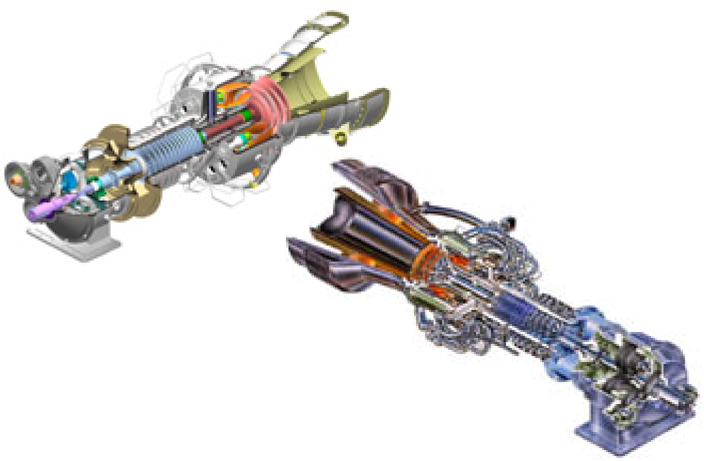
Evaluation of flow and heat transfer inside lean pre-mixed combustor systems under reacting flow conditions



Taurus 65 and Taurus 70 Turbines
Courtesy of Solar Turbines Inc.

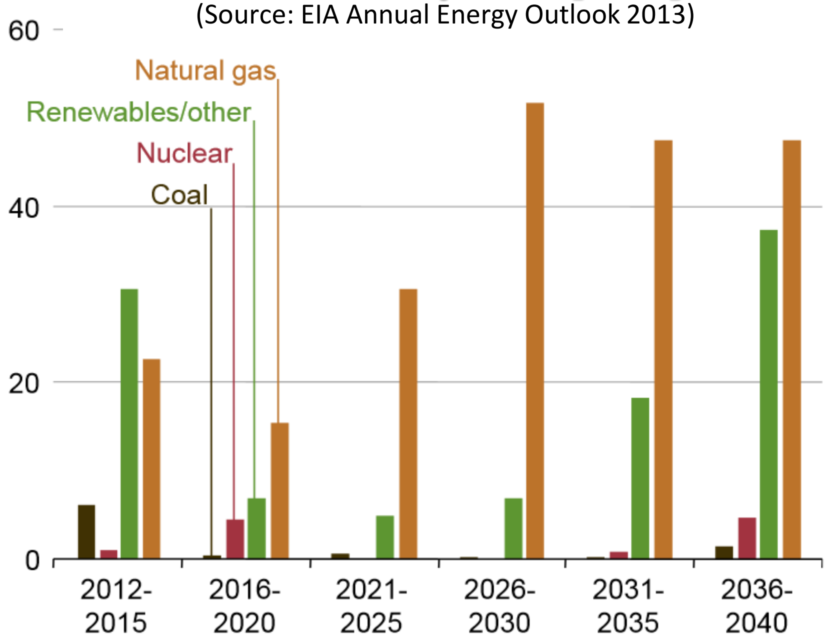
Presented by:
Srinath V. Ekkad, PhD. P.E.

Project sponsored by:
Department of Energy - *UTSR*
Solar Turbines, Inc.
Acknowledgments:
Prof. Uri Vandsburger
Dr. Jaideep Pandit
David Gomez
Sandeep Kedukodi

VirginiaTech Invent the Future®

Natural gas technologies key for energy future

Electricity generation capacity addition by fuel [GW]
(Source: EIA Annual Energy Outlook 2013)



Natural gas predicted to be **crucial** for future electric generation

↓

Further develop gas turbine technology

Liner durability target: ~30 000 hours

Critical aspects:

- **Durability/Operating cycle**
- **Pollutant emission management**
- **Higher efficiency**

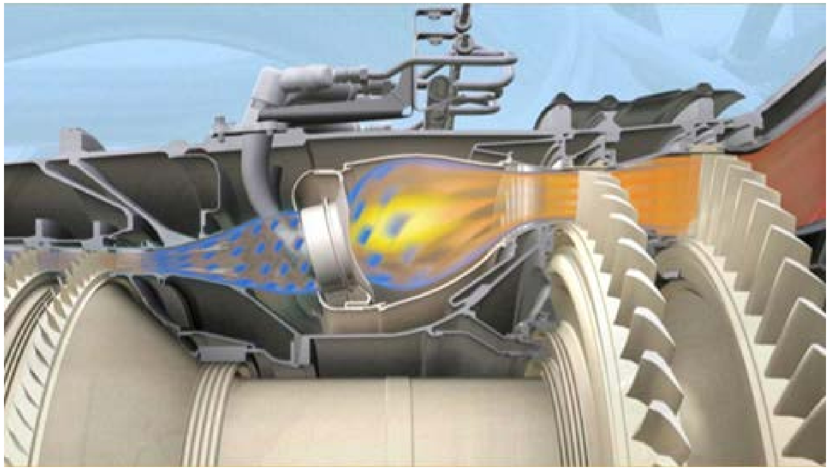
Higher turbine inlet temperatures

15-42 ppm NO_x (15% O_2)

Environmental Protection Agency (EPA) requirement for new turbines firing natural gas for electric generation.

Other pollutants: Unburned hydrocarbons, SO_2 (CO_2 in the future?)

Introduction and Motivation



Source: www.geae.com

- **Dry Low Emission (DLE) Combustors are designed to reduce emissions (Both CO and NOx) by reducing liner film cooling**
- **Reduced film cooling results in need for highly effective backside cooling**
- **The lack of knowledge of the local gas side convective heat transfer distribution on the combustor liner makes design of effective backside cooling of liners more difficult**

The study will shed light into understanding and predicting swirling reacting flow effects on the local convective heat load to the combustor liner and thus will support the development of more effective cooling schemes for low NOx liners.

Improved emissions and efficiency: Lean pre-mixed combustors

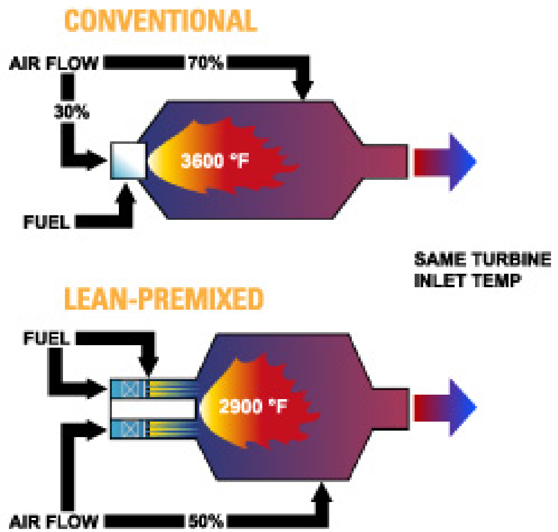
High flame temperatures = **NO_x formation**

Lean pre-mixed combustors

- Pre-mixing prevents local flame hotspots
- Lean combustion = low temperatures/emissions

Challenges:

- Operating close to the lean blowoff fuel-air ratio.
- Auto-ignition/flashback during pre-mixing
- **Compressor air used for pre-mixing limits availability of cooling air**
  - 70% in conventional vs 50% in lean pre-mixed (SoLoNOx, Solar Turbines Inc.)
- **New cooling schemes:**
  - Backside cooling



SoLoNOx vs Conventional combustor

Courtesy of Solar Turbines Inc.

Pre-mixed combustors ***aka*** Dry Low Emission, Dry Low NO_x, and SoLoNOx

Technology challenges impact liner/dome cooling

Backside cooling

Solution ←

- **Cooling technologies:** Film injection leads to non-uniform temperature pattern factors.
  - **CO emissions** increase
  - Larger **thermal stresses** at the guide vanes/turbine blades
- **Injector design:** Improve pre-mixing, reduce local hotspots in the flame, and increase flame stability
  - **Introduce complex flow fields to the Combustor**

Solar fuel nozzles with swirlers
Courtesy of Solar Turbines Inc.

- **Combustor air management**:
  Avoid flameout, expand low emission operating range

All impact liner/dome cooling →

Critical need to characterize and predict local heat load
Particularly convective component

Liner thermal design: Inaccurate convective heat transfer

Heat load sources affecting combustor liners

1. **Radiative heat load**
   - **Uniform**: Function of peak gas temperature to wall temperature ratio.

2. **Convective heat load**
   - **Non-uniform**: Depends on reaction and swirling flow dynamics

Current **liner design** based on heat transfer correlations in straight pipes

- Ignores radial temperature distribution and effects of swirling flow
- Does not aid in estimating back-side cooling requirements realistically

Local convective heat load prediction important for effective liner design

Project scope: Improve combustor liner cooling design and technology

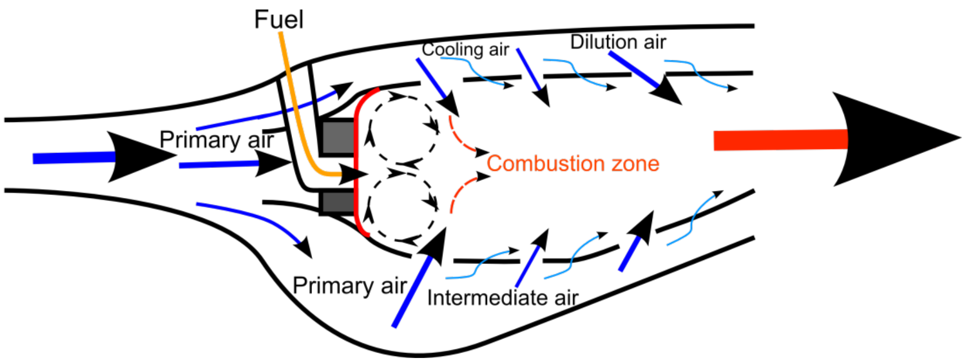
- **Quantify local heat loads** on the combustor liner and dome due to reacting and swirling flows
- **Develop cooling methods** to address realistic liner cooling requirements of next generation gas turbines

Impact and significance:

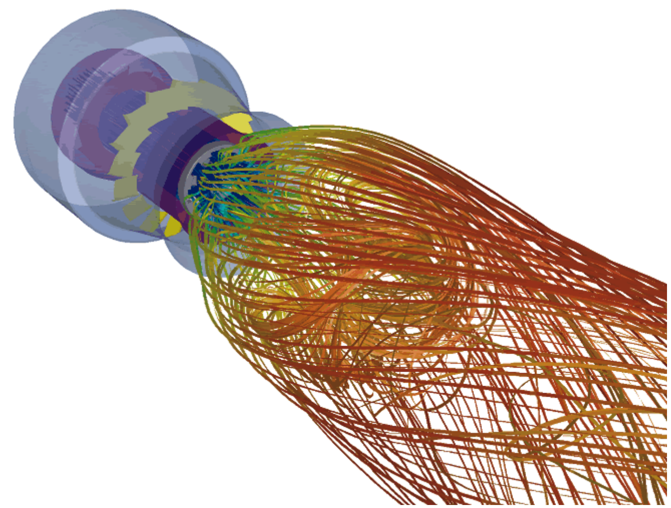
- First comprehensive **study of local heat transfer** estimation in reactive flows
- Improved **prediction methods for combustion liner cooling** for low emission combustors
- Greatly **caters industrial gas turbine community** towards designing liners effectively

Key objective: Swirling flow and its effects on liner heat transfer

1. Evaluate the swirling flow (reactive & non-reactive) characteristics
   - Experimental and computational
2. Evaluate the effects of swirling flow on liner/dome/shield heat transfer
   - Can combustor
   - Annular combustor
   - Experimental and computational

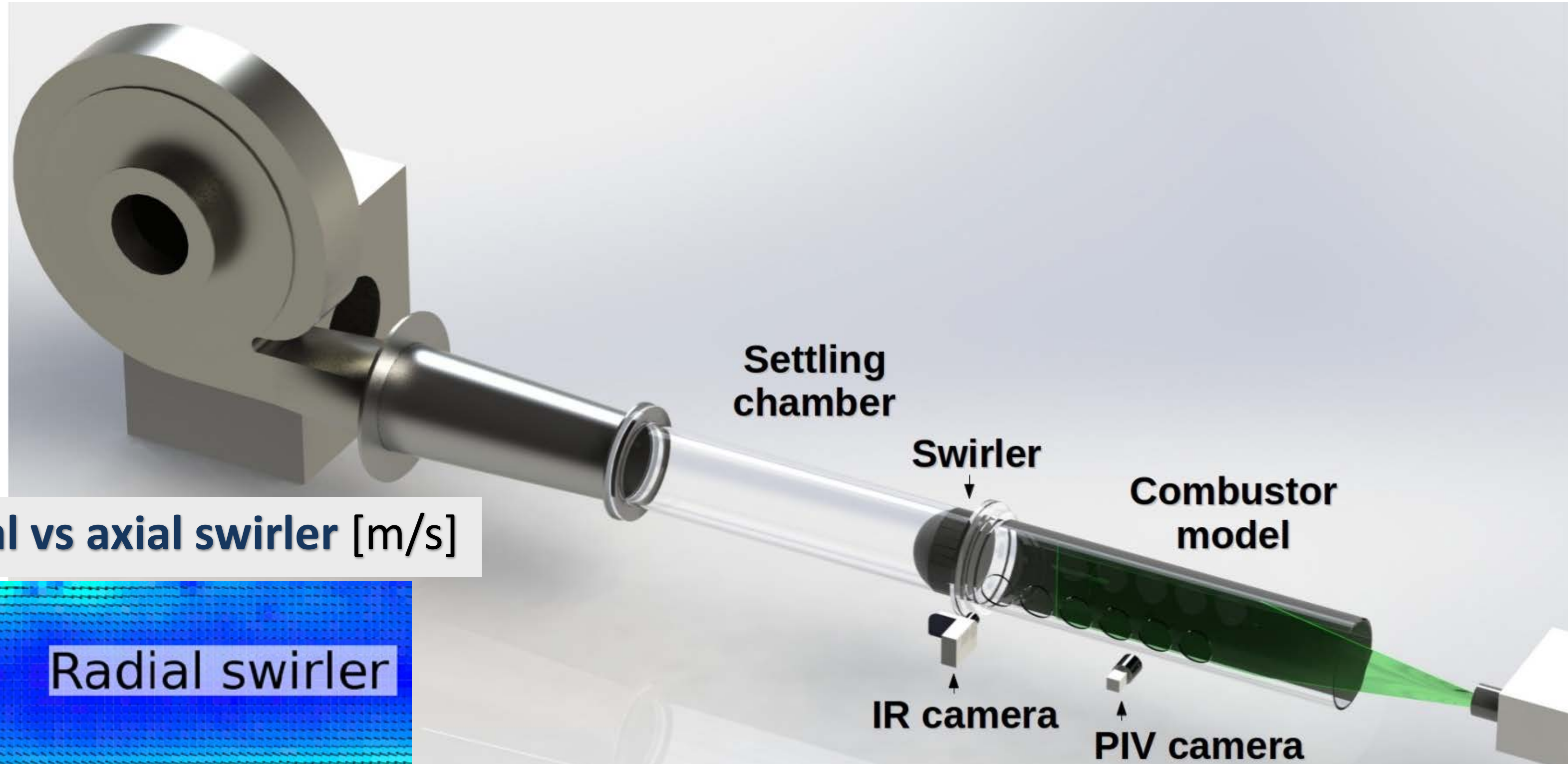


Air management within a typical combustor
http://en.wikipedia.org/wiki/File:Combustor_diagram_airflow.png

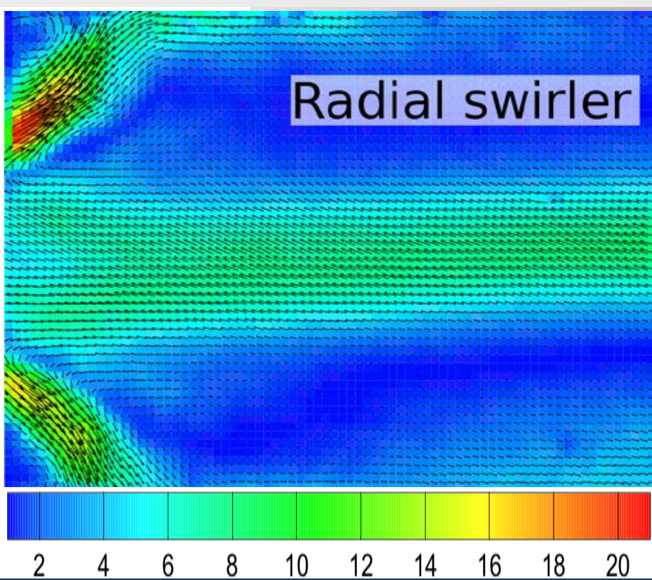


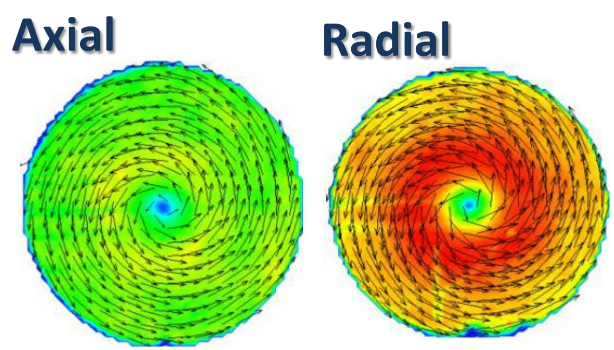
ANSYS Fluent simulation of reacting flow
http://www.edr.no/en/courses/ansys_cfd_advanced_modeling_reacting_flows_and_combustion_in_ansys_fluent

Previous work: Can combustor swirling flow characterization



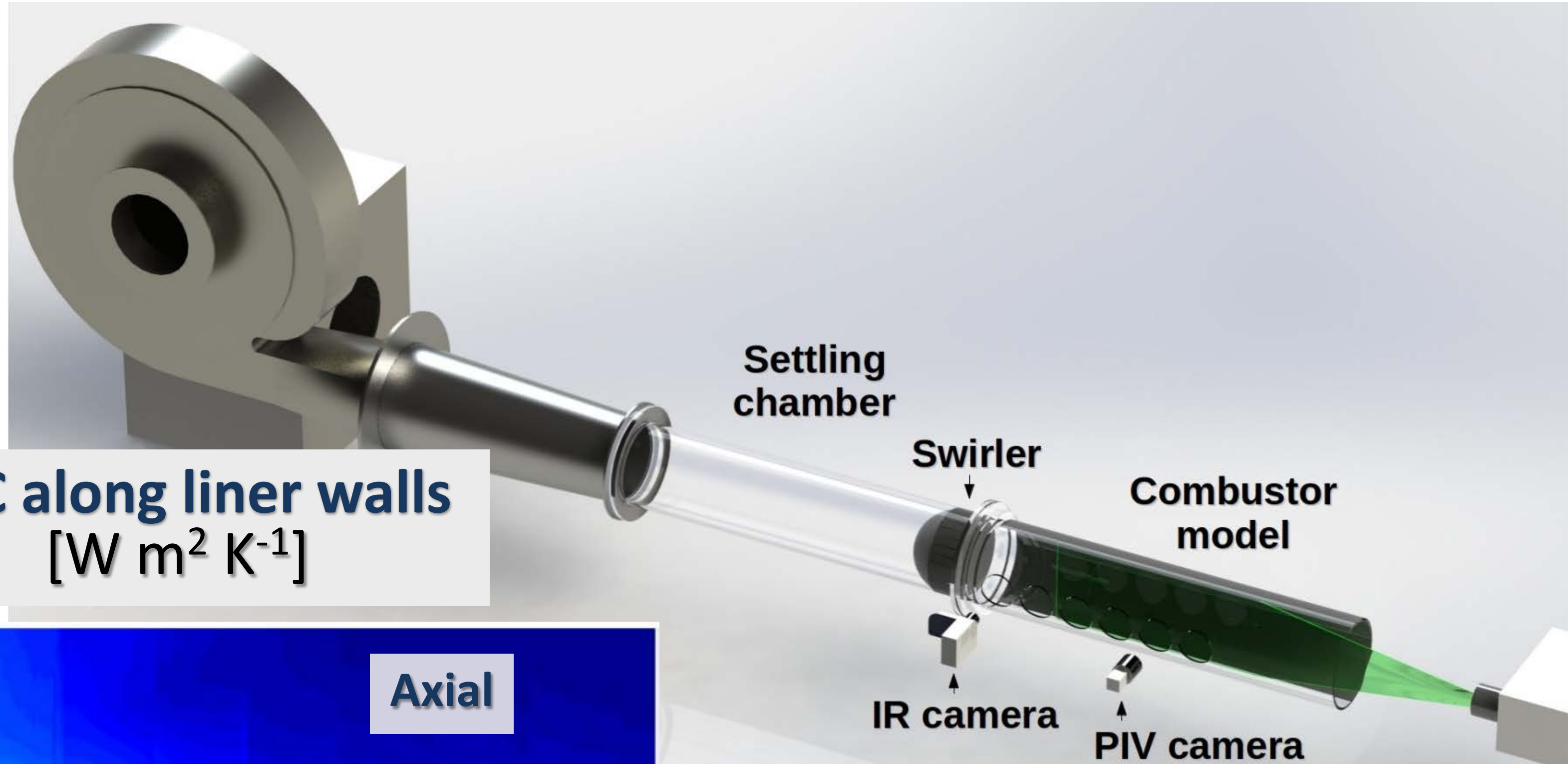
2D PIV, radial vs axial swirler [m/s]



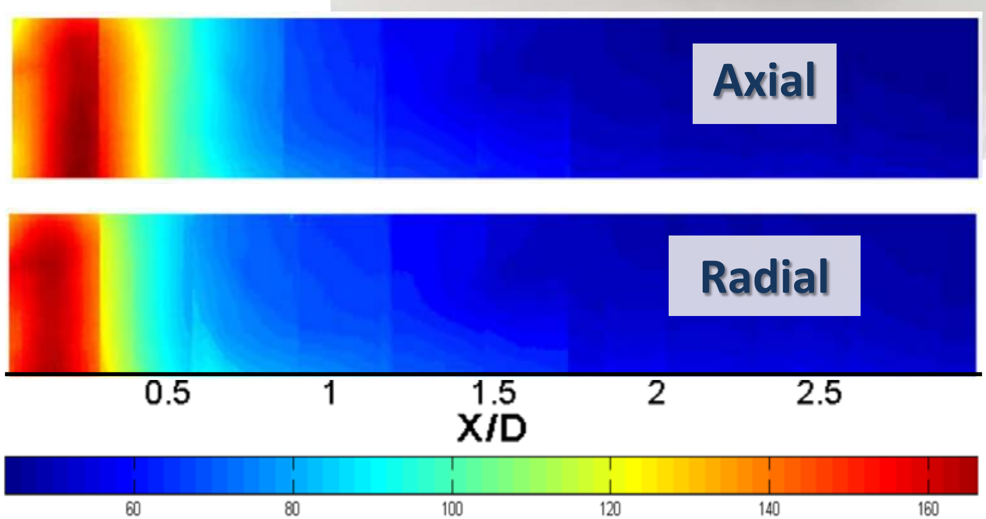


PIV cross-sections at X/D= 2

Previous work: Can combustor liner heat transfer



HTC along liner walls
[W m^2 K^{-1}]



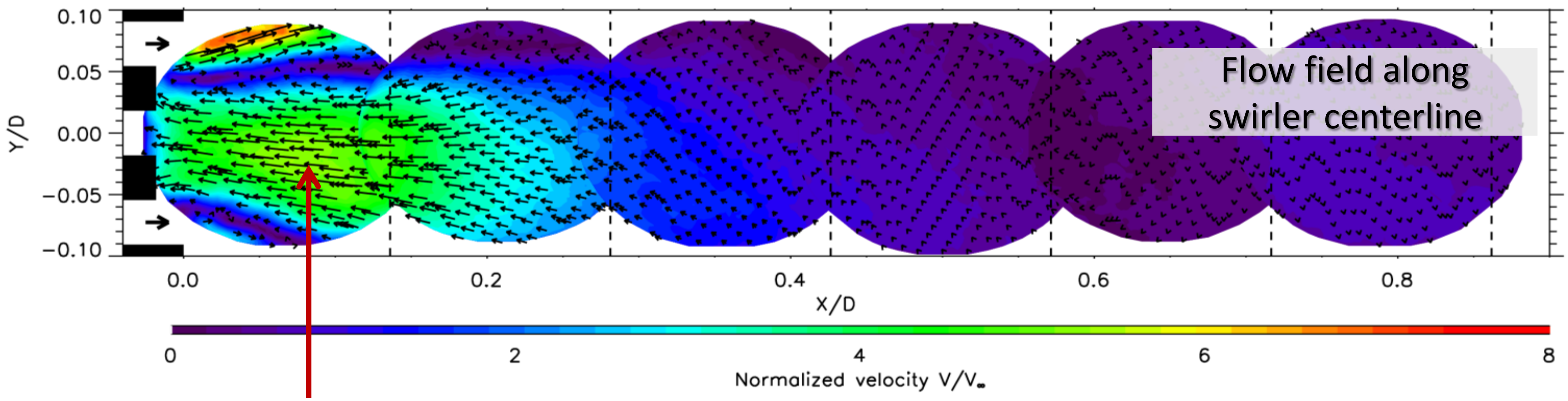
Convective heat transfer is **non-uniform** along liner

↓

Thermal stresses, liner failure

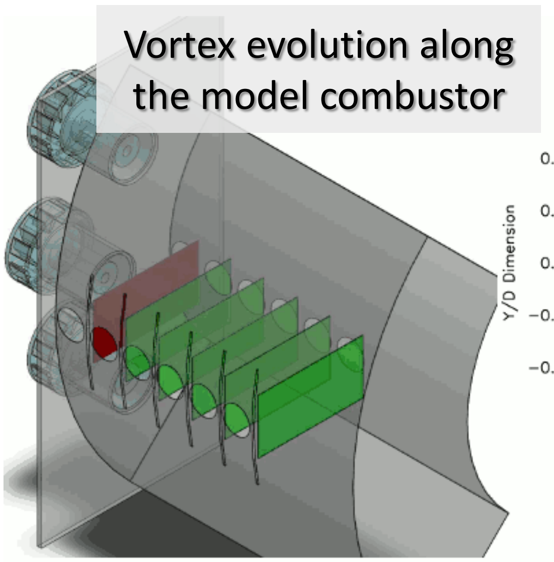
Previous work: Annular combustor flow field

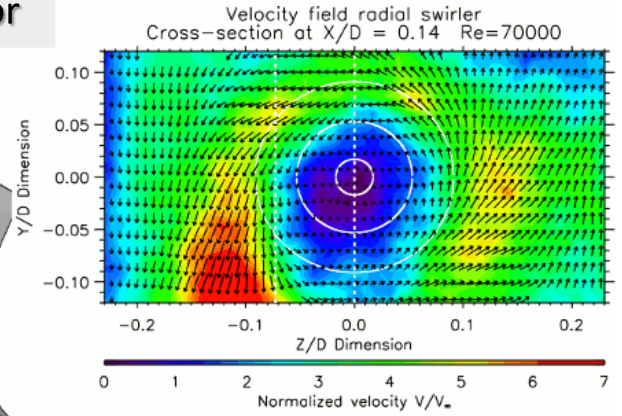
2D Particle Image Velocimetry (PIV) of flow in a model combustor with **radial swirlers**.



Recirculation zone improves:
- Mixing
- Combustion efficiency

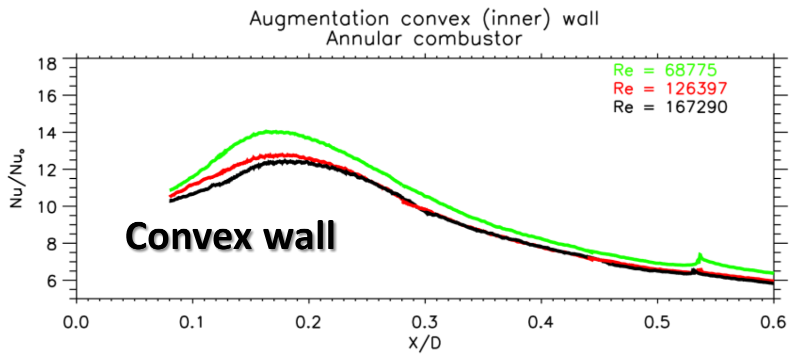
Additional studies performed:
- **Axial swirlers**
- **CFD modeling**
- Turbulent kinetic energy of the flow
- Induced vorticity

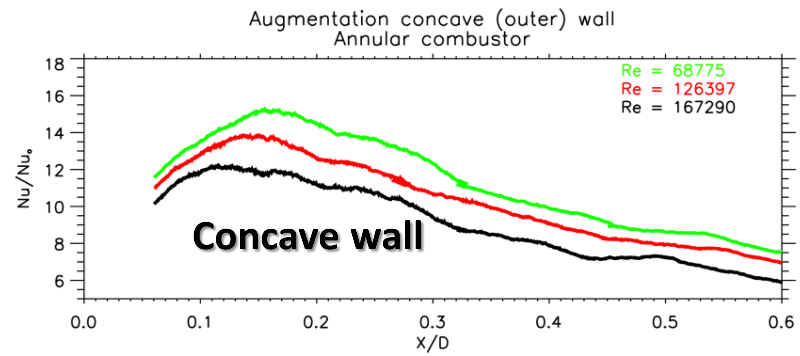




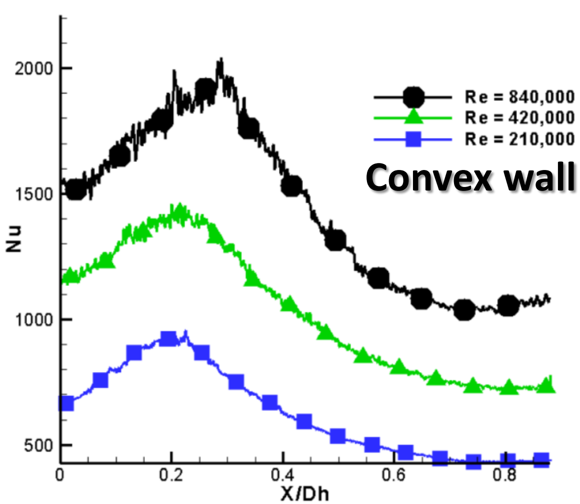
Previous work: Annular combustor heat transfer

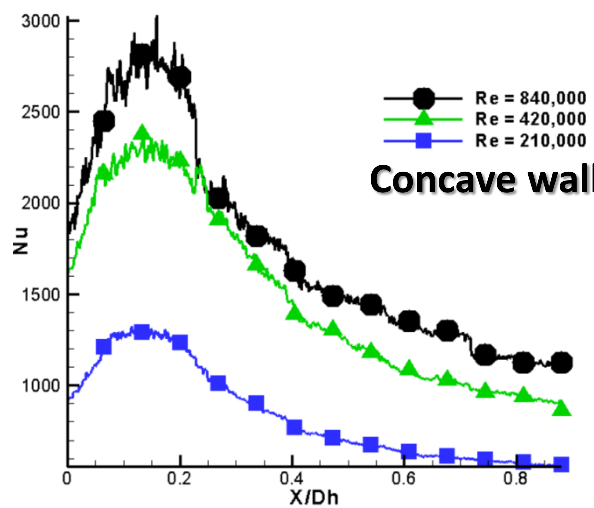
Radial swirlers





Axial swirlers





Peak HT locations remain ~**constant**

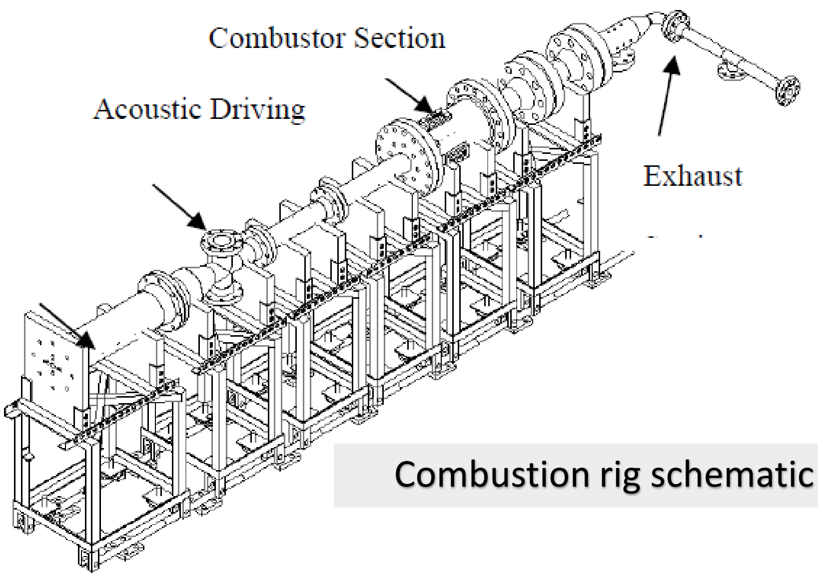
Comparative studies between radial and axial swirlers

Previous work: Reacting flow characterization

Additional Virginia Tech facilities:

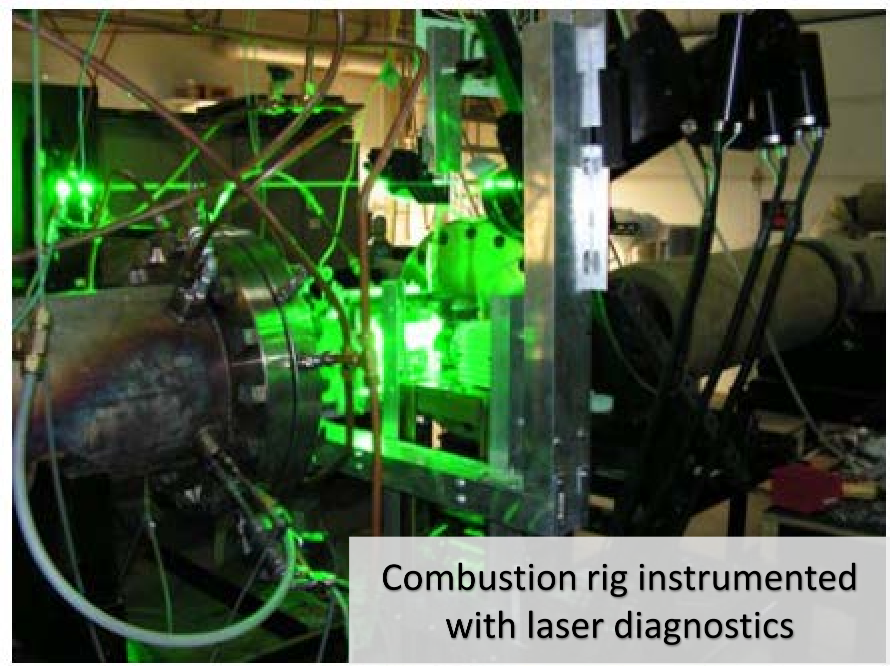
- Advanced Power and Propulsion lab
- Active Combustion Control group/lab

- Fuel blending studies
- Laser diagnostics
- High speed cameras
- Gas analyzers for CO, CO_2, NO_x, UHC, and O_2



Combustion rig schematic

Combustion studies, do not include heat transfer or liner design



Combustion rig instrumented with laser diagnostics

Current status of the project

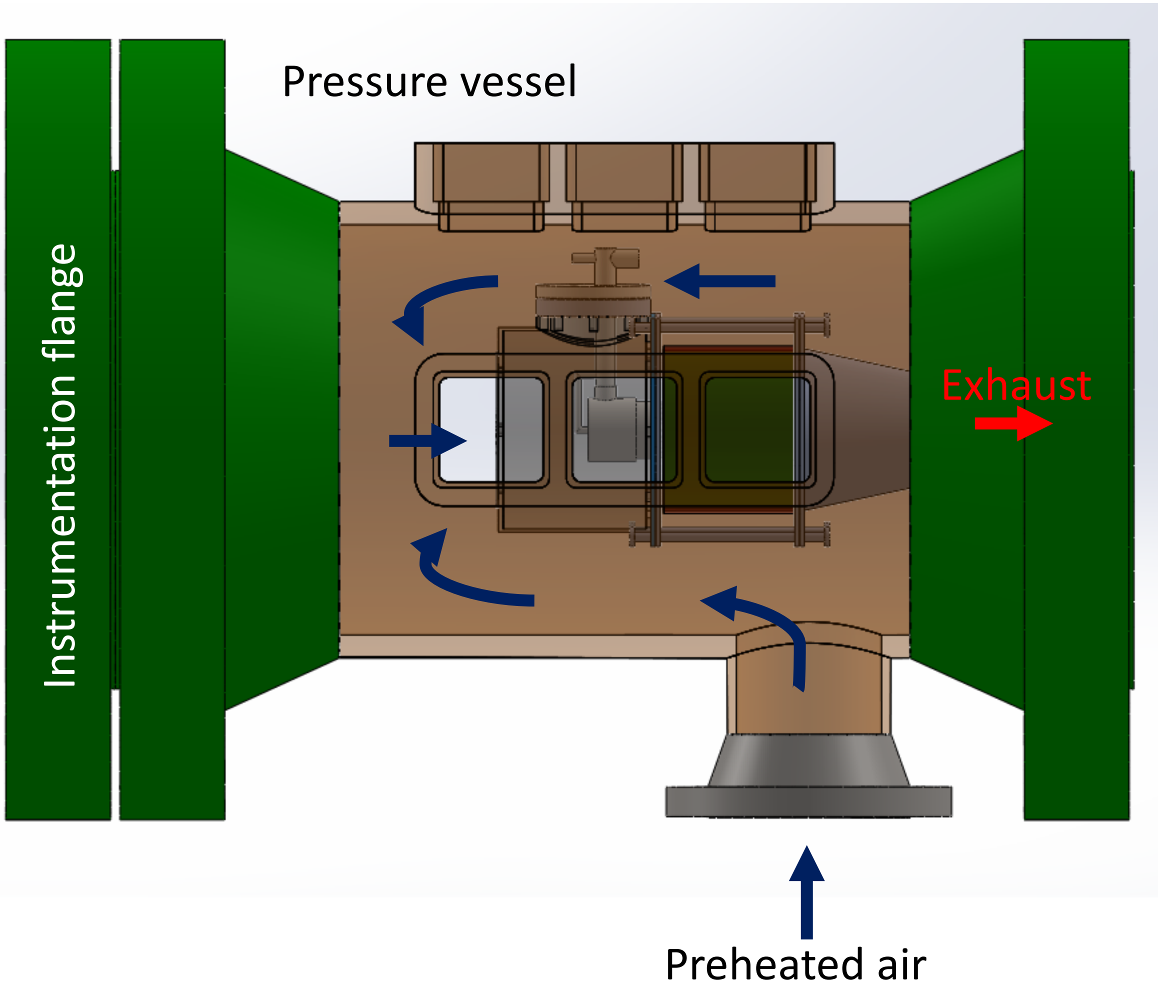
The initial design of the system has accounted for reacting flow and industrial nozzles

Plan for Solar/UTSR combustor

Year 1	
Combustor simulator design	Jan-14
Fabrication of apparatus	Apr-14
Shakedown and testing of apparatus (non-reacting)	Jul-14
Baseline Computations on Simulated Combustor	Oct-14
Year 2	
Design/Modification necessary for reacting flow testing in simulator	Dec-14
Shakedown/Testing of apparatus (reacting)	Feb-15
Comparison of non-reacting and reacting flow apparatus data	Jun-15
Comparison of turbulence models	Sep-15
Year 3	
Retrofit of industrial nozzles into apparatus design	Sep-15
Testing of industrial nozzles in simulator	Feb-16
Testing in industrial apparatus	Jul-16
Comparison of Computational Effort to Industrial tests	Jul-16
Final report	Aug-16

Blue = Working on it
Red = Delayed
Green = Completed

System design: Low pressure combustor within a high pressure vessel



- Pressurized vessel will contain the pressure at high temperatures according to design.
- Flow will enter the inner combustor that will be manufactured and tested independently at low pressures.
- Fuel and coolant lines will go through the instrumentation flange.
- Inner combustor section does not see a large pressure differential across its walls.

System design: Modularity, incremental complexity

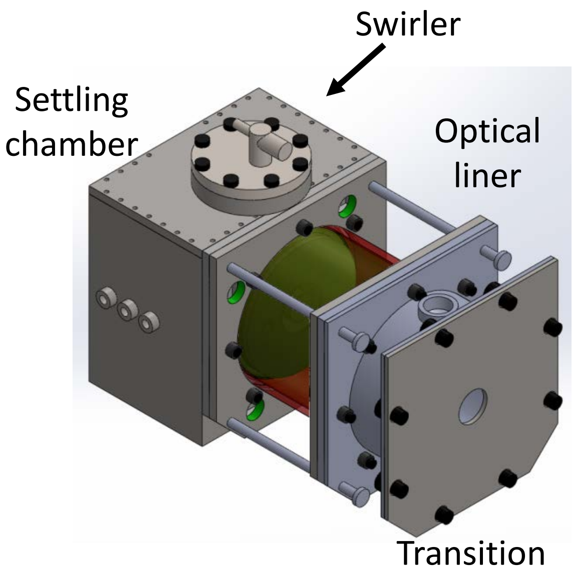
Low-pressure, cold experiment → Low- pressure, reactive experiment
- Quenching unit

→ High-pressure, cold experiment
- Back pressure valve
- Pressure vessel

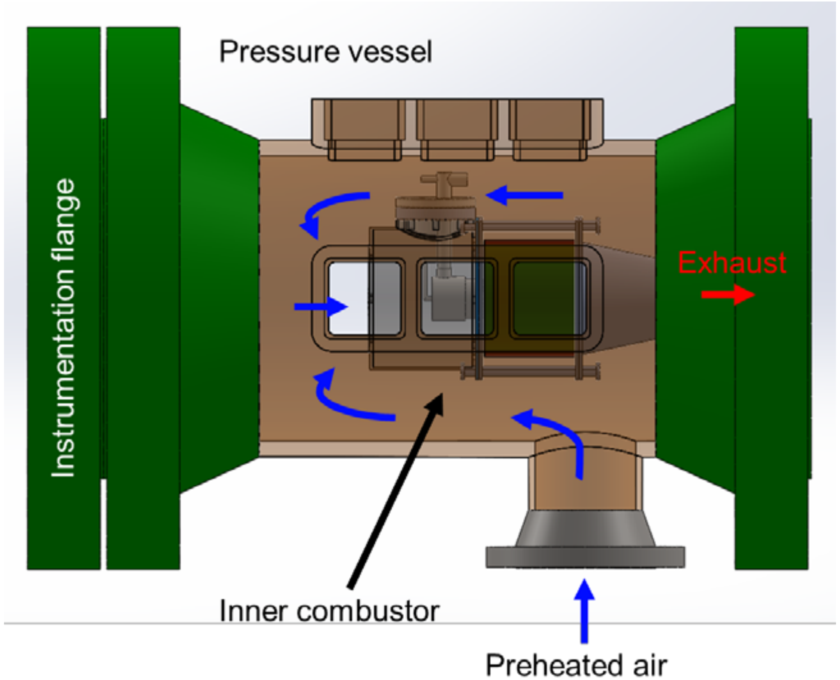
→ High-pressure, reactive experiment

Low pressure design

High pressure design

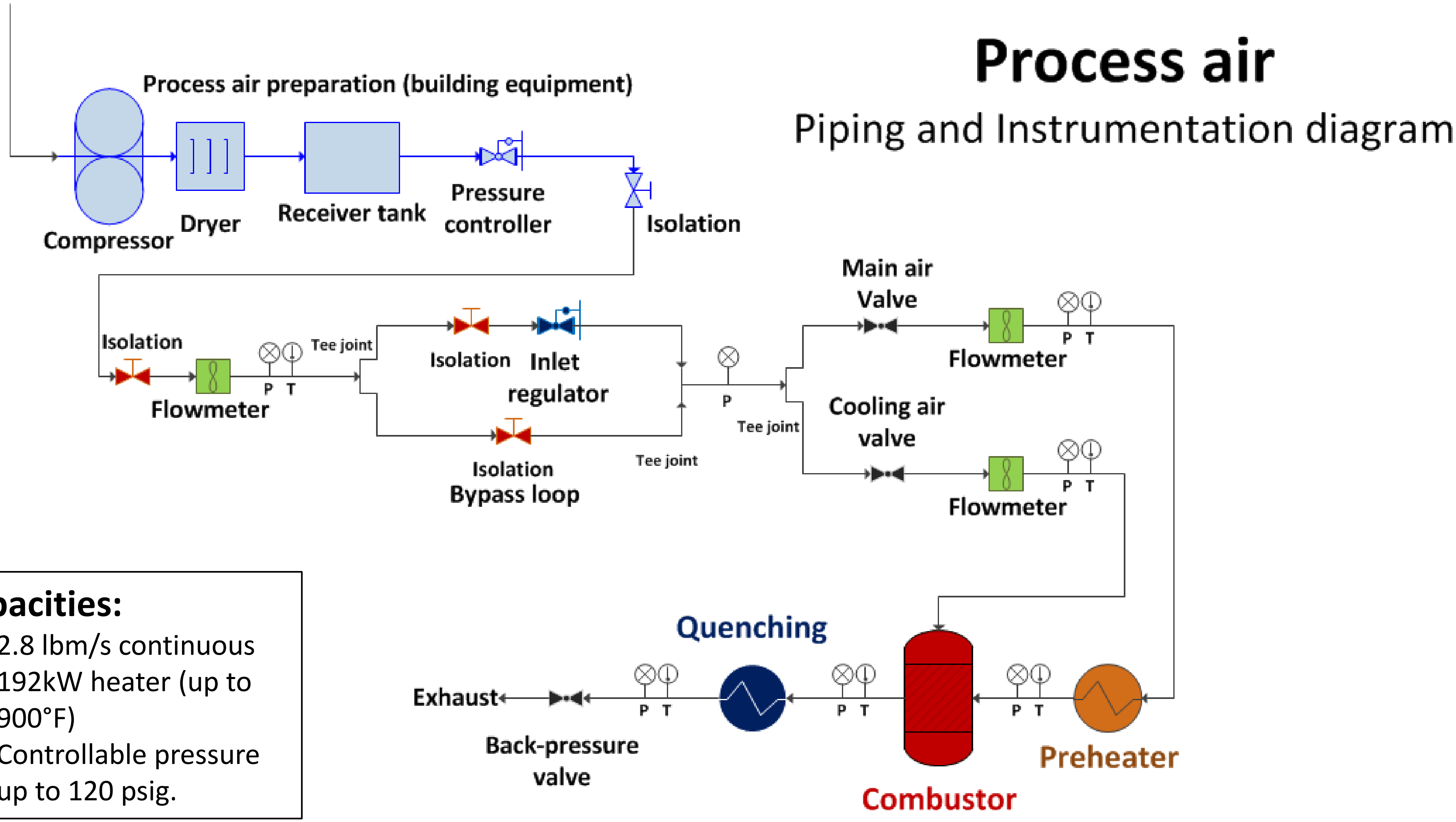


Inner combustor (low pressure)



Pressure vessel with inner combustor

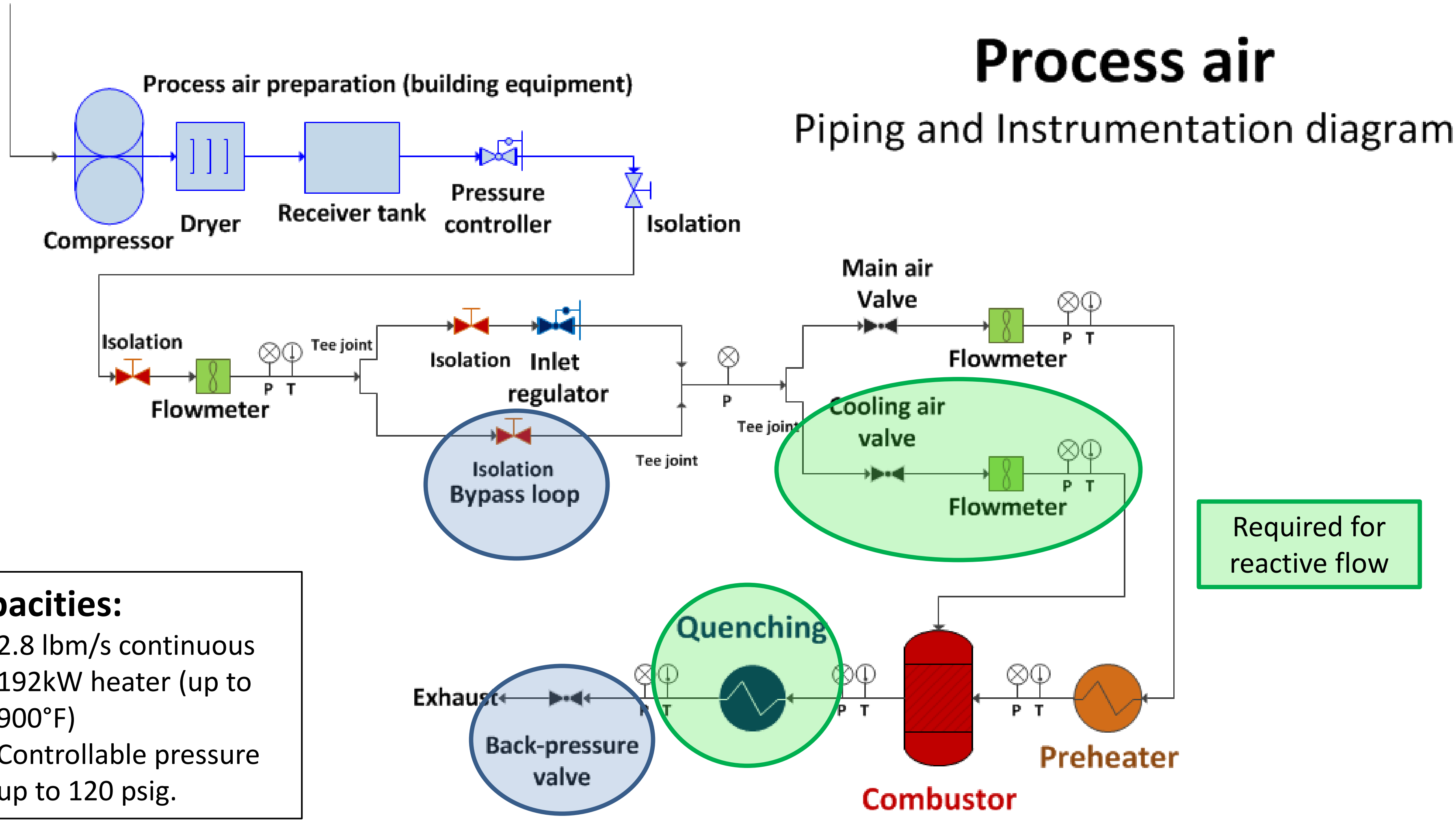
Process design: Control over pressure, flow rate, and temperature



Capacities:

- 2.8 lbm/s continuous
- 192kW heater (up to 900°F)
- Controllable pressure up to 120 psig.

Process design: Control over pressure, flow rate, and temperature

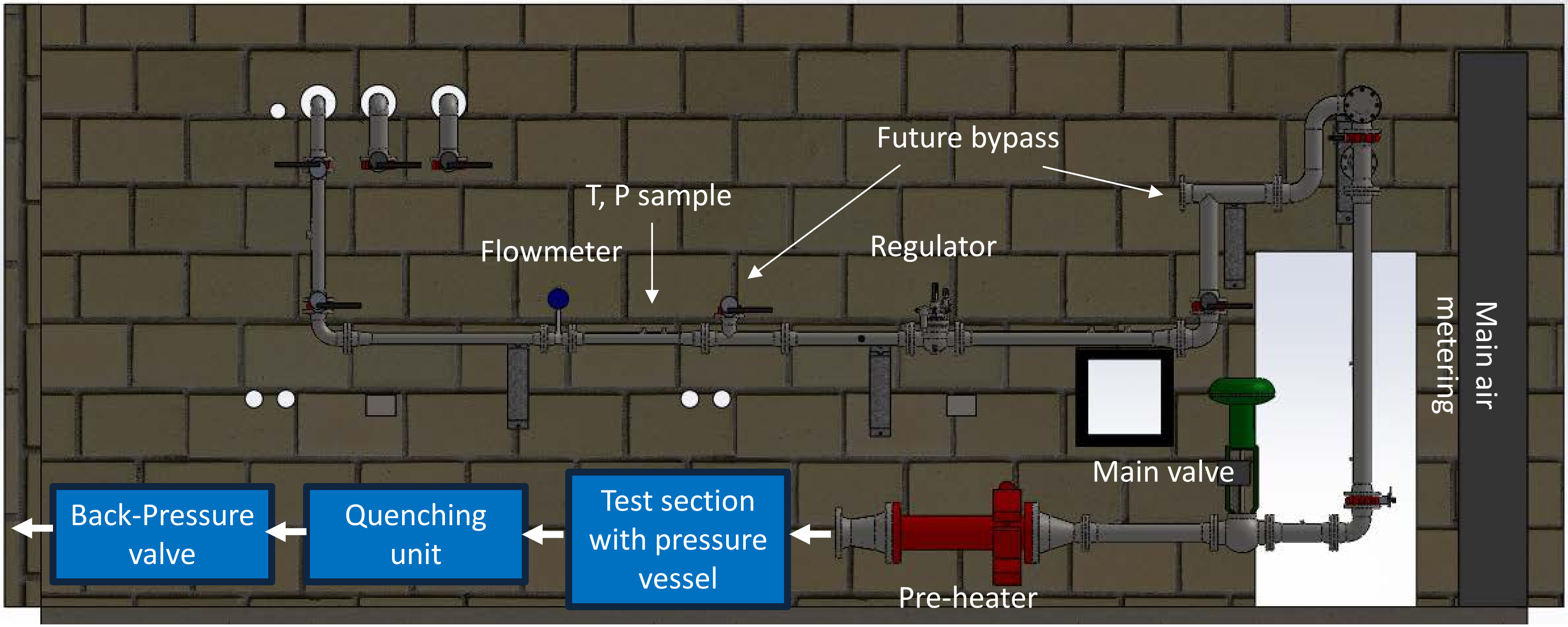


Capacities:

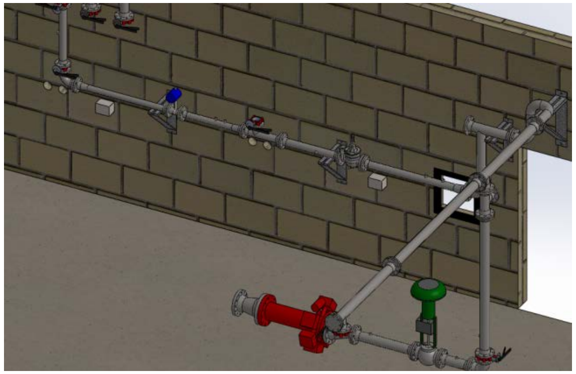
- 2.8 lbm/s continuous
- 192kW heater (up to 900°F)
- Controllable pressure up to 120 psig.

Required for high pressure

Progress with construction: Lines for metering & pressure control installed

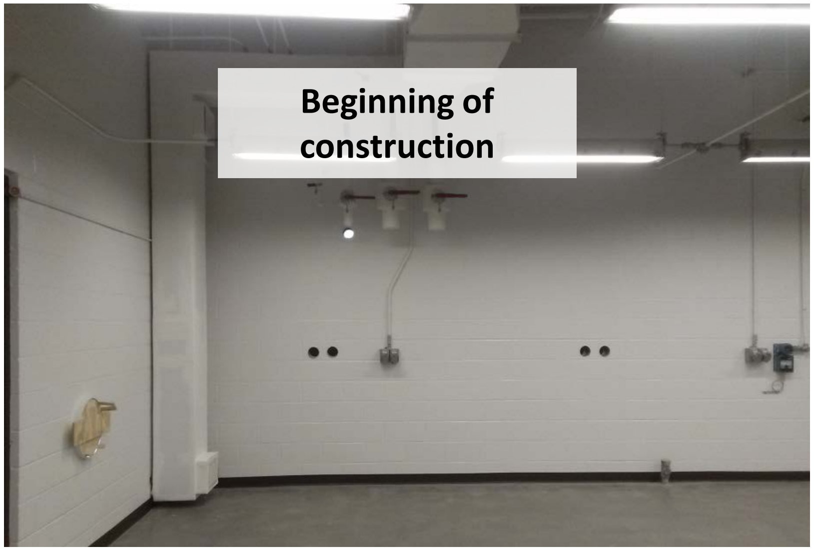


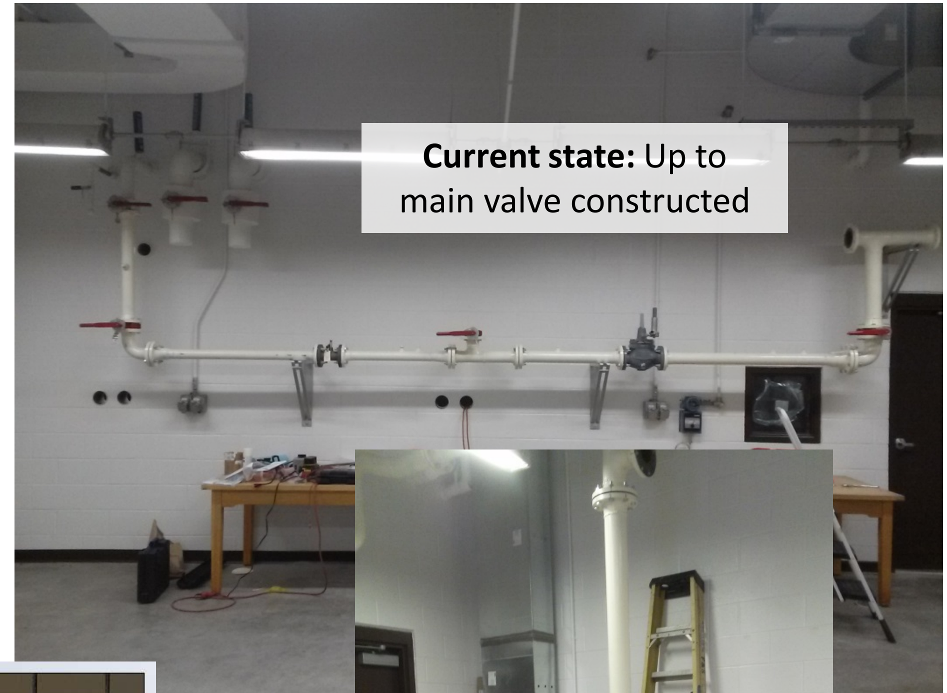
- Components and piping have been designed and selected
- Construction has begun

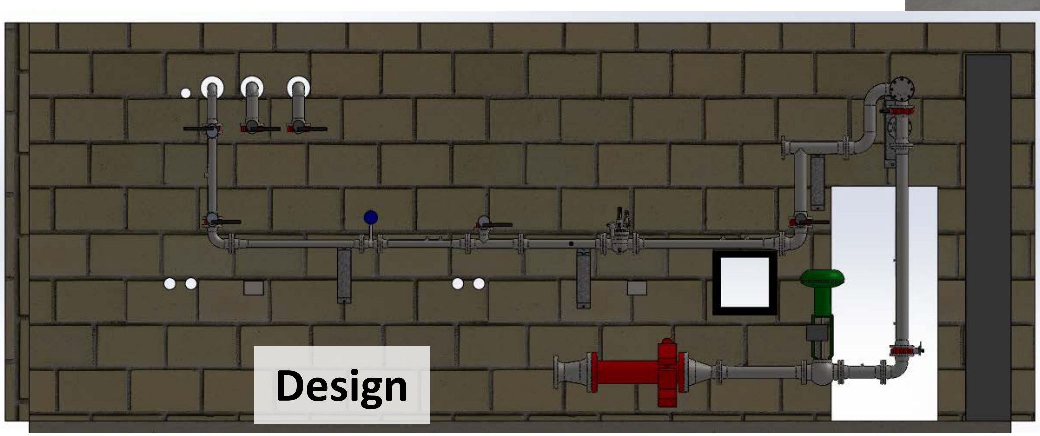


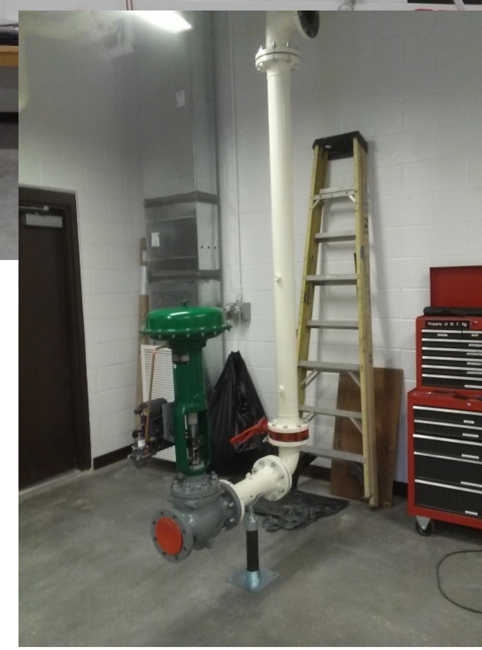
Current objective: Manufacture the test section.

On going construction: The facility is built up to the main valve

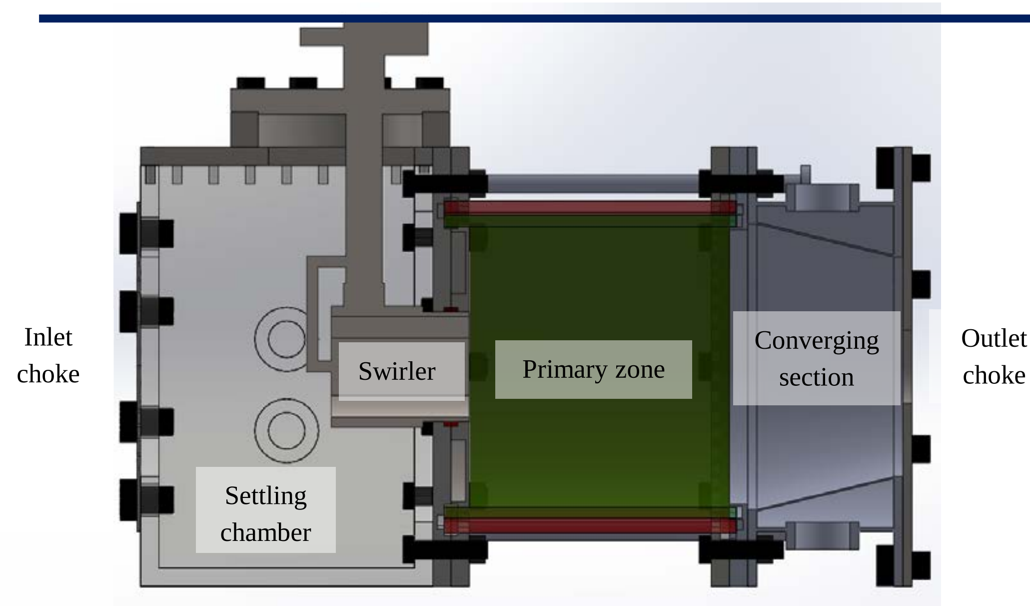


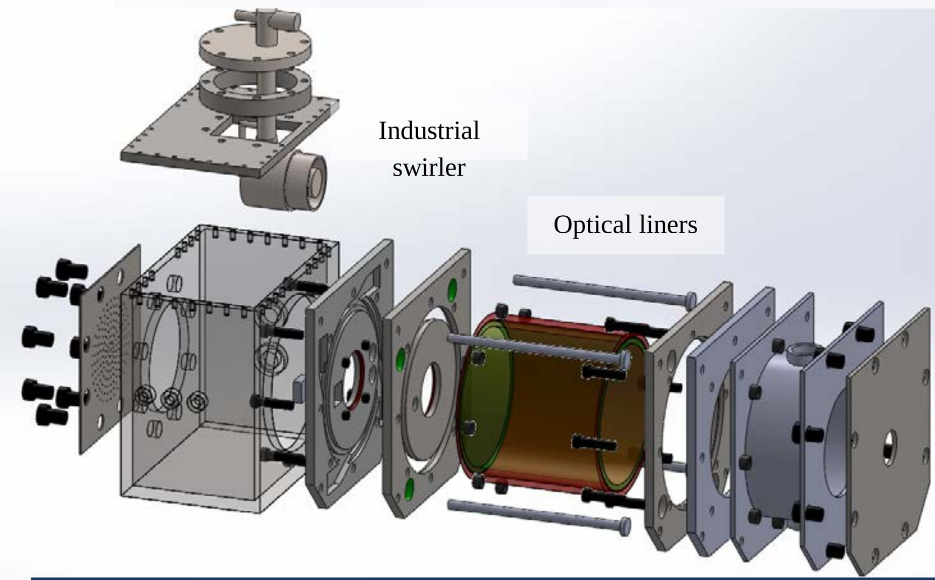






Combustor simulator design: Features of low pressure design

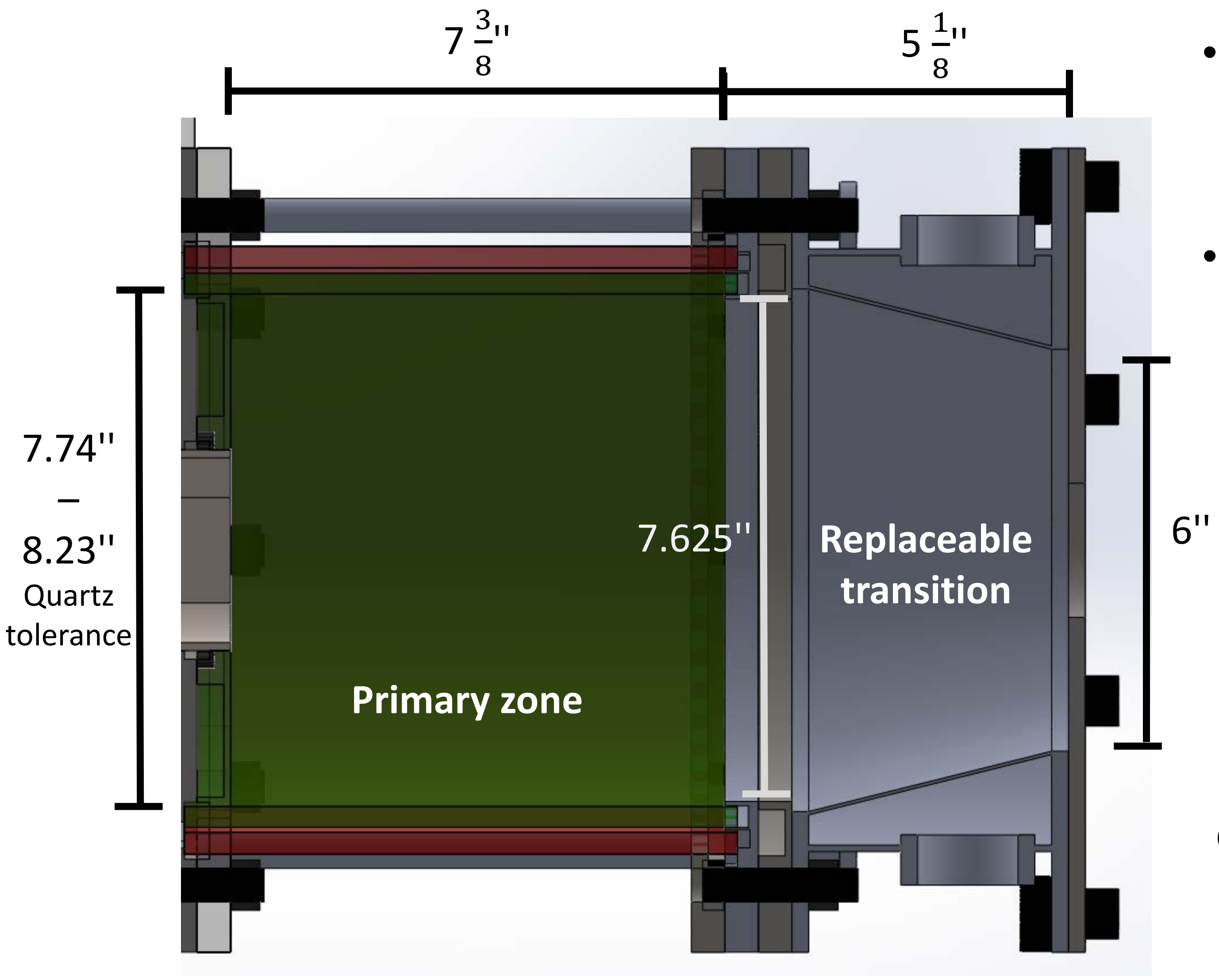




Assumed air temperatures from 1800 to 2336 K.

- **No film cooling or dilution**
  Air cooling between optical liners below 1300 K.
- Symmetric, **can** combustor
- Inner diameter 7.74'' (worst case) due to optical quartz tolerances (design is 8'').
- Metal pieces are water cooled to below 883 K (1130 °F, maximum allowable temperature of 1500 ° F)
- **Replaceable transition**

Combustor simulator dimensions: **Design based on actual dimensions**



- Double quartz liner with coolant air flowing in between.
- Water cooling for all the metal pieces (stainless steel 304 or 303)

Transition piece outlet diameter must be adjusted depending on pressure

Types of Measurements Planned

Measurements:

- Infrared thermography of liner outer wall – back out temperature on gas side using conduction model
- PIV measurements of reacting flow – proven concept already with an afterburner test at VT
- Chemiluminescence for qualitatively determining hot gas temperature distribution – currently developing a new technique to provide quantitative values from chemiluminescence
- Also considering a new novel acoustic technique for velocity and temperature simultaneous measurement – developing this technique currently

Experiment plan: Conditions to be considered

Test case	Pressure at test section	Air temperature at inlet of test section	Mass flow rate to test section	Cooling mass flow rate
Cold flow / low pressure (construction phase 1)				
[redacted]	0	Ambient (293 K)	0.5-2.5 lbm/s	0 lbm/s
[redacted]	0	Pre-heat (400-600 K)	0.5-2.5 lbm/s	0 lbm/s
Reacting flow / low pressure (construction phase 2)				
[redacted]	0	Ambient (293 K)	0.5-2.0 lbm/s	0.5 lbm/s
[redacted]	0	Pre-heat (500 K)	0.5-1.5 lbm/s	1.0 lbm/s
Cold flow / high pressure (construction phase 3)				
[redacted]	40-120 psig	Ambient (293 K)	0.5-2.5 lbm/s	0 lbm/s
[redacted]	40-120 psig	Pre-heat (500 K)	0.5-2.5 lbm/s	0 lbm/s
Reacting flow / high pressure (construction phase 4)				
[redacted]	40-120 psig	Ambient (293 K)	0.5-2.0 lbm/s	0.5 lbm/s
[redacted]	40-120 psig	Pre-heat (500 K)	0.5-1.5 lbm/s	1.0 lbm/s

Currently targeting the two first construction phases and experiments.

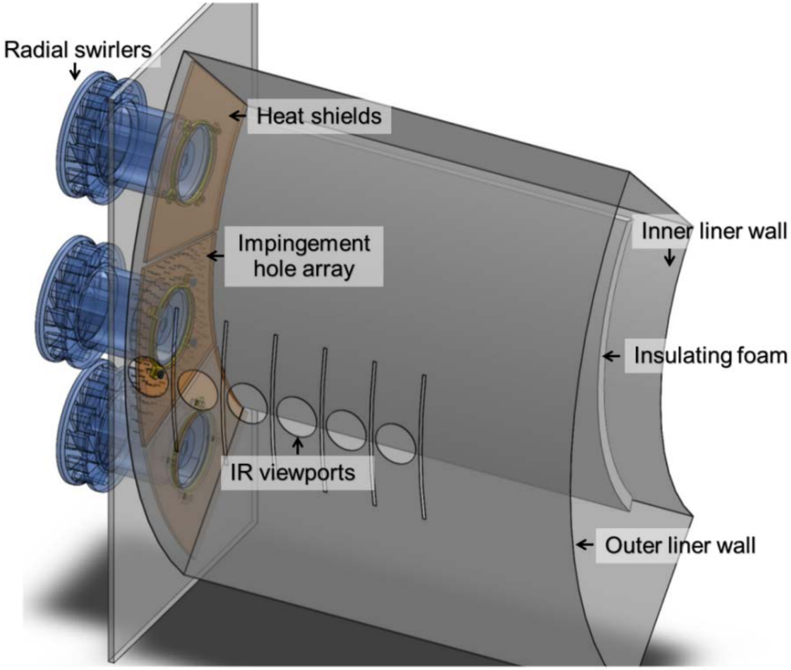
Objective: Run at several operating conditions to characterize how the flow and heat transfer behave as a function of these variables.

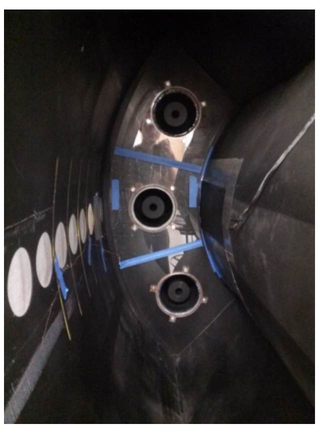
Time line: Low pressure tests by the end of the year, high pressure by the next

Goal/Objective	Date (End of the month)
Start cold flow experiments at low pressures • Design and fabrication of burner • Installation/Instrumentation • Heater • Operational compressor	10/2014
Start reactive flow experiments at low pressures • Exhaust designed and fabricated • Quenching designed and fabricated • Operational water and fuel lines	12/2014
Have pressure vessel designed	12/2014
Deal with any experimental issues (simultaneous)	10-12/2014
Finalize any modifications to the inner combustor/pressure vessel	02/2014
Send pressure vessel to manufacture	03/2014
Start high pressure cold flow tests • Wait for manufacturing of pressure vessel • Selection/purchasing of outlet valve	05/2015
Start high pressure reactive flow tests	08/2015

VirginiaTech Invent the Future®

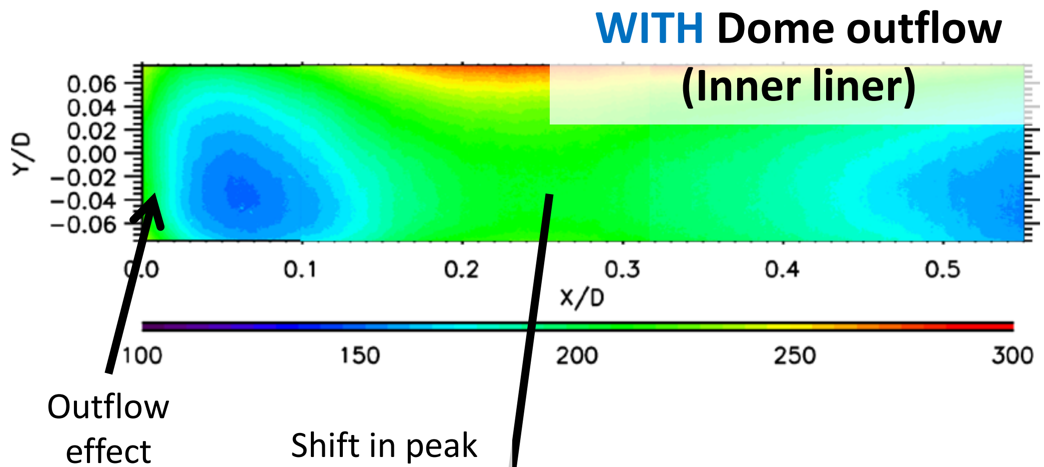
Additional experimental efforts: Dome cooling and its effects on liner heat transfer

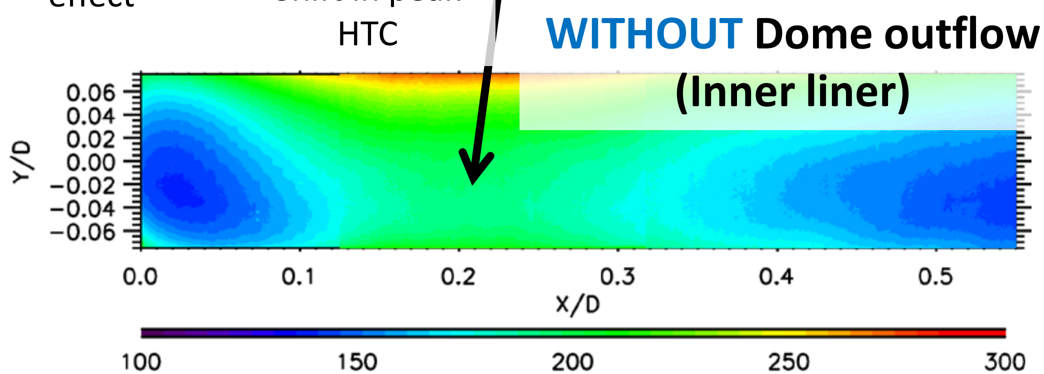




Steady state IR measurements at the liner walls

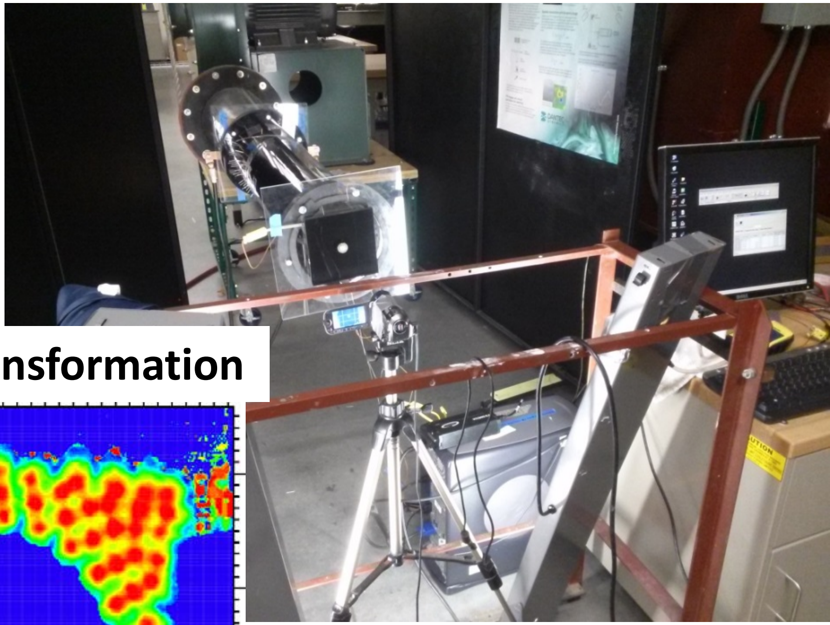
Effects of outflow from dome cooling on liner heat transfer coefficients (Re # = 125 000)



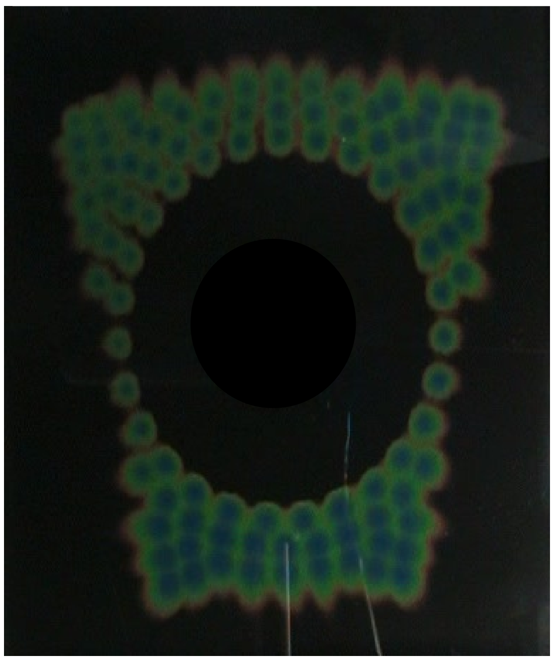


Cold flow studies: Heat shield impingement cooling characterization

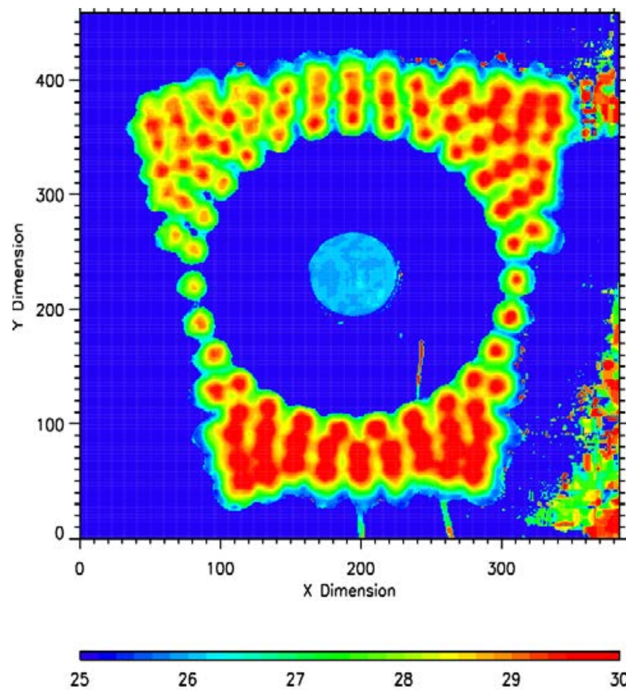
Liquid crystal thermography of impingement cooling.
Preliminary results for hole Reynolds # of 2500.



Liquid crystal video



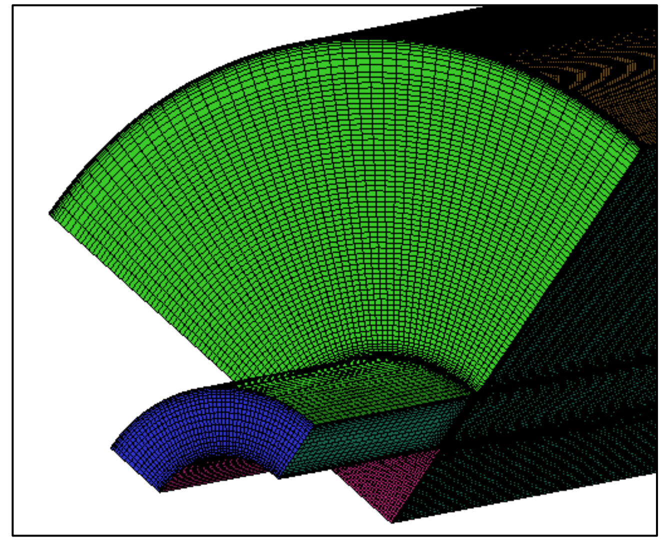
Temperature transformation

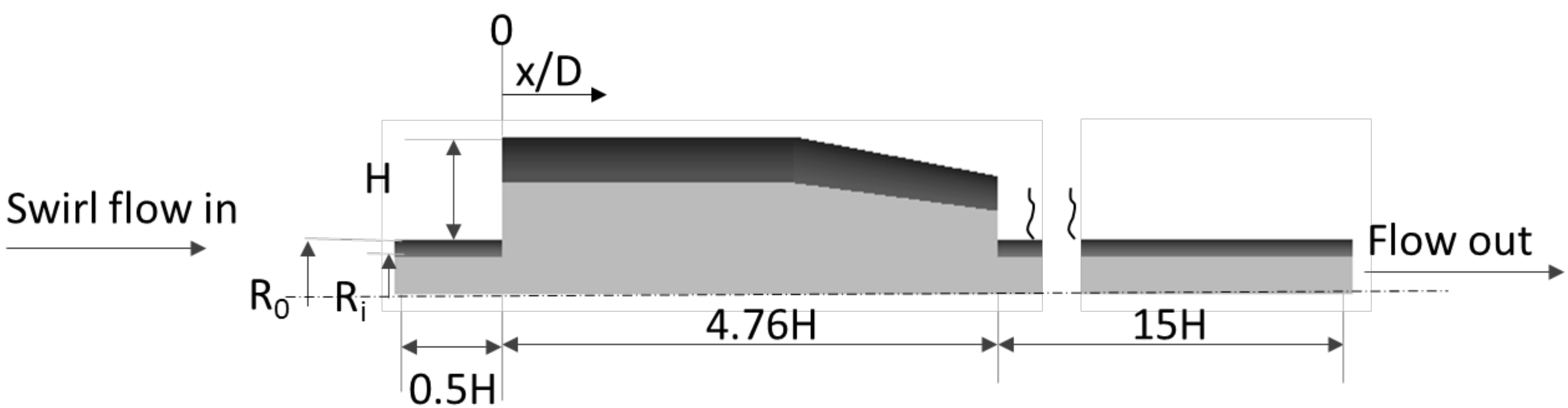


Computational efforts: Cold flow studies of swirling flow and heat transfer

CFD Domain of 3D combustor sector(90^0) :

- Refined hexahedral grid (4MM)
- Combustor has cylindrical and a downstream converging section
- Domain ends with a small diameter pipe outlet section (R 1.375")



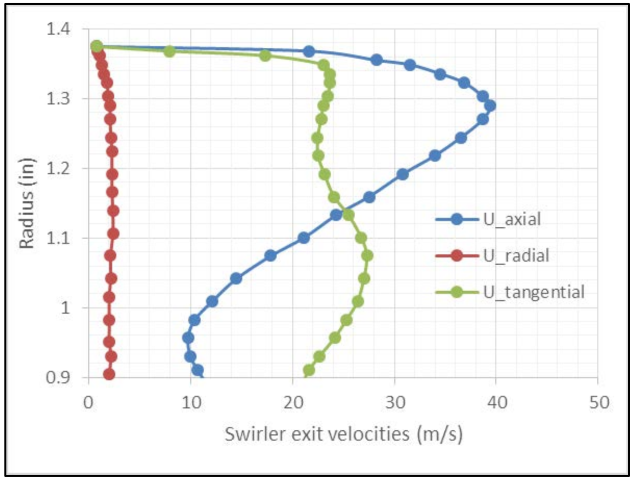


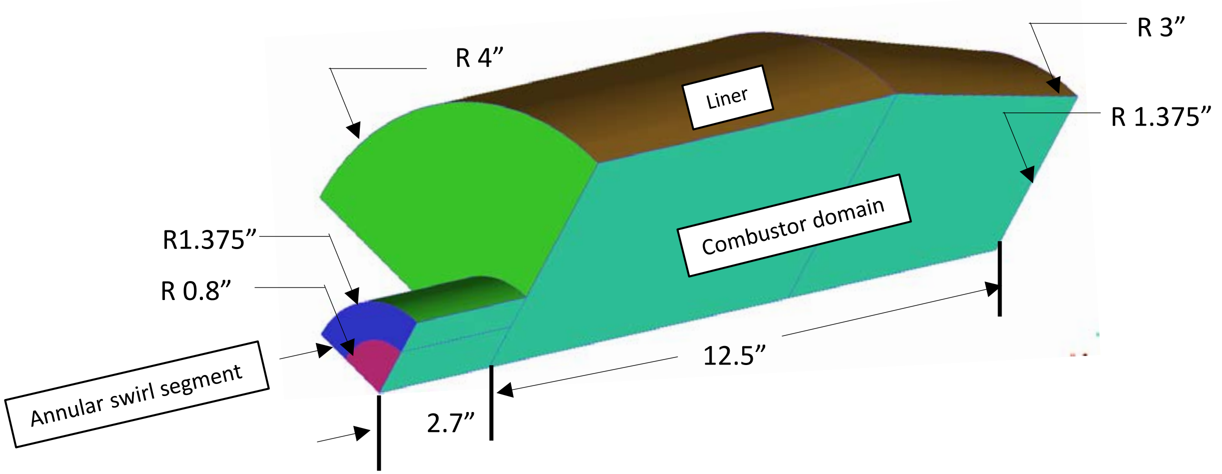
Computational efforts: Cold flow studies of swirling flow and heat transfer

CFD Domain of 3D combustor sector(90^0) :

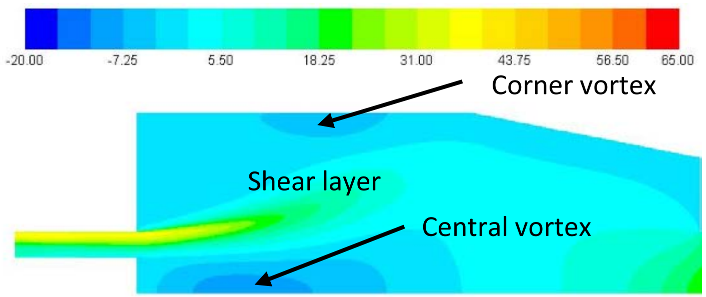
- Liner heat flux ***(1500 W/m²)***
- Pressure outlet ***(atmospheric)***
- k-ω SST turbulence model
- Inlet flow profiles

(based on earlier studies on swirler flow(* Patil *et al.), Re_D=50000)

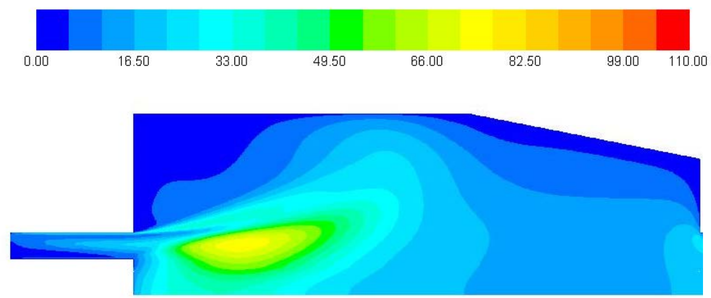




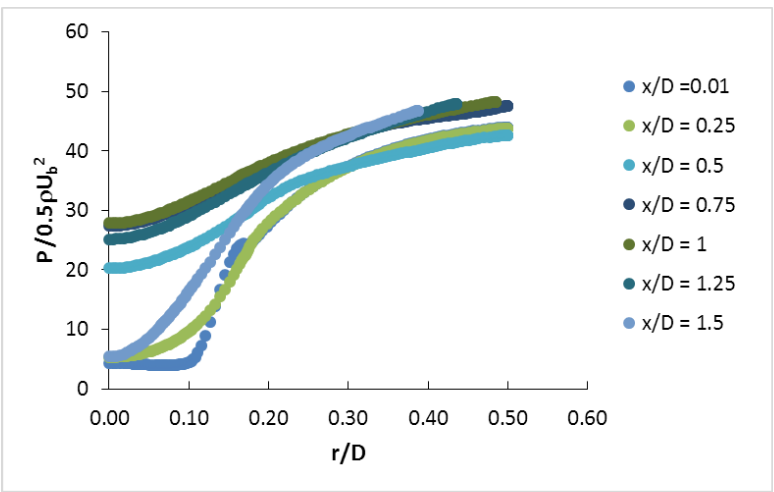
Computational efforts: Cold flow studies of swirling flow and heat transfer



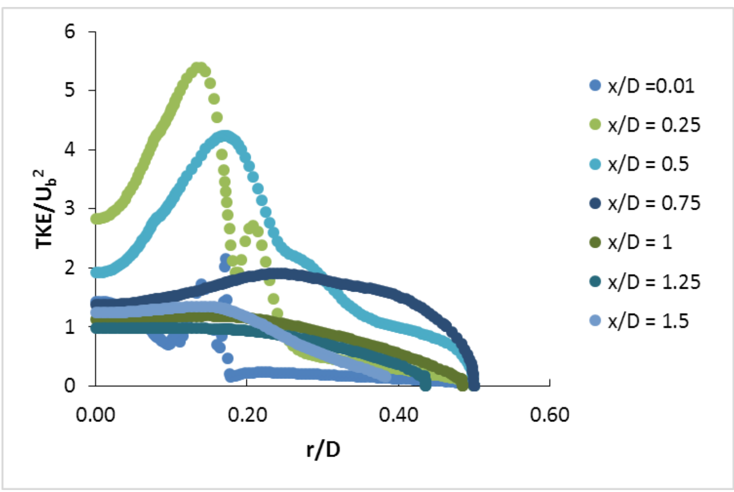
Velocity magnitude (m/s)



Turbulent Kinetic energy (kgm^2/ s^2)



Normalized Pressure distribution



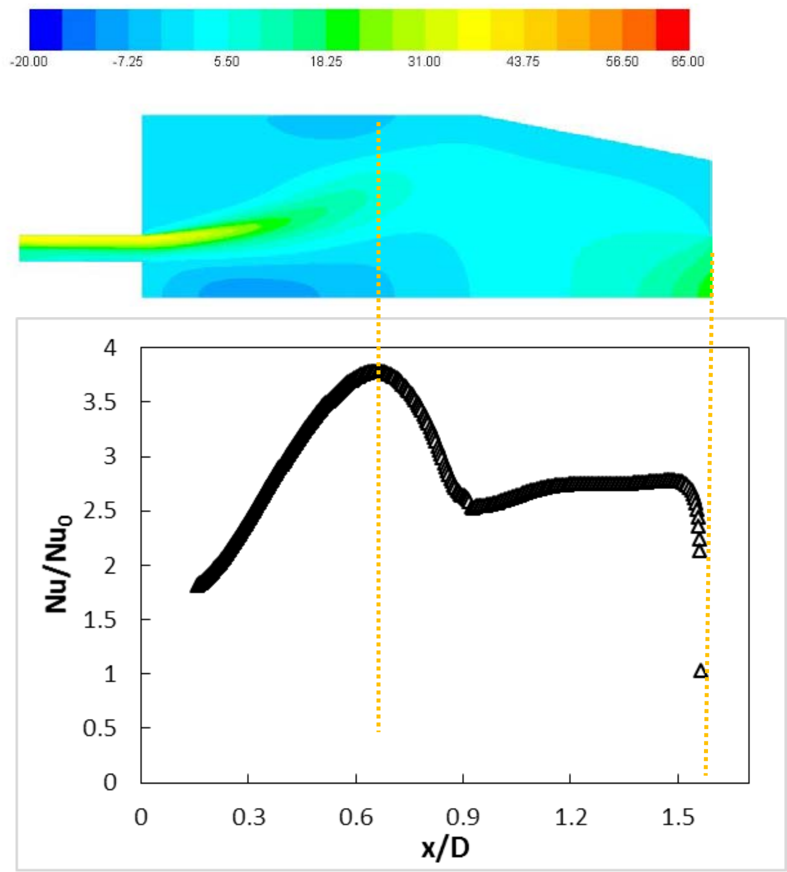
Normalized Turbulent kinetic energy distribution

- k-w SST model solves the swirl dominated flow with better stability for future studies

Computational efforts: Cold flow studies of swirling flow and heat transfer

Observations:

- *Peak heat transfer occurs along the liner near the mid-section of combustor axial length*
- *The presence of converging downstream section directs the shear layer axially instead of deviating radially towards the liner*
- *Turbulent kinetic energy distribution is oriented in the axial direction rather than radial*
- *Hence, the thermal load on the liner is reduced due to converging section of the combustor*



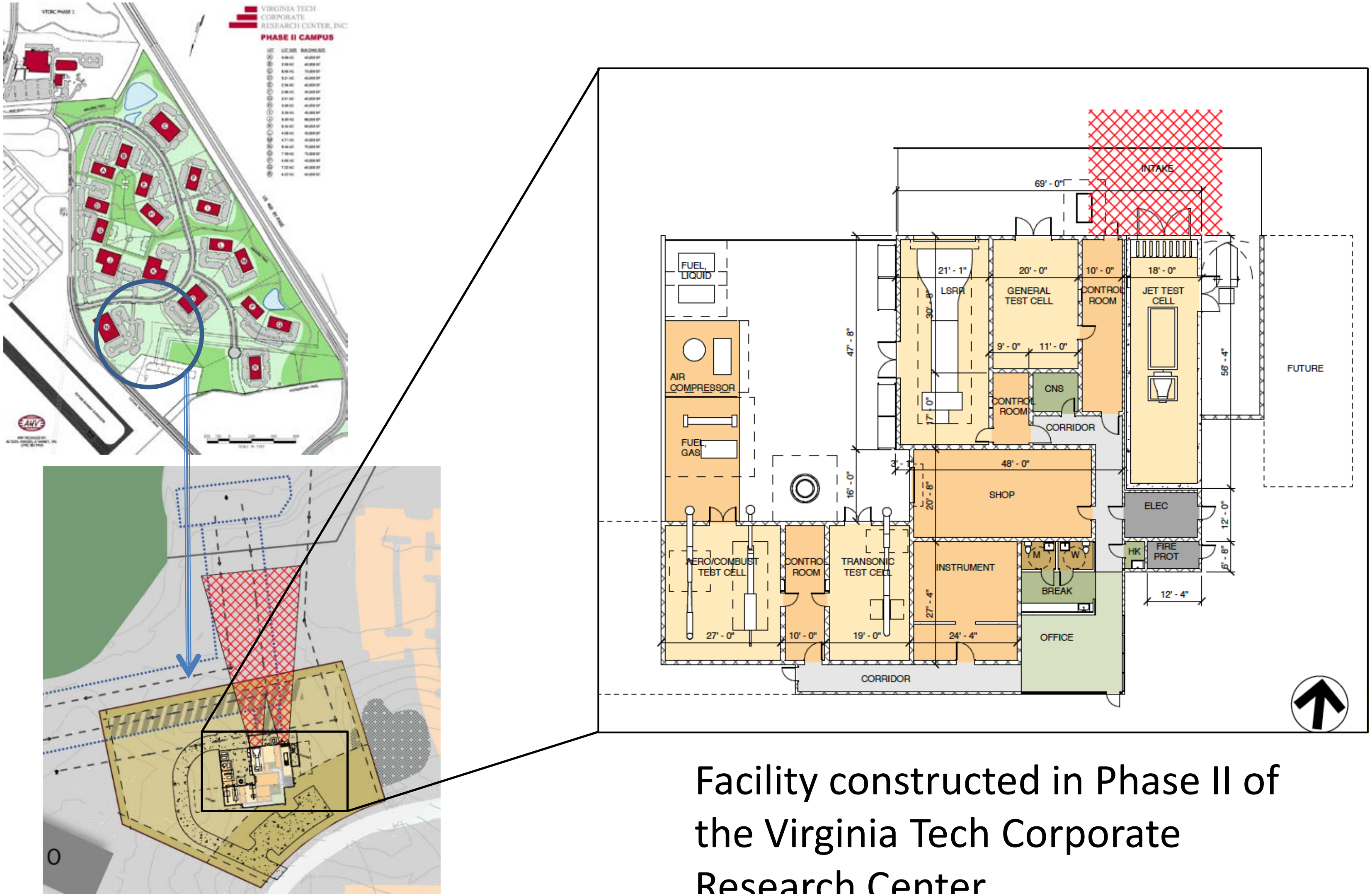
Normalized Nusselt number distribution

Impingement location is predicted to be at ~ 40% downstream of combustor entrance for the current combustor geometry

Virginia Tech Advanced Propulsion and Power Lab

- Located near Virginia Tech campus and local airport
- Overall budget for building - $3.5M
- Architect – LORD, AECK & SARGENT ARCHITECTURE
- November 2012 – Broke ground
- First stage of construction – March 2013
- June 2014 – Completed construction

Plan View



Facility constructed in Phase II of the Virginia Tech Corporate Research Center

VT APPL Finished Pictures

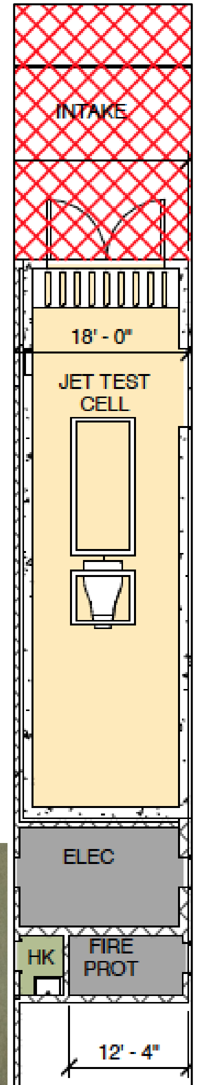
Advanced Propulsion and Power Lab: **Facility**

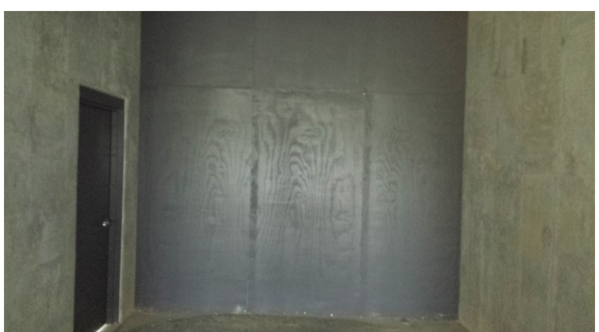
Shop air

Dryer and storage tank for main air line
5000gal capacity

Compressors for main air line
2.8 lbm/s, 150 PSIG

JET TEST CELL





Virginia Tech Advanced Propulsion and Power Lab

Test Cell Rigs


Figure 28 - Aero-Thermal Testing Rig (Back Side)

Figure 27 - Similar LSRR Facility in Bangalore, India


Figure 36 - Small Rotating Channel Rig Enclosure and Work Space


Figure 72 - Test Chamber

Engine Test Cells


Figure 4 - Engine Test Platform


Figure 5 - Engine Test Platform


Figure 13 - Turbo-Shaft Test Water Break Dynamometer

AE 3007 – test vehicle for Advanced Diagnostics;
To be possibly installed and operated in 2015.

Lab space: Virginia Tech Advanced Propulsion and Power Lab

Capabilities:

- Multi-fuel: Natural gas, Jet-A fuels
- Compressor air supply
  - 2.8 lbm/s continuous flow at 150 psig
  - 5000 gallon storage tank providing up to 7 lbm/s for 3mins
- Experimental
  - Particle image velocimetry (PIV), IR thermography, Chemiluminescence, Laser Doppler Velocimetry (LDV/PDPA)
  - Advanced diagnostics (support from the Advanced Diagnostics Lab at VT)

Concluding remarks: Expected results and deliverables

Expected results:

- Testing of industrial fuel nozzles
- Development of heat transfer coefficient correlations that aid in the combustor design process
- Evaluation of computational models and their applicability to industrial combustor design.

Questions?

VirginiaTech
Invent the Future®

Heat, Energy and Fluids Transport (HEFT) Lab

Solar Turbines
A Caterpillar Company

Thank you!