Development of Criteria for Flameholding Tendencies within Premixer Passages for High Hydrogen Content Fuels

Elliot Sullivan-Lewis, Richard Hack, and Vincent McDonell

UCI COMBUSTION LABORATORY
UNIVERSITY *of* CALIFORNIA · IRVINE

UTSR Workshop

Oct 4, 2012

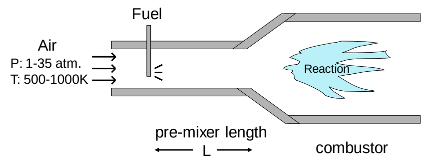
Contract DE-FE0007045; Joe Stoffa, Contract Monitor

Outline

- **Motivation**
- **Background**
- **Research Questions and Project Goal**
- **Approach and Schedule**
- **Test Rig Development**
- **Current Status**

Motivation

- <u>Trends in Advanced Lean Burning Gas Turbines*</u>
  - Higher Combustor Inlet Temperatures
  - Improved Fuel/Air Mixing
  - Risk of Auto-Ignition/Flashback
  - Role of Fuel Type/Composition



Major Question

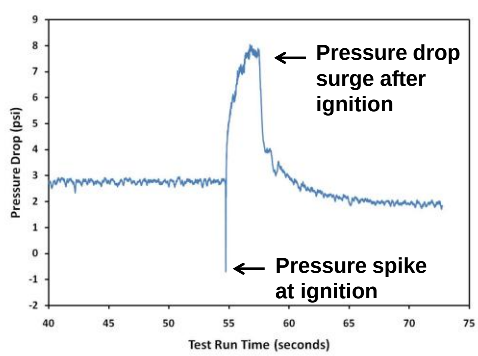
If a Reaction is Initiated in the Premixer,

Will the Reaction be "Held" on a Wall Recess?

* Stationary Gas Turbine Engines

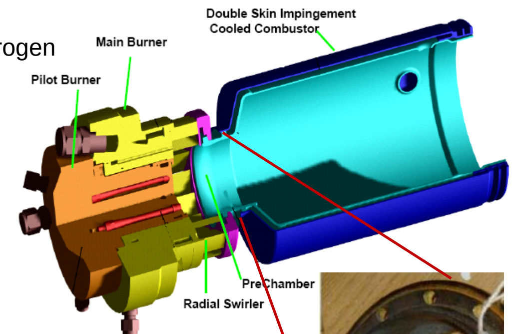
Motivation

- Ignition/reignition of all fuels (natural gas and hydrogen) leads to a pressure spike that can allows flame to propagate up into premixer
- Natural Gas reaction disgorges
- Hydrogen reaction anchors in premixer zone



Motivation

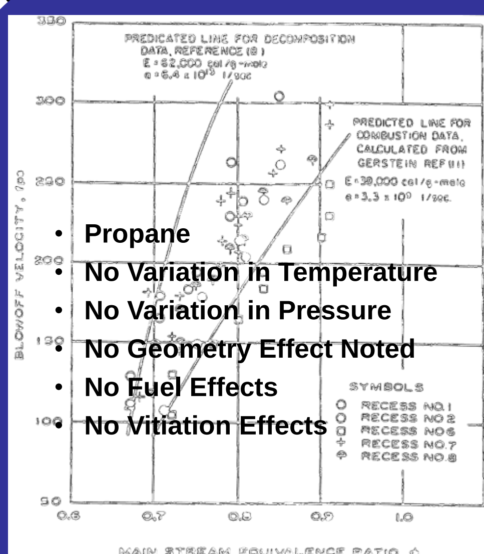
High Hydrogen Content Fuels On N.G. injectors



Desired:
Tools to guide premixer design for robustness relative to flame attachment and disgorgement

Background

- Large Body of ...
- Findings
  - Only ~2...
  - Most F...
  - Most S...
- Studies of ...
  - Cambe...
    - Wal...
    - Lim...



- Propane
- No Variation in Temperature
- No Variation in Pressure
- No Geometry Effect Noted
- No Fuel Effects
- No Vitiation Effects

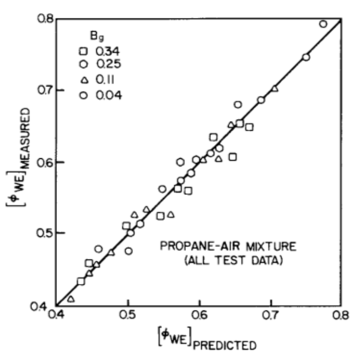
Background

Large Body of Literature on Blowoff/Flameholding

- **Findings**
  - **Only ~25% Focus on Natural Gas, <10% Hydrogen**
  - **Most Focus on Centerbody Stabilization vs. Wall Effects**
  - **Most Seek How to Stabilize, Not How to Avoid**
- **Studies of Particular Relevance**
  - **Cambel, et al. (1957, 1962)**
    - **Wall Perturbations**
    - **Limited Conditions**
  - **Cambel suggested mechanism "similar to centerbody stabilized"**
  - **If true….correlation work for CB Stabilized**
    - **Damköhler scaling seems to capture behavior**
    - **e.g., work of Lefebvre, others**
    - **e.g., Shanbhogue, Husain, and Lieuwen**

Damköhler Scaling

$$\phi_{LBO} = \left\{ \frac{2.25\left[1 + 0.4U\left(1+u'\right)\right]}{P^{0.25} T_o e^{\left(T_o/150\right)} D_c \left(1-B_g\right)} \right\}^{0.16}$$



Ballal and Lefebvre, 1979

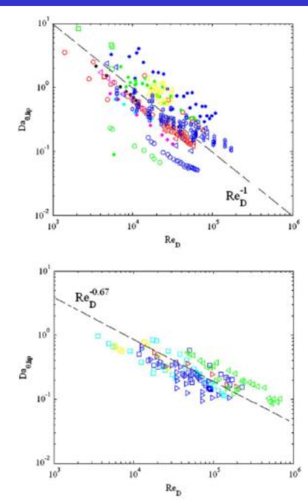


Fig. 17. Correlation of two-dimensional (top) and axisymmetric (bottom) bluff body data sets showing $Da_{\phi,lip}$ at blowoff as a function of Re_D utilizing τ_{PSR} as the chemical time. See text and Table 1 for explanation of notations and symbols.

Shanbhogue, Husain, and Lieuwen, 2009

Research Questions

Major Question

If a Reaction is Initiated in the Premixer,

Will the Reaction be "Held" on a Wall Recess?

Related Question #1

To What Extent do "Damköhler Type" expressions (based mainly on bluff body stabilized flames) apply to "small" wall recesses and/or perturbations?

(*Wall quenching/heat transfer mechanism should influence situation more so than bluff body situation*)

Research Questions

Major Question

If a Reaction is Initiated in the Premixer,

Will the Reaction be "Held" on a Wall Recess?

Related Question #2

If the reaction holds on a wall feature, what is required to dislodge it (experience suggests strong hysteresis)

Research Questions

Major Question

If a Reaction is Initiated in the Premixer,

Will the Reaction be “Held” on a Wall Recess?

Related Question #3

What is role of T, P, fuel composition, and level of vitiation?

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Research Questions

Major Question

If a Reaction is Initiated in the Premixer,

Will the Reaction be “Held” on a Wall Recess?

Related Question #4

How does the geometry of the wall feature affect the flameholding tendency?

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Project Goal

- **Develop design guides to predict flameholding tendencies within premixer passages as a function of:**
  - **Pressure**
  - **Temperature**
  - **Fuel Type/Composition**
  - **%O_2 in the air (vitiation levels)**
  - **Geometry Features**

Approach and Schedule

Task Description	Year 1		Year 2		Year 3	
	M1	M7	M13	M19	M25	M31
Task 1—Project Management and Planning*		*	*	*		
Task 2—Preparation -Task 2.1—Fuel/Module Selection -Task 2.2—Fabrication -Task 2.3—Diagnostics/Rig Setup -Task 2.4--Commissioning						
Task 3—Experimental Studies -Phase I -Phase II						
Task 4—Analysis and Model Development						

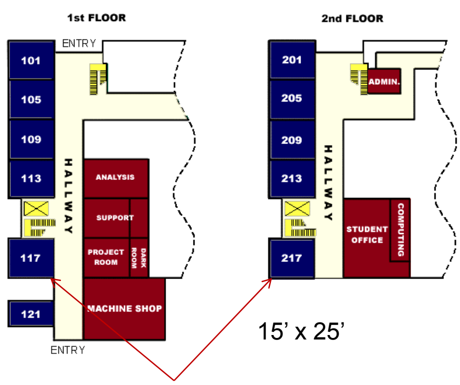
Approach

- **Preparation**
  - **Fuel/Module Selection***
  - **Fabrication**
  - **Diagnostics / Rig Setup**
  - **Commissioning**
- **Experimental Studies**
- **Analyze and Correlate Results**

*Input from OEMs in early stages of project

Preparation

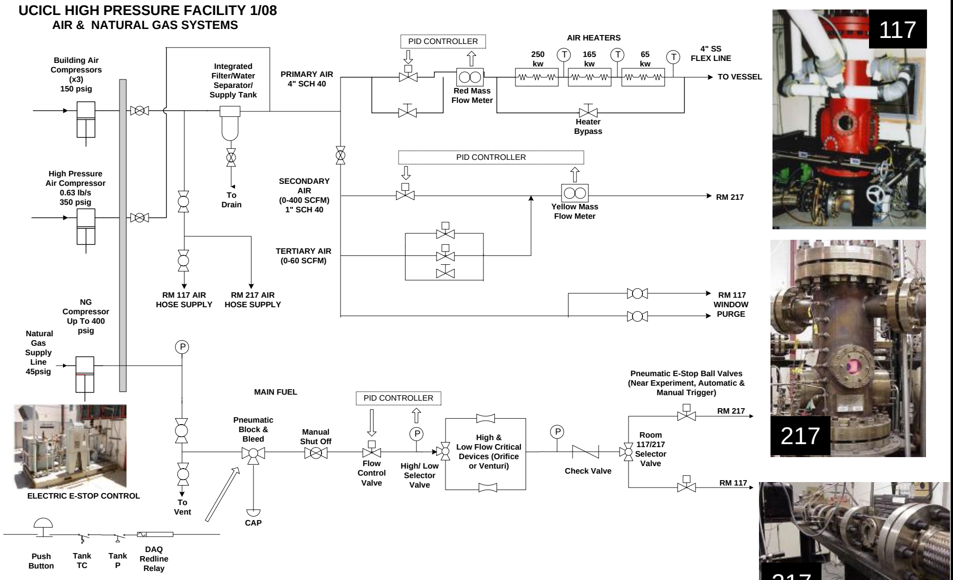
- **The test rig will leverage existing high pressure testing capability developed through support of NASA, DOE, and industry**

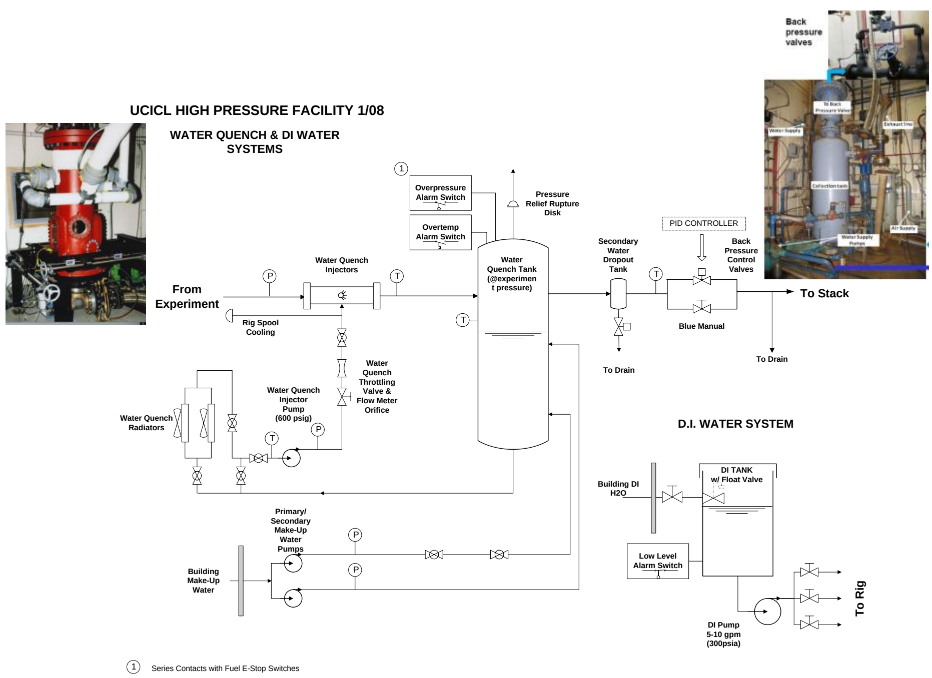


15’ x 25’

High Pressure Test Cells

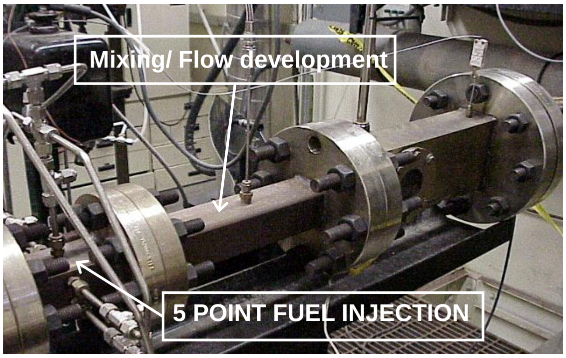
4 lb/s air; 1000 deg F preheat; diluents (stored tanks)
Pressures to 18 atm



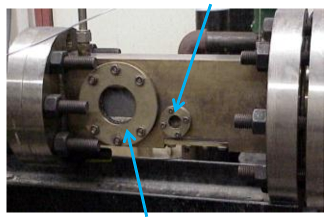


Test Rig Development

- **Initial test plan envisioned using an existing "go/no go" test section**

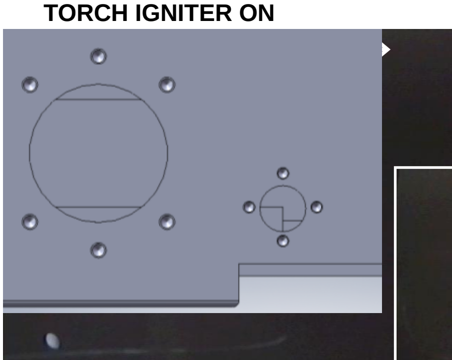


Test feature optical access

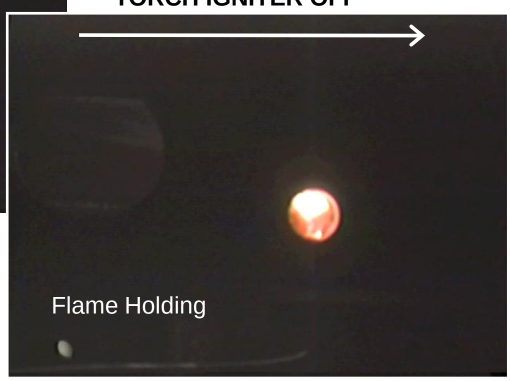


Upstream optical access

TORCH IGNITER ON



TORCH IGNITER OFF



Current Project:
High Speed OH* Imaging will be used as well
Phantom 7.2 CMOS w/ external intensifier

Test Conditions

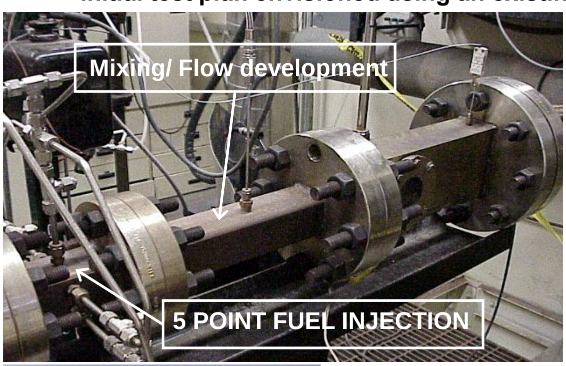
Test Conditions

- **Pressure:** **Up to 7 atm (*more if possible**)**
- **Velocity:** **Up to 70 m/s (*higher if possible**)**
- **Preheat:** **500°F-1000°F (may be limited by autoignition)**
- **Fuel:** **Φ=0.6-1.0**
  - **Hydrogen Containing Fuels (expected to be limiting case)**
  - **Natural Gas Fuels**

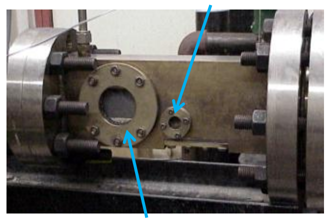
*Input from OEMs in early stages of project

Test Rig Development

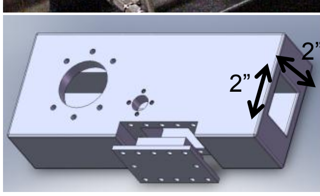
- **Initial test plan envisioned using an existing “go/no go” test section**



Test feature optical access



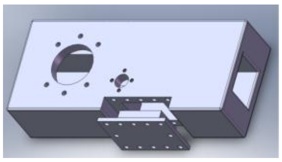
Upstream optical access



- Discussions with OEMs indicated a mismatch with desired test conditions
  - Limited to 6 atm, 60 m/s

Updated Test Section

- **While available test section seemed attractive…..**
  - **Too large to hit the desired velocities and pressures**



2" x 2"

?????? → Updated Test Section

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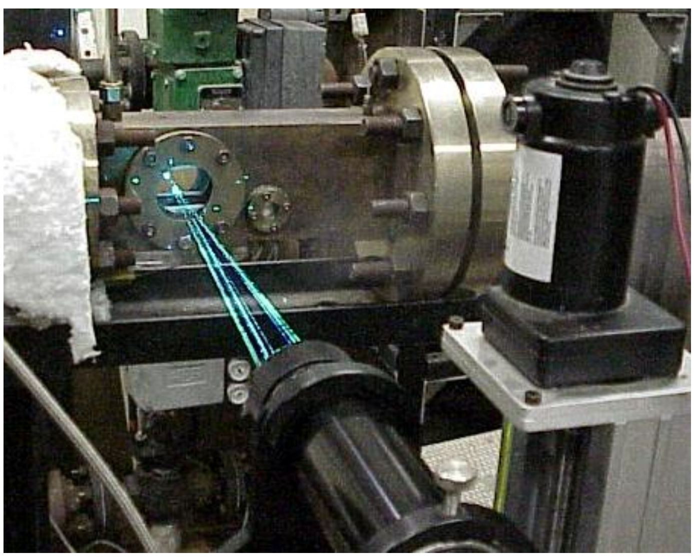
Velocity/Turbulence Mapping



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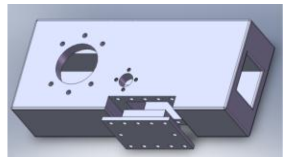
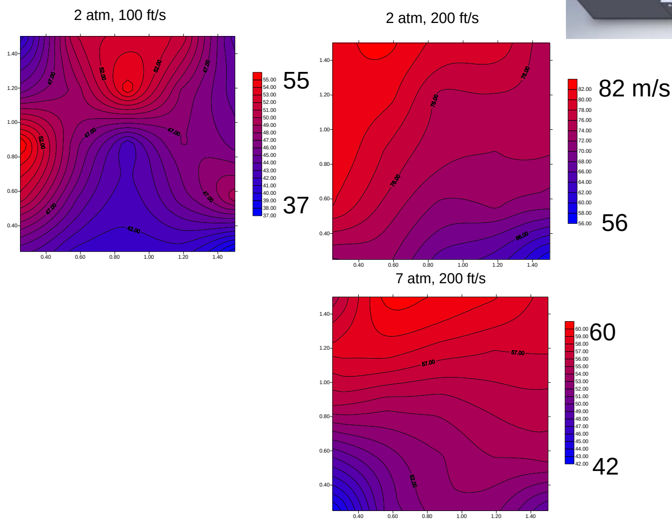
Velocity/Turbulence Mapping

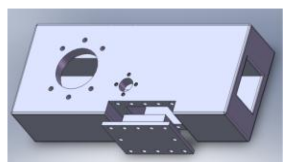
- **Mean Velocity**

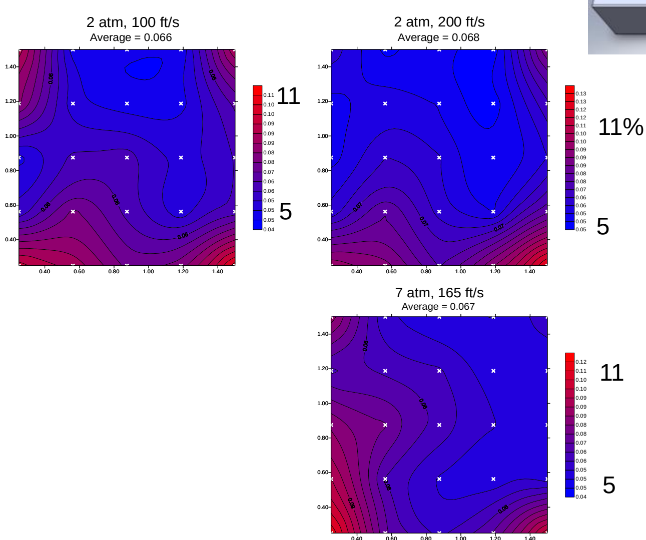




Velocity/Turbulence Mapping

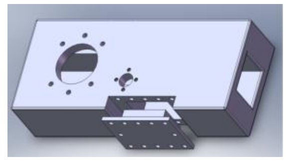
- **u'/U**



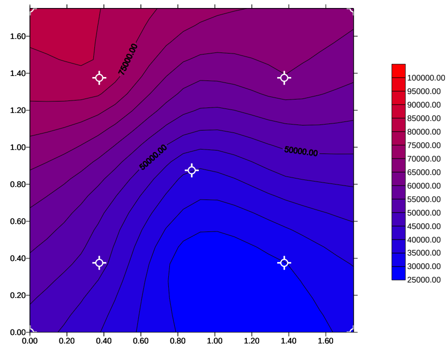


Fuel Distribution

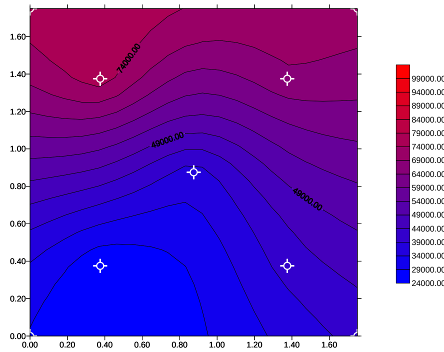
- [HC], ppm



2 atm, 100 ft/s



7 atm, 200 ft/s



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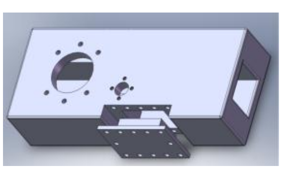
Updated Test Section

- **While available test section seemed attractive…..**
  - **Too large to hit the desired velocities and pressures**
  - **Insufficient flow conditioning/fuel distribution**
    - **Need to revise injection strategy**



2" x 2"

Updated Test Section

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Facility Air Flow = f(Vel, T, P)

Limit 3.1 lb/sec (<10 atm)
0.37 lb/sec (>10 atm)

Temperature →

Velocity ↓

Deg. F

1 ATM	500	600	700	800	900	1000
40	0.050	0.046	0.042	0.038	0.036	0.033
50	0.063	0.057	0.052	0.048	0.045	0.041
60	0.076	0.069	0.063	0.058	0.053	0.050
Velocity 70	0.088	0.080	0.073	0.067	0.062	0.058
80	0.101	0.091	0.084	0.077	0.071	0.066
90	0.114	0.103	0.094	0.087	0.080	0.075
100	0.126	0.114	0.104	0.096	0.089	0.083

3 ATM	500	600	700	800	900	1000
40	0.151	0.137	0.125	0.115	0.107	0.100
50	0.189	0.171	0.157	0.144	0.134	0.124
60	0.227	0.206	0.188	0.173	0.160	0.149
Velocity 70	0.265	0.240	0.219	0.202	0.187	0.174
80	0.303	0.274	0.251	0.231	0.214	0.199
90	0.341	0.309	0.282	0.260	0.241	0.224
100	0.379	0.343	0.313	0.288	0.267	0.249

5 ATM	500	600	700	800	900	1000
40	0.252	0.229	0.209	0.192	0.178	0.166
50	0.315	0.286	0.261	0.240	0.223	0.207
60	0.379	0.343	0.313	0.288	0.267	0.249
Velocity 70	0.442	0.400	0.366	0.337	0.312	0.290
80	0.505	0.457	0.418	0.385	0.356	0.332
90	0.568	0.514	0.470	0.433	0.401	0.373
100	0.631	0.571	0.522	0.481	0.445	0.415

Deg. F

7 ATM	500	600	700	800	900	1000
40	0.353	0.320	0.292	0.269	0.249	0.232
50	0.442	0.400	0.366	0.337	0.312	0.290
60	0.530	0.480	0.439	0.404	0.374	0.349
70	0.618	0.560	0.512	0.471	0.436	0.407
80	0.707	0.640	0.585	0.538	0.499	0.465
90	0.795	0.720	0.658	0.606	0.561	0.523
100	0.883	0.800	0.731	0.673	0.624	0.581

9 ATM	500	600	700	800	900	1000
40	0.454	0.411	0.376	0.346	0.321	0.299
50	0.568	0.514	0.470	0.433	0.401	0.373
60	0.681	0.617	0.564	0.519	0.481	0.448
70	0.795	0.720	0.658	0.606	0.561	0.523
80	0.909	0.823	0.752	0.692	0.641	0.597
90	1.022	0.926	0.846	0.779	0.722	0.672
100	1.136	1.029	0.940	0.865	0.802	0.747

10 ATM	500	600	700	800	900	1000
40	0.505	0.457	0.418	0.385	0.356	0.332
50	0.631	0.571	0.522	0.481	0.445	0.415
60	0.757	0.686	0.627	0.577	0.534	0.498
70	0.883	0.800	0.731	0.673	0.624	0.581
80	1.010	0.914	0.835	0.769	0.713	0.664
90	1.136	1.029	0.940	0.865	0.802	0.747
100	1.262	1.143	1.044	0.961	0.891	0.830

Deg. F

11 ATM	500	600	700	800	900	1000
40	0.555	0.503	0.460	0.423	0.392	0.365
50	0.694	0.629	0.574	0.529	0.490	0.456
60	0.833	0.754	0.689	0.635	0.588	0.548
70	0.972	0.880	0.804	0.740	0.686	0.639
80	1.111	1.006	0.919	0.846	0.784	0.730
90	1.249	1.131	1.034	0.952	0.882	0.821
100	1.388	1.257	1.149	1.058	0.980	0.913

13 ATM	500	600	700	800	900	1000
40	0.656	0.594	0.543	0.500	0.463	0.431
50	0.820	0.743	0.679	0.625	0.579	0.539
60	0.984	0.891	0.815	0.750	0.695	0.647
70	1.148	1.040	0.950	0.875	0.811	0.755
80	1.312	1.189	1.086	1.000	0.926	0.863
90	1.476	1.337	1.222	1.125	1.042	0.971
100	1.641	1.486	1.358	1.250	1.158	1.079

14 ATM	500	600	700	800	900	1000
40	0.707	0.640	0.585	0.538	0.499	0.465
50	0.883	0.800	0.731	0.673	0.624	0.581
60	1.060	0.960	0.877	0.808	0.748	0.697
70	1.237	1.120	1.023	0.942	0.873	0.813
80	1.413	1.280	1.170	1.077	0.998	0.929
90	1.590	1.440	1.316	1.211	1.122	1.046
100	1.767	1.600	1.462	1.346	1.247	1.162

OEM Input: higher velocity→mass flow→iterate on cross section

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Facility Preheating T = f(Vel, P)

Limt 205 kw

Temperature →

Velocity ↓

Deg. F

1 ATM	500	600	700	800	900	1000
40	6.0292	6.7303	7.3105	7.7986	8.2149	8.5742
50	7.5365	8.4129	9.1381	9.7483	10.269	10.718
60	9.0438	10.095	10.966	11.698	12.322	12.861
Velocity 70	10.551	11.778	12.793	13.648	14.376	15.005
80	12.058	13.461	14.621	15.597	16.43	17.148
90	13.566	15.143	16.449	17.547	18.484	19.292
100	15.073	16.826	18.276	19.497	20.537	21.436

3 ATM	500	600	700	800	900	1000
40	18.088	20.191	21.932	23.396	24.645	25.723
50	22.61	25.239	27.414	29.245	30.806	32.153
60	27.132	30.286	32.897	35.094	36.967	38.584
Velocity 70	31.653	35.334	38.38	40.943	43.128	45.015
80	36.175	40.382	43.863	46.792	49.29	51.445
90	40.697	45.43	49.346	52.641	55.451	57.876
100	45.219	50.477	54.829	58.49	61.612	64.307

5 ATM	500	600	700	800	900	1000
40	30.146	33.652	36.553	38.993	41.075	42.871
50	37.683	42.064	45.691	48.741	51.343	53.589
60	45.219	50.477	54.829	58.49	61.612	64.307
Velocity 70	52.756	58.89	63.967	68.238	71.881	75.024
80	60.292	67.303	73.105	77.986	82.149	85.742
90	67.829	75.716	82.243	87.734	92.418	96.46
100	75.365	84.129	91.381	97.483	102.69	107.18

Deg. F

7 ATM	500	600	700	800	900	1000
40	42.205	47.112	51.174	54.59	57.505	60.02
50	52.756	58.89	63.967	68.238	71.881	75.024
60	63.307	70.668	76.76	81.885	86.257	90.029
70	73.858	82.446	89.554	95.533	100.63	105.03
80	84.409	94.224	102.35	109.18	115.01	120.04
90	94.96	106	115.14	122.83	129.39	135.04
100	105.51	117.78	127.93	136.48	143.76	150.05

9 ATM	500	600	700	800	900	1000
40	54.263	60.573	65.795	70.187	73.934	77.168
50	67.829	75.716	82.243	87.734	92.418	96.46
60	81.395	90.859	98.692	105.28	110.9	115.75
70	94.96	106	115.14	122.83	129.39	135.04
80	108.53	121.15	131.59	140.37	147.87	154.34
90	122.09	136.29	148.04	157.92	166.35	173.63
100	135.66	151.43	164.49	175.47	184.84	192.92

10 ATM	500	600	700	800	900	1000
40	60.292	67.303	73.105	77.986	82.149	85.742
50	75.365	84.129	91.381	97.483	102.69	107.18
60	90.438	100.95	109.66	116.98	123.22	128.61
70	105.51	117.78	127.93	136.48	143.76	150.05
80	120.58	134.61	146.21	155.97	164.3	171.48
90	135.66	151.43	164.49	175.47	184.84	192.92
100	150.73	168.26	182.76	194.97	205.37	214.36

Deg. F

11 ATM	500	600	700	800	900	1000
40	66.322	74.033	80.416	85.785	90.364	94.316
50	82.902	92.542	100.52	107.23	112.96	117.9
60	99.482	111.05	120.62	128.68	135.55	141.47
70	116.06	129.56	140.73	150.12	158.14	165.05
80	132.64	148.07	160.83	171.57	180.73	188.63
90	149.22	166.58	180.93	193.02	203.32	212.21
100	165.8	185.08	201.04	214.46	225.91	235.79

13 ATM	500	600	700	800	900	1000
40	78.38	87.494	95.037	101.38	106.79	111.46
50	97.975	109.37	118.8	126.73	133.49	139.33
60	117.57	131.24	142.55	152.07	160.19	167.2
70	137.16	153.11	166.31	177.42	186.89	195.06
80	156.76	174.99	190.07	202.76	213.59	222.93
90	176.35	196.86	213.83	228.11	240.29	250.8
100	195.95	218.73	237.59	253.45	266.99	278.66

14 ATM	500	600	700	800	900	1000
40	84.409	94.224	102.35	109.18	115.01	120.04
50	105.51	117.78	127.93	136.48	143.76	150.05
60	126.61	141.34	153.52	163.77	172.51	180.06
70	147.72	164.89	179.11	191.07	201.27	210.07
80	168.82	188.45	204.69	218.36	230.02	240.08
90	189.92	212	230.28	245.66	258.77	270.09
100	211.02	235.56	255.87	272.95	287.52	300.1

OEM Input: 1000 F acceptable→velocity→iterate on cross section

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Facility Heat Rejection = f(phi, Vel, T, P)

400 kW Rejection

Temperature →

Velocity ↓

Deg. F

1 ATM	500	600	700	800	900	1000
40	33.431	31.547	29.988	28.676	27.557	26.592
50	41.789	39.434	37.485	35.845	34.447	33.24
60	50.147	47.321	44.982	43.014	41.336	39.888
Velocity 70	58.505	55.208	52.479	50.183	48.226	46.536
80	66.862	63.094	59.976	57.353	55.115	53.184
90	75.22	70.981	67.473	64.522	62.004	59.832
100	83.578	78.868	74.97	71.691	68.894	66.48

3 ATM	500	600	700	800	900	1000
40	100.29	94.641	89.964	86.029	82.672	79.776
50	125.37	118.3	112.45	107.54	103.34	99.72
60	150.44	141.96	134.95	129.04	124.01	119.66
Velocity 70	175.51	165.62	157.44	150.55	144.68	139.61
80	200.59	189.28	179.93	172.06	165.34	159.55
90	225.66	212.94	202.42	193.56	186.01	179.5
100	250.73	236.6	224.91	215.07	206.68	199.44

5 ATM	500	600	700	800	900	1000
40	167.16	157.74	149.94	143.38	137.79	132.96
50	208.94	197.17	187.42	179.23	172.23	166.2
60	250.73	236.6	224.91	215.07	206.68	199.44
Velocity 70	292.52	276.04	262.39	250.92	241.13	232.68
80	334.31	315.47	299.88	286.76	275.57	265.92
90	376.1	354.91	337.36	322.61	310.02	299.16
100	417.89	394.34	374.85	358.45	344.47	332.4

Deg. F

7 ATM	500	600	700	800	900	1000
40	234.02	220.83	209.92	200.73	192.9	186.14
50	292.52	276.04	262.39	250.92	241.13	232.68
60	351.03	331.25	314.87	301.1	289.35	279.22
70	409.53	386.45	367.35	351.28	337.58	325.75
80	468.04	441.66	419.83	401.47	385.8	372.29
90	526.54	496.87	472.31	451.65	434.03	418.82
100	585.05	552.08	524.79	501.83	482.26	465.36

9 ATM	500	600	700	800	900	1000
40	300.88	283.92	269.89	258.09	248.02	239.33
50	376.1	354.91	337.36	322.61	310.02	299.16
60	451.32	425.89	404.84	387.13	372.03	358.99
70	526.54	496.87	472.31	451.65	434.03	418.82
80	601.76	567.85	539.78	516.17	496.03	478.65
90	676.98	638.83	607.26	580.69	558.04	538.49
100	752.2	709.81	674.73	645.22	620.04	598.32

10 ATM	500	600	700	800	900	1000
40	334.31	315.47	299.88	286.76	275.57	265.92
50	417.89	394.34	374.85	358.45	344.47	332.4
60	501.47	473.21	449.82	430.14	413.36	398.88
70	585.05	552.08	524.79	501.83	482.26	465.36
80	668.62	630.94	599.76	573.53	551.15	531.84
90	752.2	709.81	674.73	645.22	620.04	598.32
100	835.78	788.68	749.7	716.91	688.94	664.8

Deg. F

11 ATM	500	600	700	800	900	1000
40	367.74	347.02	329.87	315.44	303.13	292.51
50	459.68	433.77	412.33	394.3	378.92	365.64
60	551.61	520.53	494.8	473.16	454.7	438.77
70	643.55	607.28	577.27	552.02	530.48	511.89
80	735.49	694.04	659.74	630.88	606.26	585.02
90	827.42	780.79	742.2	709.74	682.05	658.15
100	919.36	867.55	824.67	788.6	757.83	731.28

13 ATM	500	600	700	800	900	1000
40	434.61	410.11	389.84	372.79	358.25	345.7
50	543.26	512.64	487.3	465.99	447.81	432.12
60	651.91	615.17	584.77	559.19	537.37	518.54
70	760.56	717.7	682.23	652.39	626.93	604.97
80	869.21	820.23	779.69	745.58	716.49	691.39
90	977.86	922.75	877.15	838.78	806.06	777.81
100	1086.5	1025.3	974.61	931.98	895.62	864.24

14 ATM	500	600	700	800	900	1000
40	468.04	441.66	419.83	401.47	385.8	372.29
50	585.05	552.08	524.79	501.83	482.26	465.36
60	702.05	662.49	629.75	602.2	578.71	558.43
70	819.06	772.91	734.71	702.57	675.16	651.5
80	936.07	883.32	839.66	802.94	771.61	744.57
90	1053.1	993.74	944.62	903.3	868.06	837.65
100	1170.1	1104.2	1049.6	1003.7	964.51	930.72

Managing required heat rejection:
Actual run times not expected to be long enough to require full heat rejection

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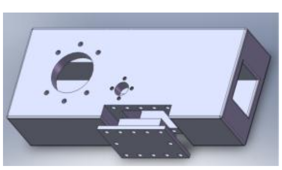
Updated Test Section

- **While available test section seemed attractive…..**
  - **Too large to hit the desired velocities and pressures**



2” x 2”

Updated Test Section
1.76” x 0.76”
Hits velocities
at temperatures
of interest
while allowing
sufficient heat rejection

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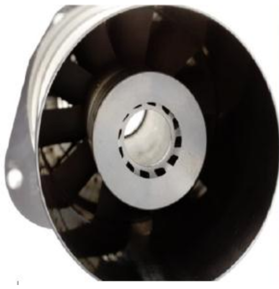
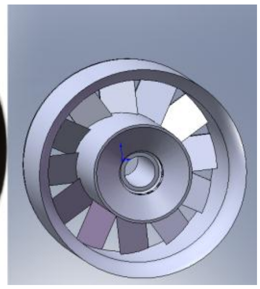
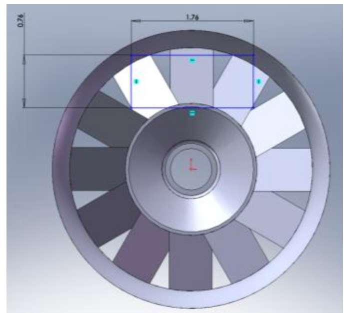
Test Section Sizing

Is 1.76” x 0.76” cross section representative of engine premixing sections?

GE DLN



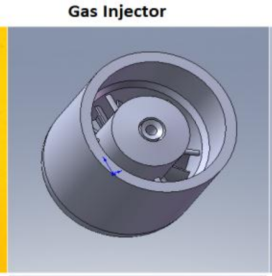


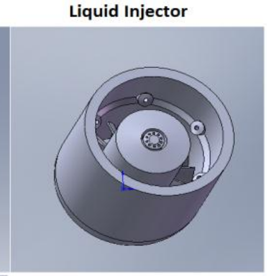


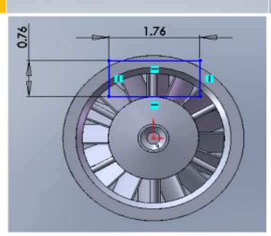
Test Section Sizing

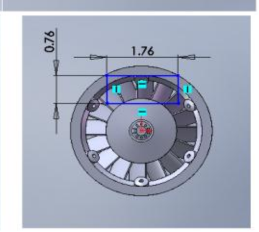
Is 1.76” x 0.76” cross section representative of engine premixing sections?

Solar Gas/Liquid Injector **Gas Injector** **Liquid Injector**





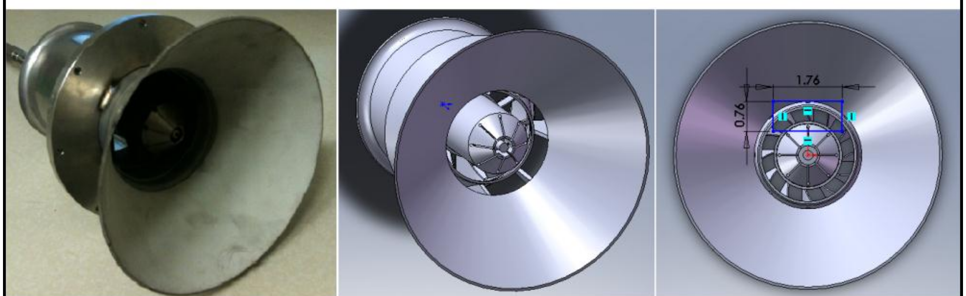




Test Section Sizing

Is 1.76” x 0.76” cross section representative of engine premixing sections?

Siemens Gas Injector/Premixer



Updated Test Section

- While available test section seemed attractive…..
  - Too large to hit the desired velocities and pressures
  - Insufficient flow conditioning/fuel distribution
    - Need to revise injection strategy

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Flow Development

- **Previous test section had poor velocity and fuel distributions. Attributed to short entrance length.**
- **The proper entrance length is calculated as:**

Entrance Length Calculation: $L_E = 4.4 D Re^{1/6}$ $\quad Re = \frac{\rho V D}{\mu} = \frac{\dot{m} D}{\mu A}$

For rectangular pipes use hydraulic diameter: $D_H = \frac{4A}{P}$

Where P is the perimeter: 2(L+W). Reynolds number is then: $Re = \frac{4\dot{m}}{\mu P}$

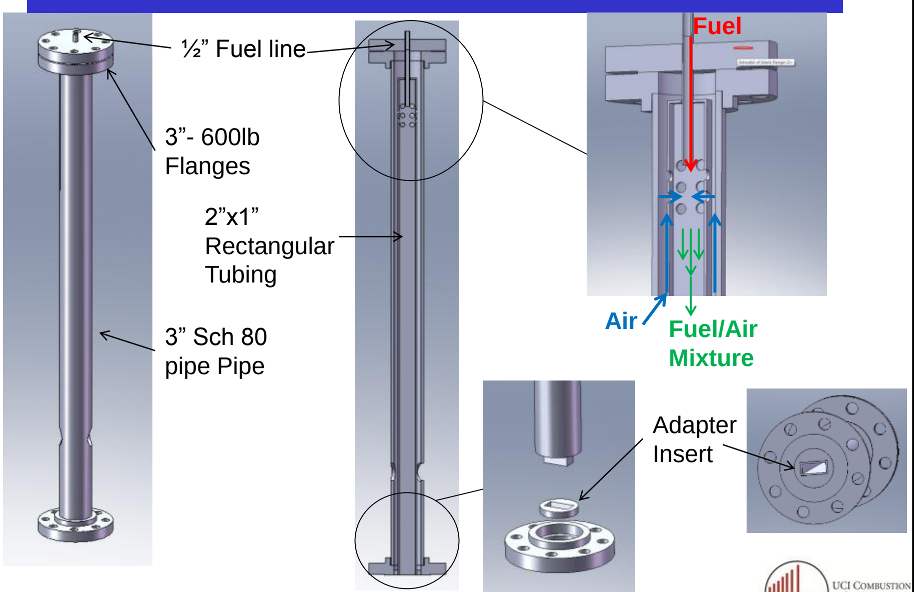
Entrance length is: $L_E = 4.4 \cdot \frac{4A}{P} \cdot \left(\frac{4\dot{m}}{\mu P}\right)^{1/6} = 4.4\left(\frac{4LW}{2(L+W)}\right)\left(\frac{4\dot{m}}{\mu P}\right)^{1/6} = 8.8\frac{LW}{L+W}\left(\frac{2\dot{m}}{\mu(L+W)}\right)^{1/6}$

Substituting in dimensions:
L= 1.76" = .0447m
W= 0.76"=0.0193m
$\dot{m}$ =1.3 lb/s=0.59 kg/s
μ (500F)=2.8x10^{-5} Ns/m^2

$$L_E = 8.8\frac{(.0447)(.0193)}{.0447 + .0193}\left(\frac{2(0.59)}{2.8 \cdot 10^{-5}(.0447 + .0193)}\right)^{1/6} = (0.1186)(6.58 \cdot 10^{-5})^{1/6}$$

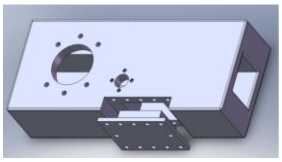
$$\boxed{L_E = 1.11m = 44"}$$

Flow Development

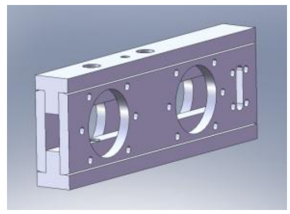


Updated Test Section

- **While available test section seemed attractive…..**
  - Too large to hit the desired velocities and pressures
  - Insufficient flow conditioning/fuel distribution
    - Need to revise injection strategy
  - **Limited Optical Access??**

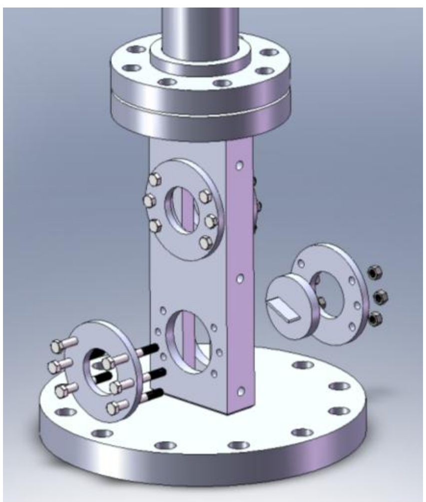


2” x 2”



1.76” x 0.76”

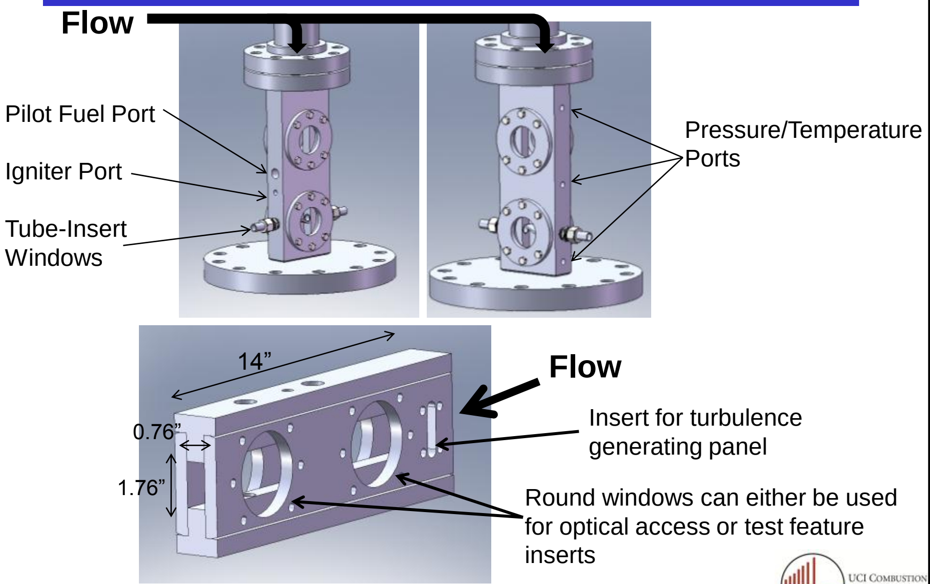
Updated Test Section



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

Updated Test Section



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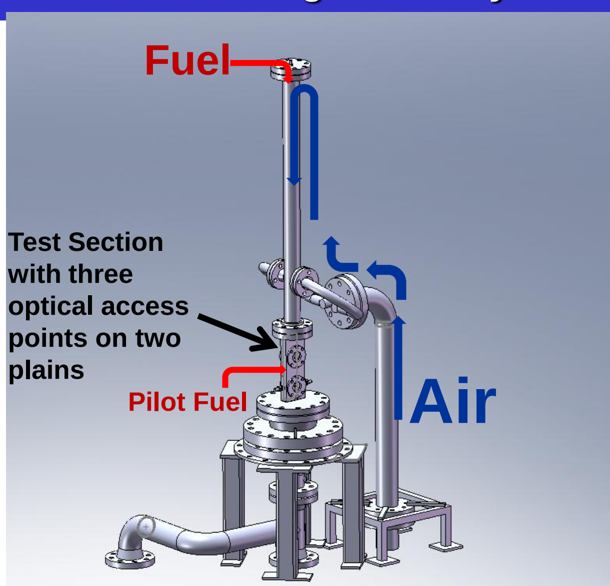
Test Rig Assembly



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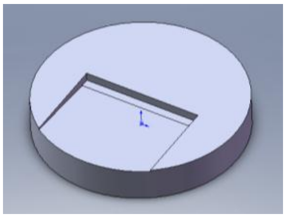
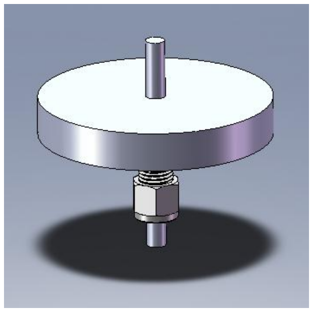
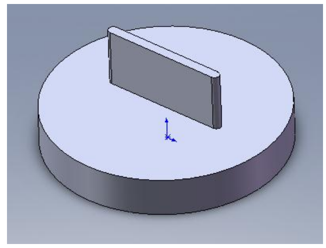
Initial Test Features*



Reverse Step



Rivet/bolt-exposed length can be varied by loosening swage fitting on underside



Vane/Strut- Feature can be rotated

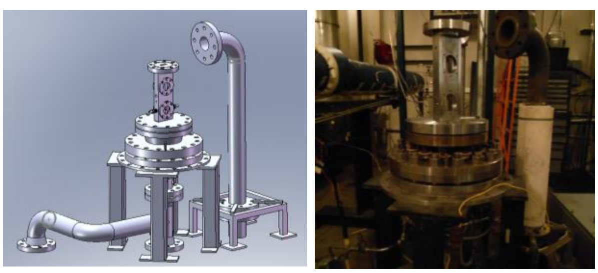
* Based on OEM Input

Status

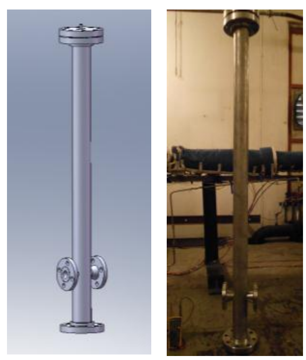
Test Section Development: 80% Complete

Test Facility Interfacing: 60% Complete

Ready For Commissioning: end of 2012



Flameholder Test Section



Flameholder Flow Developer

Status

Task Description	Year 1		Year 2		Year 3	
	M1	M7	M13	M19	M25	M31
		*	*	*		
Task 1—Project Management and Planning*						
Task 2—Preparation -Task 2.1—Fuel/Module Selection -Task 2.2—Fabrication -Task 2.3—Diagnostics/Rig Setup -Task 2.4--Commissioning						
Task 3—Experimental Studies -Phase I -Phase II						
Task 4—Analysis and Model Development						

mcdonell@ucicl.uci.edu; 949 824 5950 x121

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