Parametric Study of Pulse-Combustor-Driven Ejectors at High-Pressure

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Overview

- **Objectives**
  - Investigate the performance characteristics of shrouded pulse-combustor configurations at high pressure conditions.
  - The goal is to design configurations that maximize pressure gain while achieving a thermal environment acceptable to a turbine, and maintain acceptable levels of NOx emissions and flow non-uniformities
- **Approach**
  - Utilize new computational platform, developed in previous studies, for studying pulse-combustors.

Introduction

- Conventional gas turbine engine combustors based on steady, constant pressure combustion incur total pressure losses that can range from 4% to 8%.
- Pressure-gain concepts:
  - Pulse Detonation-Based devices
  - Wave Rotors
  - Pulse-combustors
- Pulse-combustors are unsteady, resonant thermo-acoustic devices in which heat released by combustion is coupled with the acoustic field.
  - Experiments at atmospheric conditions demonstrated pressure gain of ~ 3.5% (Paxson and Dougherty 2005).
  - Preliminary CFD calculations at high-pressure conditions demonstrated pressure gain of ~ 1.2% (Yungster et al. 2013).
  - Maximum theoretical pressure-gains estimated at ~ 7% (Kentfield 1993).

Introduction

- Advantages of Pulse-combustors over alternative pressure gain concepts:
  - Avoids the mechanical complexities of higher pressure gain concepts.
  - Pulse combustors are known to produce low NOx.
  - Flow non-uniformities at exit of pulse-combustor are substantially reduced.
- Disadvantages of Pulse-combustors:
  - Pressure-gains attainable are typically lower than those for wave rotors or detonation based devices (which can reach up ~ 35%).

Introduction

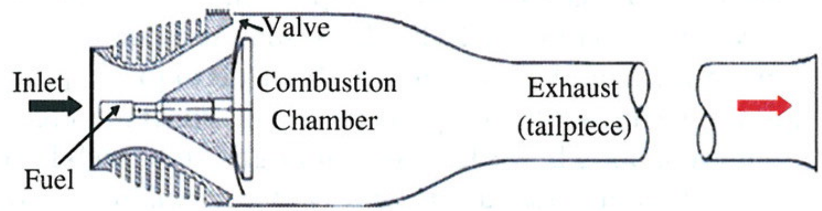
- Most previous studies of pulse-combustors have been carried out at atmospheric conditions.
- Practical aerospace applications of pressure-gain combustion systems necessitates operation at high-pressure conditions.
- Previous study (Yungster, Paxson and Perkins, 2013) analyzed differences in the operation of pulse-combustors at atmospheric ($p_0 = 1$ bar; $T_0 = 298$ K) and high-pressure conditions ($p_0 = 10$ bar; $T_0 = 550$ K).
  - Higher air temperature and pressure ⇨ shorter ignition delay times
    - ➢ Change in combustion dynamics.
    - ➢ Increased operating frequency.
    - ➢ Necessitates fuel valving (to prevent pre-ignition).
    - ➢ Lower performance (pressure gain ~ 1.2%).

Introduction

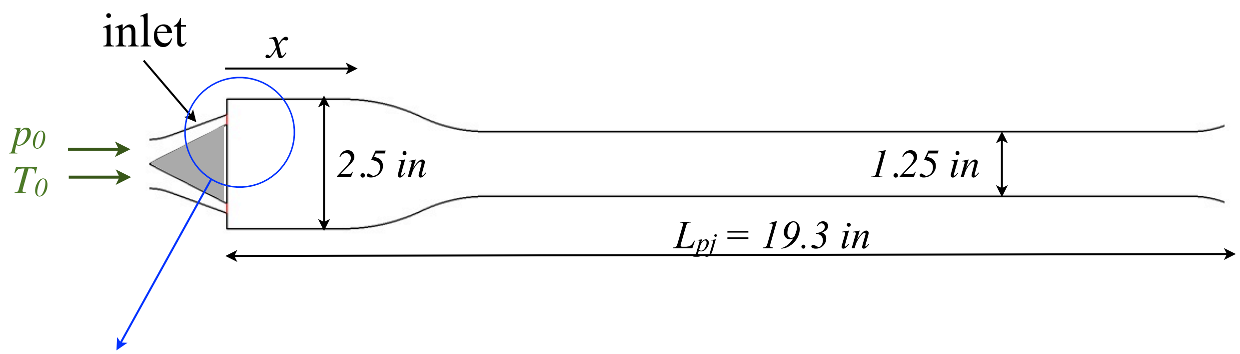
- A recent study (Yungster, Paxson and Perkins, 2014) identified the factors limiting the pressure-gain at high-pressure conditions.
  - New pulse-combustor configurations were developed which were able to achieve performance levels at high-pressure conditions comparable to those observed at atmospheric conditions.
- However, suboptimal fuel distribution within the pulse-combustor was still limiting performance.
- The pulse-combustor by itself is not suitable to replace a conventional combustor in a gas turbine engine, and must be shrouded and combined with an ejector.

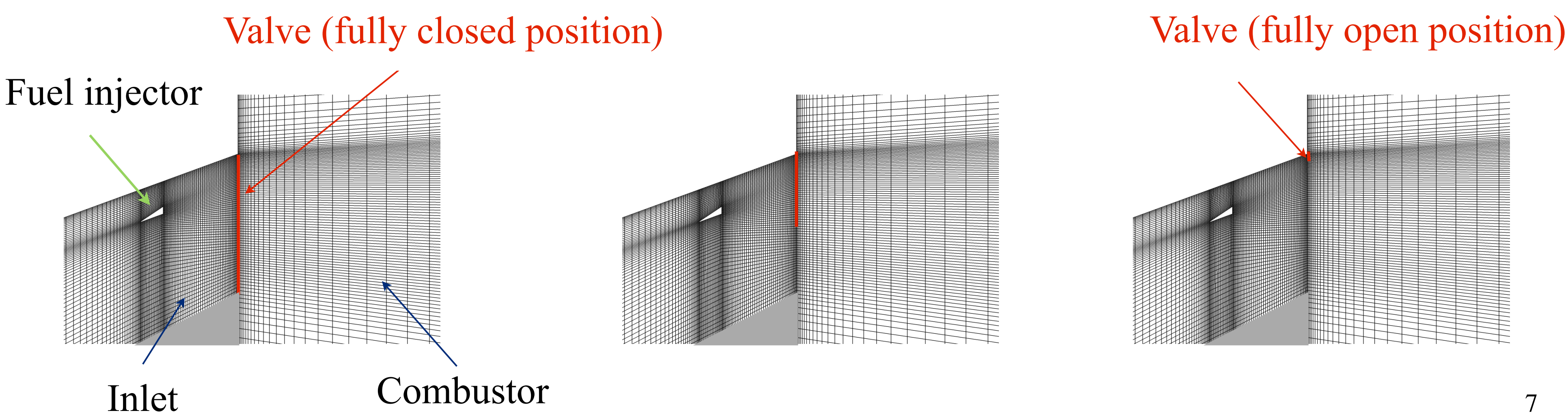
Schematic of Pulse-Combustor

Pulse-combustor device used in experiments

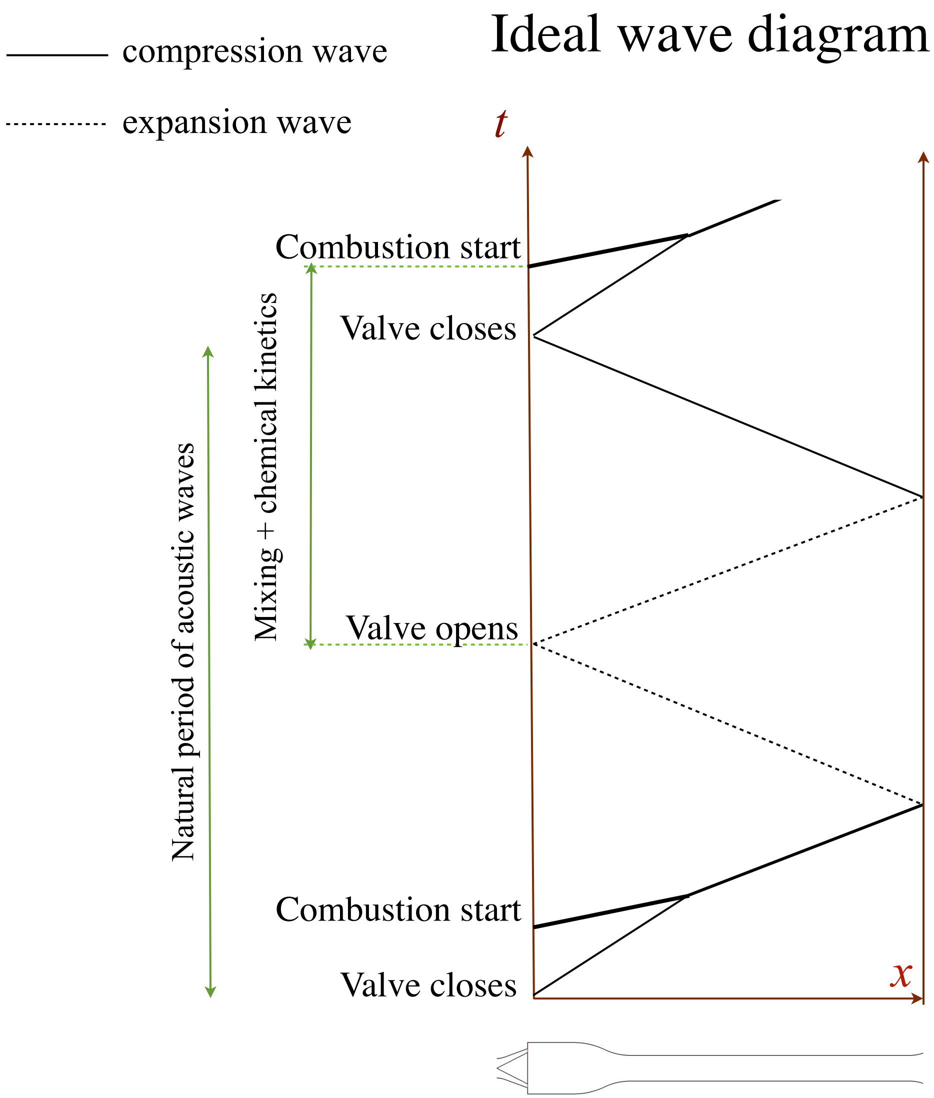


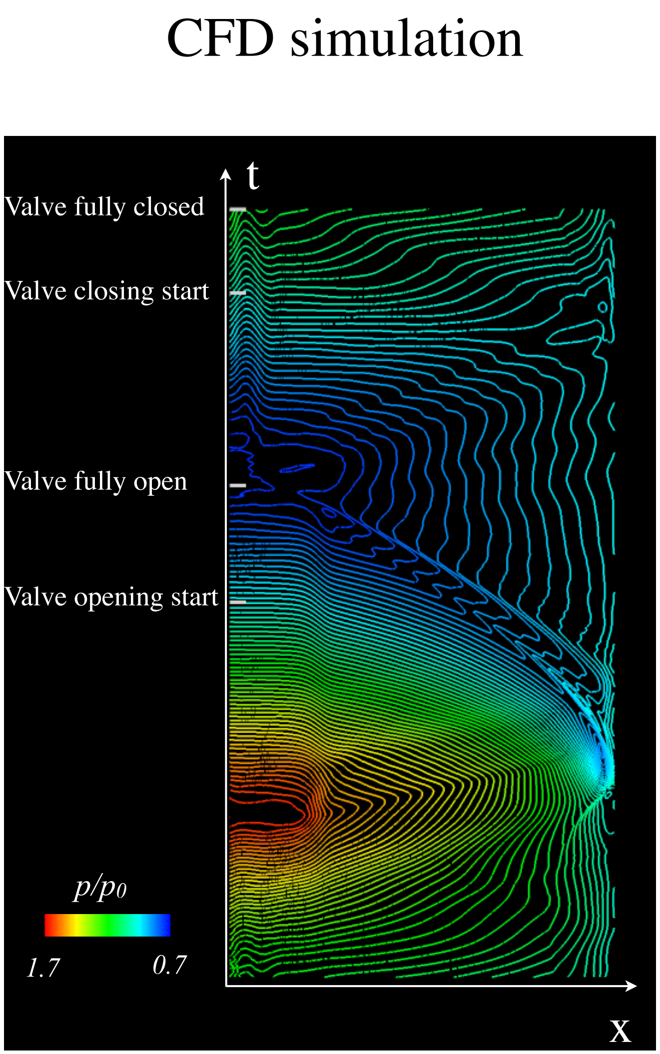
Computational model





Wave Diagram for a Pulse-Combustor



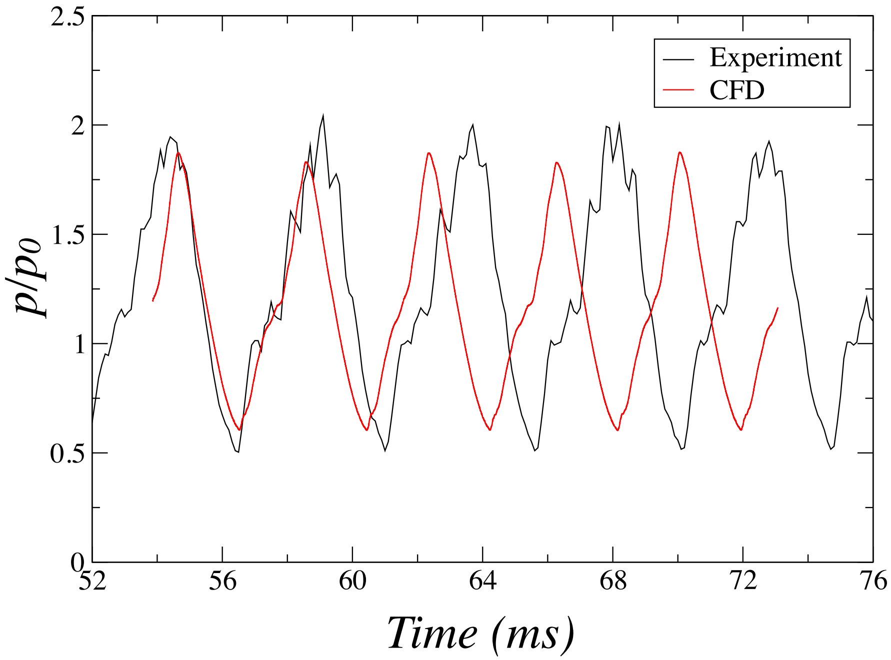


Pulse-Combustor Pressure Variation

(Yungster, Paxson and Perkins, 2013, 2014)

Fuel used in experiments: liquid gasoline
Fuel used in CFD: gaseous jet-A

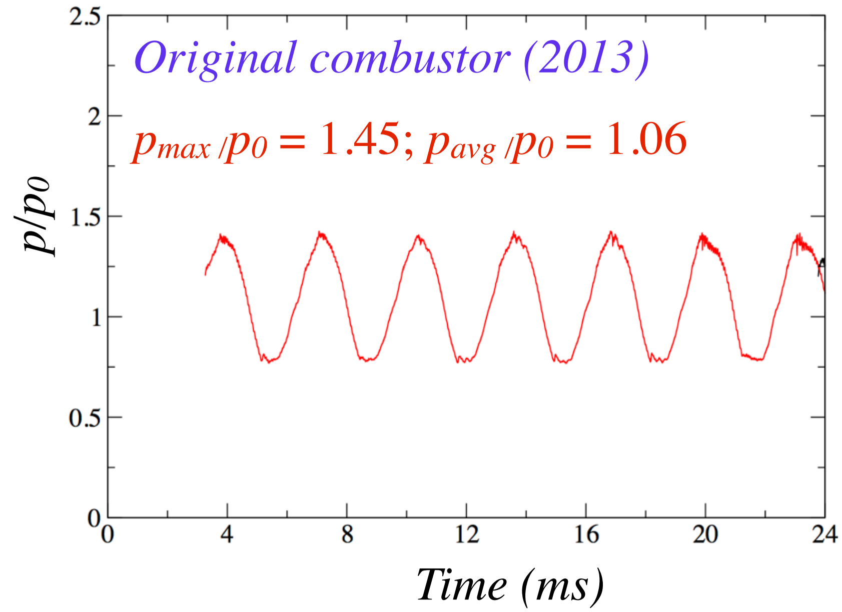
p_0 = 1 bar, T_0 = 298 K

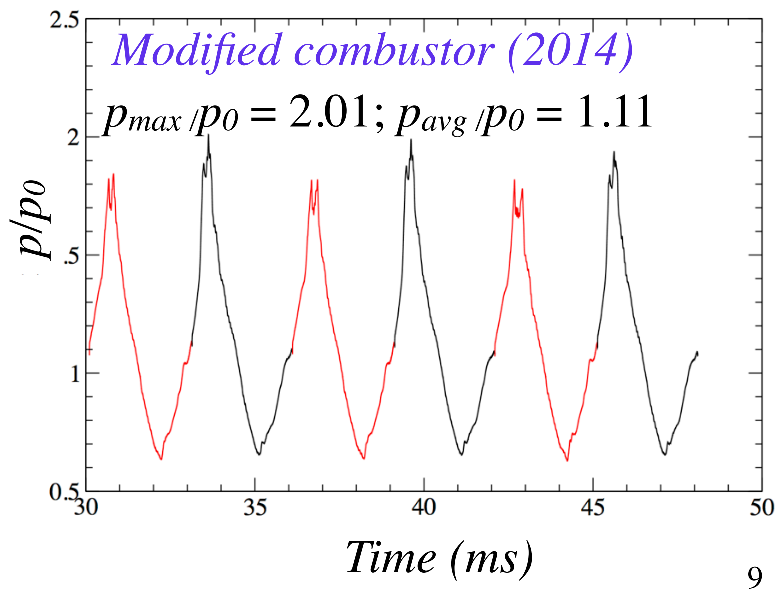


f_{exp} = 222 Hz; f_{cfd} = 255 Hz

$p_{max}/p_0 = 1.87$; $p_{avg}/p_0 = 1.16$

CFD p_0 = 10 bar, T_0 = 550 K





Numerical Model

- In-house developed CFD code.
  - *(Yungster, S. and Radhakrishnan, K., "Pulsating One-Dimensional Detonations in Hydrogen-Air Mixtures," Combustion Theory and Modelling, 8, 745-770, 2004).*
- Axisymmetric Navier-Stokes Equations for multi-species, thermally perfect, chemically reacting gas.
- Detailed chemistry capability
  - Kundu's jet-A/air reaction mechanism (14-steps, 13-species).

    (*has been successfully used in detonation and LDI combustor studies*).
- Second-order TVD differencing scheme.
- Fully implicit BDF time marching algorithm.
- Spallart-Allmaras one-equation turbulence model.

Approach

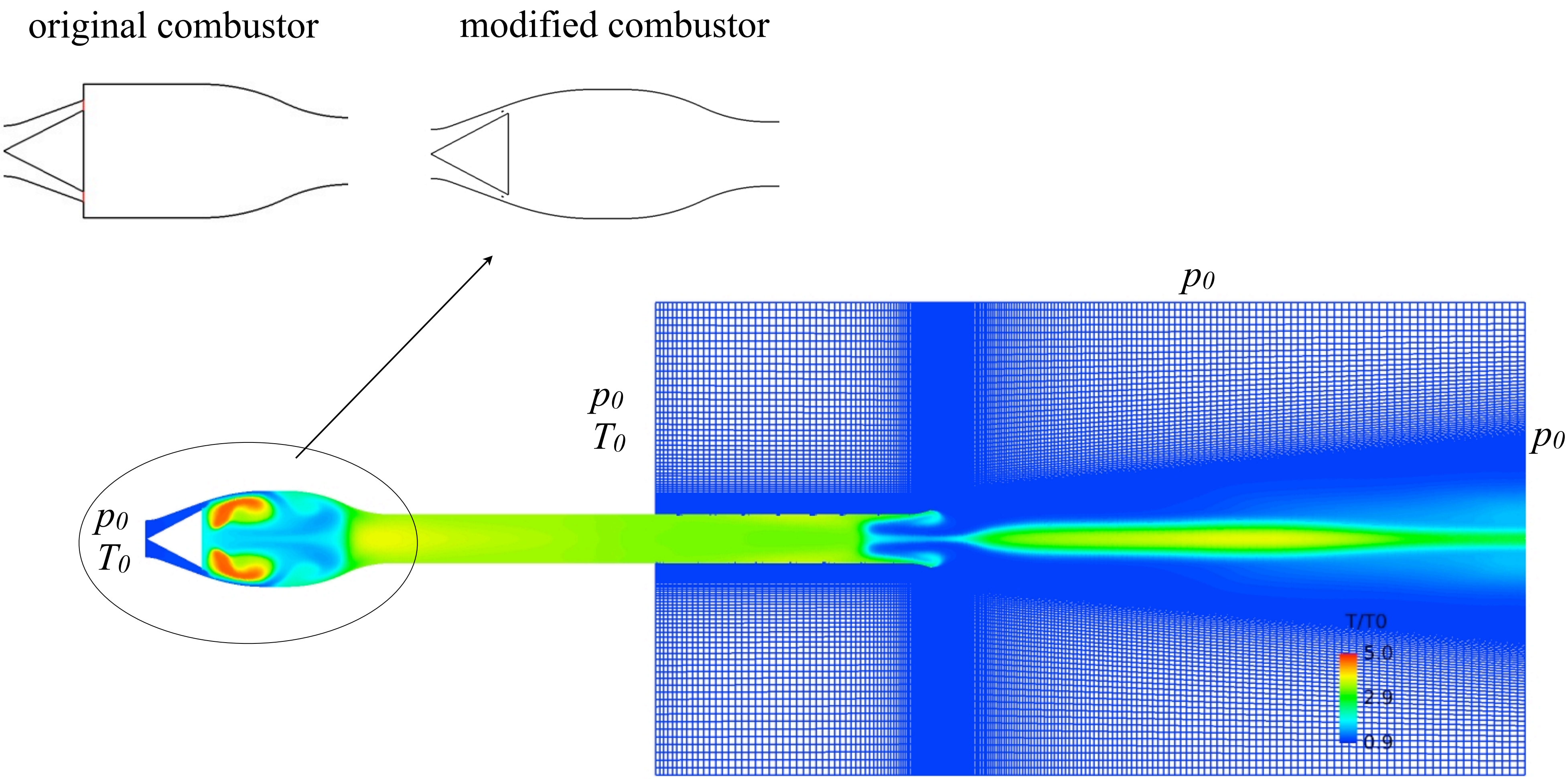
- Conduct numerical simulations of the pulsejet-based devices for multiple cycles until limit-cycle operation is reached (8-25 cycles).

Jet-A Reaction Mechanism (K. Kundu, 2010)

Jet-A Reaction Mechanism†				
No.	Reaction	A	n	E††
1	$C_{11}H_{21} + O_2 \Longrightarrow 11CH + 10H + O_2$	1.00×10^{12}	0	3.75×10^{4}
	forward /$C_{11}H_{21}$ 0.8/ ; forward /O_2 0.8/			
2	$CH + O_2 \Longrightarrow CO + OH$	2.00×10^{15}	0.00	3.00×10^{3}
3	$CH + O \Longrightarrow CO + H$	3.00×10^{12}	1.00	0.0
4	$H_2 + O_2 \Longleftrightarrow H_2O + O$	3.98×10^{11}	1.00	4.80×10^{4}
5	$H_2 + O \Longleftrightarrow H + OH$	3.00×10^{14}	0.00	6.00×10^{3}
6	$H + O_2 \Longleftrightarrow O + OH$	4.00×10^{14}	0.00	1.80×10^{4}
7	$H_2O + O_2 \Longleftrightarrow H_2O + 2O$	3.17×10^{12}	2.00	1.12×10^{5}
8	$CO + OH \Longleftrightarrow CO_2 + H$	5.51×10^{7}	1.27	-7.58×10^{2}
9	$CO + H_2O \Longleftrightarrow CO_2 + H_2$	5.50×10^{4}	1.28	-1.00×10^{3}
10	$CO + H_2 + O_2 \Longleftrightarrow CO_2 + H_2O$	1.60×10^{14}	1.60	1.80×10^{4}
11	$N + N + M \Longleftrightarrow N_2 + M$	2.80×10^{17}	-0.75	0.0
12	$N + O_2 \Longleftrightarrow NO + O$	6.40×10^{9}	1.00	6.30×10^{3}
13	$N + NO \Longleftrightarrow N_2 + O$	1.60×10^{13}	0.00	0.0
14	$N + OH \Longleftrightarrow NO + H$	6.30×10^{11}	0.50	0.0

†Forward rate coefficient ; units are moles, seconds, centimeters, calories and Kelvins.

Modified Pulse-Combustor and Axisymmetric Computational Domain.

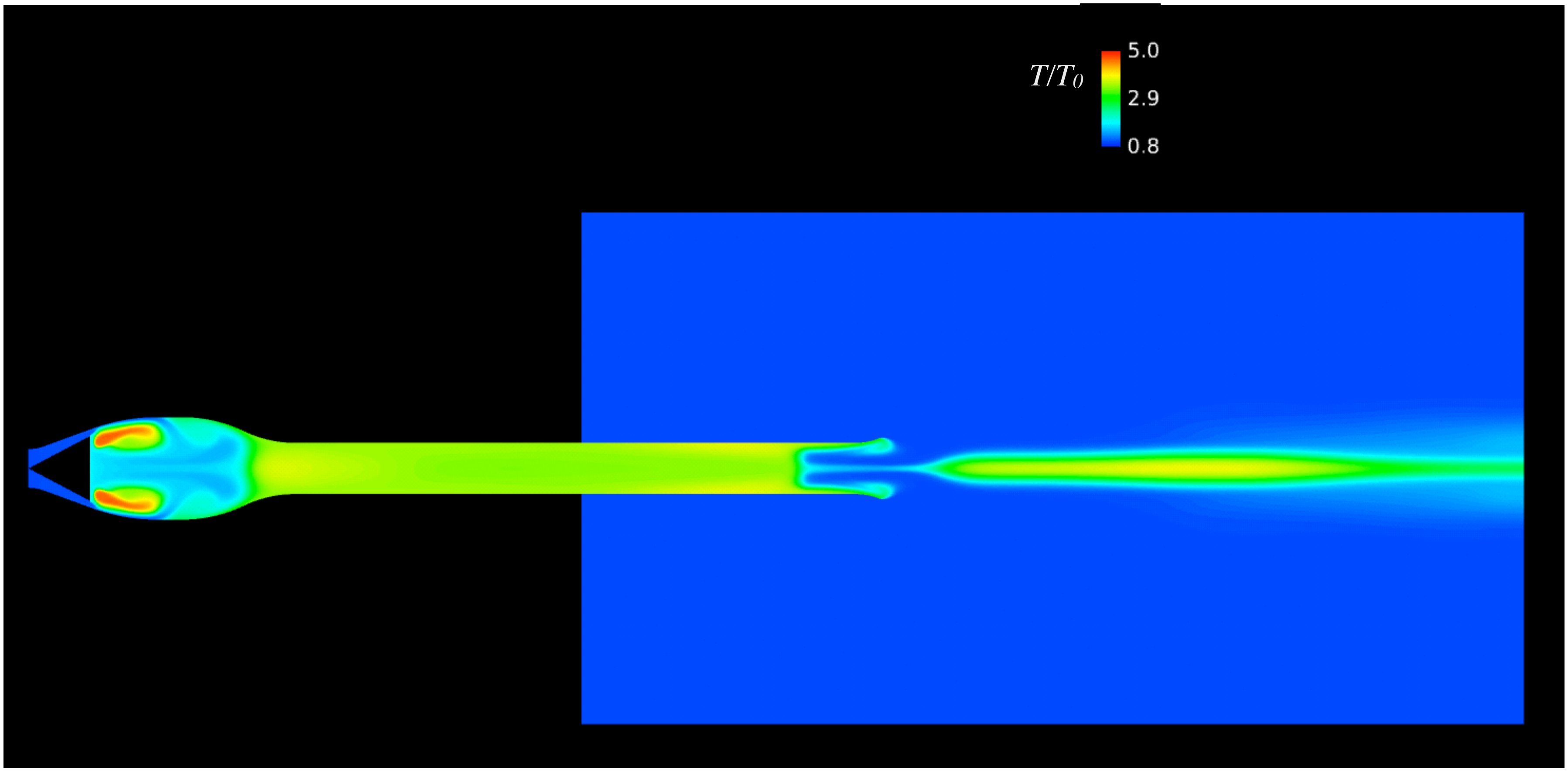


Pulse-Combustor Simulations at High-Pressure

Baseline configuration

p_0 = 10 bar, T_0 = 550 K, $\Phi = 0.66$

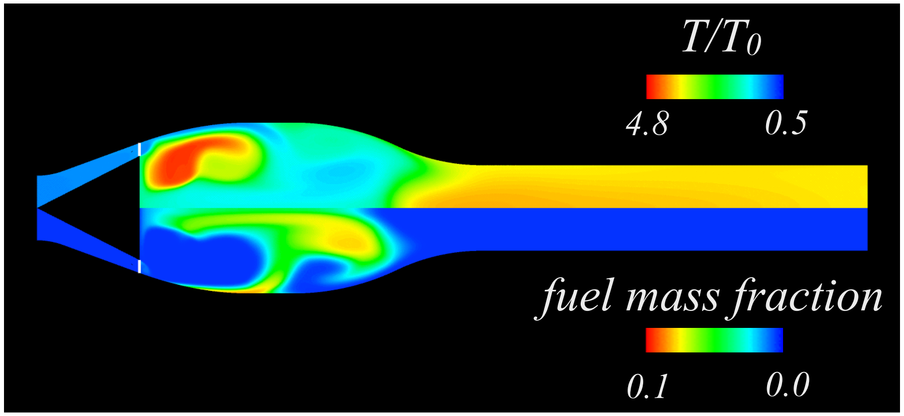
f = 325 Hz



Pulse-Combustor Simulations at High-Pressure

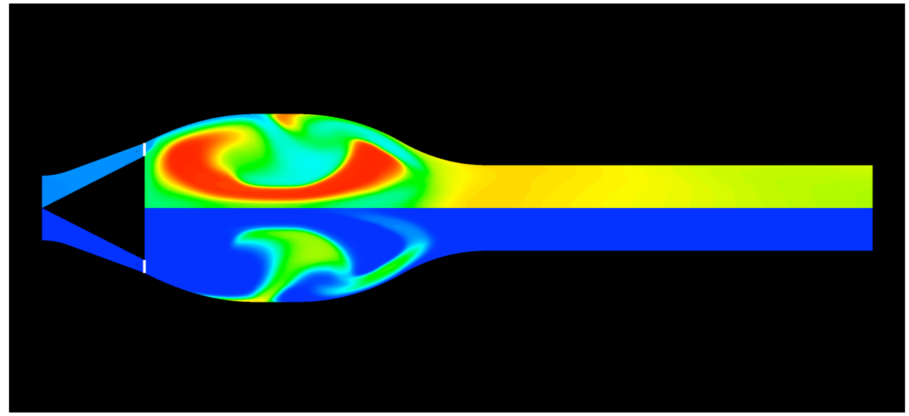
p_0 = 10 bar, T_0 = 550 K, Φ = 0.72

f = 337 Hz



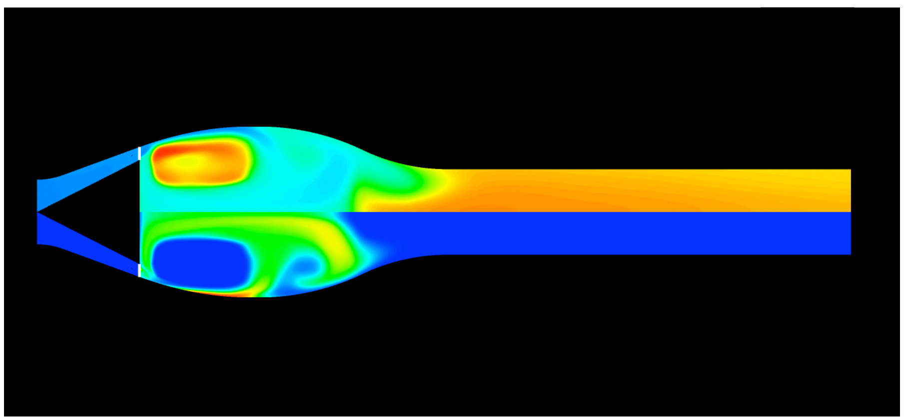
Baseline

f = 342 Hz



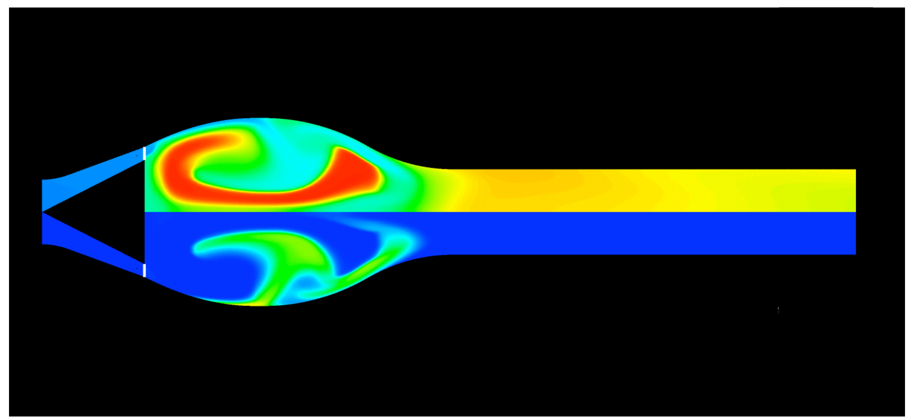
10% larger combustor diameter

f = 342 Hz



10% shorter combustor

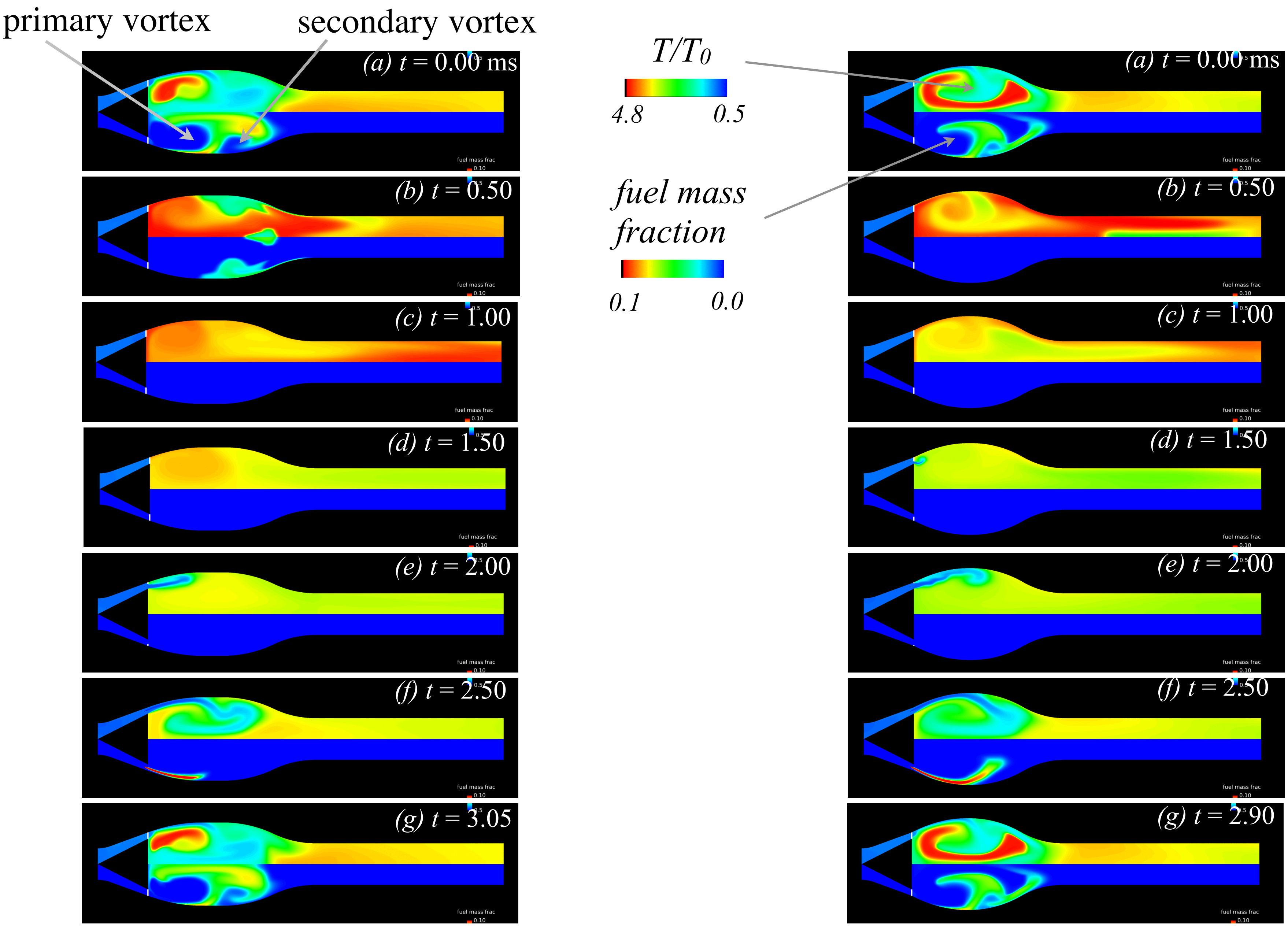
f = 344 Hz



“fat & short" (FASH)

Pulse-Combustor Simulation at High-Pressure

$p_0 = 10$ bar, $T_0 = 550$ K, $\Phi = 0.72$



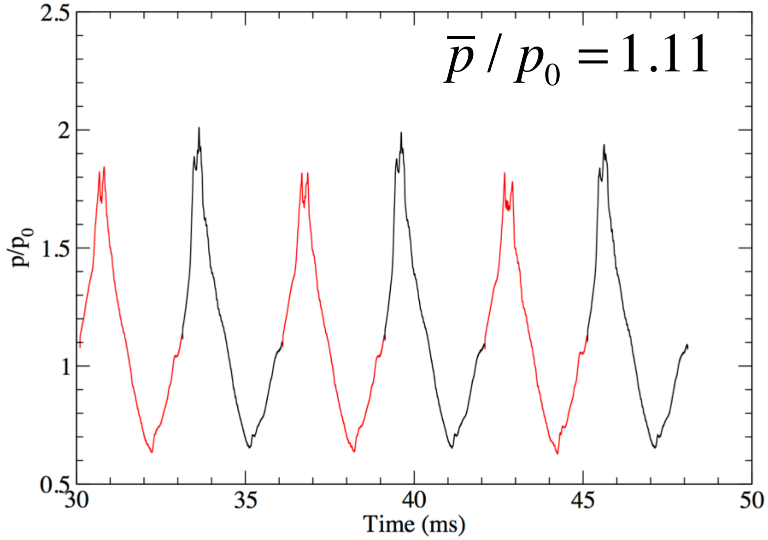
Baseline combustor

FASH combustor

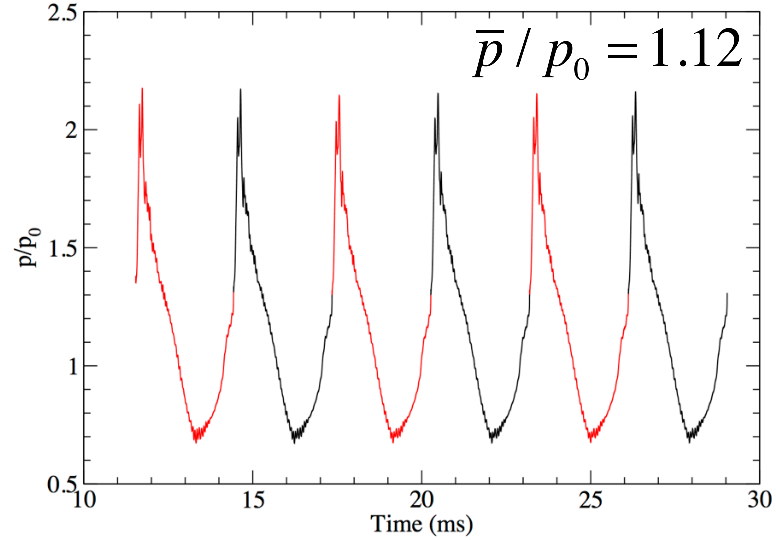
Pulse-Combustor Simulations at High-Pressure

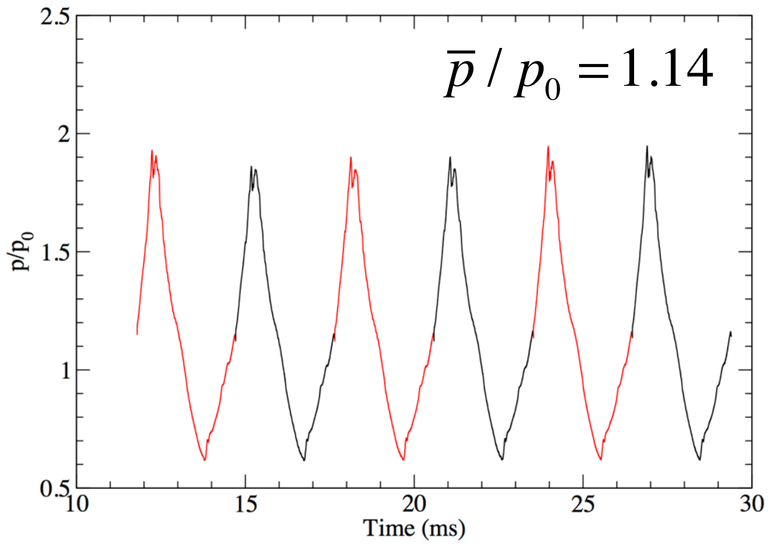
p_0 = 10 bar, T_0 = 550 K, Φ = 0.72

Baseline

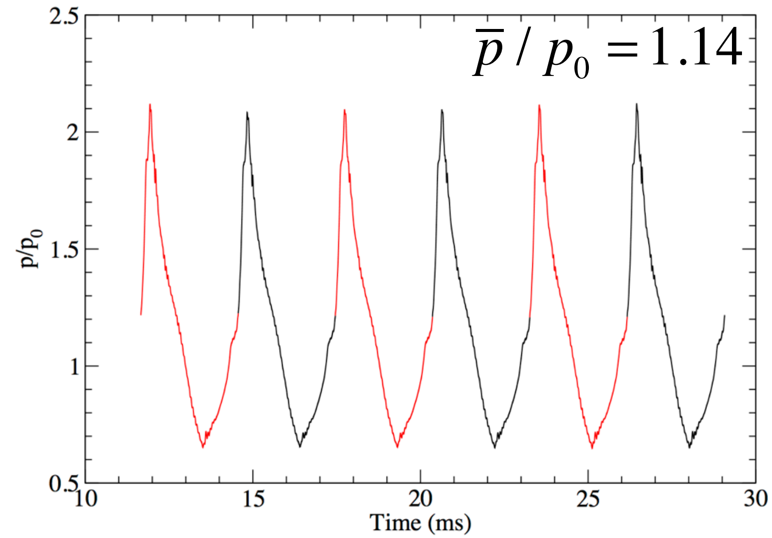


10% larger combustor diameter





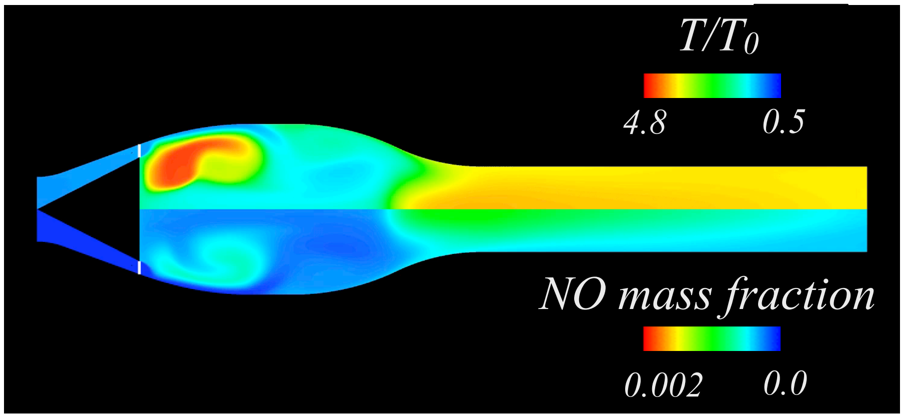
10% shorter combustor



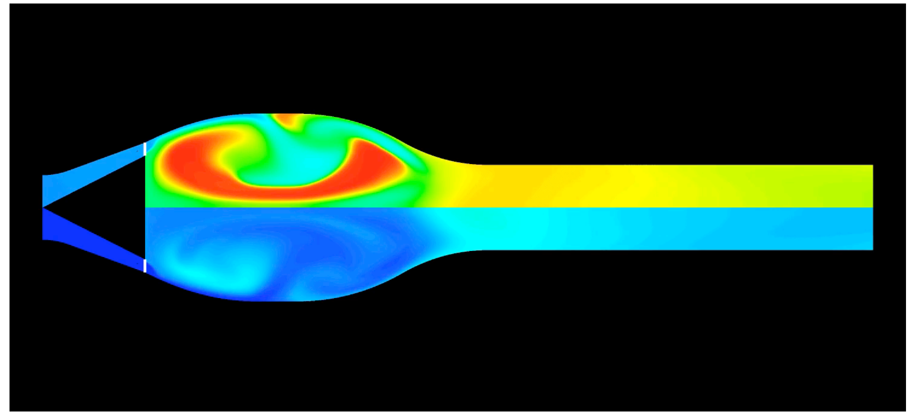
FASH combustor

Pulse-Combustor Simulations at High-Pressure

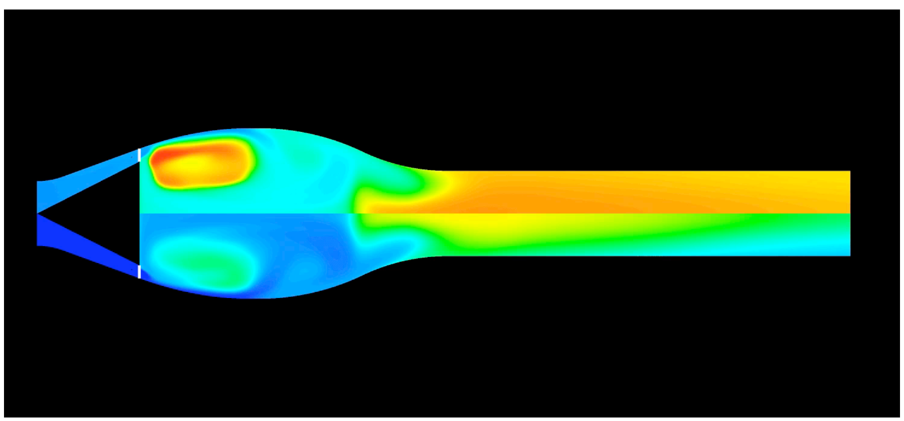
$p_0 = 10$ bar, $T_0 = 550$ K, $\Phi = 0.72$



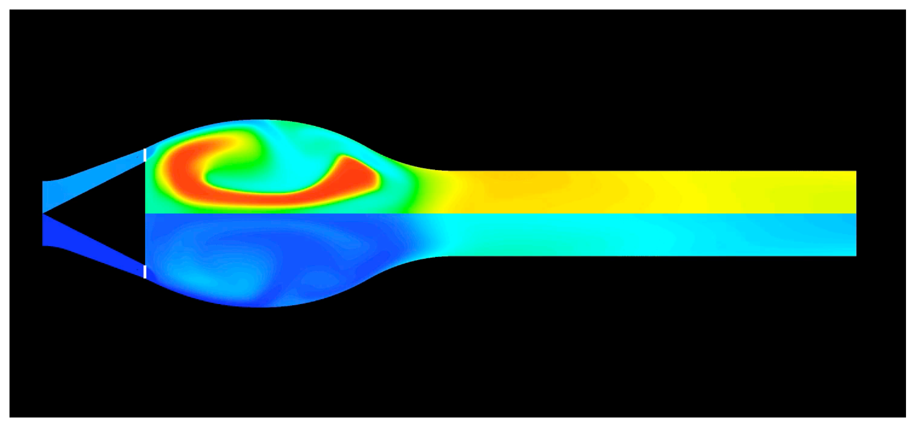
Baseline



10% larger combustor diameter



10% shorter combustor

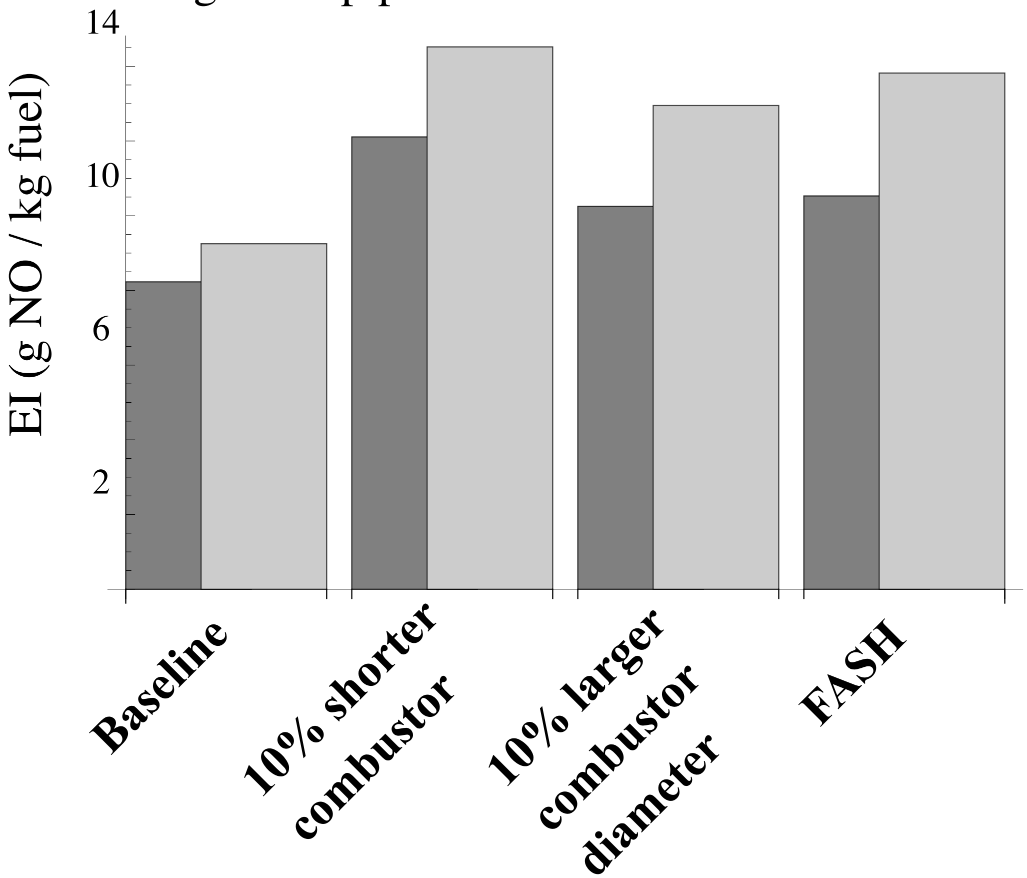


FASH combustor

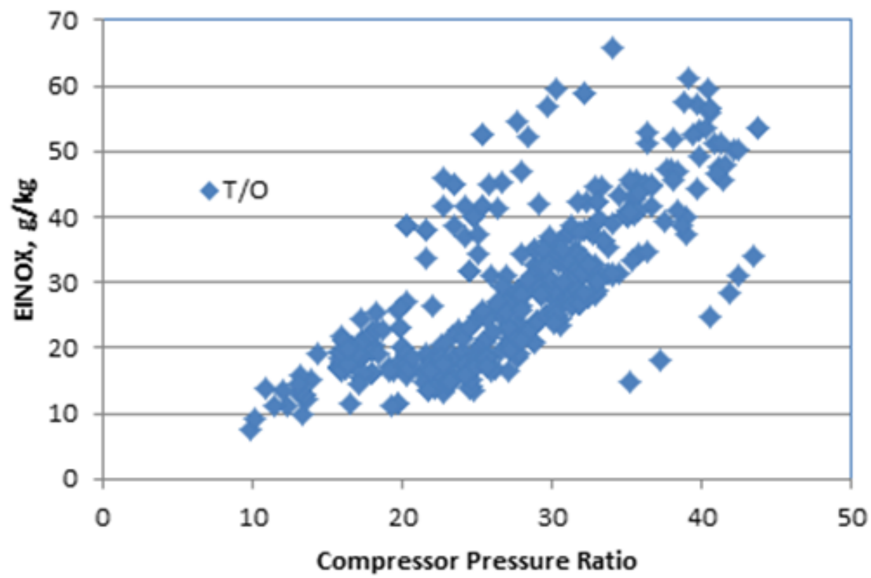
Emission Index

p_0 = 10 bar, T_0 = 550 K, Φ = 0.72

Dark: tailpipe entrance
Light: tailpipe exit



Emission Index for conventional gas turbine engines

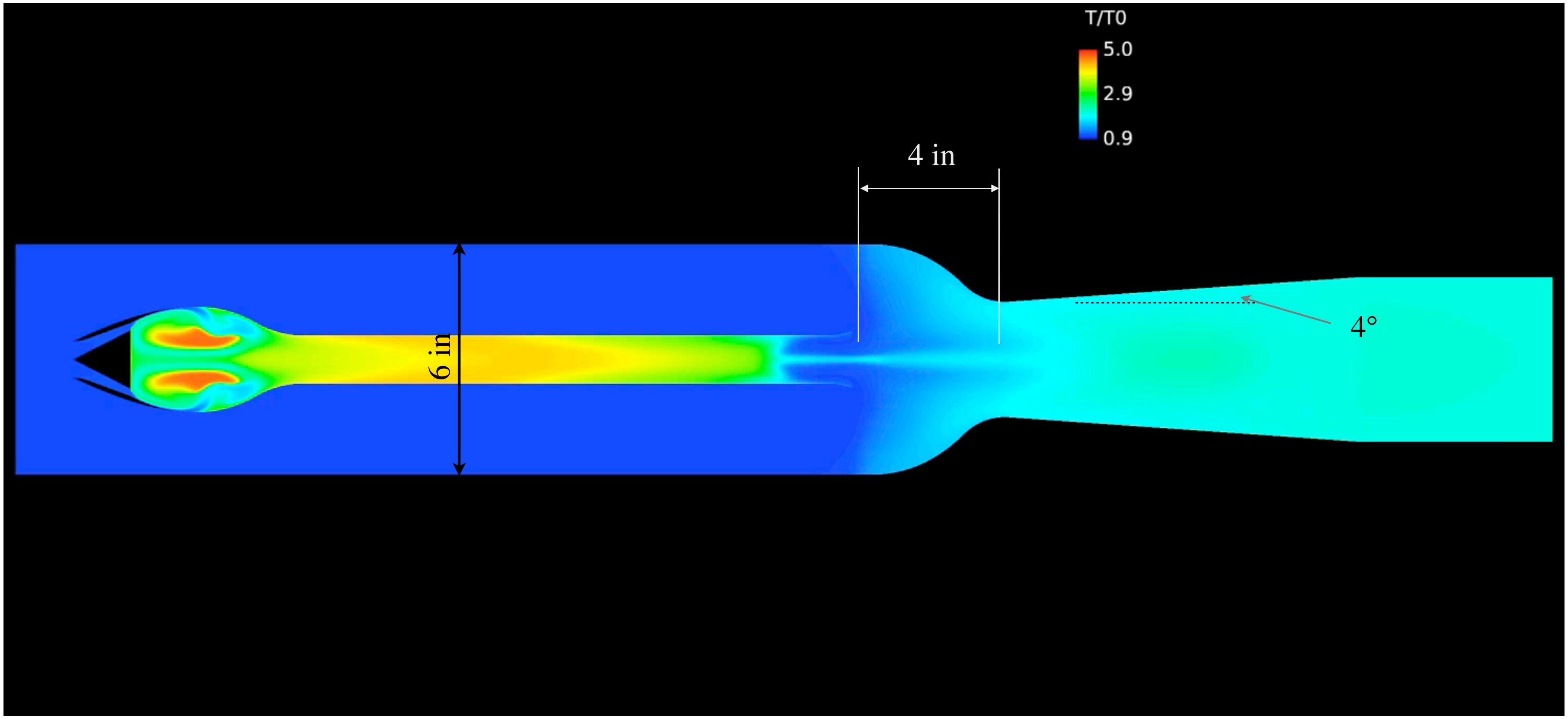


PES combustor based on the FASH configuration

p_0 = 10 bar, T_0 = 550 K, Φ = 0.67

f = 353 Hz

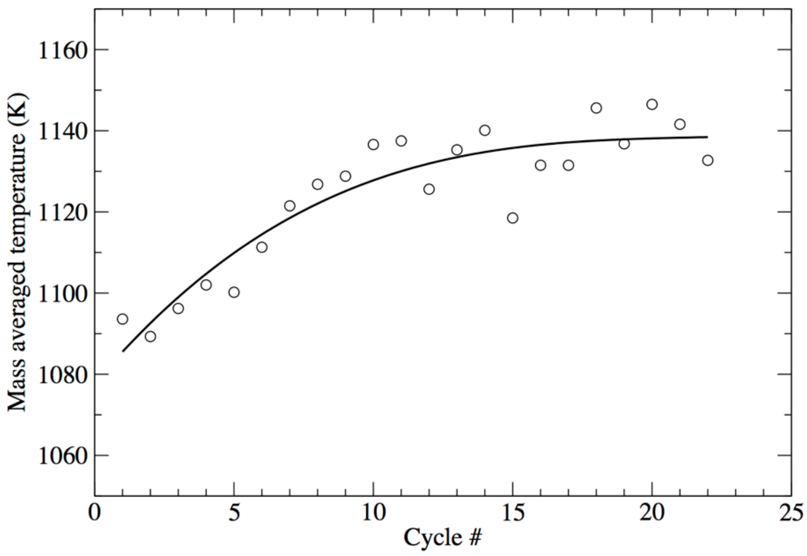
p_0
T_0

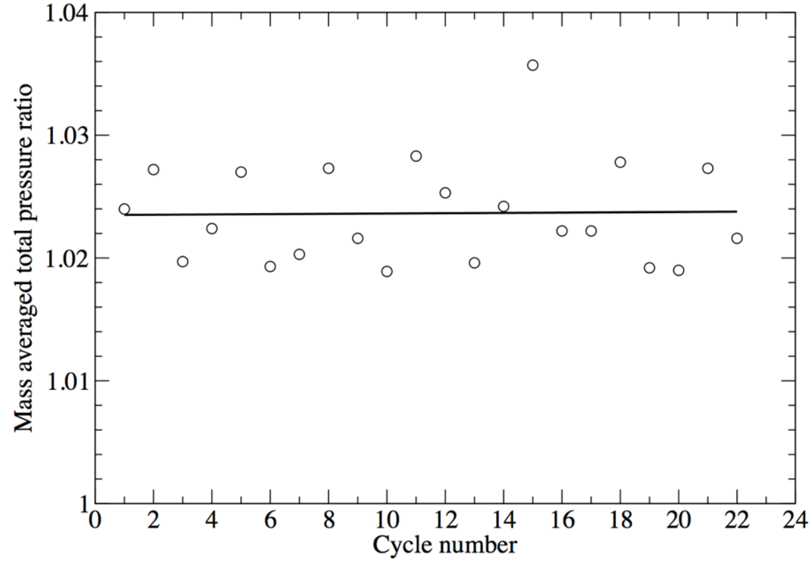


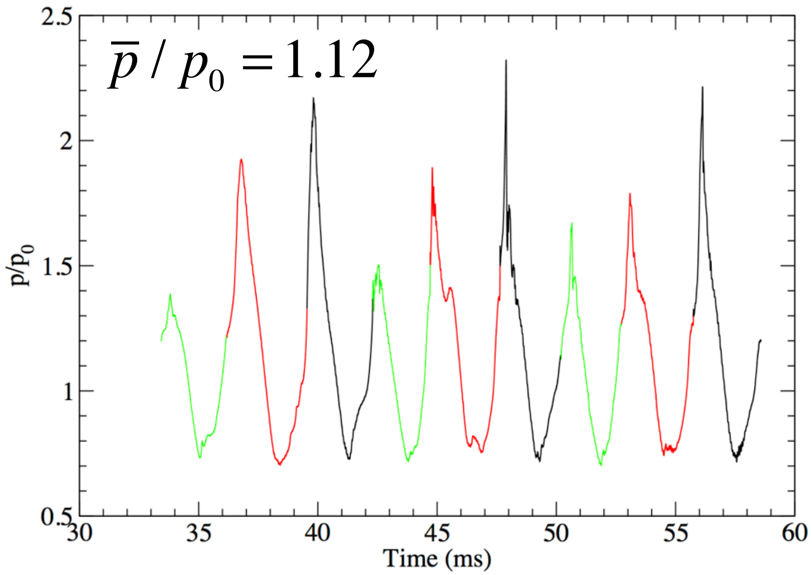
p_b

PES combustor based on the FASH configuration

p_0 = 10 bar, T_0 = 550 K, $\Phi = 0.67$



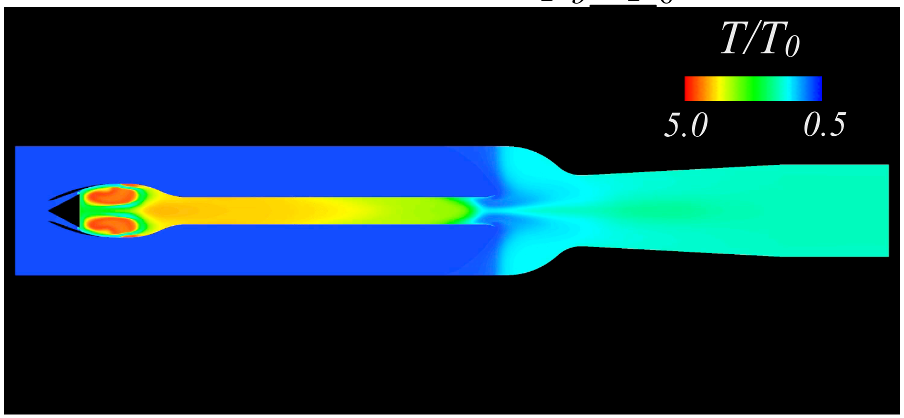




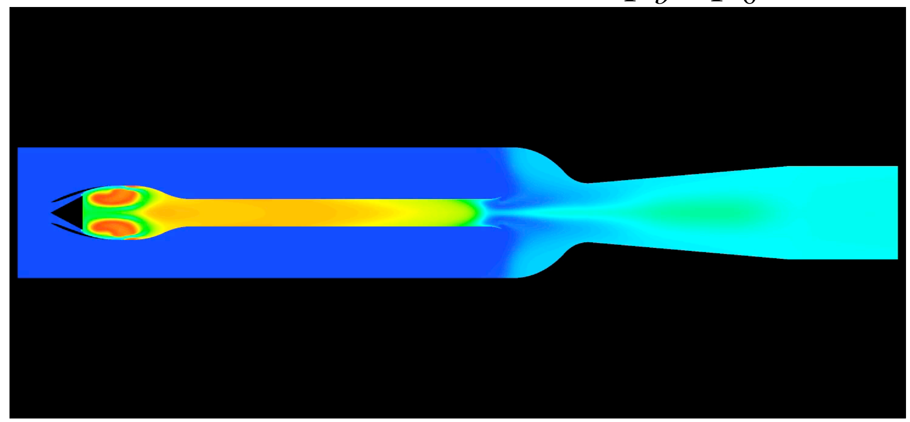
PES combustor based on the Baseline configuration

p_0 = 10 bar, T_0 = 550 K

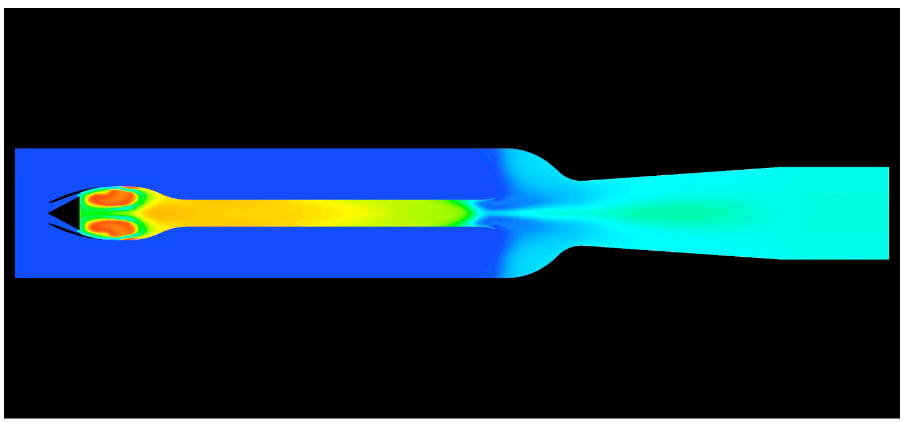
D_{th} = 3.3 in $\quad p_b / p_0 = 1.015$



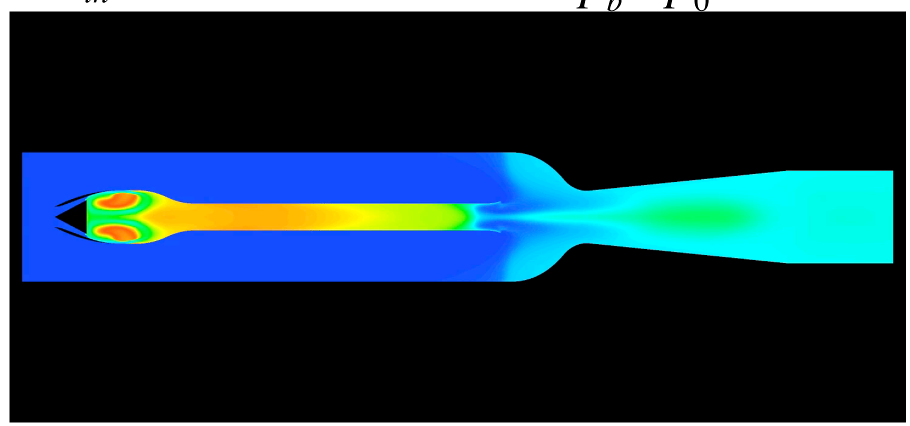
D_{th} = 2.7 in $\quad p_b / p_0 = 1.019$



D_{th} = 3.0 in $\quad p_b / p_0 = 1.017$

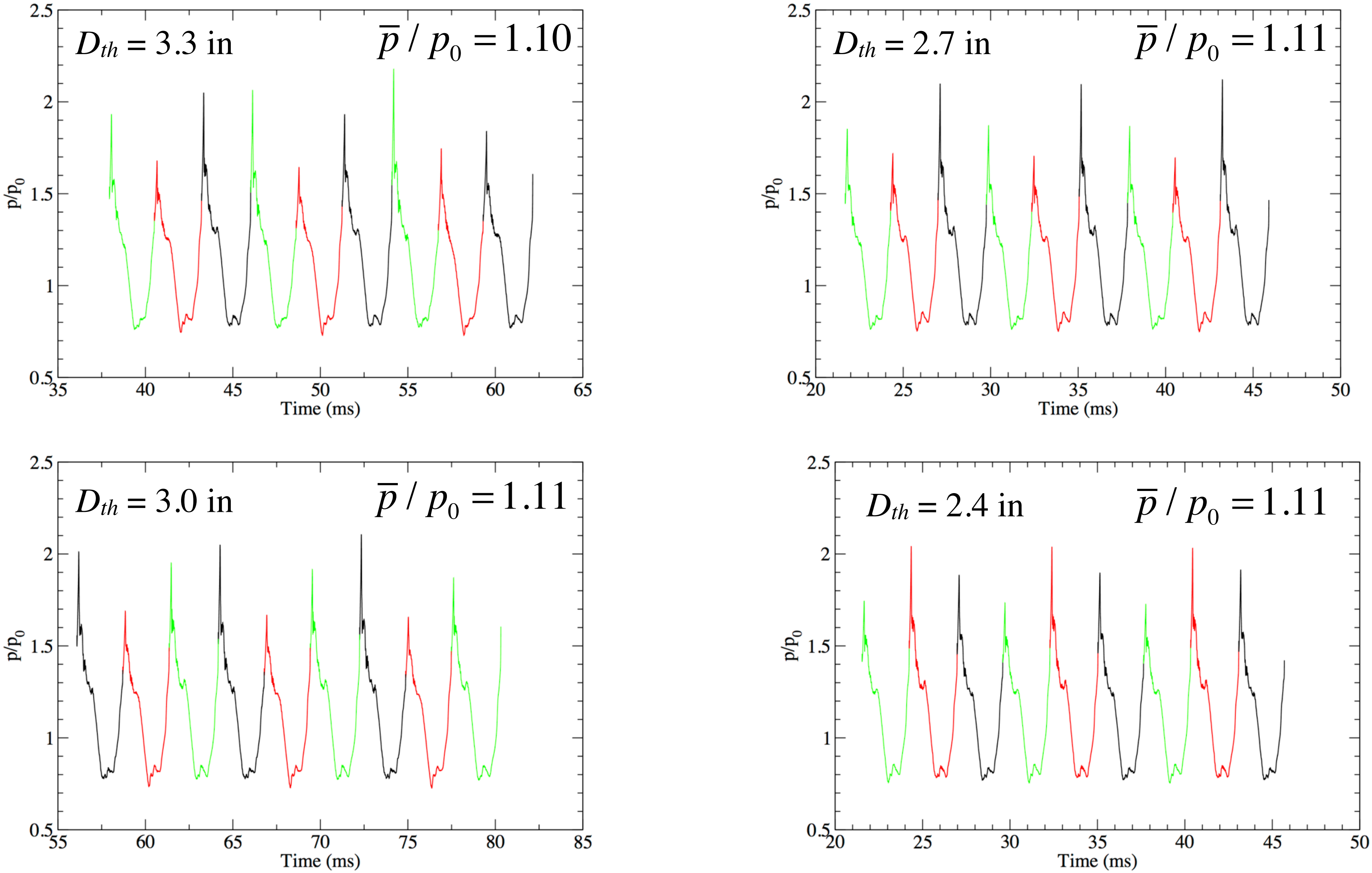


D_{th} = 2.4 in $\quad p_b / p_0 = 1.022$



PES combustor based on the Baseline configuration

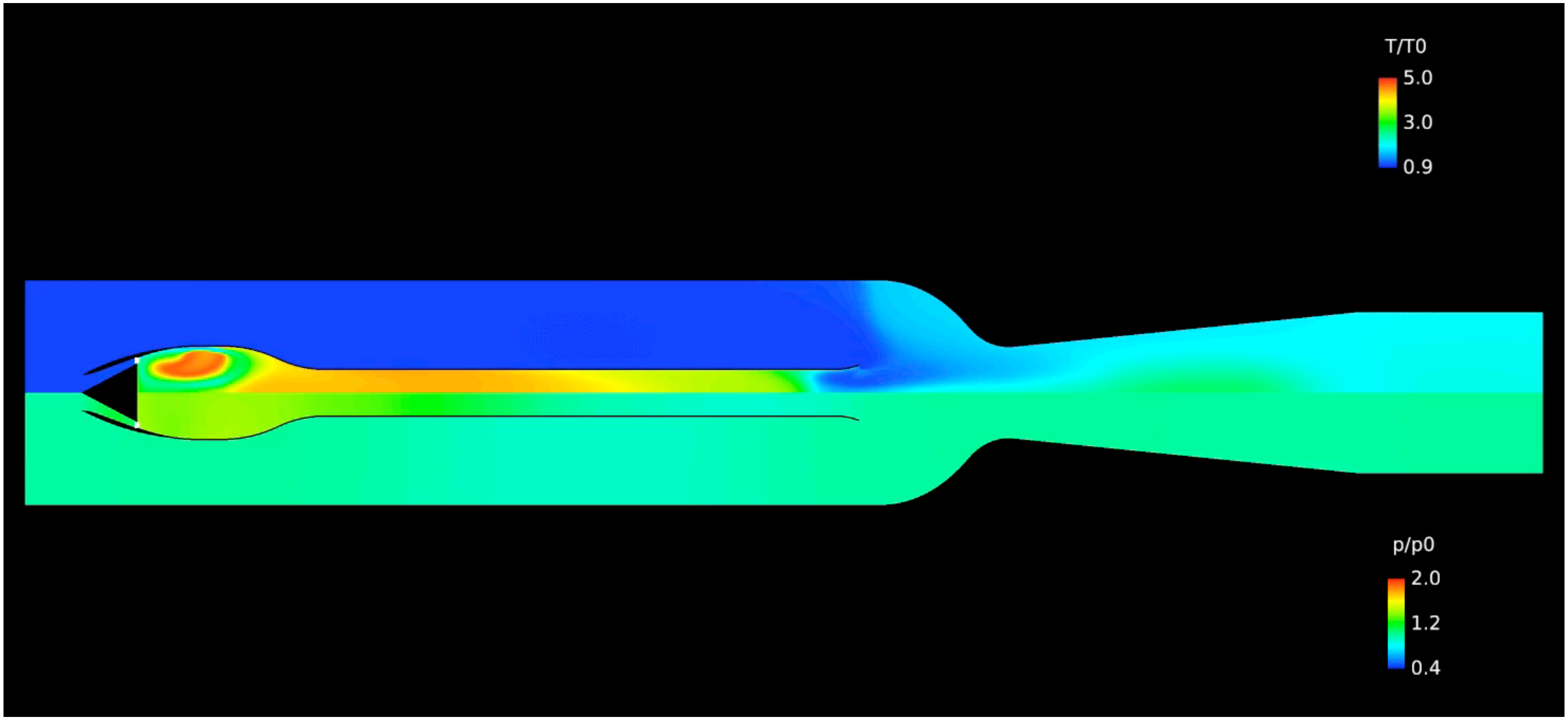
p_0 = 10 bar, T_0 = 550 K



PES combustor based on the Baseline configuration

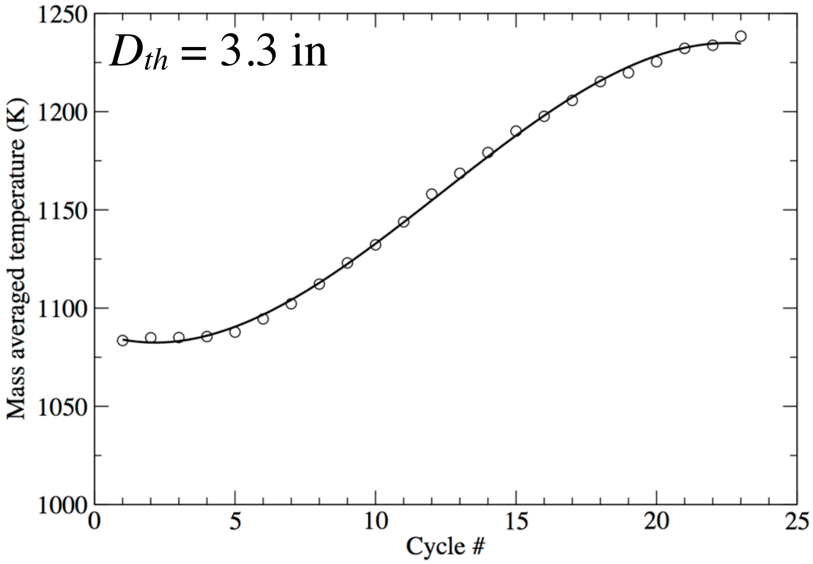
p_0 = 10 bar, T_0 = 550 K

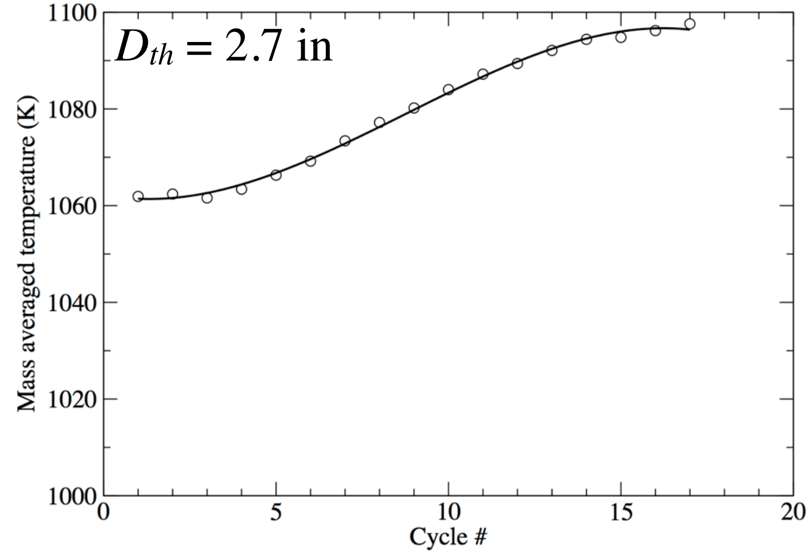
D_{th} = 2.4 in $p_b / p_0 = 1.022$

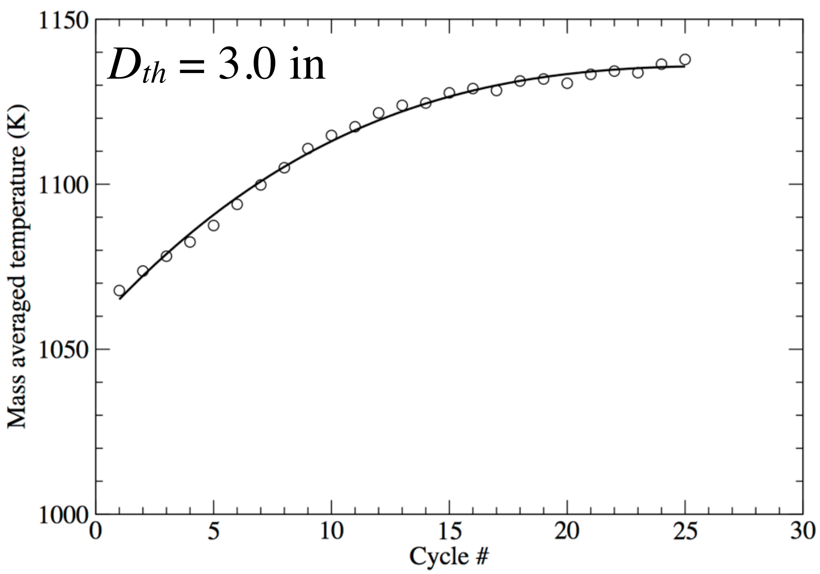


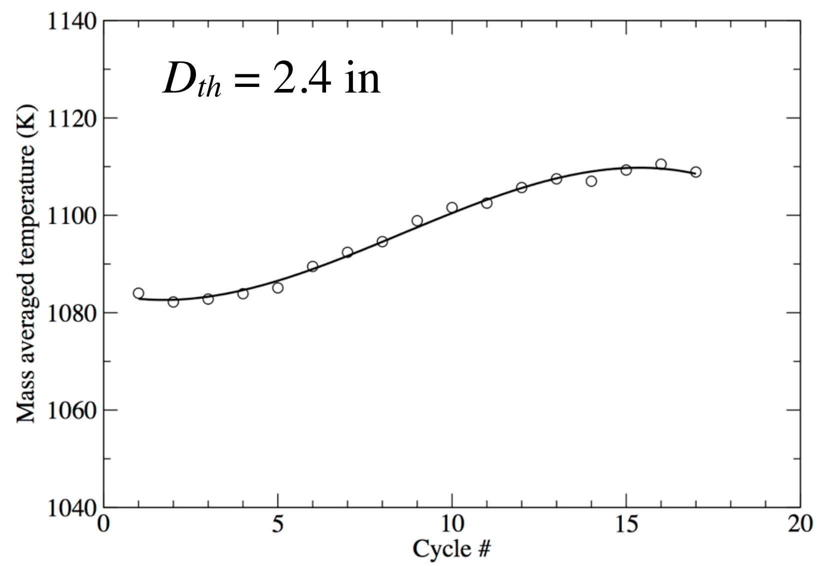
PES combustor based on the Baseline configuration

p_0 = 10 bar, T_0 = 550 K



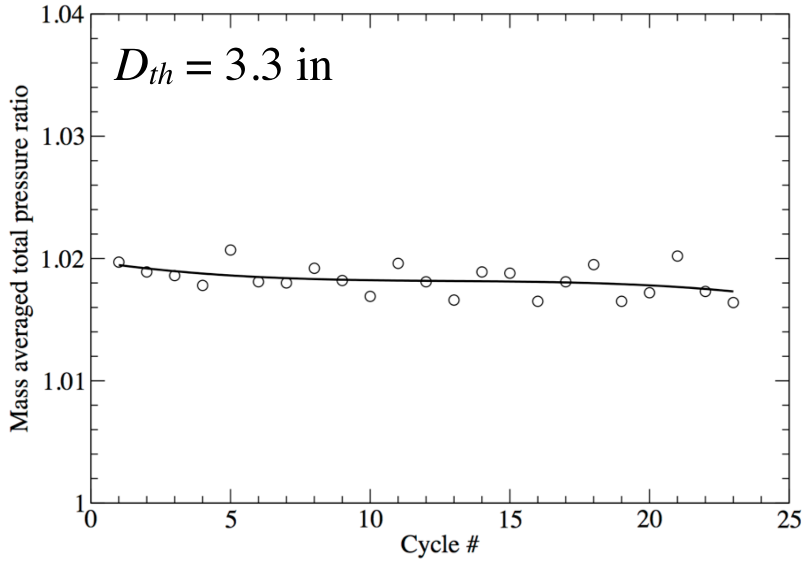


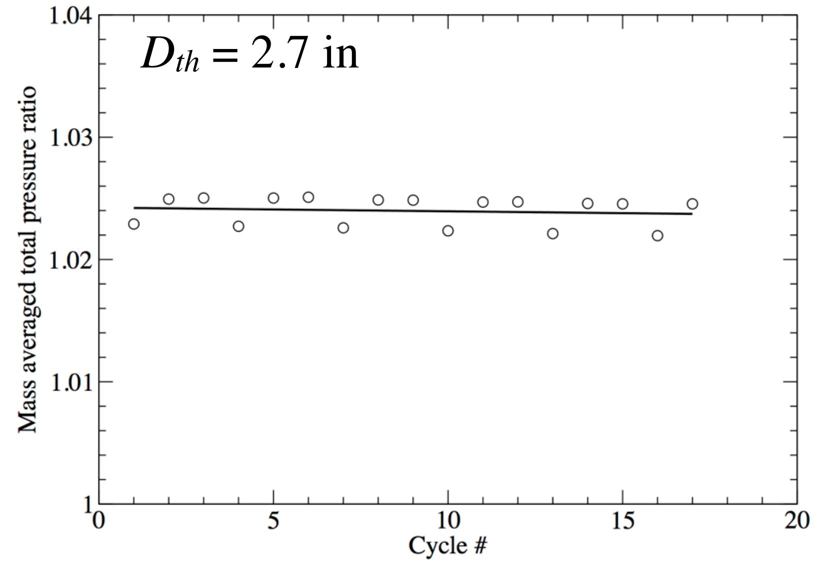


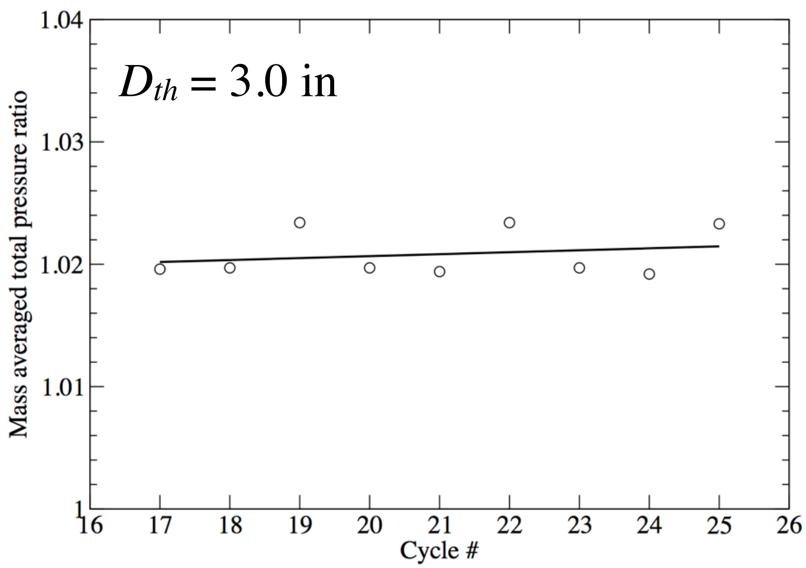


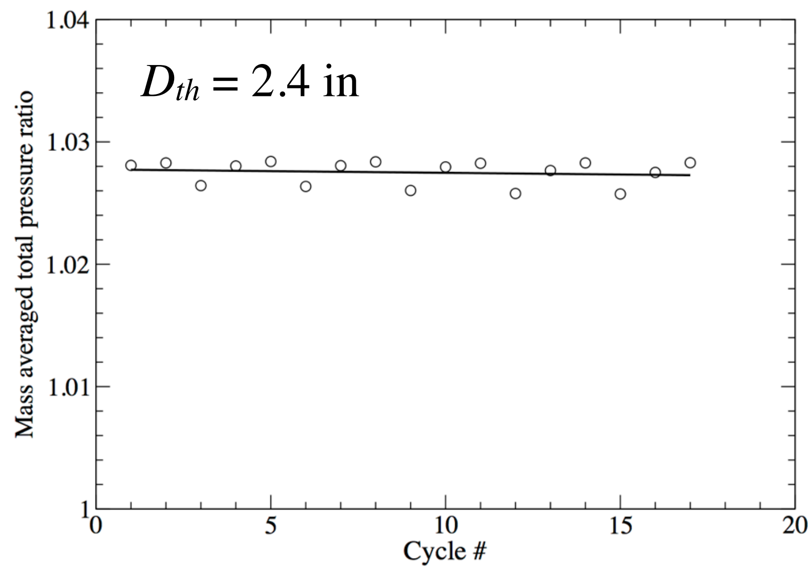
PES combustor based on the Baseline configuration

p_0 = 10 bar, T_0 = 550 K









Summary

- The first part of this study analyzed new pulse-combustor configurations that were aimed at improving the fuel distribution in the pulse-combustor.
  - The new configurations produced higher average combustor pressures.
  - The higher pressures, however, were achieved at the cost of higher NO production.
  - The emission index levels were comparable to those achieved in conventional gas turbine engines.
- The performance of various pulse-combustor driven ejector configurations were investigated computationally, focusing on the effects of ejector throat area.
  - The pressure gain of the PES combustor configuration increased inversely proportional A_{th}.
  - The highest pressure gain achieved was 2.8%, while maintaining the NOx EI < 10.

Future Work

- Based on the results presented, higher pressure gains are likely achievable by combining the FASH-based PES combustor with the 2.4 in throat diameter ejector.
- The optimal ejector throat area and its location relative to the pulse-combustor has not yet been determined.
- Further performance improvements can potentially be achieved by improving the valve and inlet configurations to minimize pressure losses.
- New configurations currently being tested completely decouple the valve dynamics from the fuel injection process, allowing for further optimization of the fuel injection timing.