., & Jensen, R. A.	Application of dimensionless numbers to flash-back and other combustion phenomena	1949
Thomas, N.	Structure and stability of burner flames	1949
Wohl, K.	Quenching, flash-back, blow-off-theory and experiment	1953



Critical boundary layer velocity gradient

- **Laminar flow**

$$U = \frac{8}{\pi}\frac{(D^2 - d^2)}{D^4}\overline{u}$$ Laminar velocity profile

$$g_c = \frac{\left(V_{flow}\right)_{y=\delta_b}}{\delta_b} = \frac{S_L}{\delta_p}$$

$$g = \frac{8\overline{u}}{D}$$

$$Pe_J \equiv \frac{D \times V}{\alpha}$$

$$Pe_J = \frac{1}{8K}(Pe_F)^2$$

$$\delta_p \approx \delta_q = K\frac{\alpha}{S_L}$$

K=2: Flame thickness

$$Pe_F \equiv \frac{D \times S_L}{\alpha}$$

Putnam and Jensen (1949)

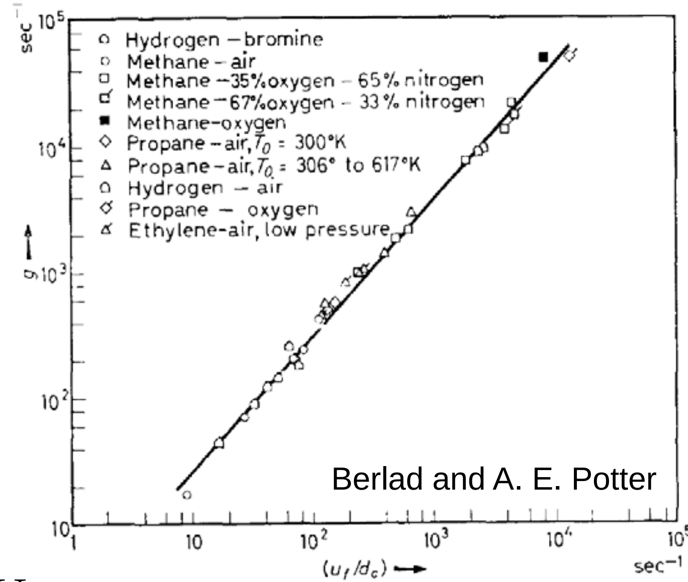
Effects of Various Factors

Grumer, J.	Predicting burner performance with interchanged fuel gases	1949
Grumer, J., & Harris, M. E.	Predicting interchangeability of fuel gases interchangeability of oil gases or propane-air fuels with natural gases	1952
Grumer, J., & Harris, M. E.	Flame-stability limits of methane, hydrogen, and carbon monoxide mixtures	1952
Grumer, J., & Harris, M. E.	Temperature dependence of stability limits of burner flames	1954
Dugger, G. L.	Flame stability of preheated propane-air mixtures	1954
Grumer, J., & Harris, M. E.	Flame-stability limits of ethylene, propane, methane, hydrogen, and nitrogen mixtures	1955
Bollinger, L. E., & Edse, R.	Effect of burner-tip temperature on flashback of turbulent hydrogen-oxygen flames	1956
Fine, B.	Stability limits and burning velocities for some laminar and turbulent propane and hydrogen flames at reduced pressure	1957
Kurz, P. F.	Stability limits of flames of ternary hydrocarbon mixtures	1957
Kurz, P. F.	Some factors influencing stability limits of Bunsen flames	1957
Berlad, A. L., & Potter Jr, A. E.	Relation of boundary velocity gradient for flash-back to burning velocity and quenching distance	1957
Van Krevelen, D. W., & Chermin, H. A. G.	Generalized flame stability diagram for the prediction of interchangeability of gases	1958
Fine, B.	Flashback of laminar and turbulent burner flames at reduced pressure	1958
Fine, B.	Effect of Initial Temperature on Flash Back of Laminar and Turbulent Burner Flames.	1959
Yamazaki, K., & Tsuji, H.	An experimental investigation on the stability of turbulent burner flames	1961
Caffo, E., & Padovani, C.	Flashback in premixed air flames	1963

Effects of Various Factors

- Fuel compositions (natural gas, propane, ethane, hydrocarbons mixtures)
- Preheated temperature
- Limited Pressures
- Burner tip temperature
- Burner diameter
- Some Turbulent flames

Not studied together



$$g = 0.023\,\mathrm{Re}^{0.8}\left(\frac{\overline{U}}{D}\right) \qquad g = 0.03955\,\mathrm{Re}^{0.75}\left(\frac{\overline{U}}{D}\right)$$

A=f(g)

Berlad, A. L. and A. E. Potter

$$g = A\left(\frac{U_f}{d_q}\right) \qquad g = 14.125\left(\frac{U_f}{d_q}\right)^{1.168}$$

Laminar flames
Cooled Tips

Fine, B.

$$\frac{g_{Critical}}{g_0} = \left(\frac{T_{\mathrm{Preheat}}}{T_0}\right)^{1.52} \qquad \frac{g_{Critical}}{g_0} = \left(\frac{P_{amb}}{P_0}\right)^{1.35}$$

Subatm. pressure

Caffo

$$g_F = a_{H_2} \times \%H_2 + \sum a_i \times \%C_i$$

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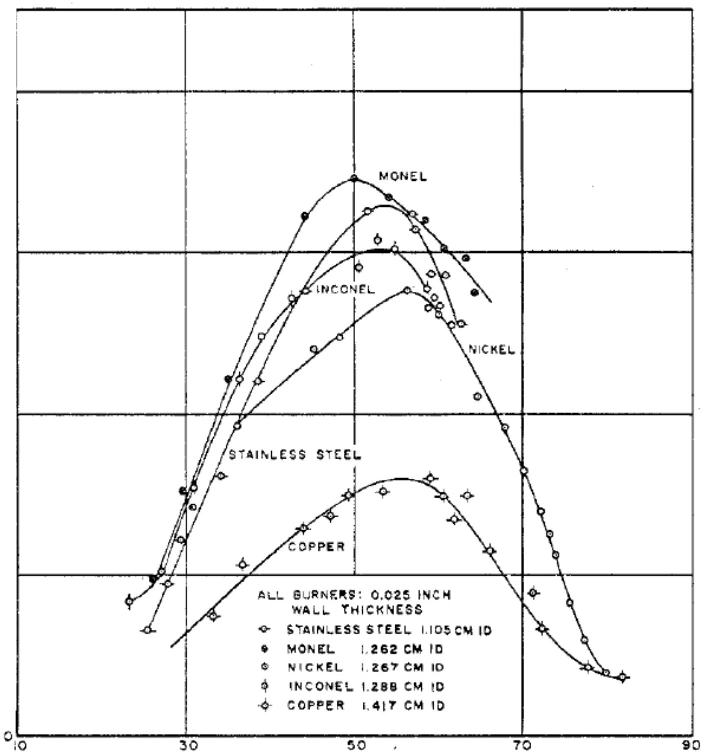
Burner Material Effect

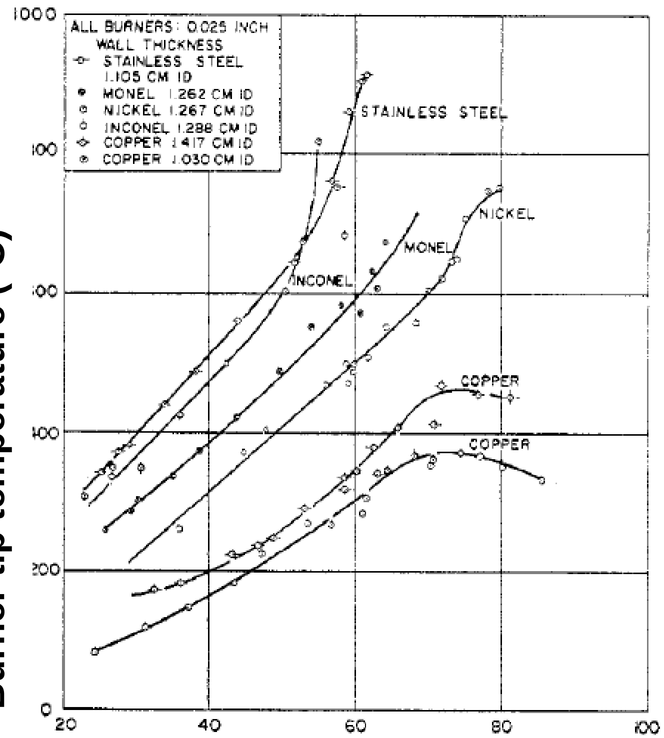
Flash Back of Turbulent Hydrogen-Oxygen Flames → **Thermal coupling**

Critical velocity gradient ×10^{-5} (1/s)



Percent hydrogen in mixture

Burner tip temperature (°C)



Percent hydrogen in mixture

- **Metal burners**
- **Oxygen as an oxidizer**
- **No correlation**

→ **Direct impacts on the flame speed and flashback propensity**

Bollinger, L. E., & Edse, R. (1956). Effect of Burner-Tip Temperature on Flash Back of Turbulent Hydrogen-Oxygen Flames. *Industrial & Engineering Chemistry*, *48*(4), 802-807.c

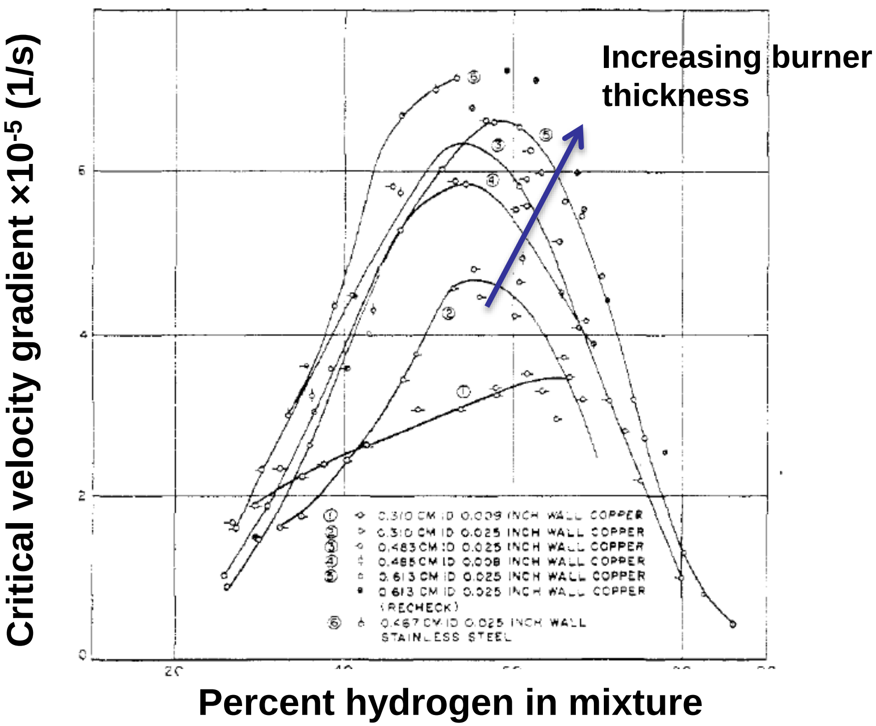
Burner Thickness Effect

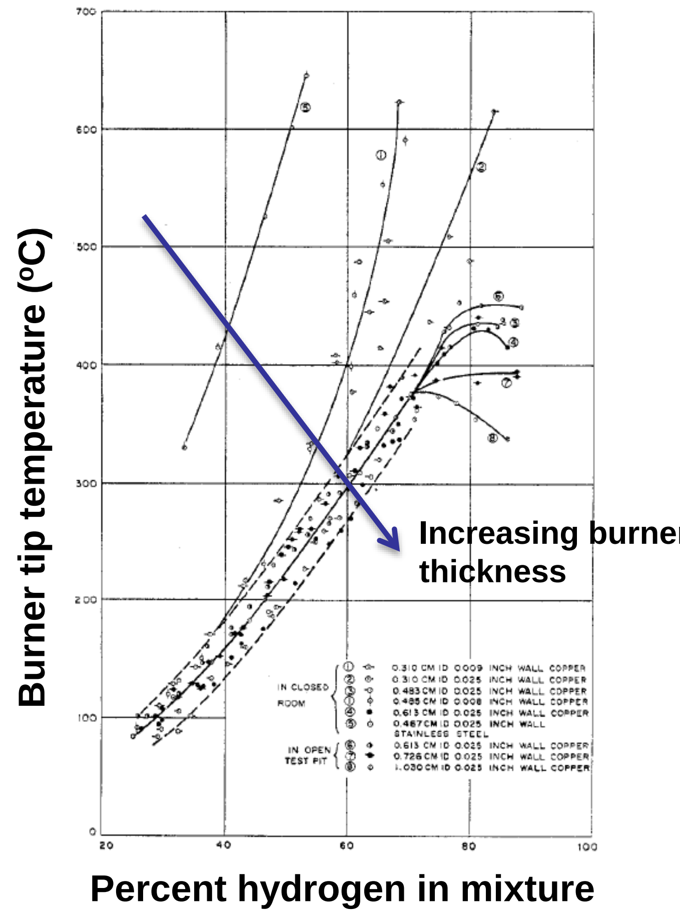
- Increase of thickness
  - Constant inside diameter

Reduces tip temperature

Increase critical velocity gradient??

- Indicates need for further investigation





Bollinger, L. E., & Edse, R. (1956). Effect of Burner-Tip Temperature on Flash Back of Turbulent Hydrogen-Oxygen Flames. *Industrial & Engineering Chemistry*, *48*(4), 802-807.c

Effects of Various Factors

Khitrin, L. N.	Peculiarities of laminar-and turbulent-flame flashbacks	1965
Cescotti, R.	Burners and flame technology	1968
Plee, S. L., & Mellor, A. M.	Review of flashback reported in prevaporizing-premixing combustors	1978
Ball, D. A.,& Putnam, A. A.	Relation to burning velocity, quenching distance, and flash-back velocity gradient for low-and intermediate-Btu gases	1978
Putnam, A. A., & Ball, D. A.	Effect of fuel composition on relation of burning velocity to product of quenching distance and flashback velocity gradient	1980
Lee, S. T., & T'ien, J. S.	A numerical-analysis of flame flashback in a premixed laminar system	1982
Fox, J. S., & Bhargava, A.	Flame speed and flashback gradient for simulated biomass gasification products	1984
Karim, G. A., & Kibrya, M. G.	Flashback limits and flame propagation through a premixed stream of fuel and air near the lean flammability limit	1984
Karim, G. A., Wierzba, I., & Hanna, M.	The blowout limit of a jet diffusion flame in a coflowing stream of lean gaseous fuel-air mixtures	1984

Khitrin

$$g = 0.023\,\mathrm{Re}^{0.8}\left(\frac{\overline{U}}{D}\right)$$

$$g_c = \frac{S_L}{\delta_b}$$

$$Pe_f = \frac{\delta_b}{D}\mathrm{Re}^{1.8}\,\mathrm{Pr} \xrightarrow{\delta_b = K\frac{\alpha}{S_L}} \mathrm{Re} = const.Pe_f^{1.10}$$

Methane

Tip Temperature/Materials?

Lee, S. T. and J. S. Tien (1982)

$$Pe_J = \frac{1}{8K}(Pe_F)^2 \Rightarrow \frac{Pe_F^{\,2}}{Pe_J} = \frac{\left(\frac{D*S_L}{\alpha}\right)^2}{\frac{D*V}{\alpha}} = \frac{S_L^{\,2}D}{\alpha V} = \frac{D}{V}\frac{S_L}{\left(\frac{\alpha}{S_L}\right)} = \frac{\tau_{flow}}{\tau_{reaction}} = Da$$

Different Flashback Mechanisms

Kroner, M., and Fritz, J.,	Flashback limits for combustion induced vortex breakdown in a swirl burner	2002
Kroner, M., and Fritz, J.,	Flashback limits for combustion induced vortex breakdown in a swirl burner	2003
Davu, D., Franco, R.	Investigation on flashback propensity of syngas premixed flames	2005
Xu, G., Tian, Y.,	Flashback limit and mechanism of methane and syngas fuel	2006
Burmberger, S., Hirsch, C.,	Designing a radial swirler vortex breakdown burner	2006
Noble, D. R., Zhang, Q.,	Syngas Mixture Composition Effects Upon Flashback and Blowout	2006
Noble, D. R., Q. Zhang,	Syngas fuel composition sensitivities of combustor flashback and blowout.	2006
Song, Q., Fang, A.	Dynamic and flashback characteristics of the syngas premixed swirling combustors	2008
Littlejohn, D., Cheng, R. K.	A comparison between the combustion of natural gas and partially reformed natural gas in an atmospheric lean premixed turbine-type combustor	2008
Littlejohn, D., Cheng, R. K.	Laboratory investigations of a low-swirl injector with H2 and CH4 at gas turbine conditions	2009
Shelil, N., Bagdanavicius, A.	Premixed swirl combustion and flashback analysis with hydrogen/methane mixtures	2010
Syred, N., Abdulsada, M.	The effect of hydrogen containing fuel blends upon flashback in swirl burners	2011
Jejurkar, S. Y., & Mishra, D. P.	Flame stability studies in a hydrogen-air premixed flame annular microcombustor	2011

- **Swirling Flows: Combustion induced vortex breakdown (CIVB)**
- **Flashback in the core flow**
- **Syngas**

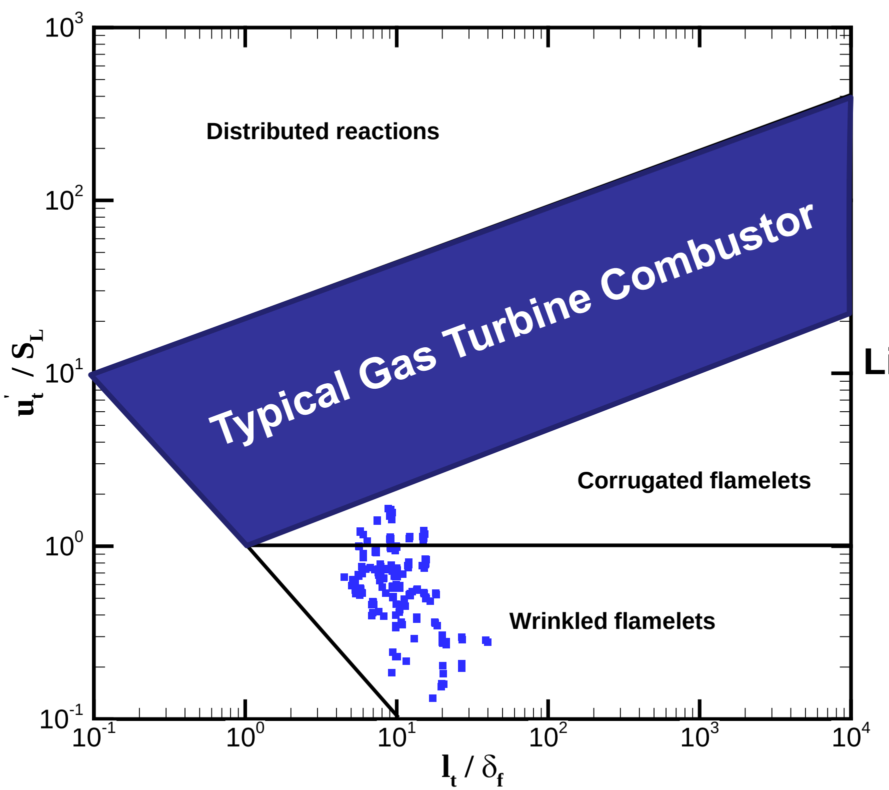
Synthesis Gas

Wang, Q., McDonell, V.	Correlating flashback tendencies for premixed injection of hydrogen and methane mixtures at elevated temperature and pressure	2009
Daniele, S., Jansohn, P.	**Flashback propensity of syngas flames at high pressure: diagnostic and control**	**2010**
Eichler, C., & Sattelmayer, T.	Experiments on flame flashback in a quasi-2D turbulent wall boundary layer for premixed methane-hydrogen-air mixtures	2011
Eichler, C., & Sattelmayer, T.	Experimental investigation of turbulent boundary layer flashback limits for premixed hydrogen-air flames confined in ducts	2011
Dam, B., Love, N.,	Flashback propensity of syngas fuels.	2011
Syred, N., Abdulsada, M.	The effect of hydrogen containing fuel blends upon flashback in swirl burners	2011
Kedia, K. S., & Ghoniem, A. F.	Mechanisms of stabilization and blowoff of a premixed flame downstream of a heat-conducting perforated plate	2012
Shaffer, B., Duan, Z.,	Study of Fuel Composition effects on flashback using a confined jet flame burner	2013
Lin, Y. C., Daniele, S.,	**Turbulent flame speed as an indicator for flashback propensity of hydrogen-rich fuel gases**	**2013**
Duan, Z., Shaffer, B.,	**Study of fuel composition, burner material, and tip temperature effects on flashback of enclosed jet flame**	**2013**
Duan, Z., Shaffer, B.,	**Influence of burner material, tip temperature, and geometrical flame configuration on flashback propensity of H2-air Jet flames**	**2014**

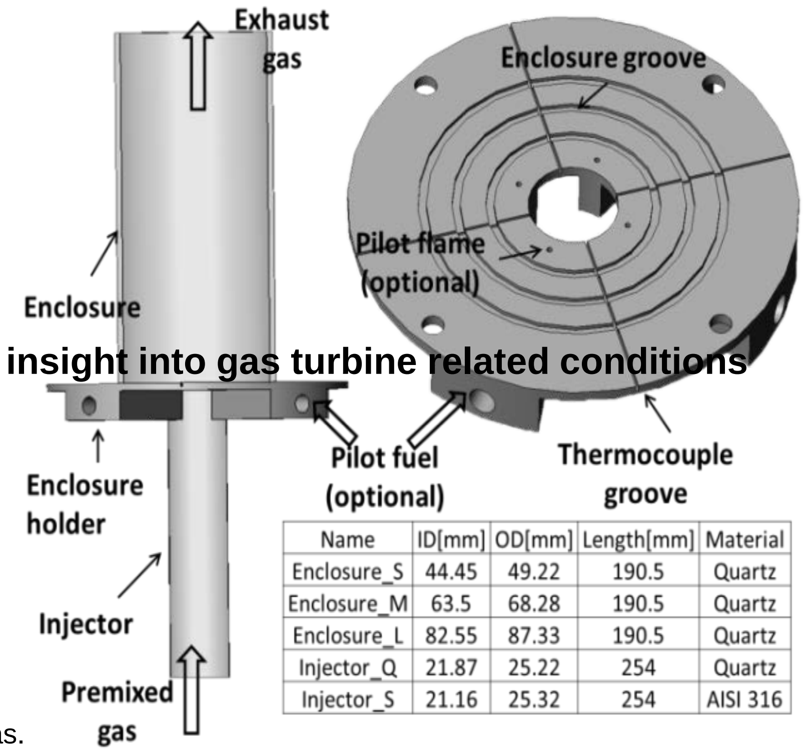
- **High Hydrogen fuels/Syngas**
- **Advanced visualization/diagnostics**
- **Computational Fluid Dynamics**

Systematic Studies

- **Atmospheric studies[1,2] found burner material, tip temperature/inlet temperature and flame confinement impact flashback propensity, while flame enclosure diameter and tube diameter play a negligible role**
- **Empirical correlations improved if burner tip temperature is used rather than the inlet temperature.**



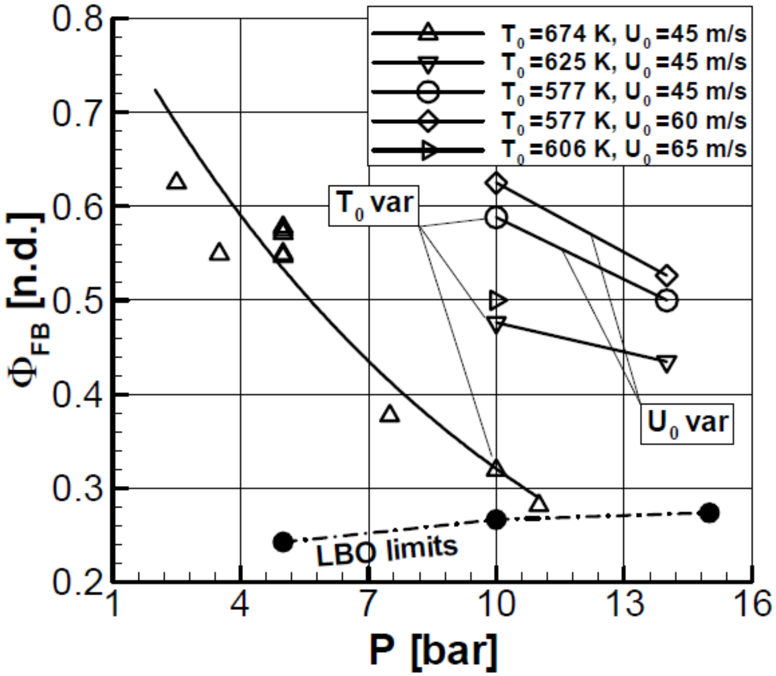
Limited insight into gas turbine related conditions



Name	ID[mm]	OD[mm]	Length[mm]	Material
Enclosure_S	44.45	49.22	190.5	Quartz
Enclosure_M	63.5	68.28	190.5	Quartz
Enclosure_L	82.55	87.33	190.5	Quartz
Injector_Q	21.87	25.22	254	Quartz
Injector_S	21.16	25.32	254	AISI 316

Gas Turbine Premixer Conditions

- **Daniele et al. (2010,2013) investigated flashback propensity of syngas flame at gas turbine conditions**
  - **Systematic studies were not carried out**
  - **Limited data set**



Daniele, S., Jansohn, P., & Boulouchos, K. (2010, October). Flashback Propensity of Syngas Flames at High Pressure: Diagnostic and Control. In *ASME Turbo Expo 2010: Power for Land, Sea, and Air* (pp. 1169-1175). American Society of Mechanical Engineers.

Goals and Objectives

Goals

- **Develop and validate a comprehensive model for prediction of flashback under gas turbine premixer conditions**
  - **The model will incorporate effect of ambient pressure as well as thermal coupling between the flame and the burner rim.**

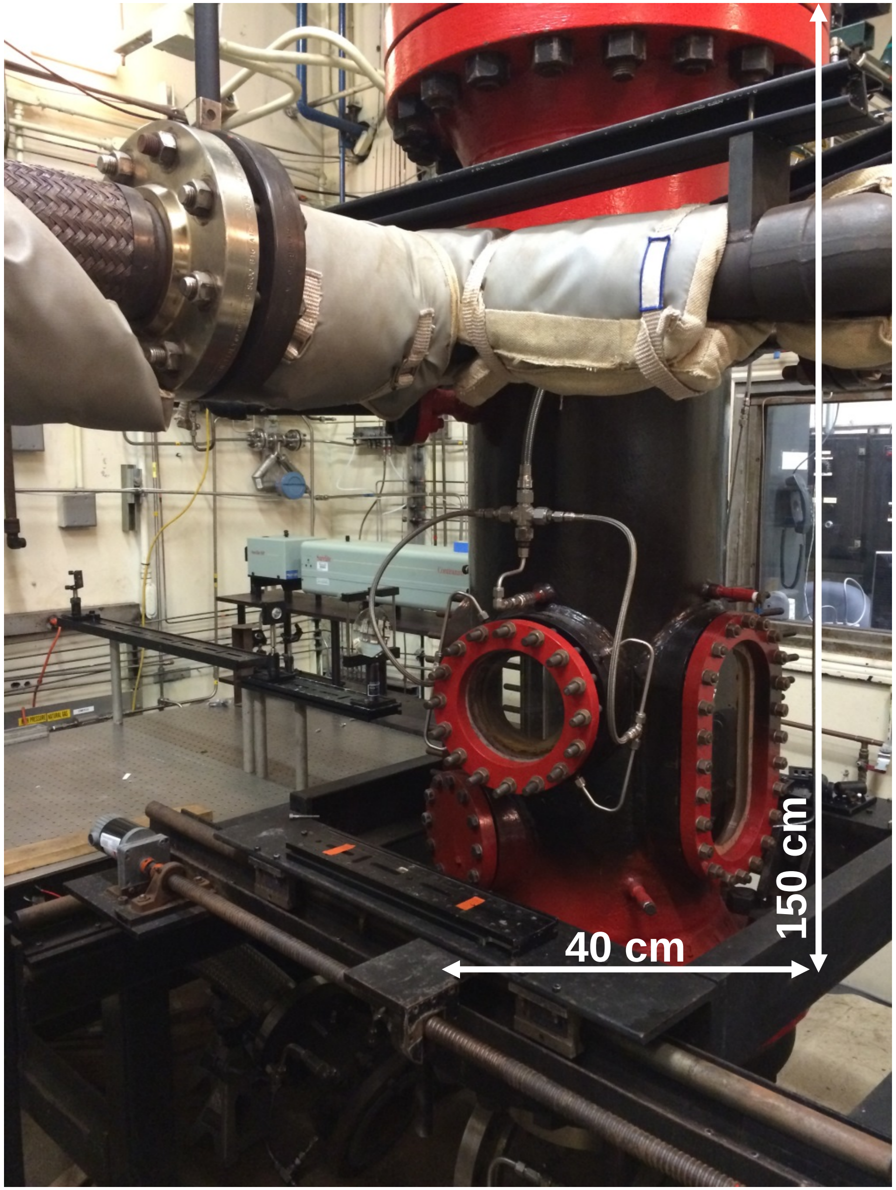
- **Provide detailed insight towards understanding flashback propensity in jet flames at gas turbine related conditions**

Objectives & Timeline

Milestone Title	Planned Completion Date	Actual Completion Date	Verification Method	Comments
Project Management	8/2016			
Test Plan Fuels/Modules **Draft** **Final**	12/2013 1/2014	3/2014	Consensus from OEMs and DOE on plan	Complete Complete
Fabrication of Modules	2/2014	5/2014-9/2015	Photos of completed installation and test hardware	Complete
Diagnostics/Rig Setup and Commissioned	5/2014	10/2014	Comparison of commissioning data with literature data	Complete
Experimental Studies **Phase I** **Phase II**	4/2015 12/2015	8/2015 8/2015	Comparison of commissioning data with literature data	90% Complete
Analysis and Model Development **Empirical Model I** **Empirical Model II** **Physics Base Model**	7/2015 1/2016 4/2016	8/2015 current	Predicted vs Actual Results, Goodness of Fit	EM: 90% Complete

Experiment

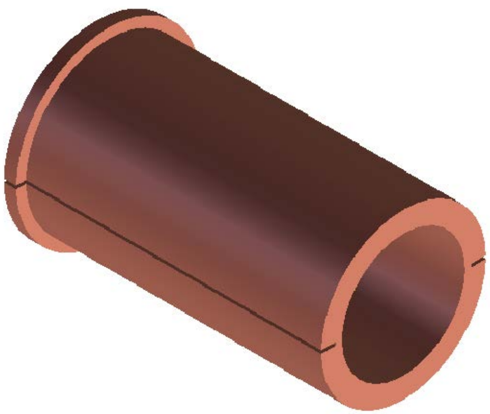
Experimental Setup

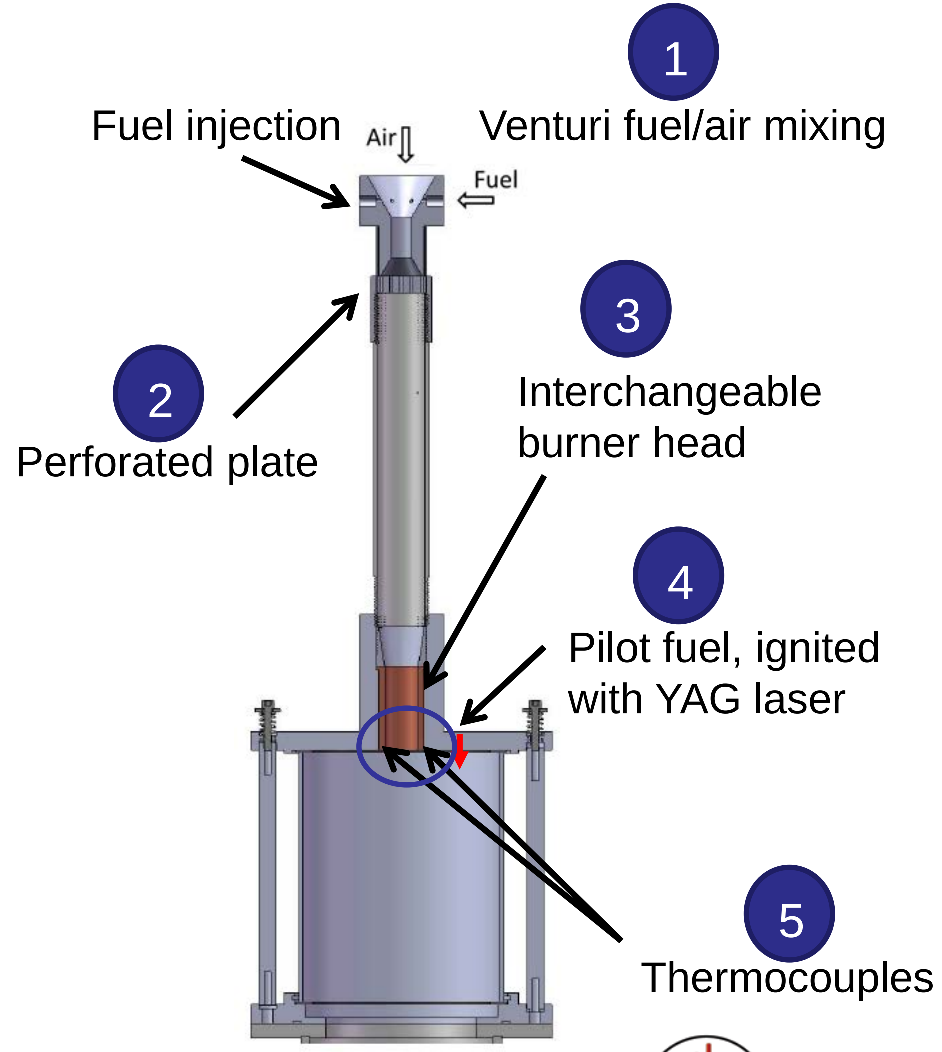


- **Pressure: 15 atm**
- **Preheat temperature: 1100 K**
- **Air flow rate: 1.5 kg/sec continuous**
- **Fuel: High-pressure supply**
  - **Liquid fuels**
  - **Gaseous fuel blends**
  - **Natural Gas: 0.1 kg/sec, 35 atm**
- **Optical access**
- **Water quench system**

Experimental Setup

Premixed Jet Flame





Experimental Setup

Nd:YAG laser

Burner

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Testing

Test Parameters

- **Pressure**
  - 3 atm to 9 atm

- **Preheated temperature**
  - 300 K to 700 K

- **Fuel compositions**

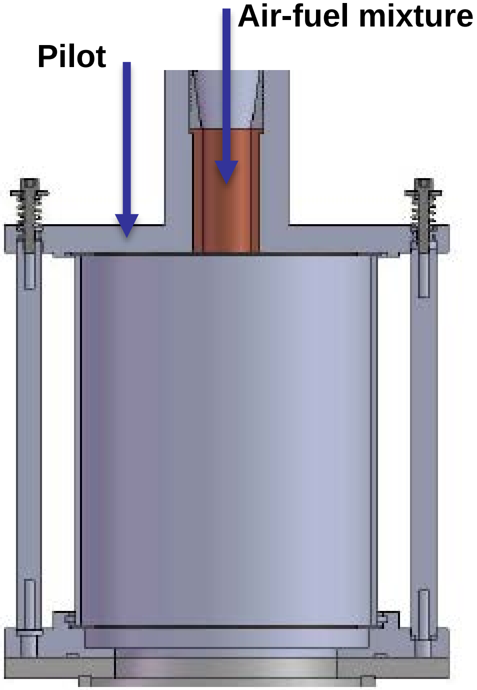
	Volume percent	
H_2	100	50
CH_4	0	50

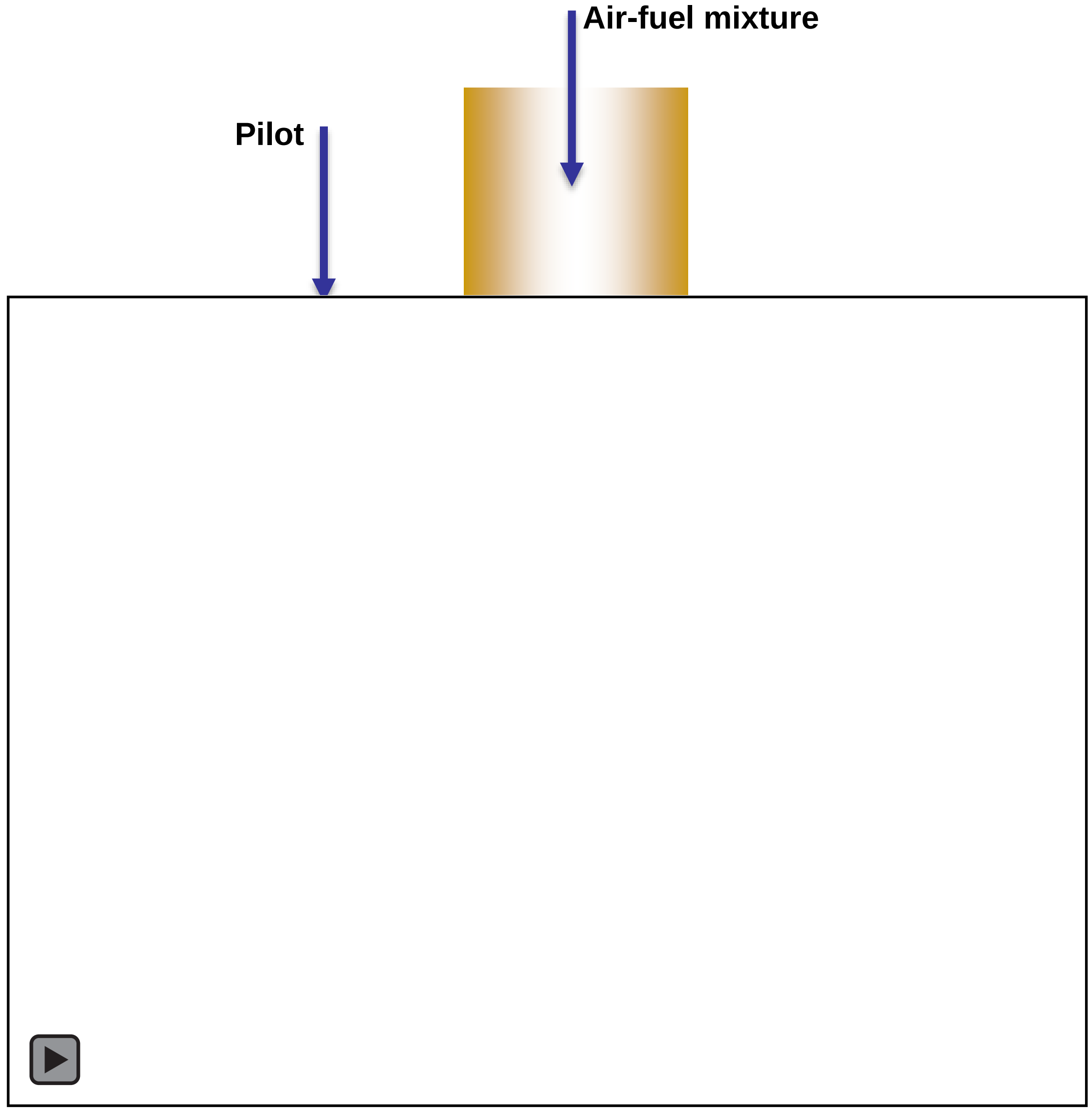
- **Burner materials**

Material	**Heat Capacity**	**Heat Conductivity**	**Density**
[-]	[J/(g*C)]	[W/(m*k)]	[g/cm^3]
SS-304	0.500	21.5	8.0
Copper	0.385	385.0	7.9
Ceramic	0.456	0.9	4.0

Testing

P=7 atm
T_u=500 K, Inlet temperature
U_b=35 m/s, Bulk Velocity
Hydrogen fuel
Stainless steel Burner head

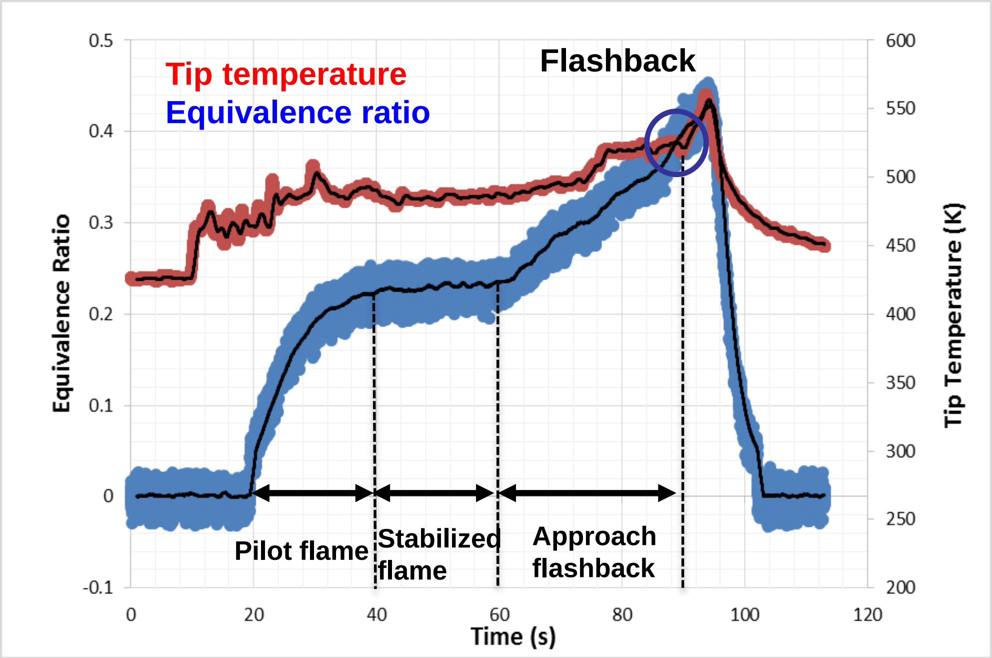


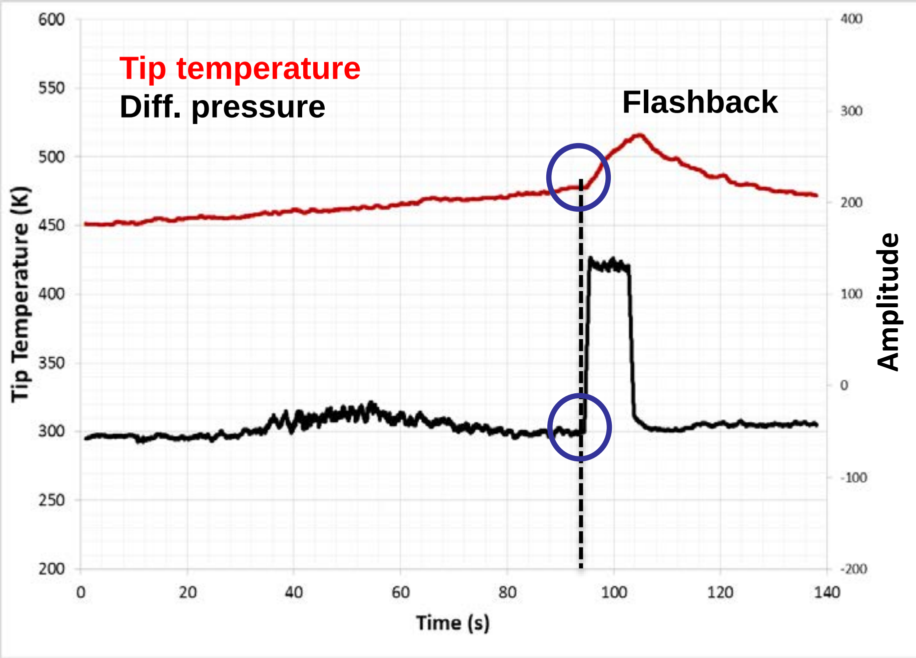


Flashback Monitoring

- **Flashback strategy**

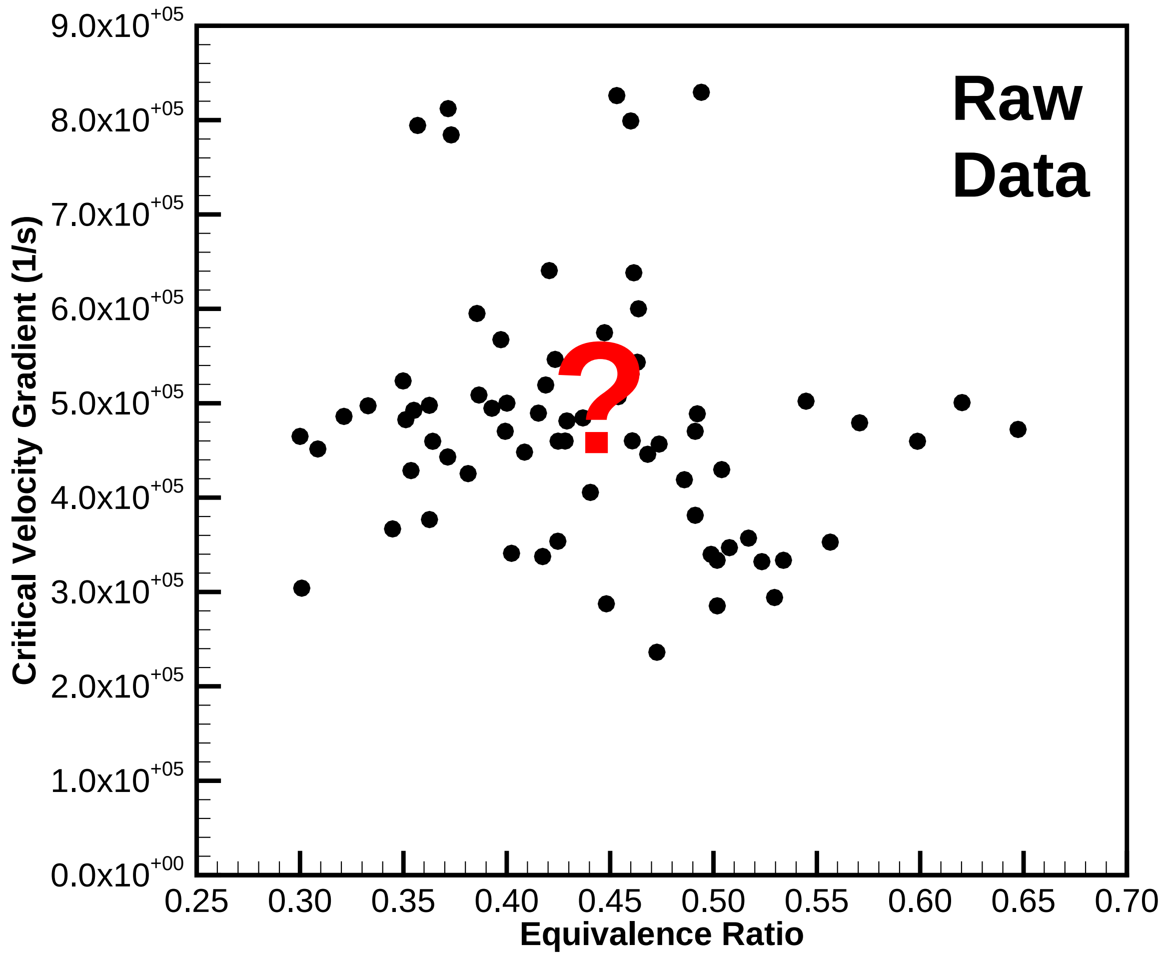
Constant air mass flow rate





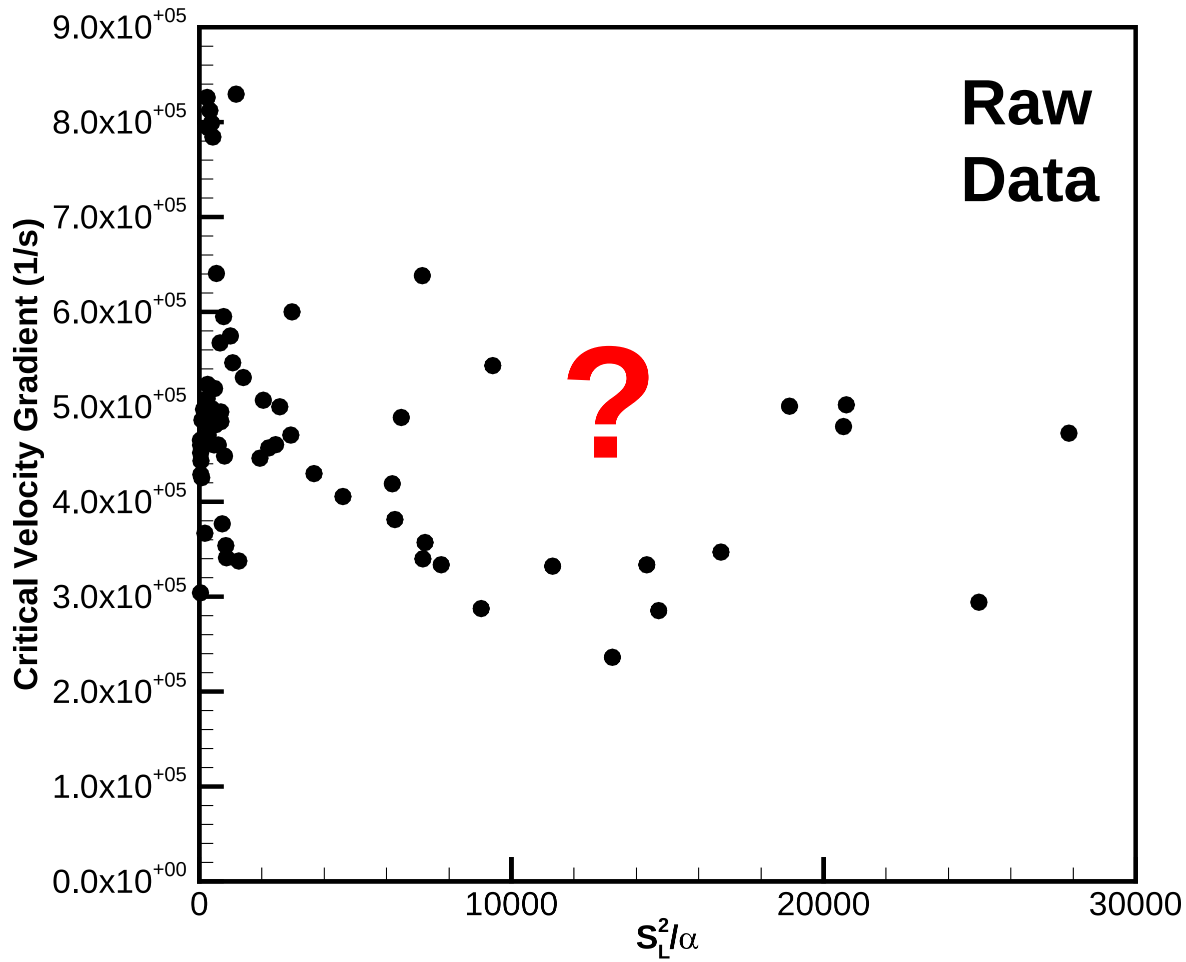
Results & Analysis

Results



Higher velocity gradient → **Higher flashback propensity**

Results



Higher velocity gradient → **Higher flashback propensity**

Analysis

Symbol	Definition
Flow characteristics	
$\overline{U}$	bulk velocity of the mixture
u'	turbulent intensity
Thermodynamics properties of flow	
ρ_u	density based on unburnt conditions
μ_u	kinetic viscosity based on unburnt conditions
T_u	Unburnt temperature
P_u	Unburnt pressure
α_u	thermal diffusivity based on unburnt conditions
C_{P_u}	thermal capacity based on unburnt conditions
k_u	thermal conductivity based on unburnt conditions
D_u	Mass diffusivity of fuel composition into the mixture

Symbol	Definition
Premixed flame characteristics	
T_f	adiabatic flame temperature based on unburnt conditions
S_{L_u}	laminar flame speed based on unburnt conditions
LHV	lower heating value based on unburnt conditions
T_{tip}	Measured burner tip temperature
g_c	critical velocity gradient when flashback happens
h'	convective heat transfer coefficient
Ambient conditions	
T_0	ambient temperature
P_0	ambient pressure
Burner properties	
k'	thermal conductivity of the burner material
d	diameter of the burner
θ'	thickness of the burner wall

Analysis

- **Non-dimensional groups**

$$\begin{cases} g_c \approx \dfrac{S_L}{\delta_p} \\ \delta_p \approx \delta_q = 2\sqrt{b}\,\dfrac{\alpha}{S_L} \end{cases}$$

$$\Pi_1 = Da = \frac{S_L^{\,2}}{\alpha \cdot g_c}$$

$$\begin{cases} g = \dfrac{1}{8}\dfrac{f\overline{U}^2}{\nu} \\ \dfrac{1}{\sqrt{f}} = 2.0\log\left(Re_D\sqrt{f}\right) - 0.8, \\ 3.1 \times 10^3 < Re_D < 3.2 \times 10^6 \\ f = \dfrac{0.3164}{Re_D^{0.25}}, \qquad 4 \times 10^3 < Re_D < 10^5 \end{cases}$$

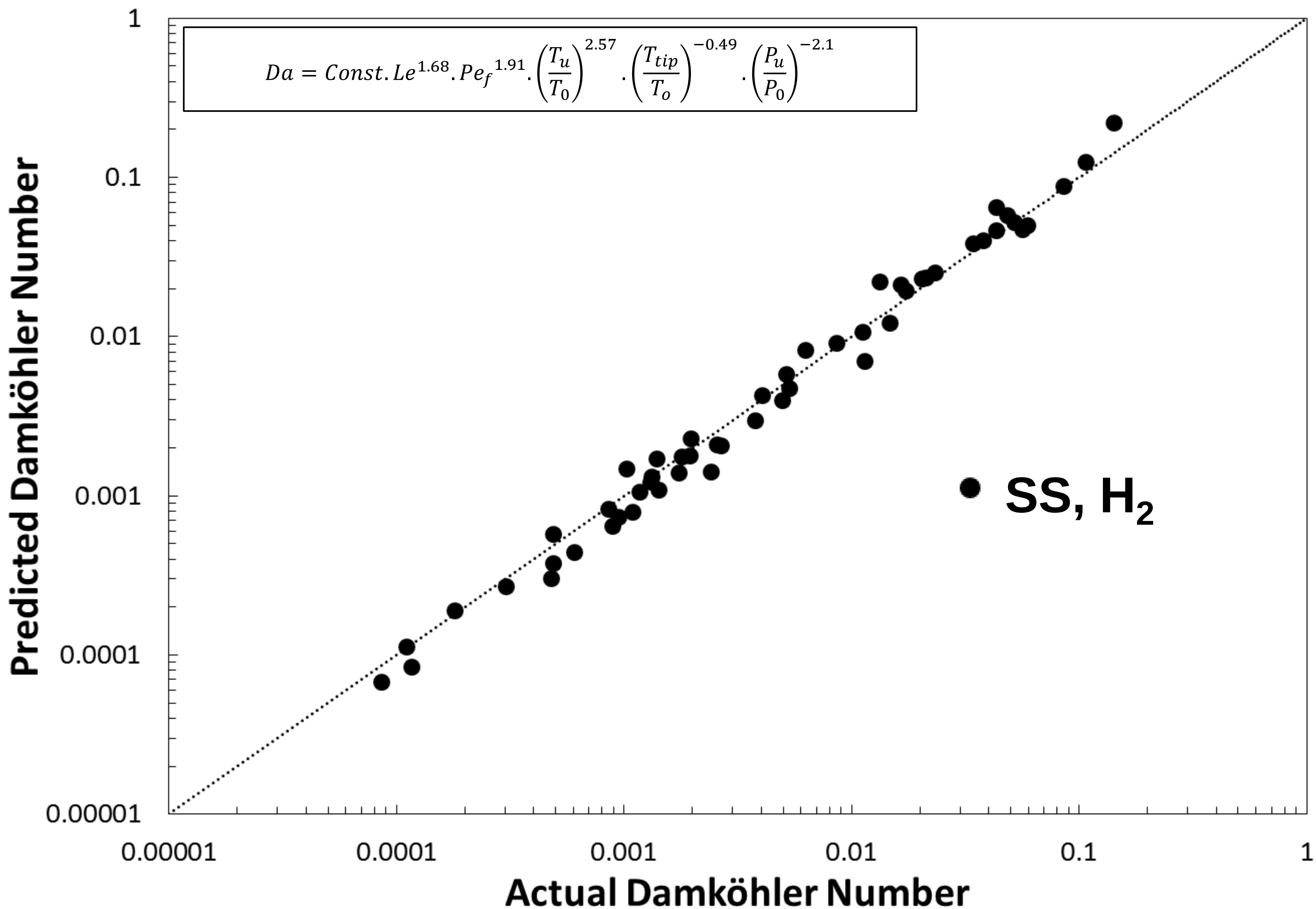
$$\Pi_1 = f(\Pi_2, \Pi_3, \Pi_4, \Pi_5, \Pi_6)$$

$$\Pi_2 = \frac{T_u}{T_0}, \Pi_3 = Le, \Pi_4 = \frac{T_{tip}}{T_0}, \Pi_5 = \frac{d \cdot S_L}{\alpha}, \Pi_6 = P_u/P_0$$

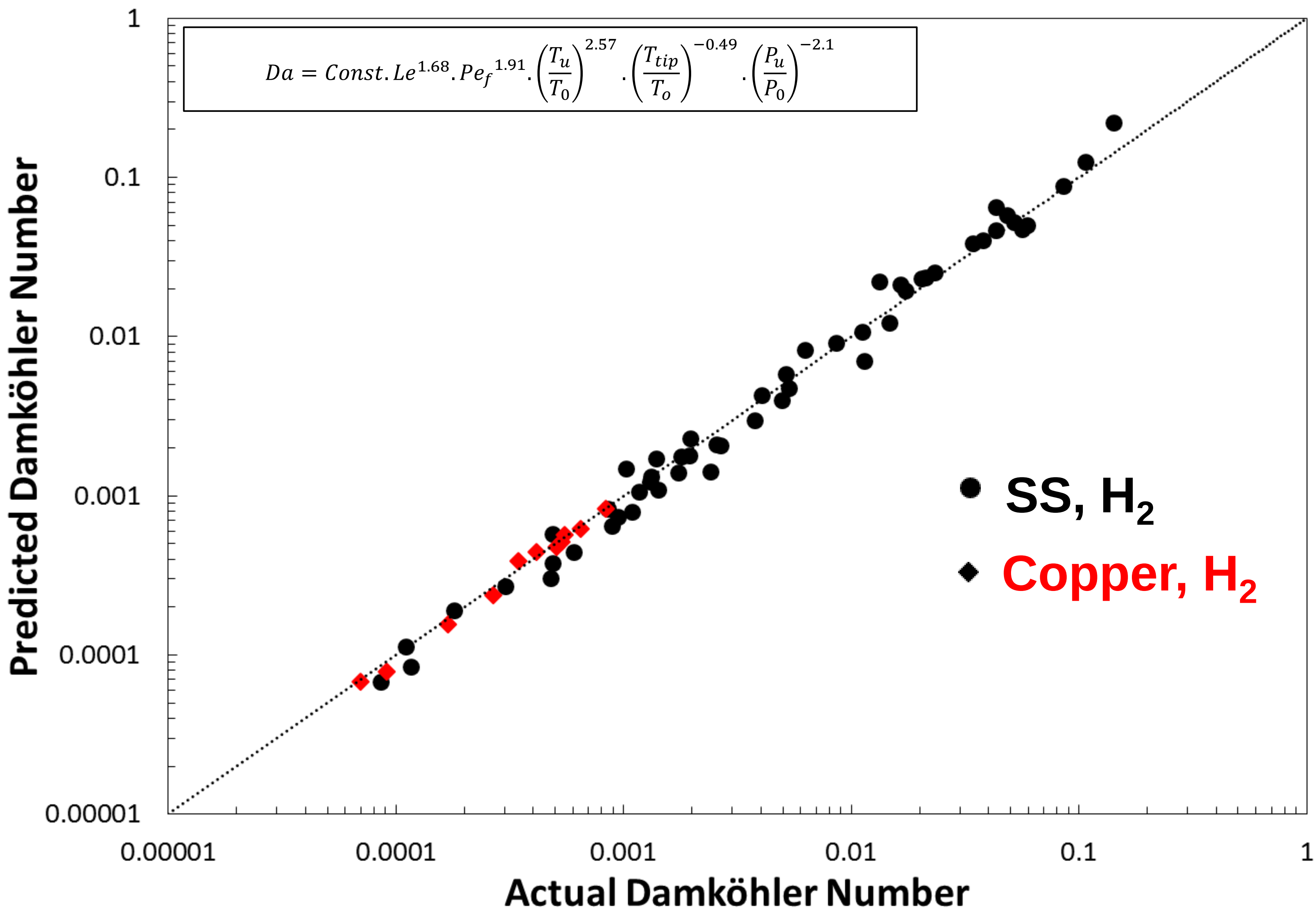
$$\Pi_5 = Pe_F = \frac{d.S_L}{\alpha}$$

$$Da = Const.Le^{1.68}.Pe_f^{\,1.91}.\left(\frac{T_u}{T_0}\right)^{2.57}.\left(\frac{T_{tip}}{T_o}\right)^{-0.49}.\left(\frac{P_u}{P_0}\right)^{-2.1}$$

Model Performance

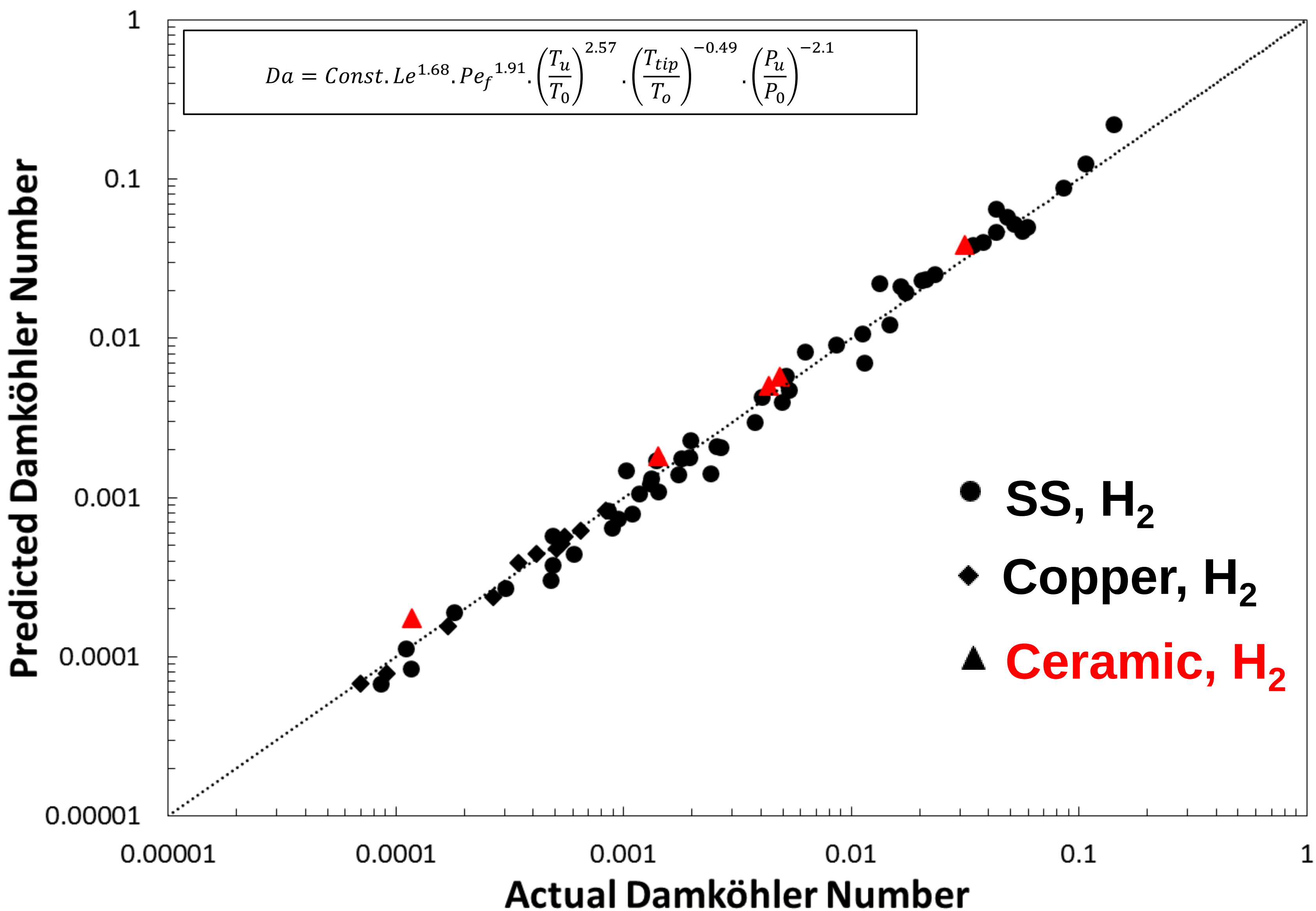


Model Performance

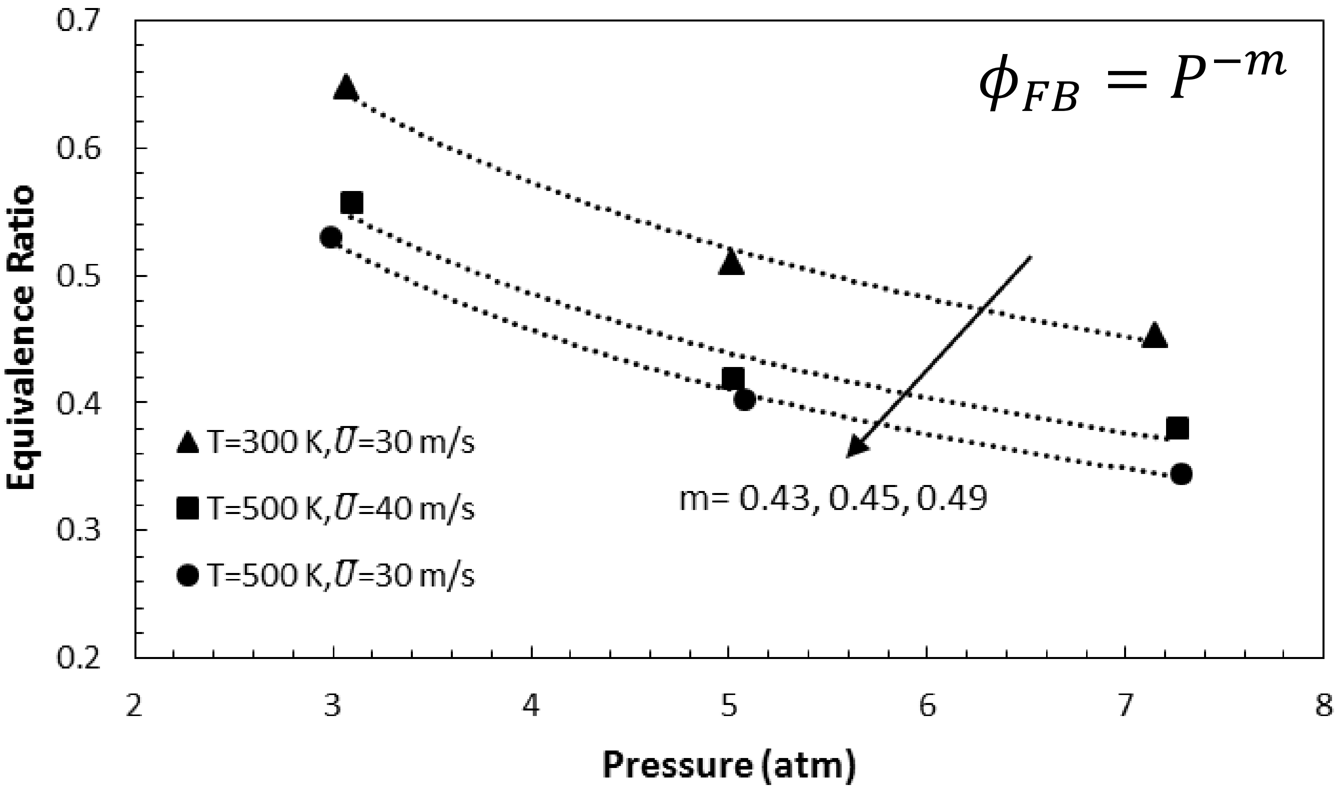


Model Performance

$$Da = Const.Le^{1.68}.Pe_f^{\,1.91}.\left(\frac{T_u}{T_0}\right)^{2.57}.\left(\frac{T_{tip}}{T_o}\right)^{-0.49}.\left(\frac{P_u}{P_0}\right)^{-2.1}$$



- **SS Burner Head**
  - **Effect of Inlet Temp, Bulk Velocity, and Pressure on Equivalence Ratio at Flashback**
    - **Measurements vs Model**



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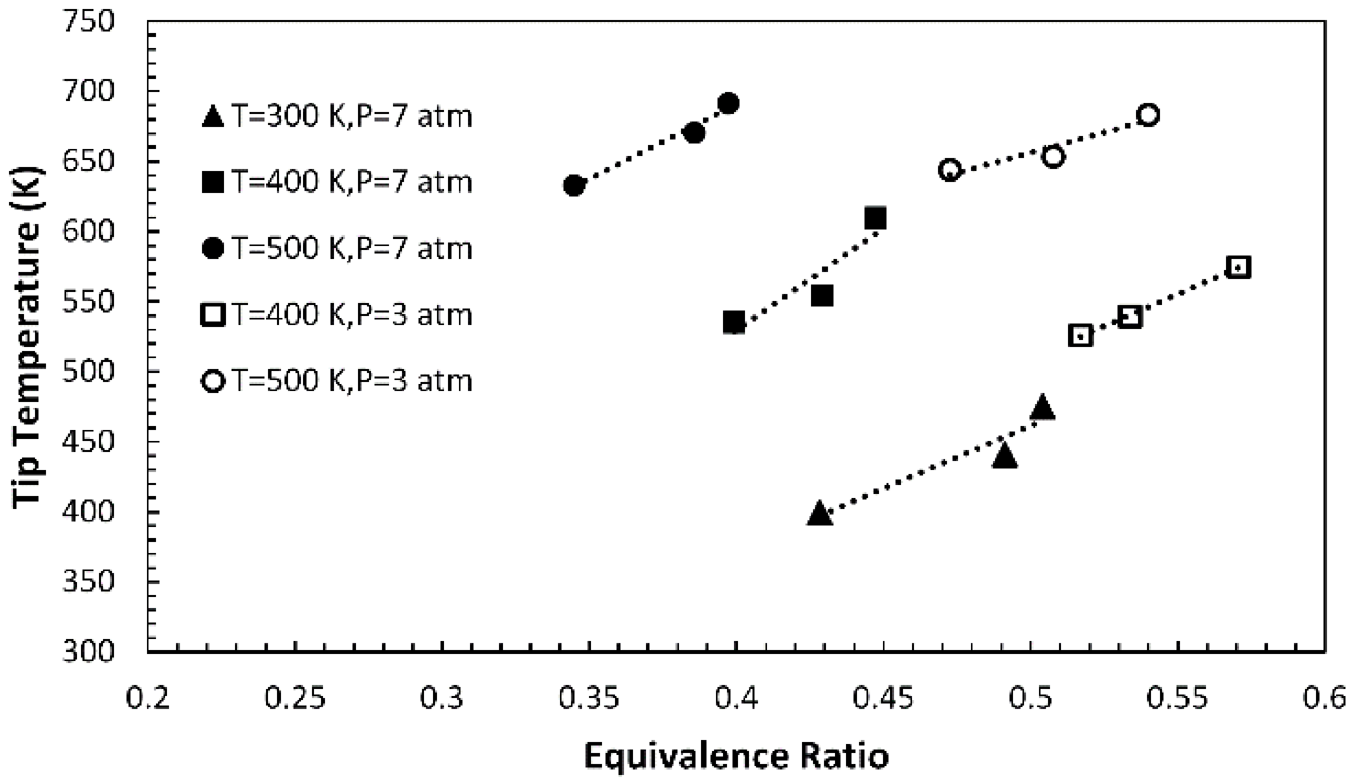
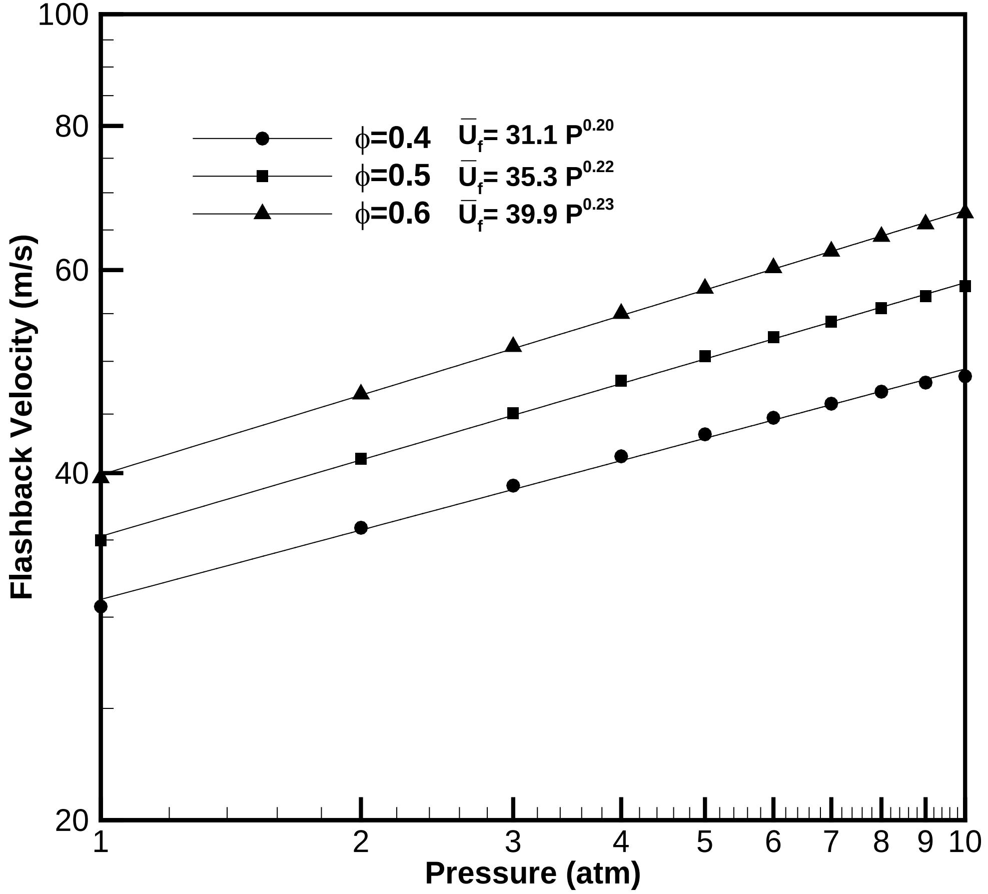
Interpretation

- **SS Burner Head**
  - **Impact of Pressure, Inlet Temperature, and Equivalence Ratio on Tip Temperature at Flashback**
    - **Model vs Measurements**



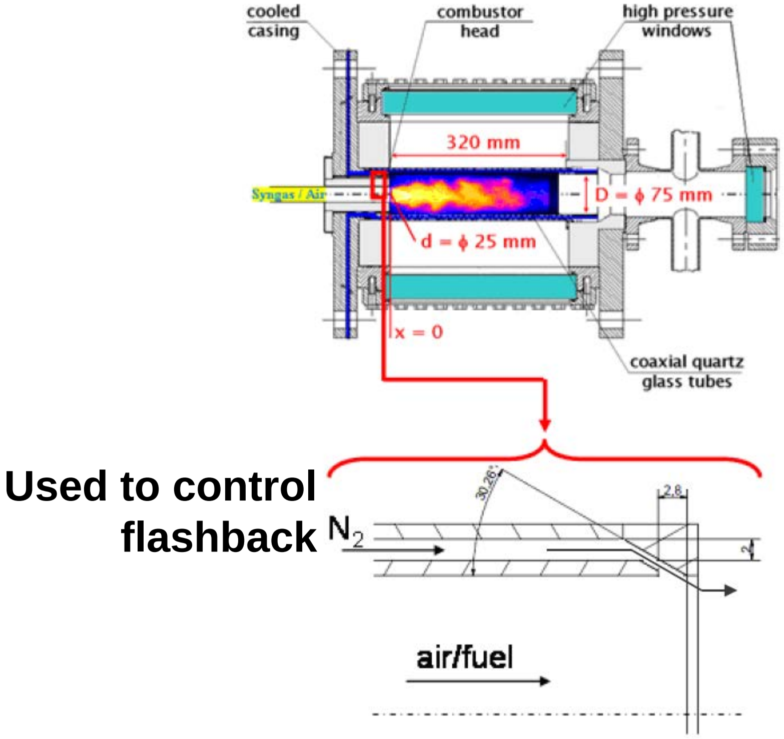
Interpretation

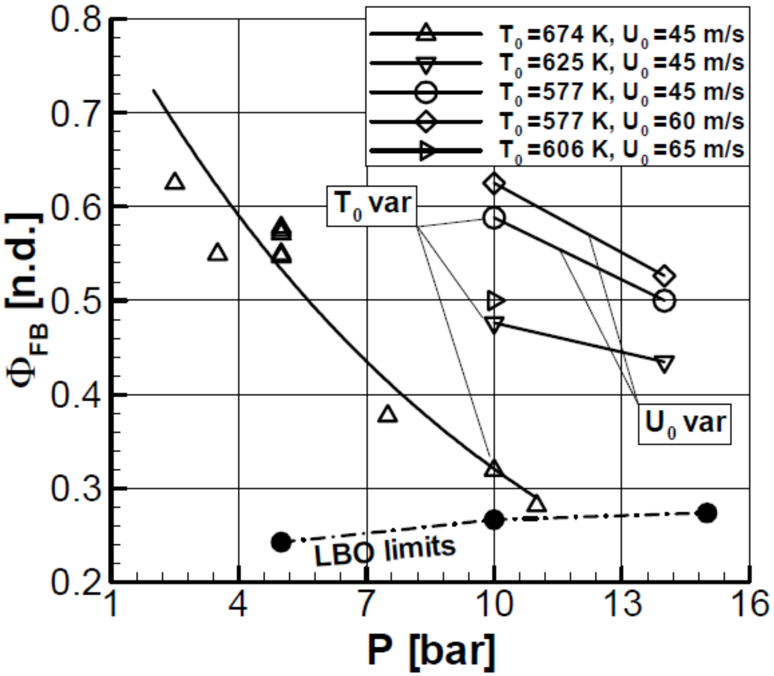
- **SS Burner Head**
  - **Effect of Pressure and Equivalence Ratio on Bulk Velocity at Flashback (Prediction)**



Validation

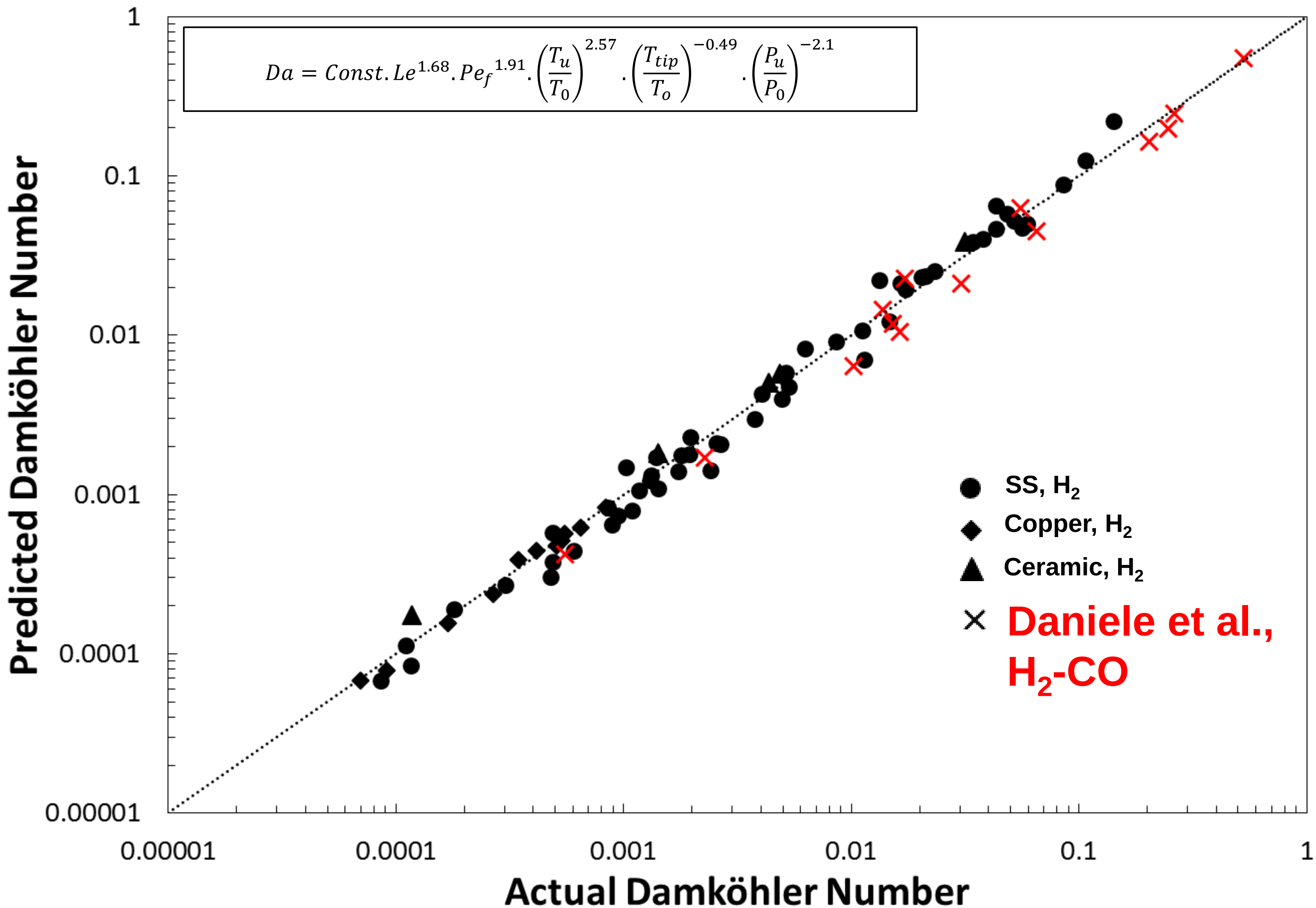
- **Comparison to Other Data Sets in Literature**
  - **Danielle, et al., 2010**
    - **Syngas/Air jet flames studied in context of global consumption based turbulent flame speed measurements**





Daniele, S., Jansohn, P., & Boulouchos, K. (2010). Flashback Propensity of Syngas Flames at High Pressure: Diagnostic and Control. Paper GT2010-23456 TurboExpo 2010, Vancouver, Canada, June

Validation



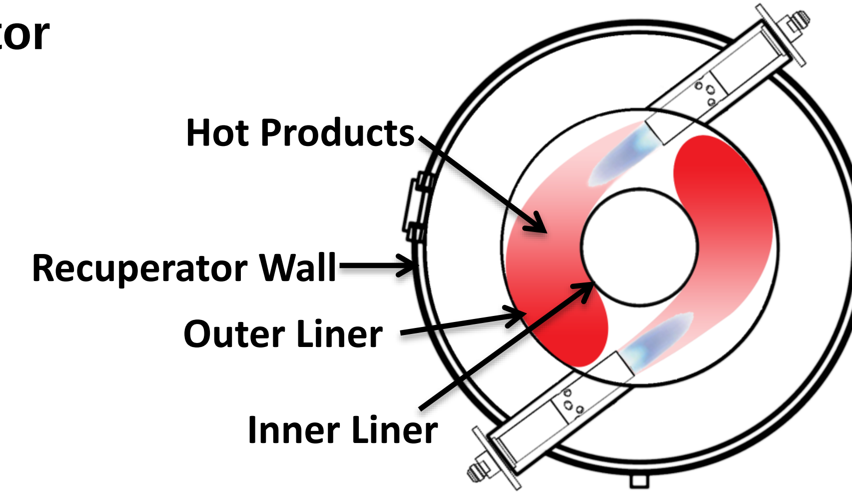
$Da = Const.Le^{1.68}.Pe_f^{1.91}.\left(\frac{T_u}{T_0}\right)^{2.57}.\left(\frac{T_{tip}}{T_o}\right)^{-0.49}.\left(\frac{P_u}{P_0}\right)^{-2.1}$
Predicted Damköhler Number
Actual Damköhler Number
1
0.1
0.01
0.001
0.0001
0.00001
1
SS, H_2
Copper, H_2
Ceramic, H_2
Daniele et al., H_2-CO

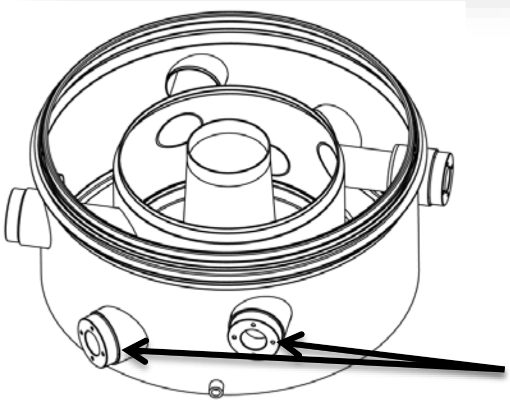
Validation

- **Comparison to Page, et al., 2012**

Capstone C65 Microturbine Combustor

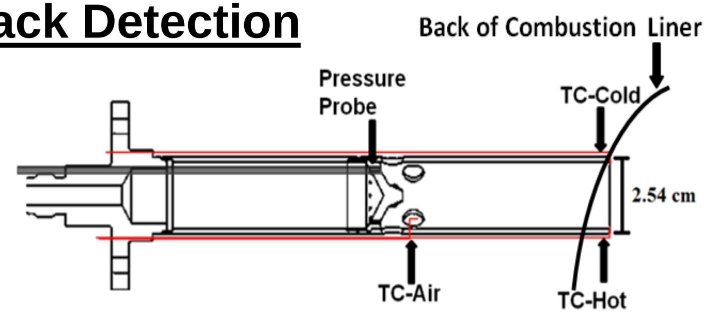
Bottom Plane





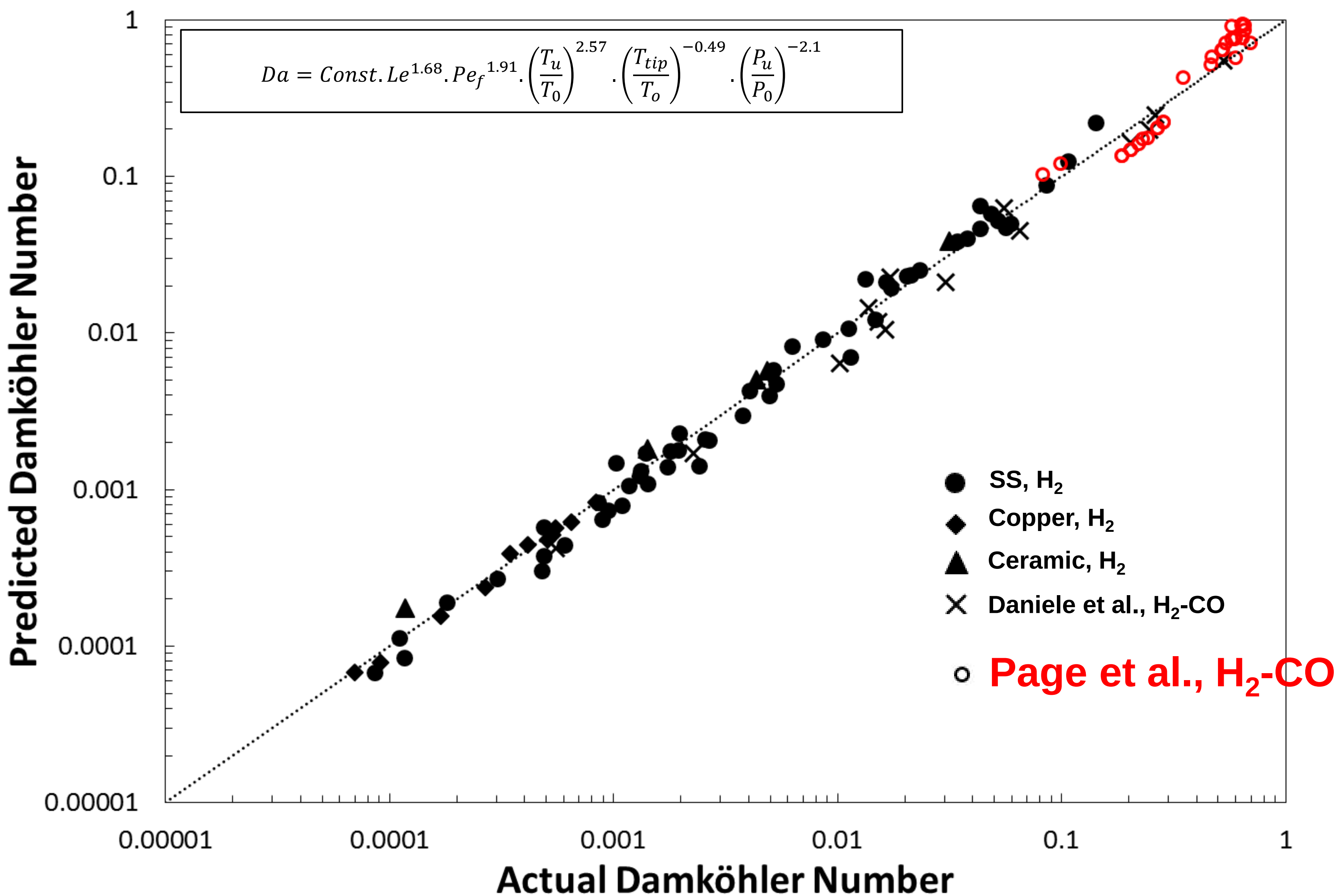
2 planes of Injectors

Flashback Detection



Page, D., Shaffer, B. and McDonell, V. (2012). Establishing Operating Limits in a Commercial Lean Premixed Combustor Operating on Synthesis Gas Pertaining to Flashback and Blowout. Paper GT2012-69355, TurboExpo 2012, Copenhagen, June

Validation



$$Da = Const.Le^{1.68}.Pe_f^{1.91}.\left(\frac{T_u}{T_0}\right)^{2.57}.\left(\frac{T_{tip}}{T_o}\right)^{-0.49}.\left(\frac{P_u}{P_0}\right)^{-2.1}$$
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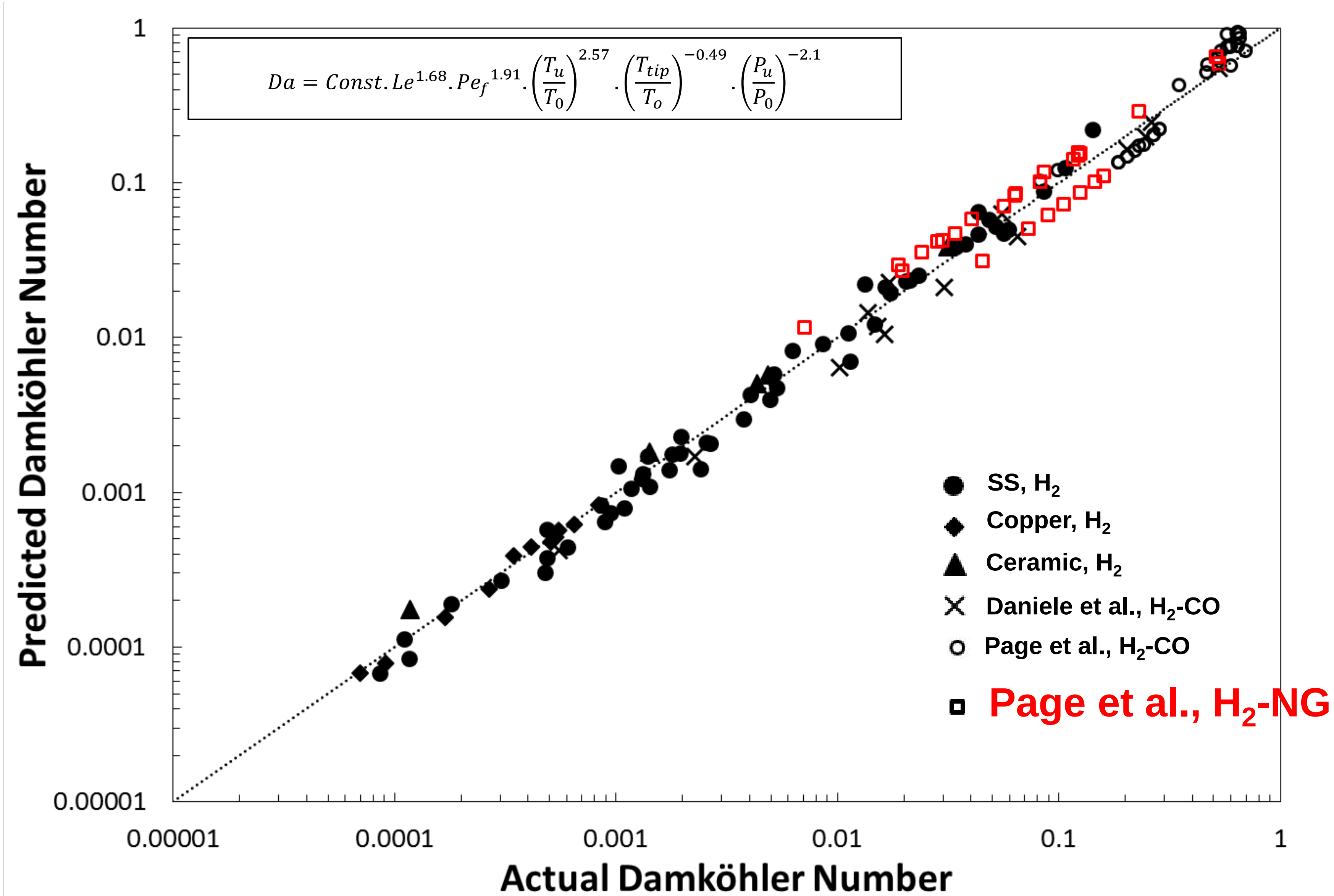
Page et al., H_2-CO

Validation



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Summary

- **Boundary layer flashback experiments have been carried out at elevated pressures and temperatures for various bulk velocities, burner materials, and equivalence ratios**
  - **Buckingham Pi theorem applied to develop correlation**

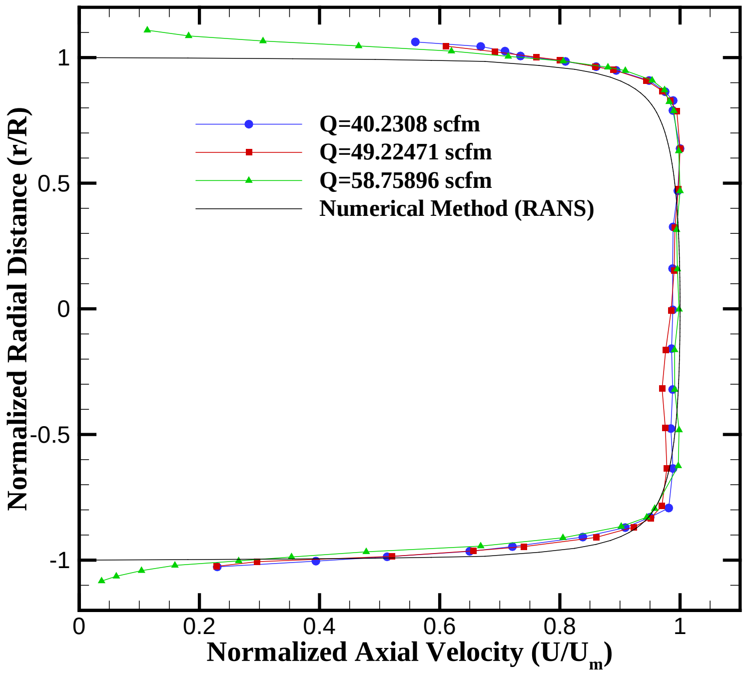
$$Da = Const.Le^{1.68}.{Pe_f}^{1.91}.\left(\frac{T_u}{T_0}\right)^{2.57}.\left(\frac{T_{tip}}{T_o}\right)^{-0.49}.\left(\frac{P_u}{P_0}\right)^{-2.1}$$

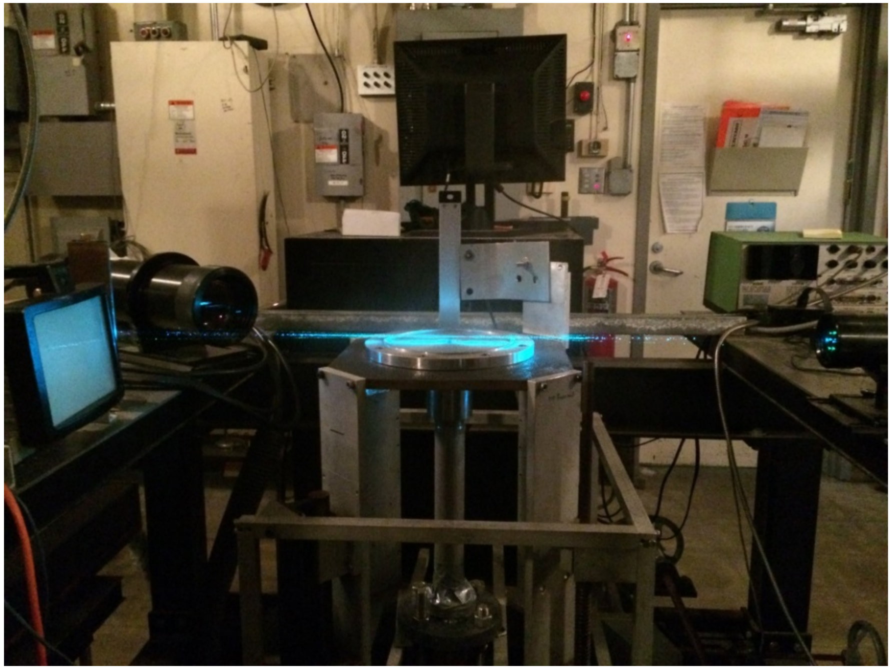
- **The resulting correlation was applied to current data as well as literature data and found to provide reasonable ability to predict flashback tendencies for the parameters studied**

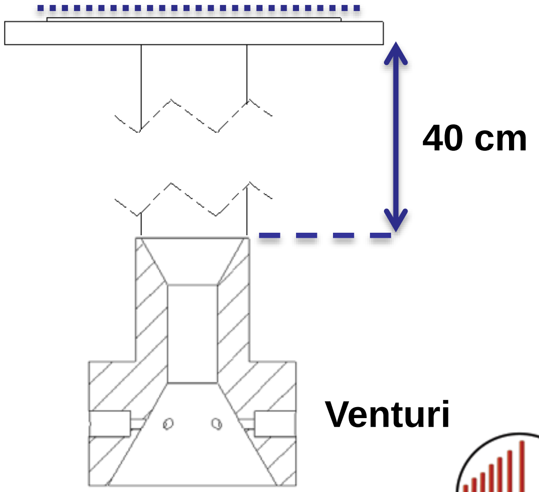
Experimental Setup

- **Velocity profile using LDV**

Fully developed turbulent flow





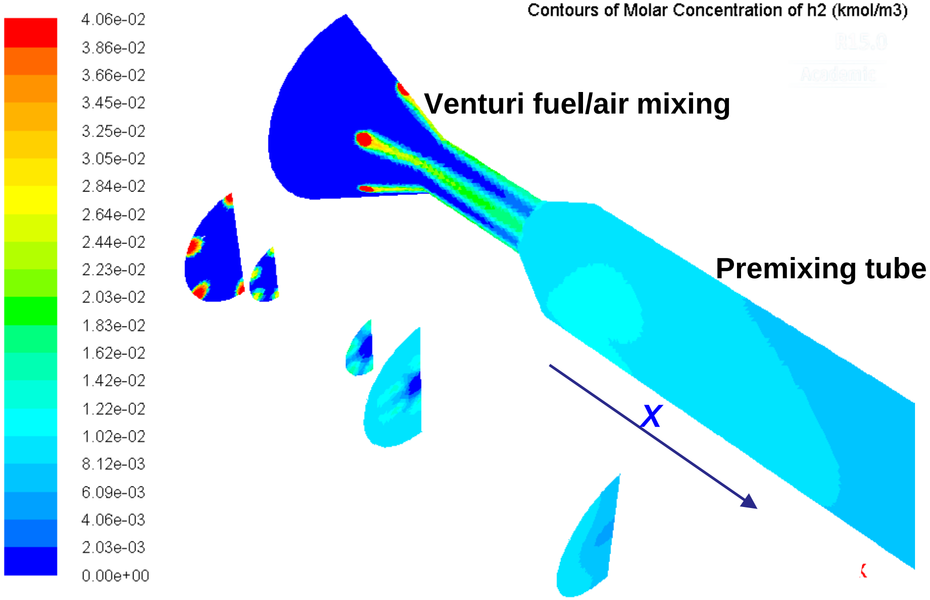


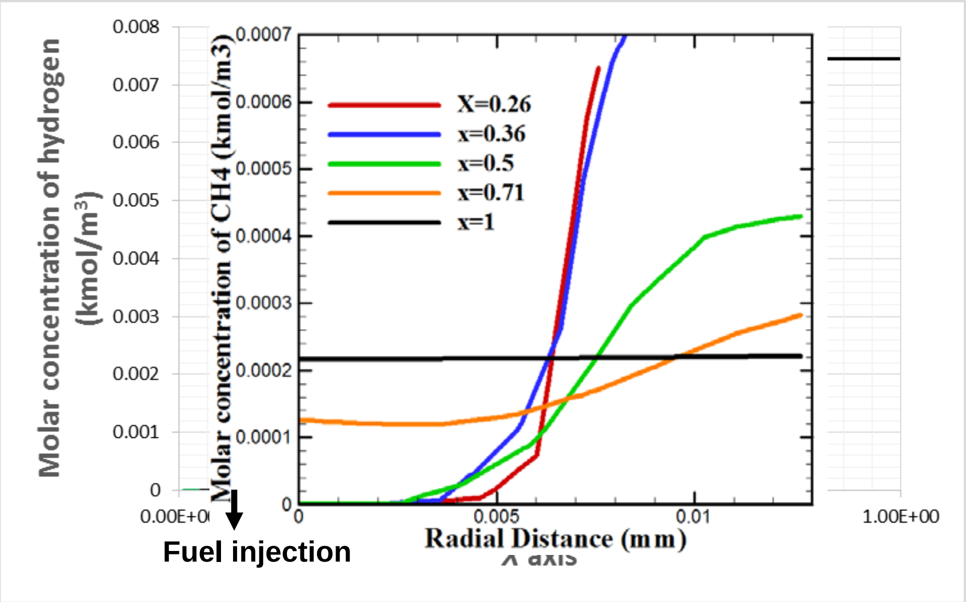
Fuel/Air Mixing

Mixing performance

- **Computational modeling**

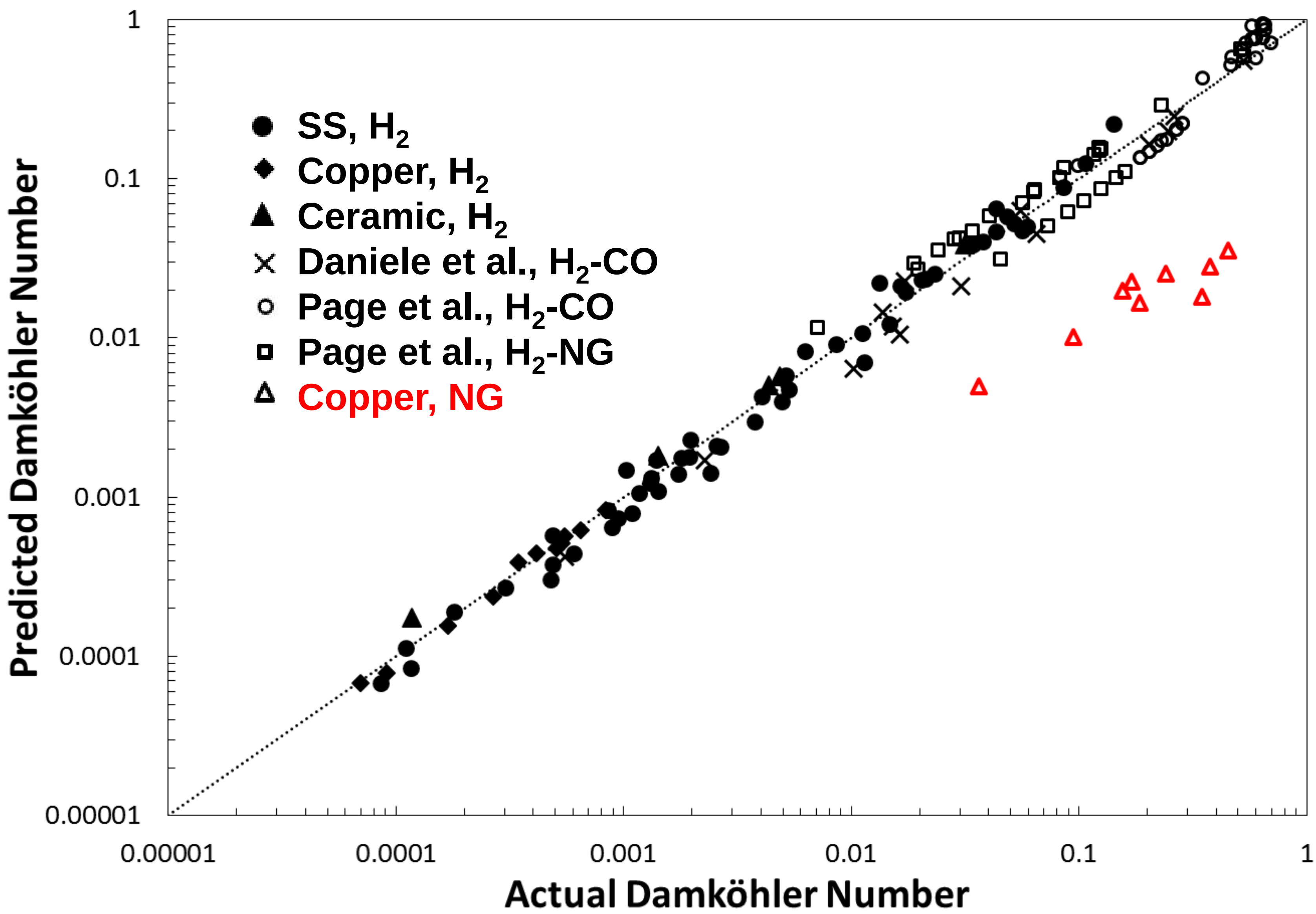
contour of molar concentration for pure hydrogen fuel





Homogeneous mixture at premixing tube outlet

Results



SS, H_2
Copper, H_2
Ceramic, H_2
Daniele et al., H_2-CO
Page et al., H_2-CO
Page et al., H_2-NG
Copper, NG
Predicted Damköhler Number
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0.001
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0.00001
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0.001
0.01
0.1
1

Alternative Formulation

- **Lin and Danielle (2013)** $g_c = S_T / (Le \times \delta_{L0})$
  - **Proposed correlation based on turbulent flame speed**

$$\frac{S_T}{S_L} \approx \left(\frac{P}{P_0}\right)^m \left(\frac{u'}{S_L}\right)^n$$

  - **Facilitates incorporation of turbulence levels**

$$g_c = f\left(Le, S_L, u', \frac{P}{P_0}, \alpha\right)$$

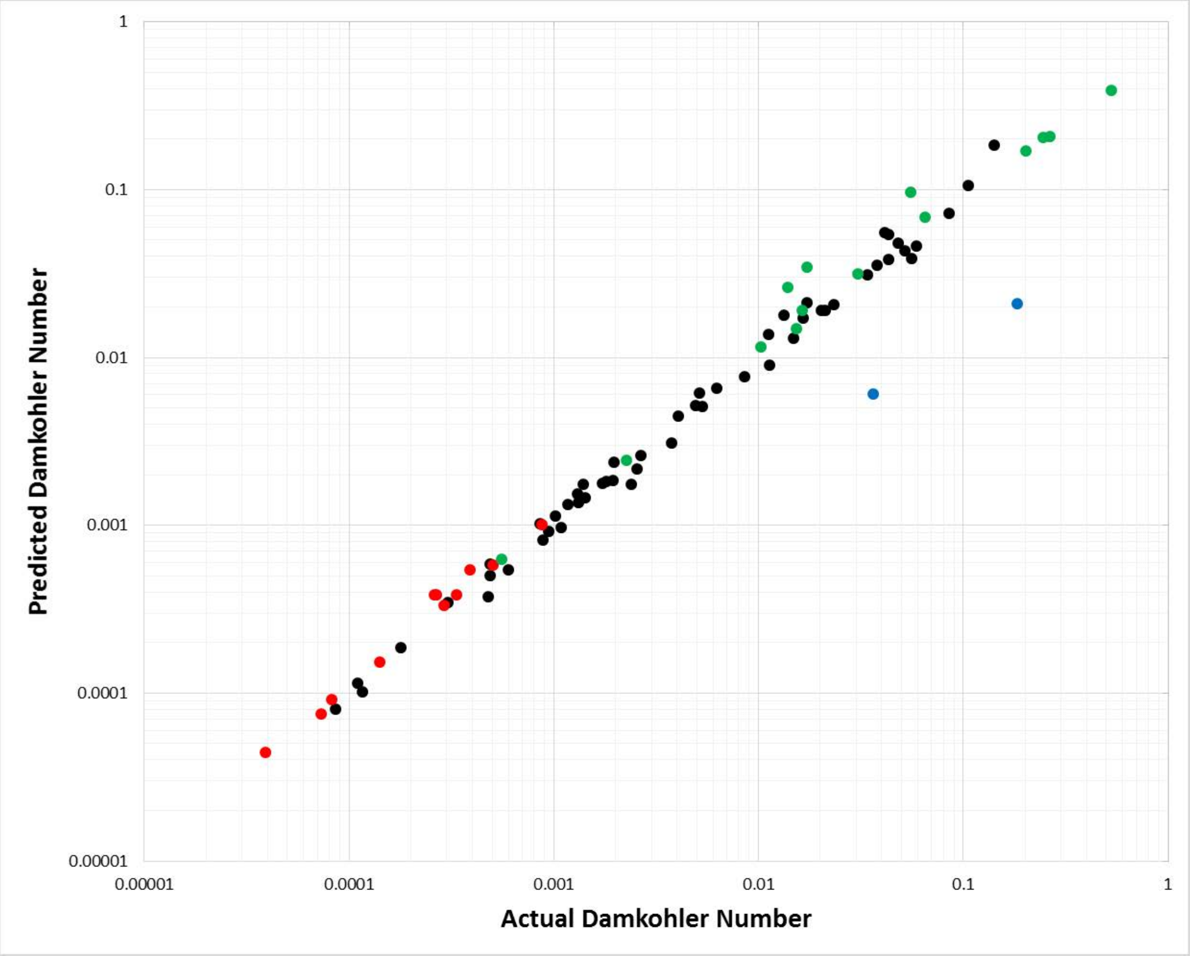
Results

Pressure
- 3 atm to 7 atm

Preheated temperature
- 300 K to 500 K

Fuel
- Hydrogen
- Daniele et al. 2010
- Methane-Hydrogen

Burner materials
- Stainless steel
- Copper



$$Da = Const\,.\,{Pe_F}^{1.93}.\,Le^{1.9}.\left(\frac{T_u}{T_0}\right)^{2.1}.\left(\frac{T_{tip}}{T_u}\right)^{-0.32}.\left(\frac{P_u}{P_0}\right)^{-1.56}$$

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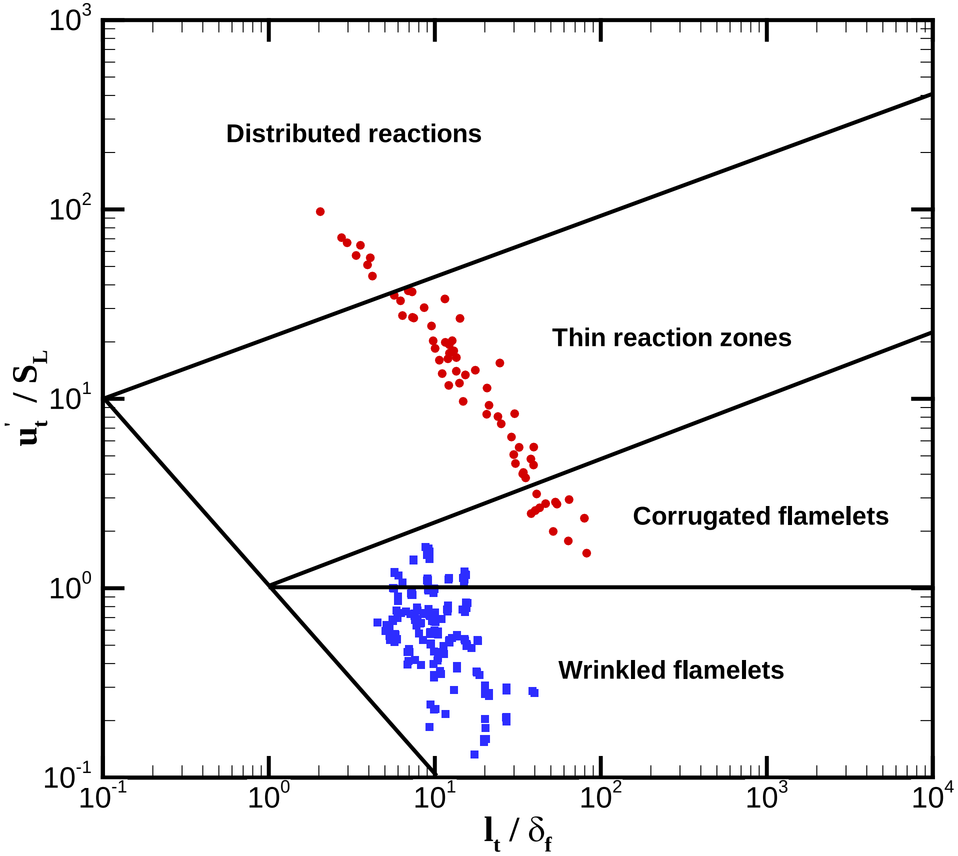
Results

Combustion regimes



$$Da = Const\,.\,Pe_F^{\,2.2}.\,Le^{-9.11}.\left(\frac{T_u}{T_0}\right)^{1.68}.\left(\frac{T_{tip}}{T_u}\right)^{-0.37}.\left(\frac{P_u}{P_0}\right)^{-1.64}$$

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Test Plan

Test Plan Approach

- **To help guide the Test Plan, additional analysis of flashback of jet flames was carried out to generate a clearer set of required information to accomplish the project goals**

Test Plan Analysis

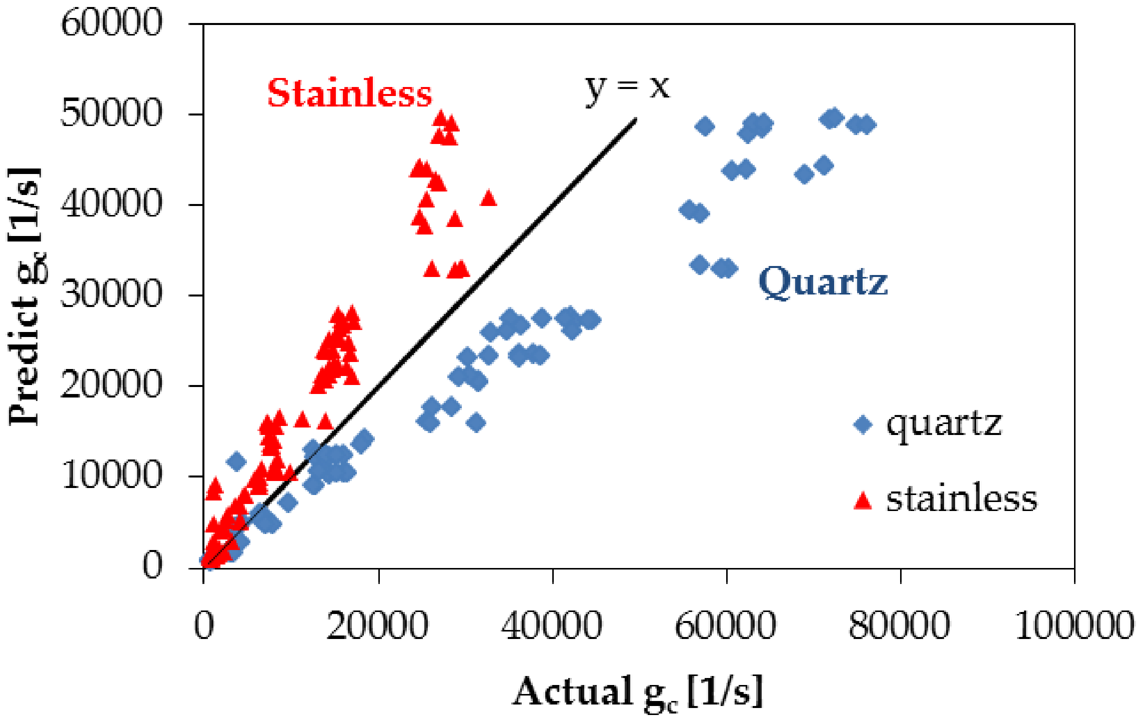
- **Atmospheric studies identified burner material, tip temperature/inlet temperature and flame confinement have a strong impact on flashback propensity, while flame enclosure diameter and tube diameter play a negligible role**
- **Better correlations can be obtained if the burner tip temperature is used as the representative temperature rather than the inlet temperature.**
  - **Ttip-based SL able to determine flashback propensity in terms of critical velocity gradient (Duan et al. 2013)**

$$g_{c\_tip} = \begin{array}{c}(155 + 546.4\alpha_{tip} + 5363.19 d_{q\_tip} - 0.71 T_{tip} - 1.1 S_{L\_tip} + 1.1 \alpha_{tip} T_{tip}{}^{2} \\ -763.3 d_{q\_tip} S_{L\_tip} - 0.0023 T_{tip} S_{L\_tip})\end{array}$$

STUDY OF FUEL COMPOSITION, BURNER MATERIAL, AND TIP TEMPERATURE EFFECTS ON FLASHBACK OF ENCLOSED JET FLAME (2013). *ASME J. Engr. Gas Turbines and Power*. Vol 135(12), pp. 121504-1 to 121504-10 (Z. Duan, B. Shaffer, and V. McDonell).

Test Plan Analysis

- **Primitive Variable Correlation**
  - **Able to collapse materials effect**



$$g_{c\_tip} = (155 + 546.4\alpha_{tip} + 5363.19d_{q\_tip} - 0.71T_{tip} - 1.1S_{L\_tip} + 1.1\alpha_{tip}T_{tip} - 763.3d_{q\_tip}S_{L\_tip} - 0.0023T_{tip}S_{L\_tip})^2$$

STUDY OF FUEL COMPOSITION, BURNER MATERIAL, AND TIP TEMPERATURE EFFECTS ON FLASHBACK OF ENCLOSED JET FLAME (2013). *ASME J. Engr. Gas Turbines and Power*. Vol 135(12), pp. 121504-1 to 121504-10 (Z. Duan, B. Shaffer, and V. McDonell).

Test Plan Analysis

- **Primitive variable approach shows reasonable performance but lacks elegance**

- **To address this**
  - **Determine *non-dimensional groups* involved in flashback propensity to capture all effects of various parameters**
    - **Buckingham Pi theorem**
  - **Find a comprehensive model to predict flashback propensity under various conditions**
  - **Verify the developed model for previous relevant data in the literature**

Test Plan Analysis

Symbol	Definition
Flow characteristics	
$\overline{U}$	bulk velocity of the mixture
u'	turbulent intensity
Thermodynamics properties of flow	
ρ_u	density based on unburnt conditions
μ_u	kinetic viscosity based on unburnt conditions
T_u	Unburnt temperature
P_u	Unburnt pressure
α_u	thermal diffusivity based on unburnt conditions
C_{P_u}	thermal capacity based on unburnt conditions
k_u	thermal conductivity based on unburnt conditions
D_u	Mass diffusivity of fuel composition into the mixture

Symbol	Definition
Premixed flame characteristics	
T_f	adiabatic flame temperature based on unburnt conditions
S_{L_u}	laminar flame speed based on unburnt conditions
LHV	lower heating value based on unburnt conditions
T_{tip}	Measured burner tip temperature
g_c	critical velocity gradient when flashback happens
h'	convective heat transfer coefficient
Ambient conditions	
T_0	ambient temperature
P_0	ambient pressure
Burner properties	
k'	thermal conductivity of the burner material
d	diameter of the burner
θ'	thickness of the burner wall

Test Plan Analysis

- **Non-dimensional groups**

$$\begin{cases} g_c \approx \dfrac{S_L}{\delta_p} \\ \delta_p \approx \delta_q = 2\sqrt{b}\,\dfrac{\alpha}{S_L} \end{cases} \Rightarrow g_c \approx \frac{S_L^2}{\alpha} \Rightarrow \Pi_1 = Da = \frac{S_L^{\,2}}{\alpha \cdot g_c}$$

$$\Pi_2 = \mathrm{Re} = \frac{\overline{\mathrm{U}}\mathrm{D}}{\nu}$$

$$\Pi_3 = Le_u = \frac{\alpha_u}{D_u}$$

$$\Pi_4 = \mathrm{Pr} = \frac{\nu}{\alpha}$$

$$\Pi_5 = \frac{P_u}{P_0}$$

$$\Pi_6 = \frac{T_u}{T_0}$$

$$\Pi_7 = \frac{\theta'}{d}$$

$$Da = f\left(\mathrm{Re}, \mathrm{Pr}, Le_u, \frac{P_u}{P_0}, \frac{T_u}{T_0}, \frac{\theta'}{d}\right)$$

- Re: Momentum equation
- Da: Flashback characteristic
- Pr: Energy equation
- Le_u: Effect of mass diffusivity in energy equation
- $\frac{P_u}{P_0}$: Pressure effect
- $\frac{T_u}{T_0}, \frac{\theta'}{d}$: Burner properties

Test Plan Analysis

- **Thermal conductivity of burner is significant in determining flashback propensity**
  - **Rate of flame regression into the premixing section differs for different burner material**

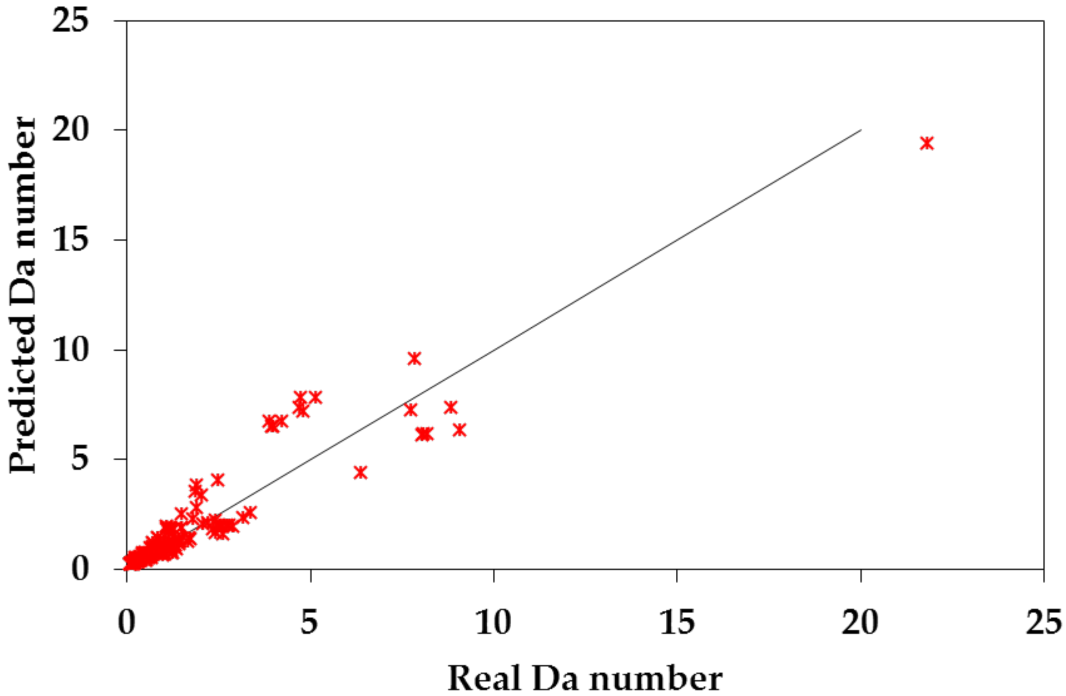
- **A comprehensive parameter survey based on Buckingham Pi theorem results in a physical correlation for flashback propensity prediction**

$$Da = C_0 \cdot Le^{-6.12} \cdot \left(\frac{T_u}{T_0}\right)^{-1.71} \cdot \left(\frac{T_{tip}}{T_u}\right)^{-3.69} \left(\frac{\alpha}{d \cdot S_L}\right)^{-1.89} \cdot f_2\left(\frac{\theta'}{d}\right) \cdot f_3\left(\frac{P_u}{P_0}\right)$$

Test Plan Analysis

- **Correlation Performance**
  - **Dataset from Duan, et al. 2013**

Z. Duan, B. Shaffer, V. McDonell, G. Baumgartner, and T. Sattelmayer, “Influence of Burner Material, Tip Temperature, and Geometrical Flame Configuration on Flashback Propensity of H 2 -Air Jet Flames,” *J. Eng. Gas Turbines Power*, vol. 136, no. 2, p. 021502, Oct. 2013.



Not varied

$$Da = Const. \cdot Le^{-6.12} \cdot \left(\frac{T_u}{T_0}\right)^{-1.71} \cdot \left(\frac{T_{tip}}{T_u}\right)^{-3.69} Pe_f{}^{-1.89} \left(f_1\left(\frac{\theta'}{d}\right) \cdot f_2\left(\frac{P_u}{P_0}\right)\right)$$

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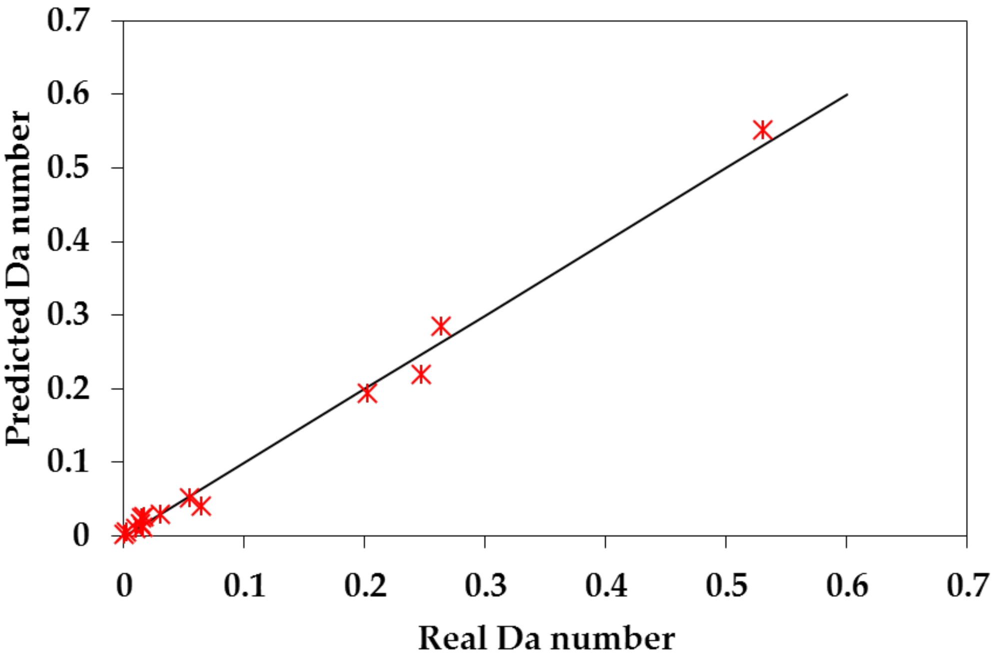
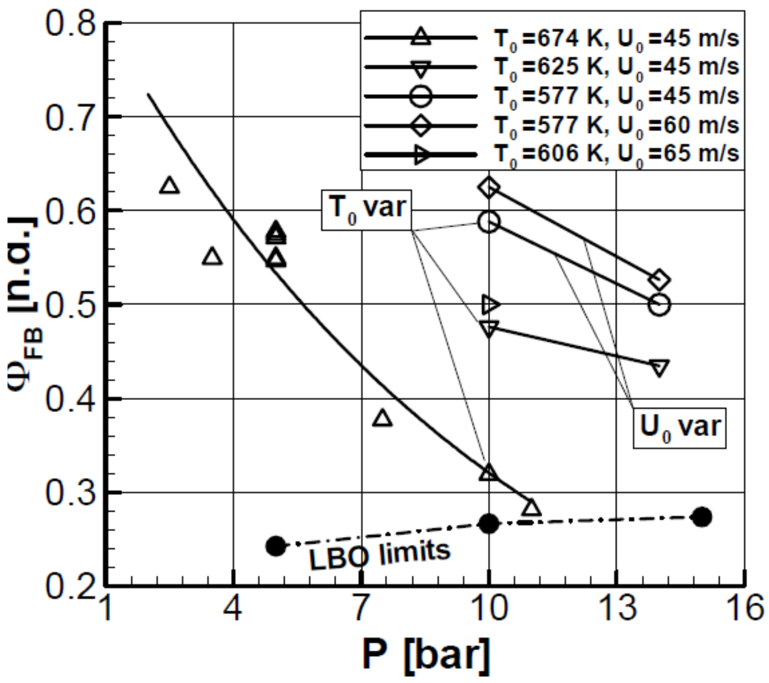
Test Plan Analysis

- **Flashback propensity of Daniele, et al (2010)**

$$Da = Const. \cdot Le^{-6.12} \cdot \left(\frac{T_{AFT}}{T_u}\right)^{-2.75} \cdot Pe_f^{\ -1.89} \cdot \left(\frac{P_u}{P_0}\right)^{-2.10}$$





Daniele, S., Jansohn, P., & Boulouchos, K. (2010, October). Flashback Propensity of Syngas Flames at High Pressure: Diagnostic and Control. In *ASME Turbo Expo 2010: Power for Land, Sea, and Air* (pp. 1169-1175). American Society of Mechanical Engineers.

Guidance from Test Plan Analysis

- **Based on Analysis:**
  - **Further investigation of effects of thermo-physical features of burner material on flashback propensity**
    - **More systematic study**
  - **Extend the investigation on jet flame flashback to more gas turbine related conditions**
    - **More systematic study**
  - **Framework to evaluate model performance as data are gathered is in place**

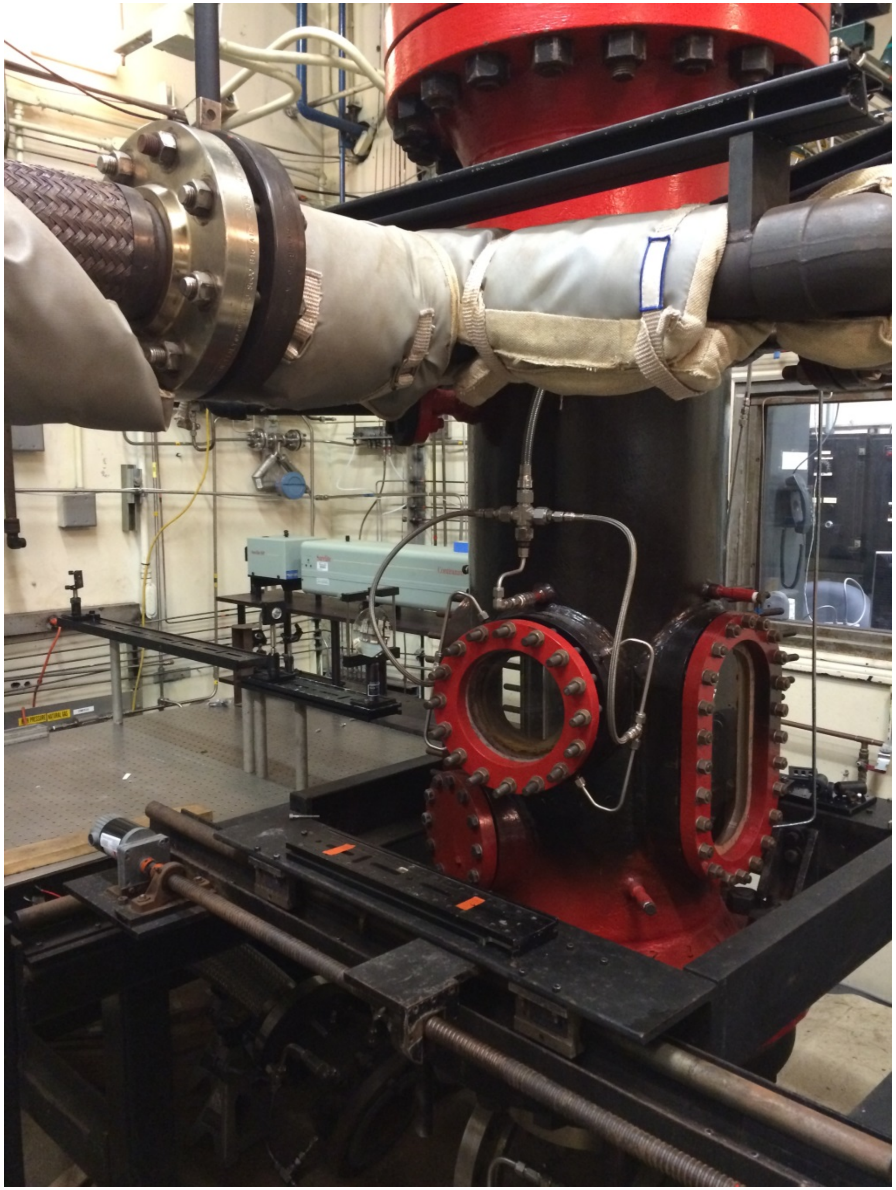
- **Eventually apply methodologies to develop/understand strategies to prevent flashback event and mitigate its damage**

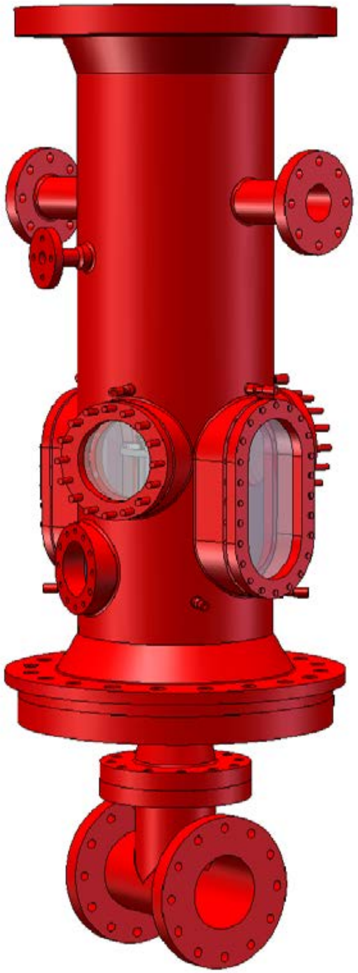
Experiments

Measurement Plan

- **Fuel Composition Variation**
  - **Effect of Pressure**
  - **Effect of Preheat Temperature**
- **Effect of Burner Head**
  - **Burner Material**
  - **Burner Thickness**

Experiment Set-up





Experiment Set-up

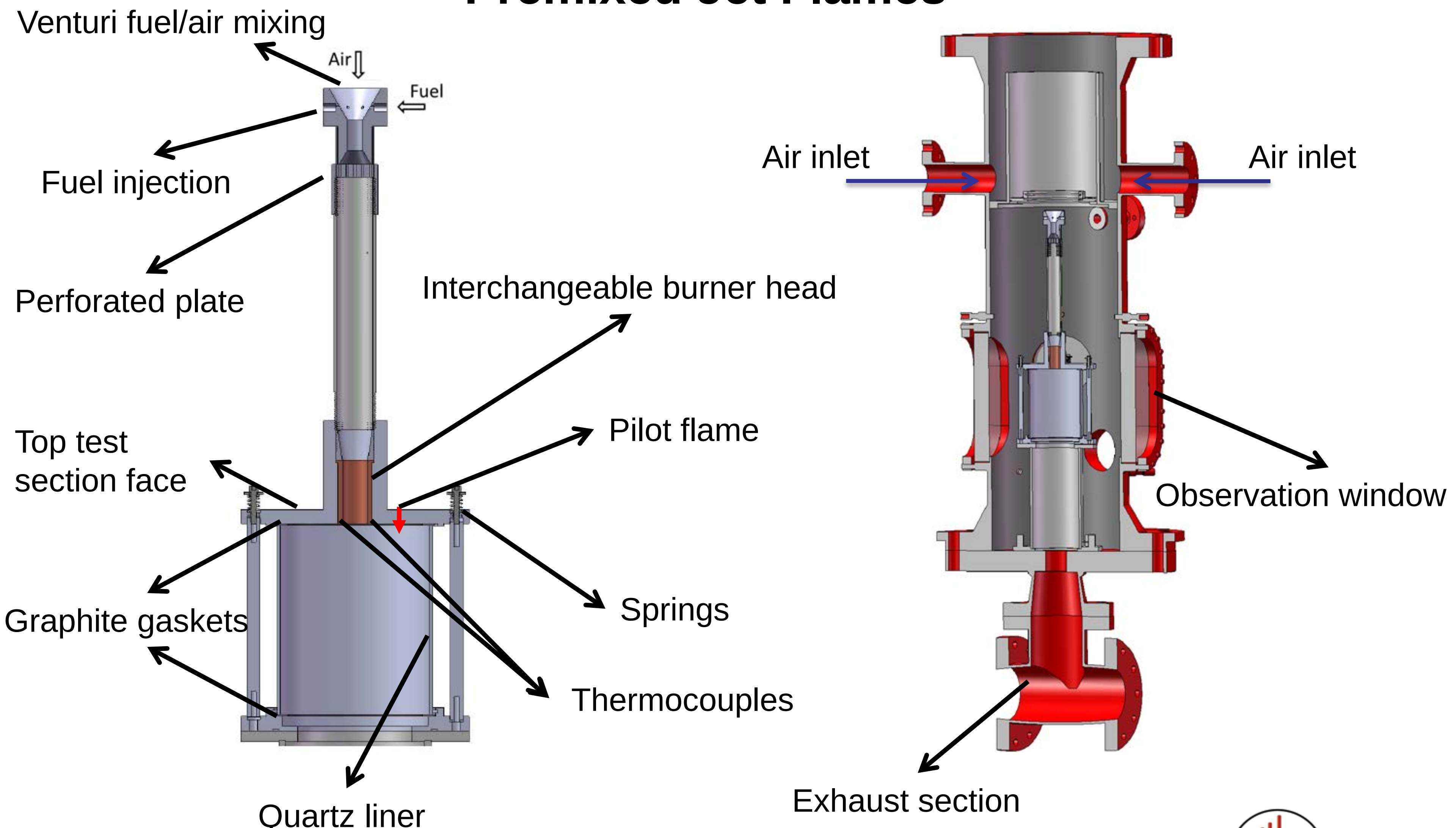
- **Air and fuel mixing through a Venturi mixer**
- **Flow straightening via honeycomb materials**
- **Interchangeable burner head**
- **Consistent burner rim temperature measurement**
- **Hydrogen pilot ignited with YAG laser to initiate reaction**

- **Overall setup is similar to that used in Beerer et al. (2014)**

FLASHBACK AND TURBULENT FLAME SPEED MEASUREMENTS IN HYDROGEN/METHANE REACTIONS STABILIZED BY A LOW-SWIRL INJECTOR AT ELEVATED PRESSURES AND TEMPERATURES (2014). ASME J. Engr. Gas Turbines and Power, Vol 136, No. 3, pg 031502-1 -- 031502-9 (D.J. Beerer, V.G. McDonell, P.Therkelsen, and R.K. Cheng)

Experiment Set-up

Premixed Jet Flames



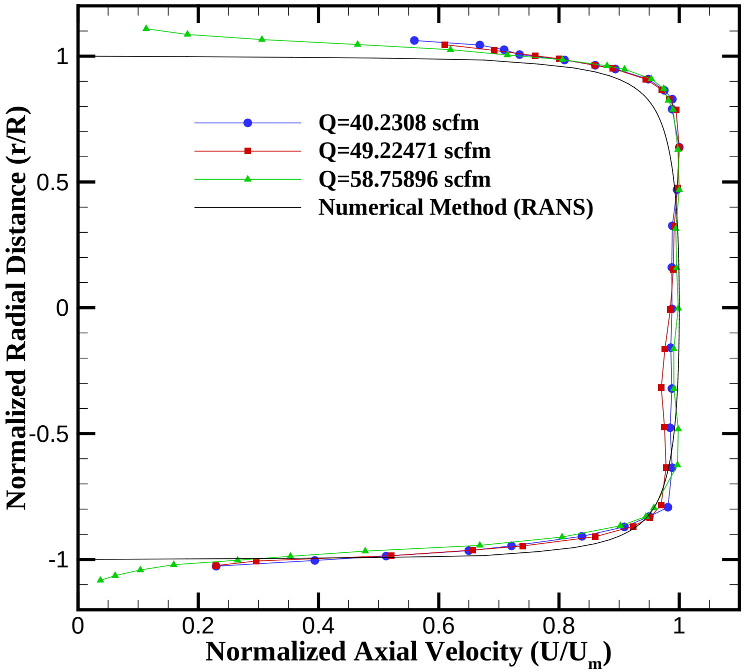
Experiment Set-up

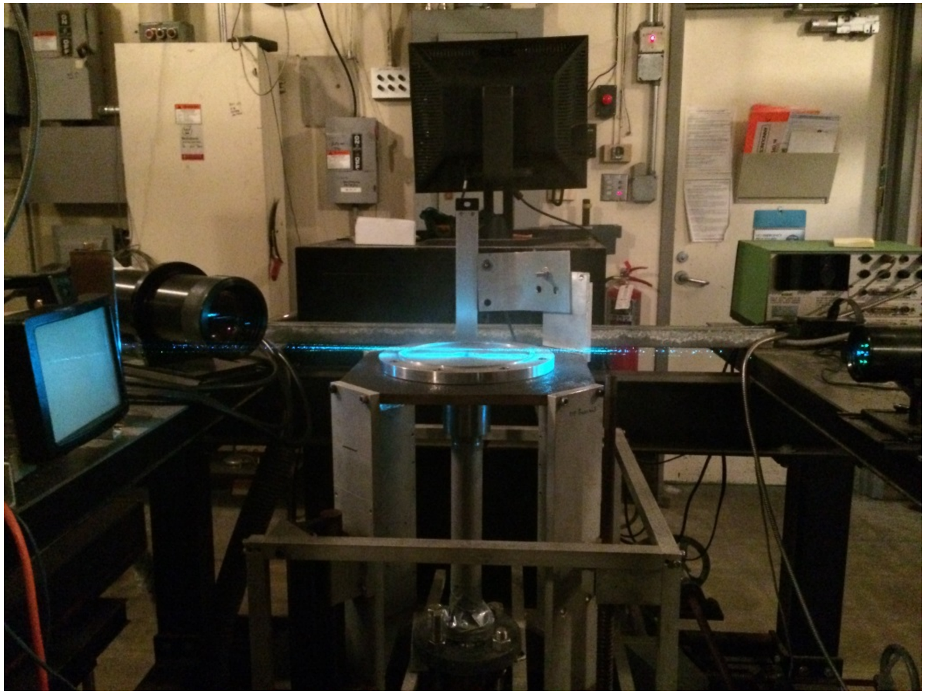
YAG laser

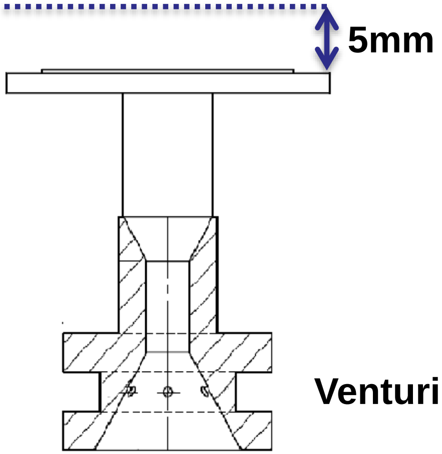
Burner

Experiment Set-up

- **Velocity profile using LDV**



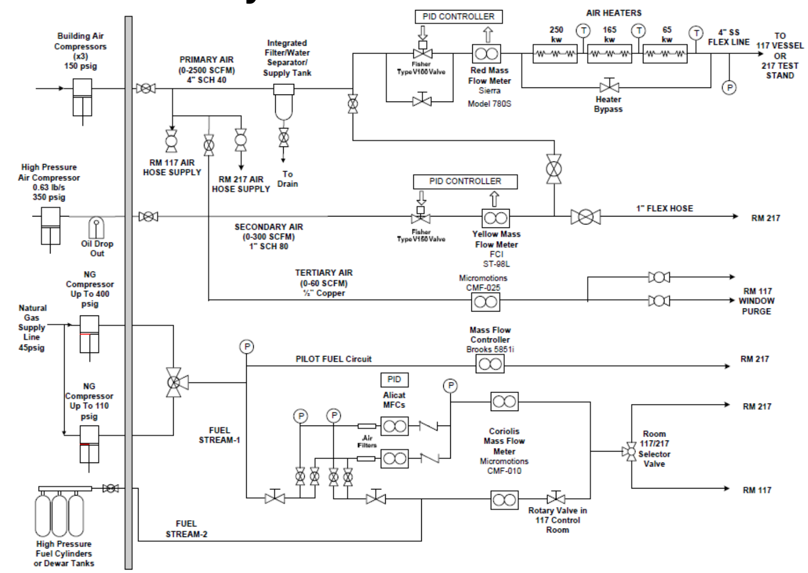




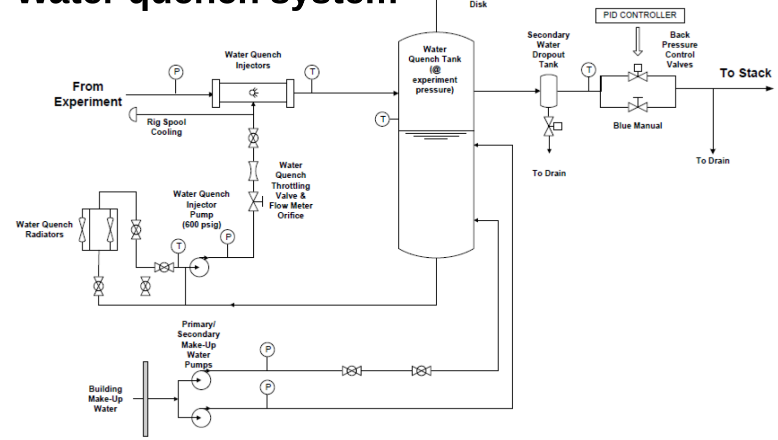
Experiment Set-up

- Injector (80% completed)
- Fuel system (80% completed)
- Air system (80% completed)
- Preheating (100% completed)
- Water quenching system (80% completed)
- Air Mass Flow rate Control (70% completed)
- Fuel Mass Flow rate Control (70% completed)
- Hardware Setup (80% completed)
- Software Setup (50% completed)
- YAG laser (50% completed)

Air and fuel system



Water quench system



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Test Parameters

- **Pressure**
  - 1 atm to 10 atm

$$\Pi_5 = \frac{P_u}{P_0}$$

- **Preheated temperature**
  - 300 K to 800 K

$$\Pi_6 = \frac{T_u}{T_0}$$

- **Fuel compositions**

H_2	100	75	50
CH_4	0	25	50

$$\Pi_1 = Da = \frac{S_L{}^2}{\alpha \cdot g_c}$$

- **Burner materials**

Material	Heat Capacity	Heat Conductivity	Density
[-]	[J/(g*C)]	[W/(m*k)]	[g/cm³]
SS-304	0.5	21.5	8
Copper	0.385	385	7.94
Quartz	0.7	1.4-2.0	2.2

$$\Pi_6 = \frac{T_f}{T_0}$$

- **Burner thickness**

Thickness [in]	Inner diameter [in]
0.07	1.2
0.12	1.1
0.17	1

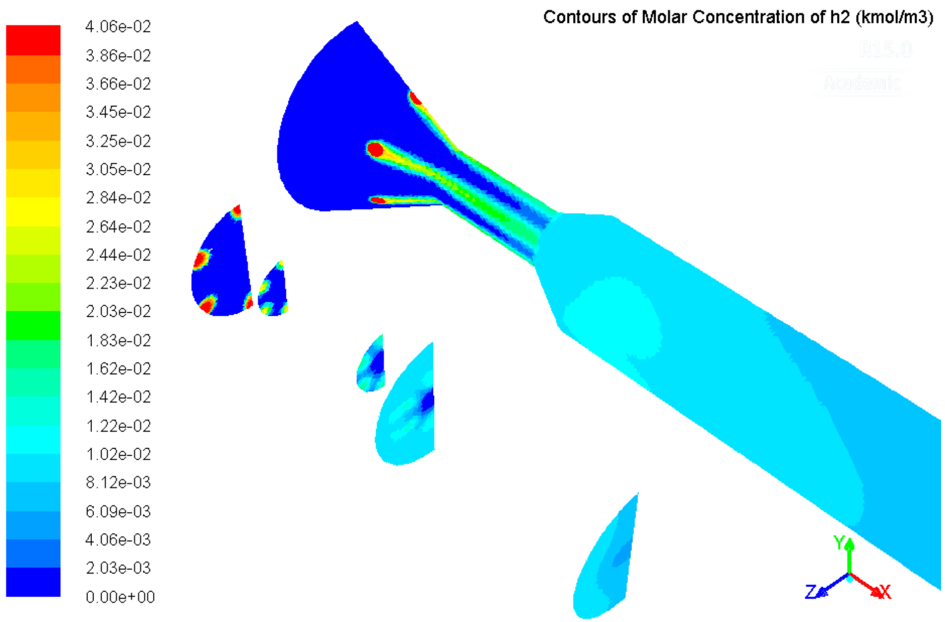
$$\Pi_7 = \frac{\theta'}{d}$$

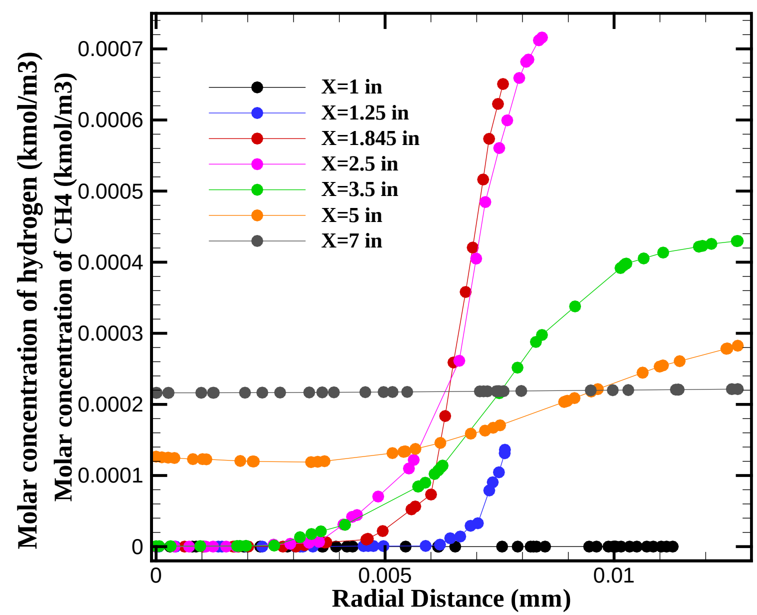
Fuel/Air Mixing

Computational Fluid Dynamics (CFD)
- **Mixing profile**

Reaction Kinetic Simulation
- **Adiabatic Flame Temperature**
- **Laminar Flame speed**

- **Venturi gas mixer**





contour of molar concentration for pure hydrogen fuel, numerical modeling

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Next Steps

Physical Modeling and Interpretation (60% completed)

Verifying the developed model for previous data in the literature

Experiment Set-up (60% completed)

Flashback diagnostic system

- Thermocouple (TC)
- Pressure Transducer (PT)
- High Speed Imaging

Flashback Data Acquisition (ongoing)

Computational Modeling (30% completed)

CFD modeling

- Combustion modeling of the premixed jet flame
- Flashback

Data Analysis and Correlation Development (0% completed)

- Single factor correlation
- General factor correlation
- Non-dimensional groups
- Comparison between current study and previous research

Conclusion and Suggestion (0% completed)