TURBINE BURNERS: Engine Performance Improvements; Mixing, Ignition, and Flame-Holding in High Acceleration Flows

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OBJECTIVES

- Analyze the thermodynamic advantages of augmentative combustion during the expansion through the turbine for turbojet , turbofan , and stationary - power gas - turbine engines.

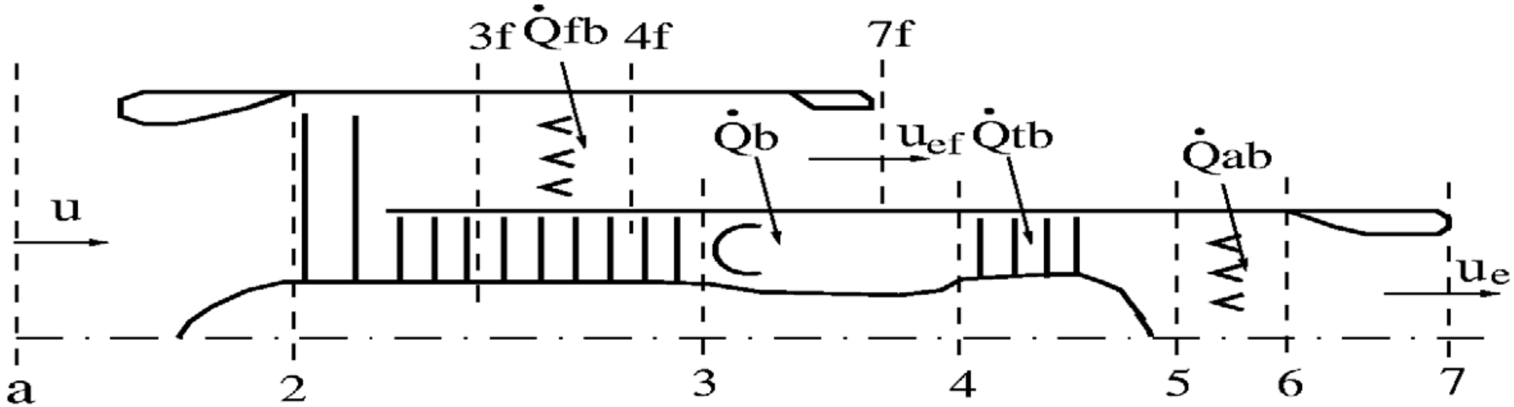
- Study combustion in accelerating , transonic mixing layers.

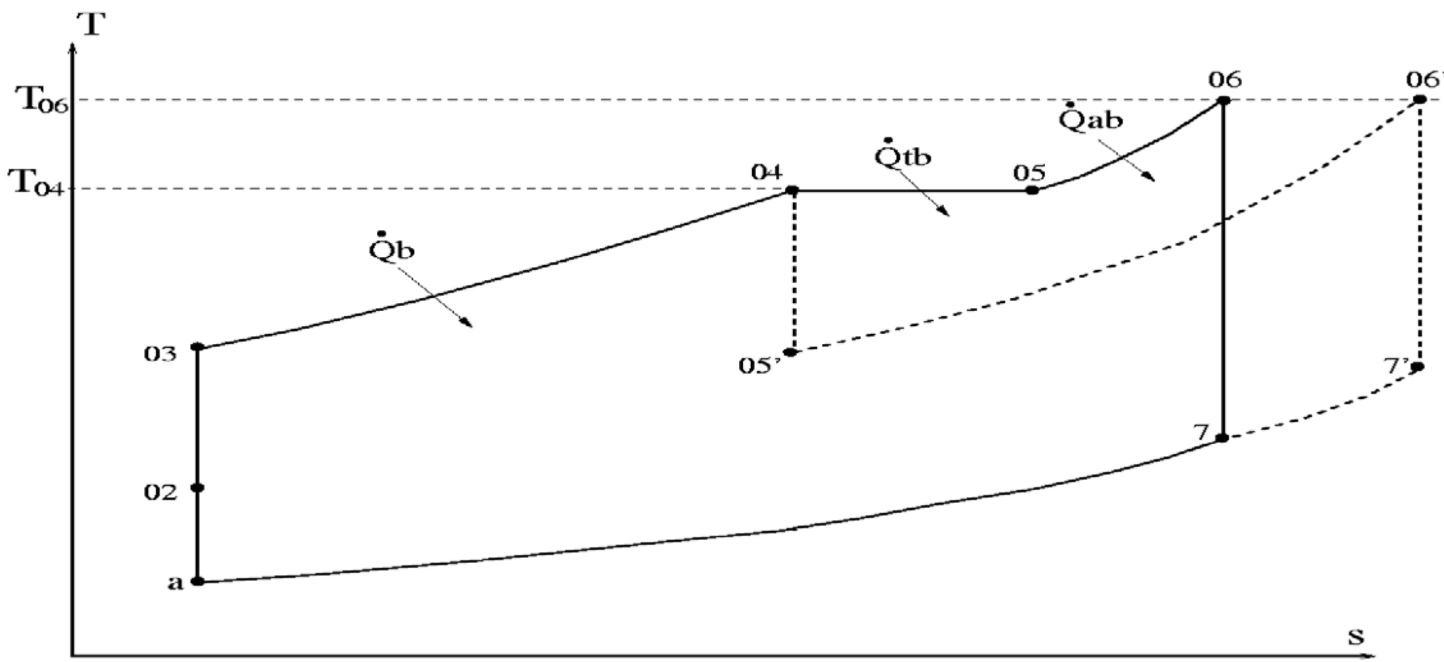
- Perform computational and experimental research on accelerating, turning transonic reacting flow.

- Examine the use of cavities for flameholding

- Contribute to the development of a new technology. Identify relevant scientific and technological challenges. Three SBIR awards were made by AFRL following our first two papers showing potential performance gains.

TURBOFAN CYCLE



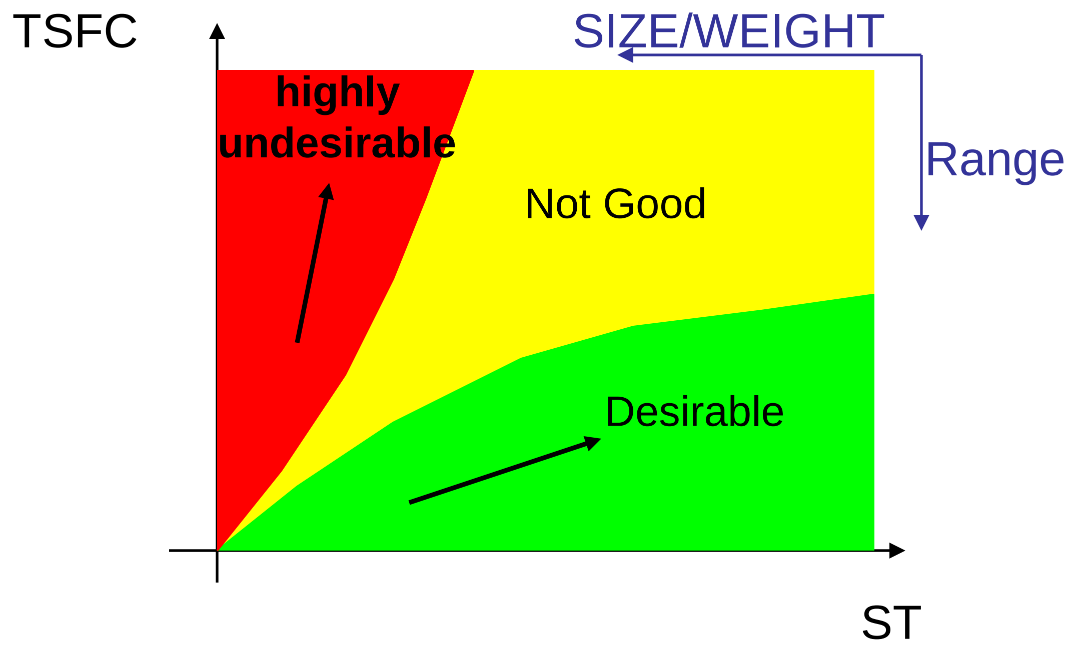


Weakness of Conventional Engines

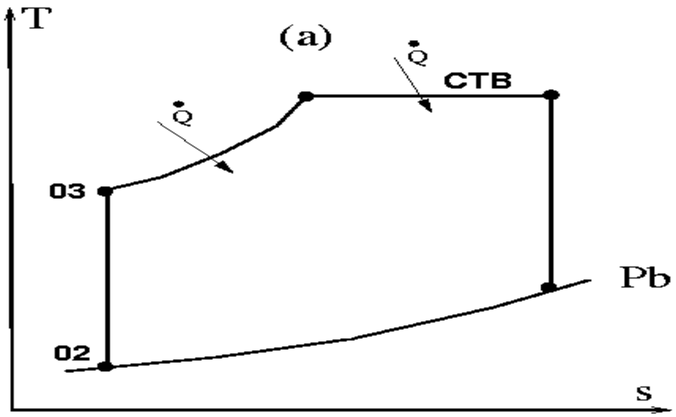
- Contention of TSFC & ST

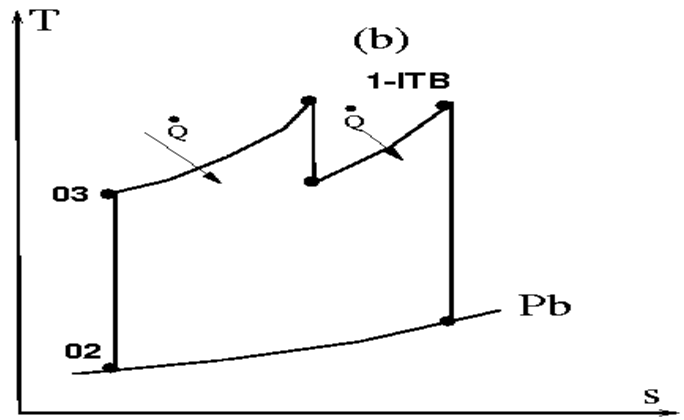
$$ST = \frac{\mathcal{T}}{\dot{m}_a}$$

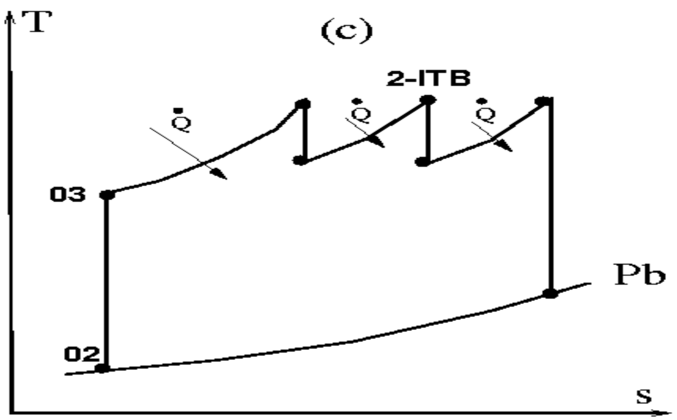
$$TSFC = \dot{m}_f \big/ \mathcal{T}$$

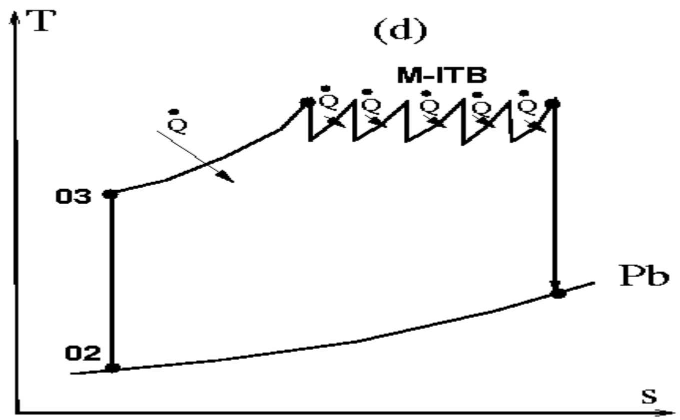


TURBINE BURNER CONCEPT



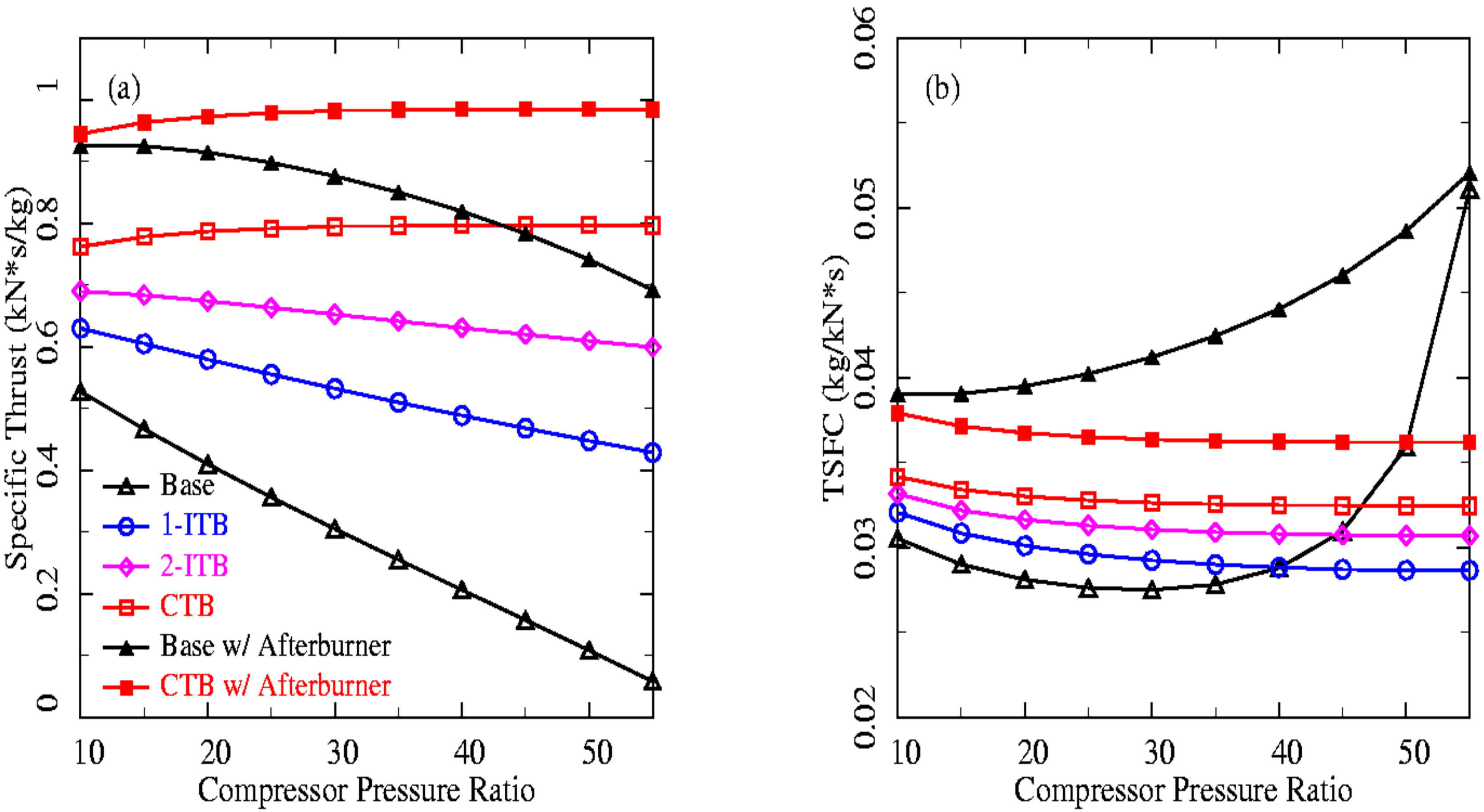






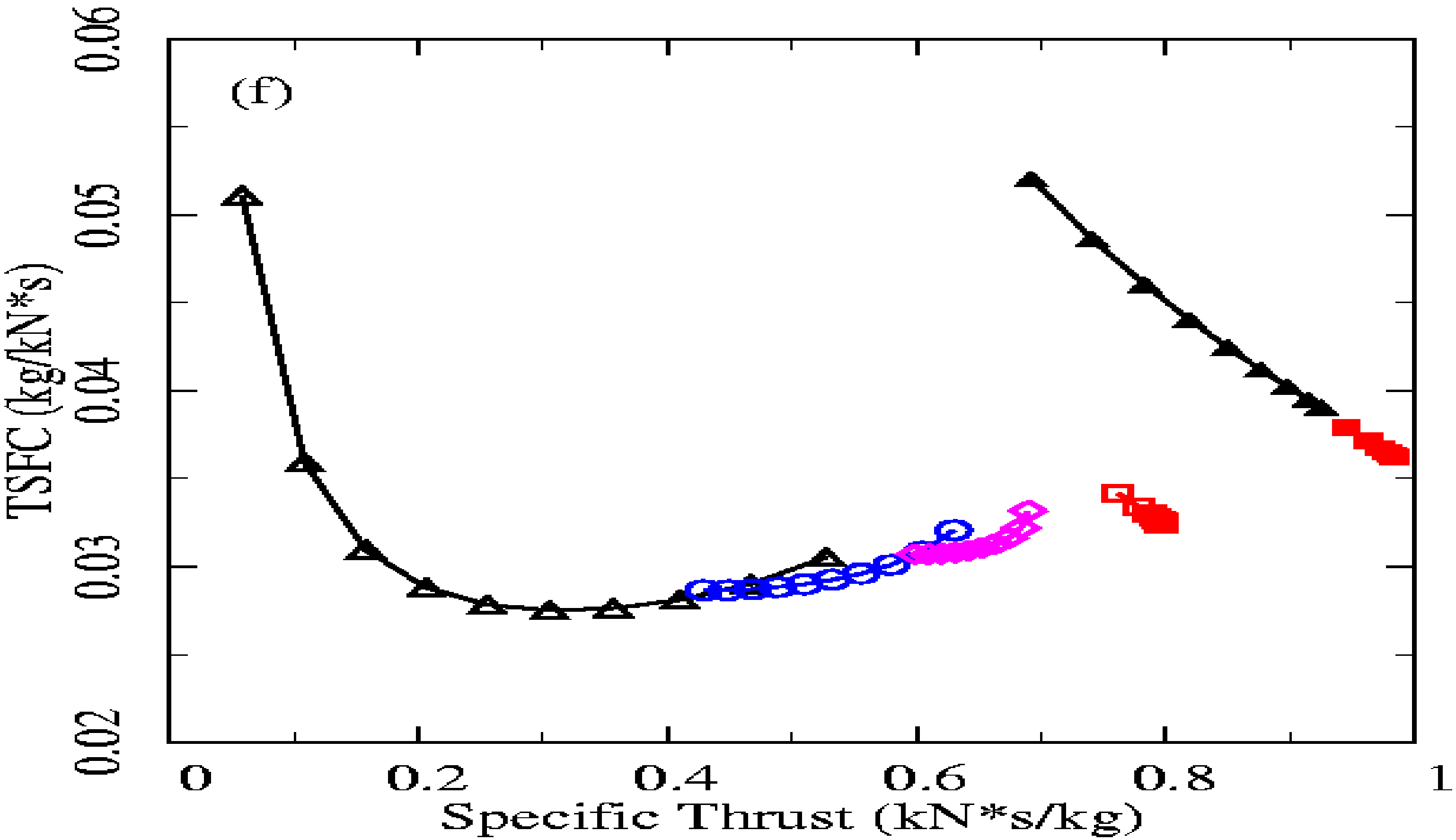
Turbine burning has advantage in a temperature - limited system; many stator burners approach continuous burner.

TURBOJET PERFORMANCE VS. COMPRESSION RATIO



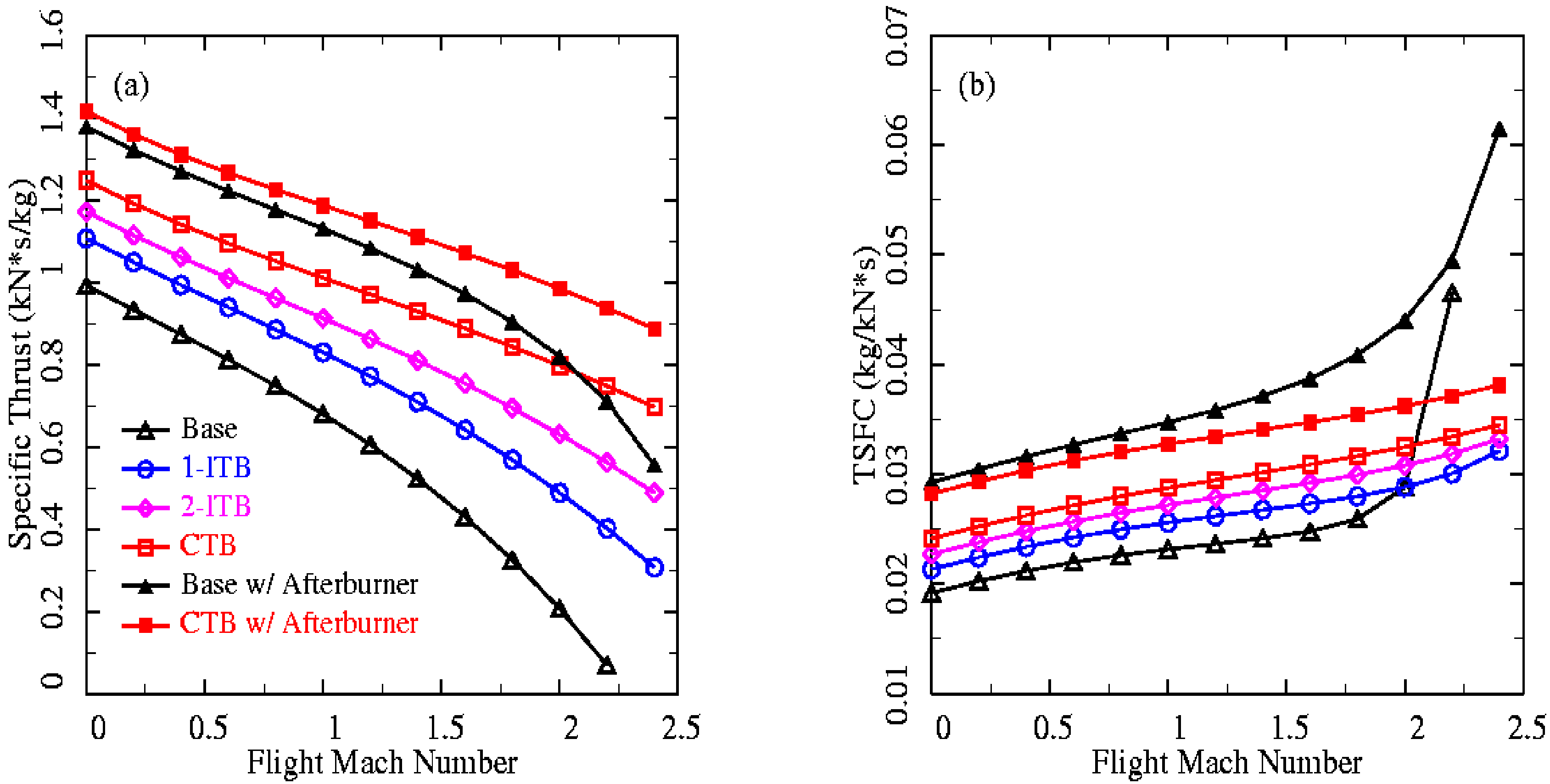
M = 2 , T_4 = 1500 K , T_6 = 1900 K

TURBOJET FUEL CONSUMPTION VS. THRUST



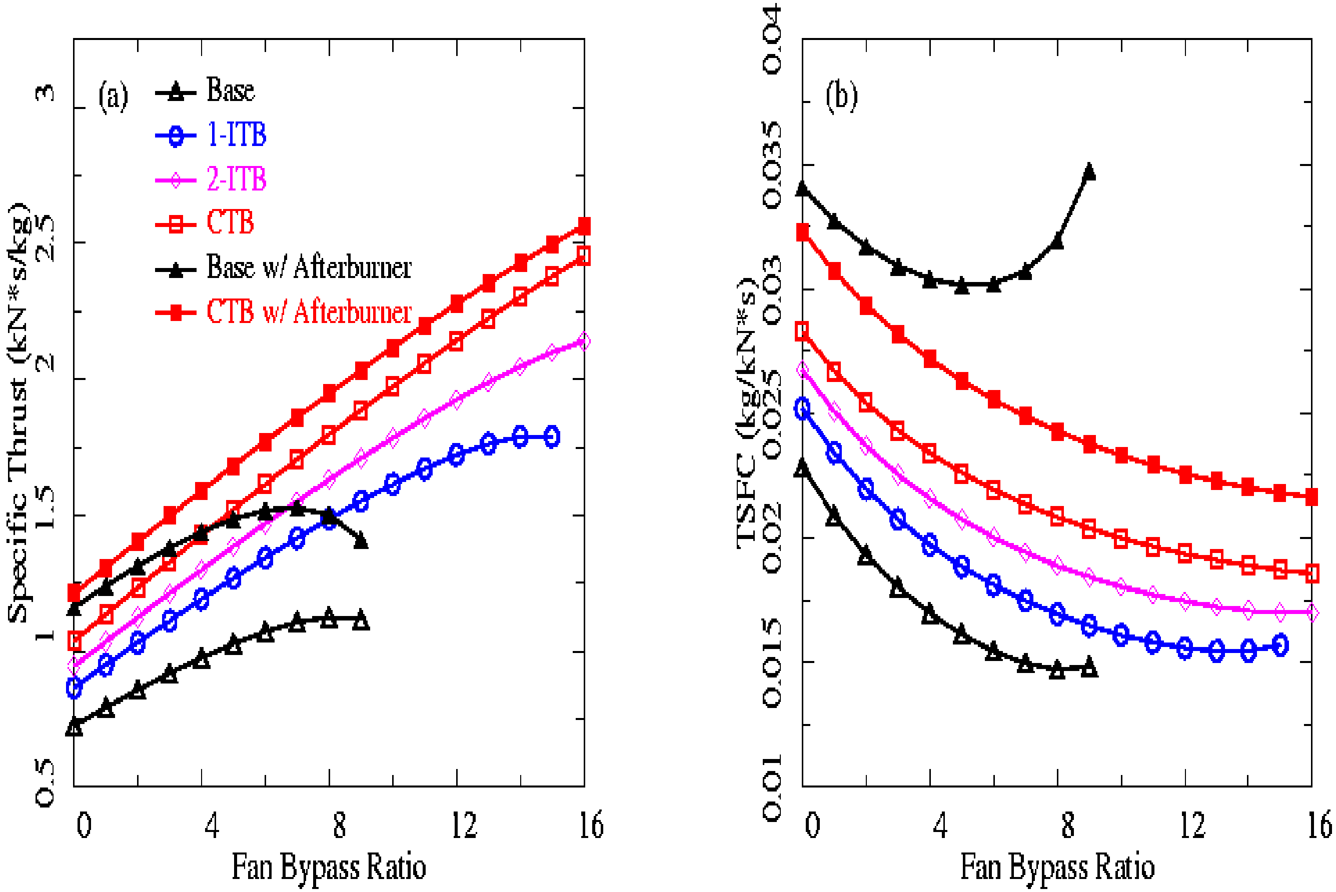
M = 2 , T_4 = 1500 K , T_6 = 1900 K

TURBOJET PERFORMANCE VS. MACH NUMBER



π_c = 40 , T_4 = 1500 K , T_6 = 1900 K

TURBOFAN PERFORMANCE VS. FAN BYPASS RATIO

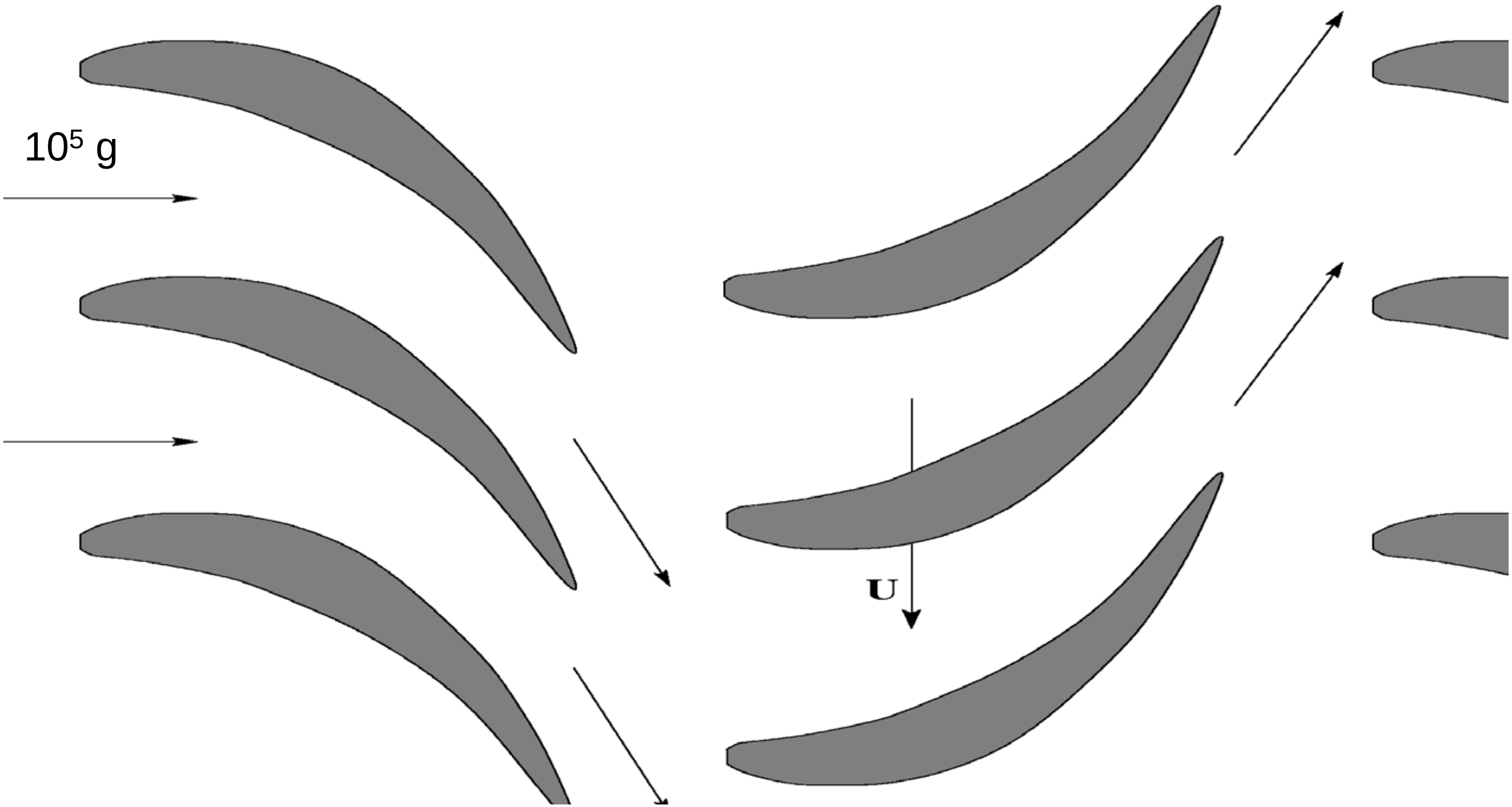


M = 0.87 , T_4 = 1500 K , T_6 = 1900 K , π_c = 40

NEW OPPORTUNITIES WITH TURBINE BURNERS

- Increased thrust for same size or same thrust at smaller size compared to engine without augmentation.
  At higher compression ratios or flight Mach numbers, higher thrust than afterburner engines
- Less fuel consumption at higher compression ratio and / or flight Mach number. Better fuel consumption than afterburner case throughout parameter range
- For stationary power, higher power and efficiency
- Lower NO_x formation due to lower temperature
- Potentially lower take - off noise compared to afterburner

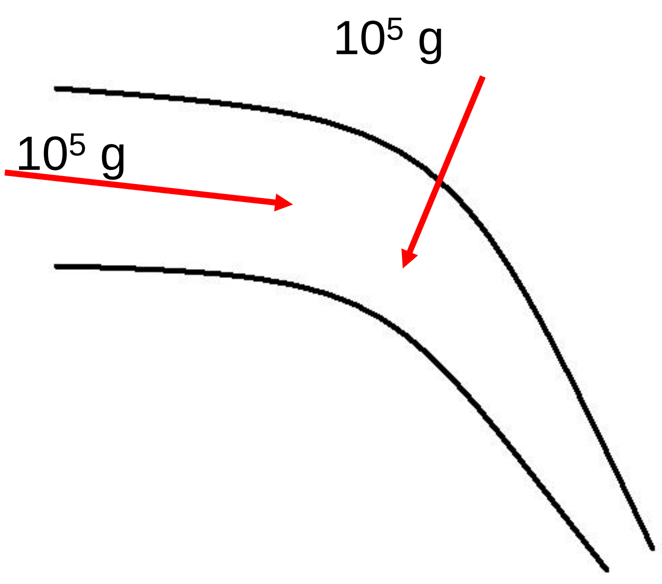
TURBINE PASSAGE FLOW



Flow accelerates through transonic range and turns ;
streamwise and transverse accelerations can be $O(10^5 g)$

CHALLENGES

- ❑ Ignition in a high acceleration flow.
- ❑ Flame-holding in a high acceleration flow.
- ❑ Combustion with short residence times.
- ❑ Burning of liquid fuels under these conditions.
- ❑ Hydrodynamic stability of stratified flow with large transverse pressure gradient.
- ❑ Modification of aerodynamic loading on turbine blades.
- ❑ Increased heating of critical components.



REACTING FLOW STUDIES

> Laminar *Mixing-Layer* Flows – axial acceleration; b.l. approx.

> Turbulent *Mixing-Layer* Flows – axial acceleration; b.l. approx., RANS equations: algebraic and two-equation models.

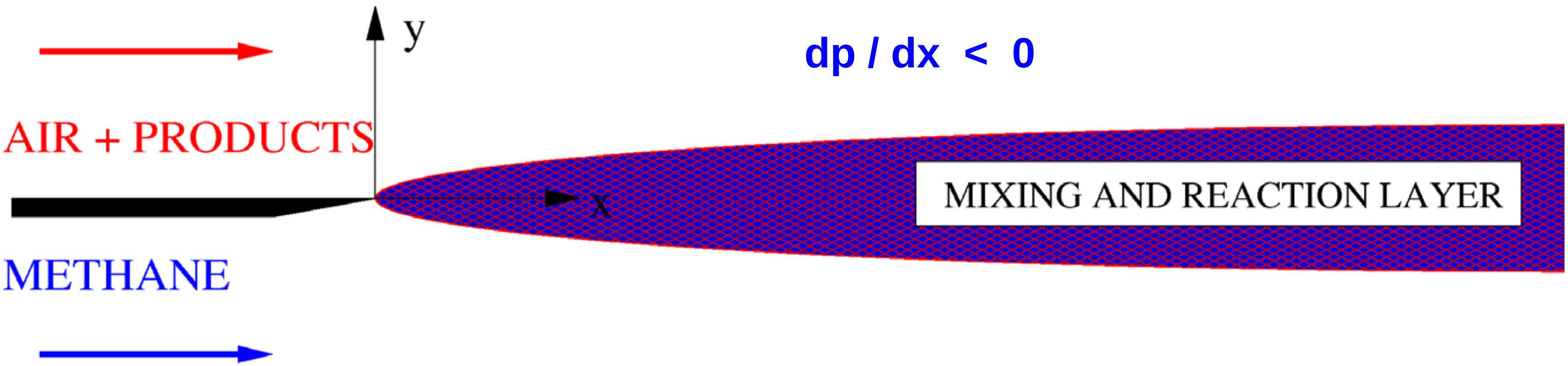
> Straight and Curved *2-D Channel* Flows – axial and transverse acceleration; RANS equations.

> *2-D Turbine- Passage* Flows -- axial and transverse acceleration; RANS equations.

> 2-D, Unsteady *Channel* Flows – axial acceleration of mixing flows in transition.

> 2-D and 3-D, Unsteady *Channel* Flows *with Cavities -* Injection and mixing flows in transition. Current computational studies; experimental work completed.

REACTING MIXING LAYER

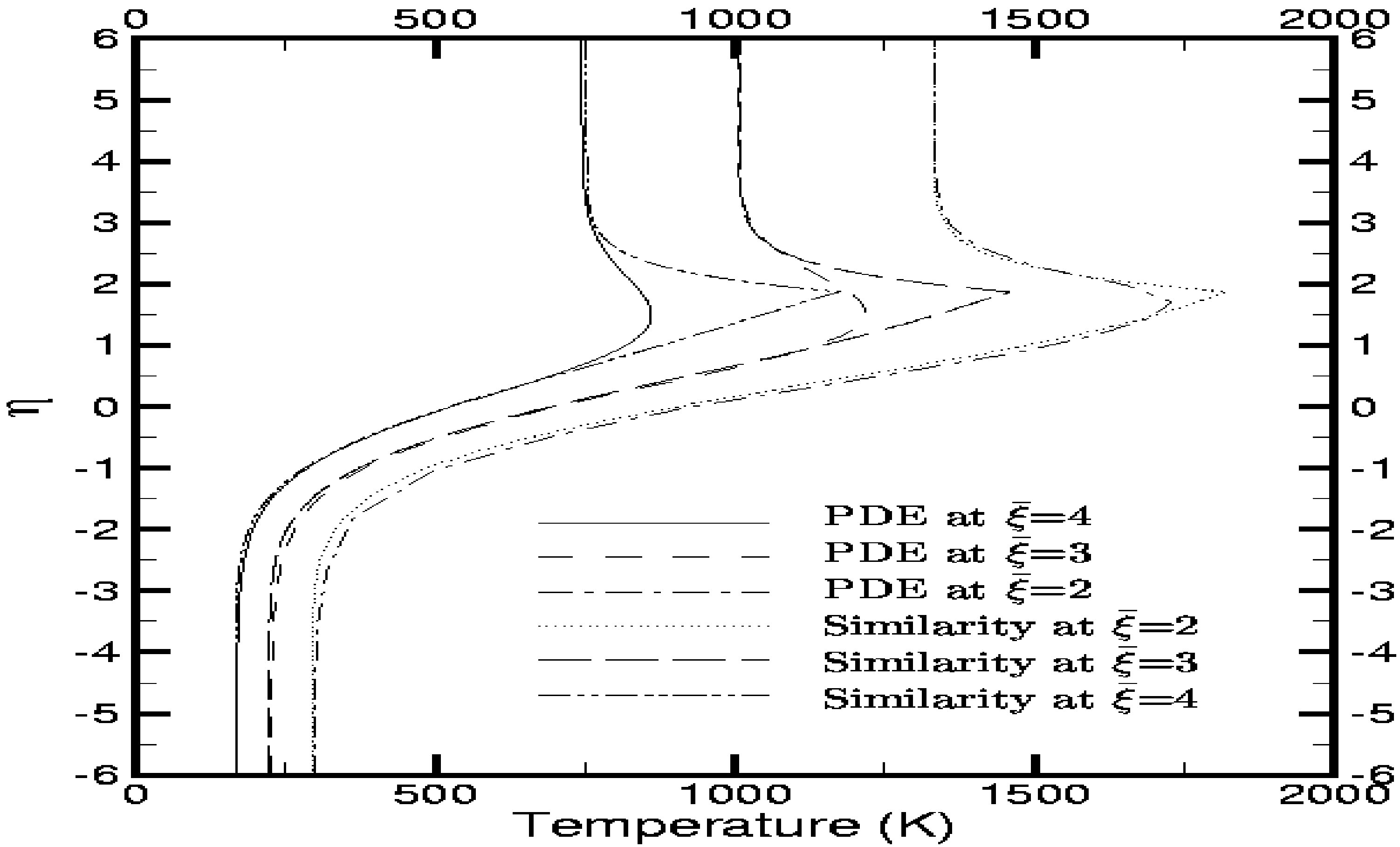


$$CH_4 + 2O_2 + 7.52N_2 \quad \longrightarrow CO_2 + 2H_2O + 7.52N_2$$

The chemical kinetics rate can be described as:

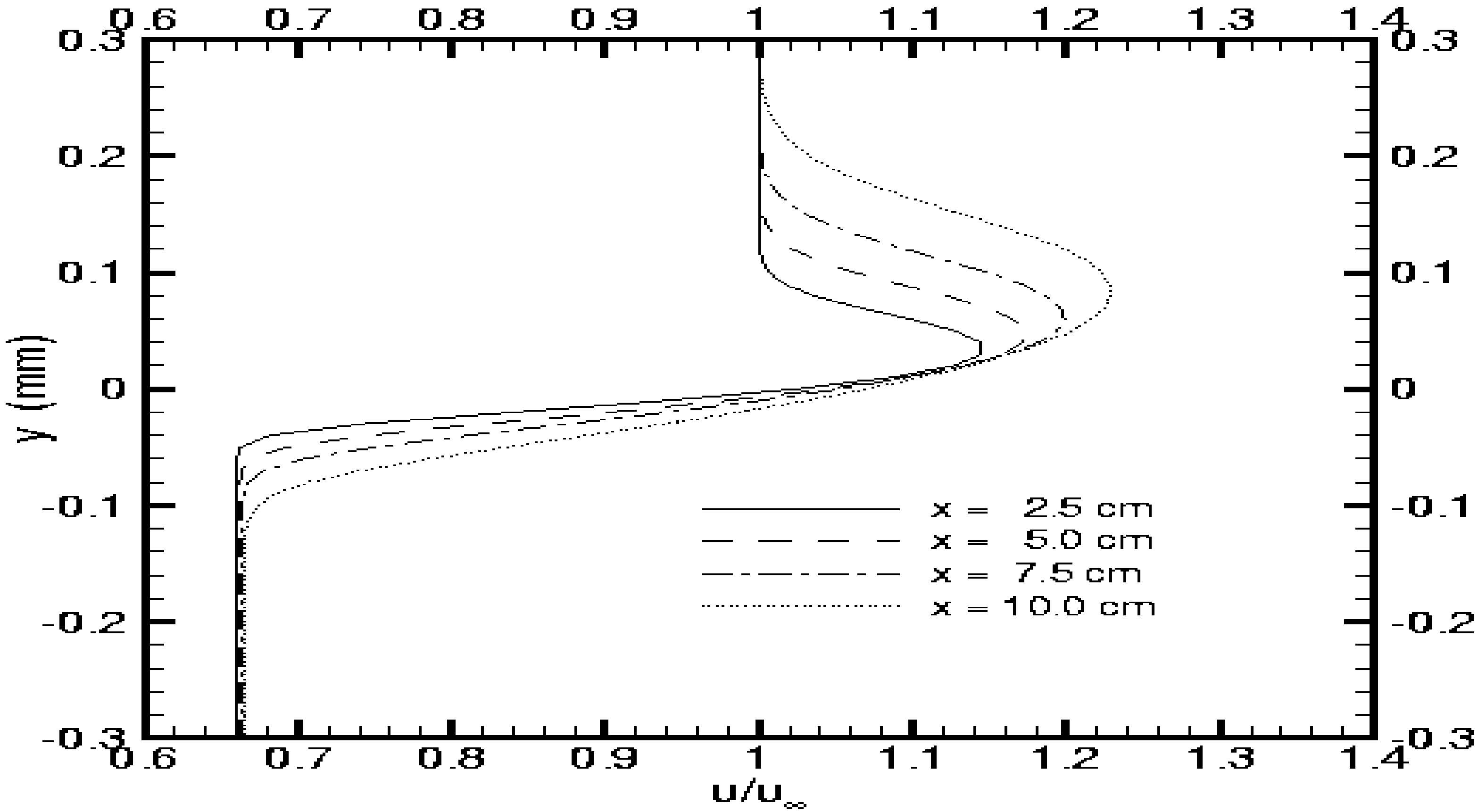
$$\dot{\omega}_F = Ae^{-E_a/RT}[Fuel]^a[O_2]^b$$

COMPARISON WITH SIMILAR SOLUTION : TEMPERATURE



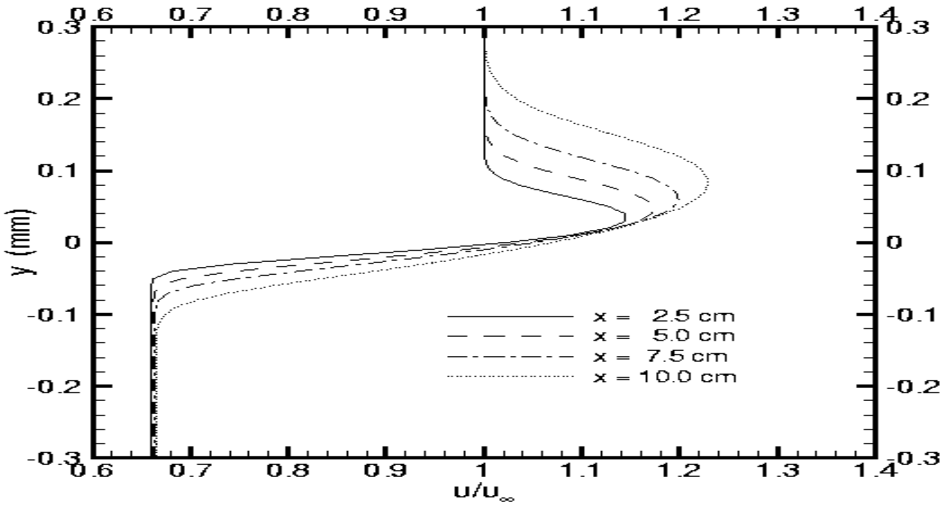
β = 2 ; K =1.673 ; ξ = 2 , 3 , 4

VELOCITY PROFILE



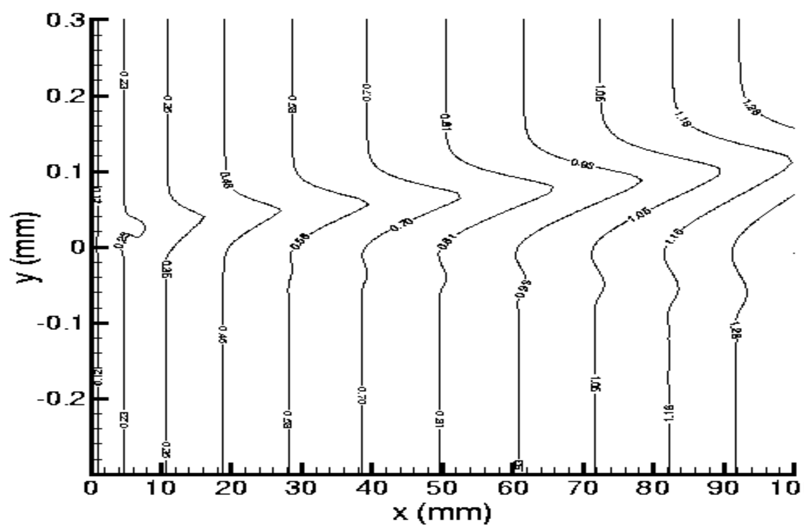
Case 1

VELOCITY PROFILES AND MACH NUMBER CONTOURS



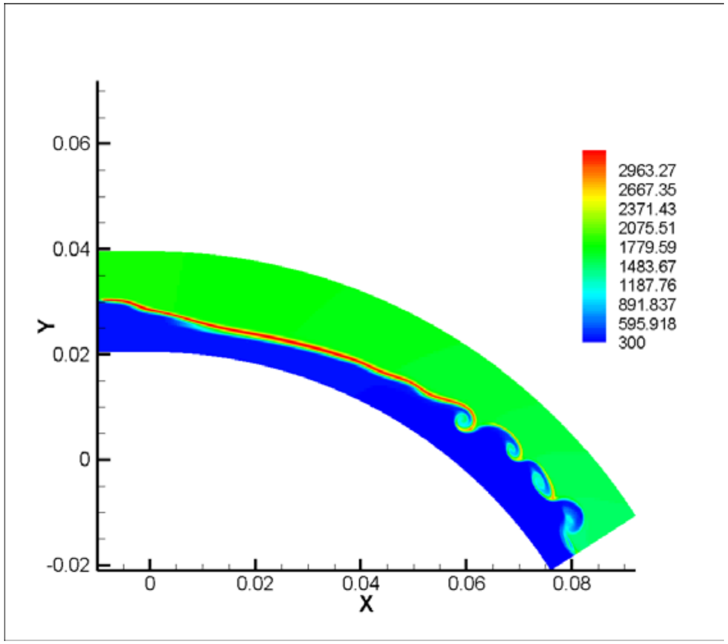
Lighter density portion of flow accelerates faster with overshoot developing. Note that u_∞ increases with x.

Flow accelerates from subsonic to supersonic; Mach number is lower in hot, high - velocity region.

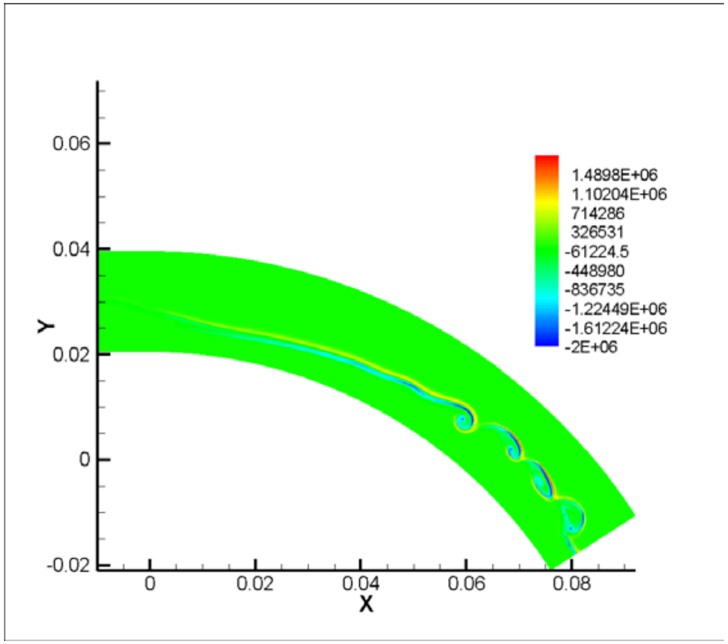


Curved Channel: Reacting, Accelerating Mixing Layer with Faster Fluid on the Outside

Temperature



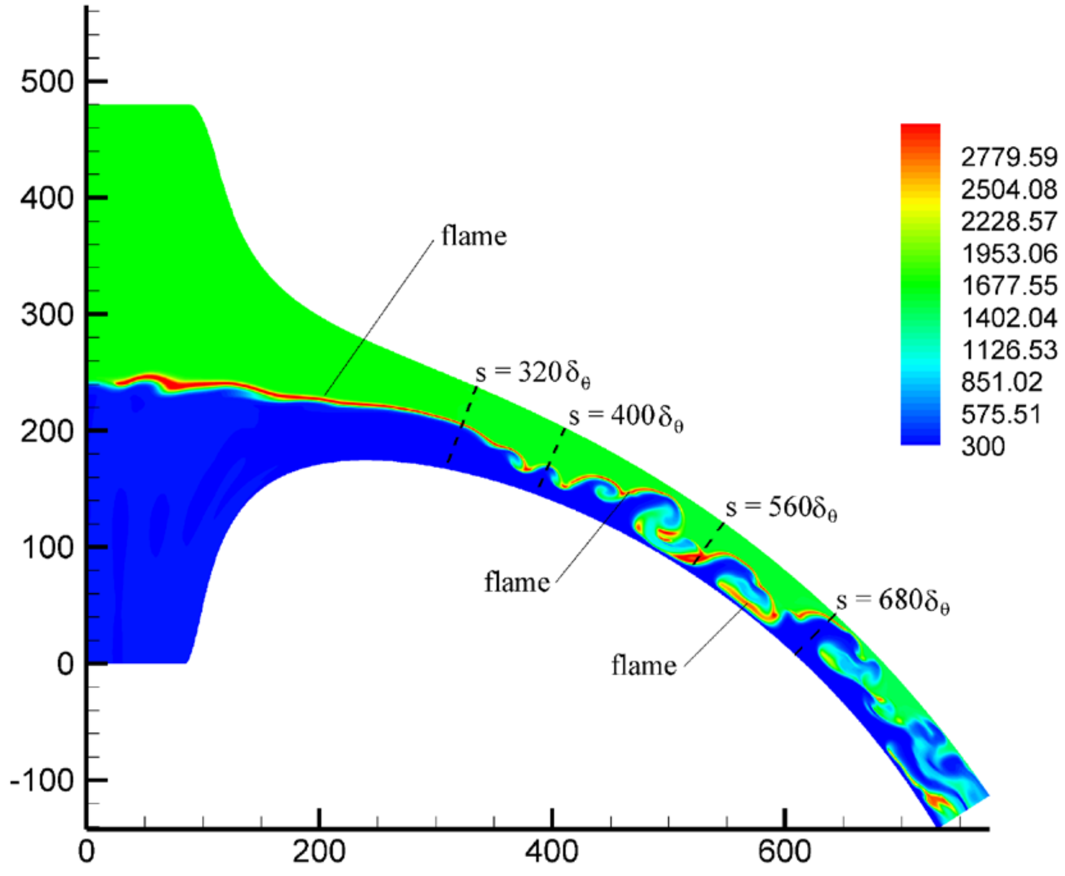
Vorticity

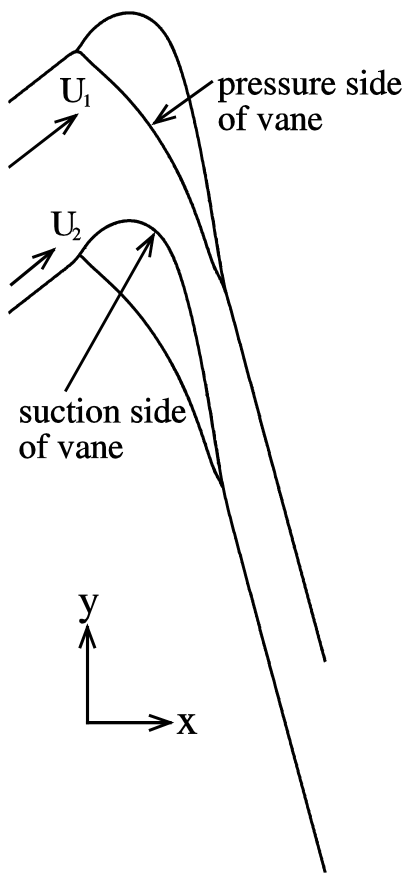


- **Compared to the non-accelerating case, the formation of large eddies by pairing is delayed. The streamwise accelaration has a stabilizing effect.**
- **The combustion region curves slight inward due to varying pressure gradient.**

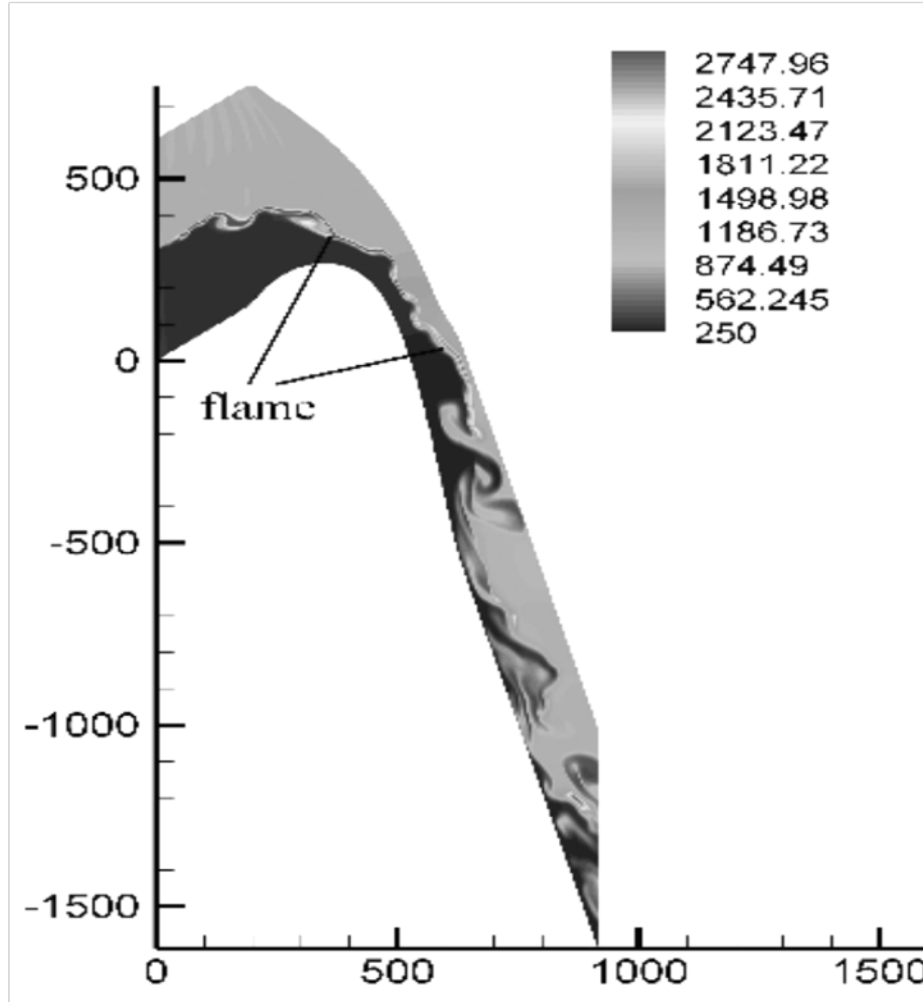
Converging-diverging Curved Channel: Reacting, Accelerating Mixing Layer with Faster Fluid on the Outside

Temperature



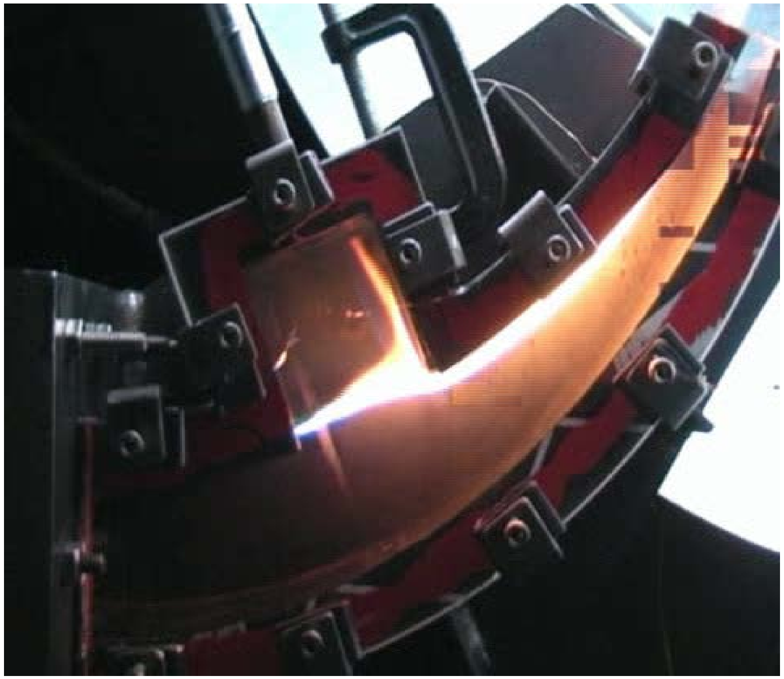


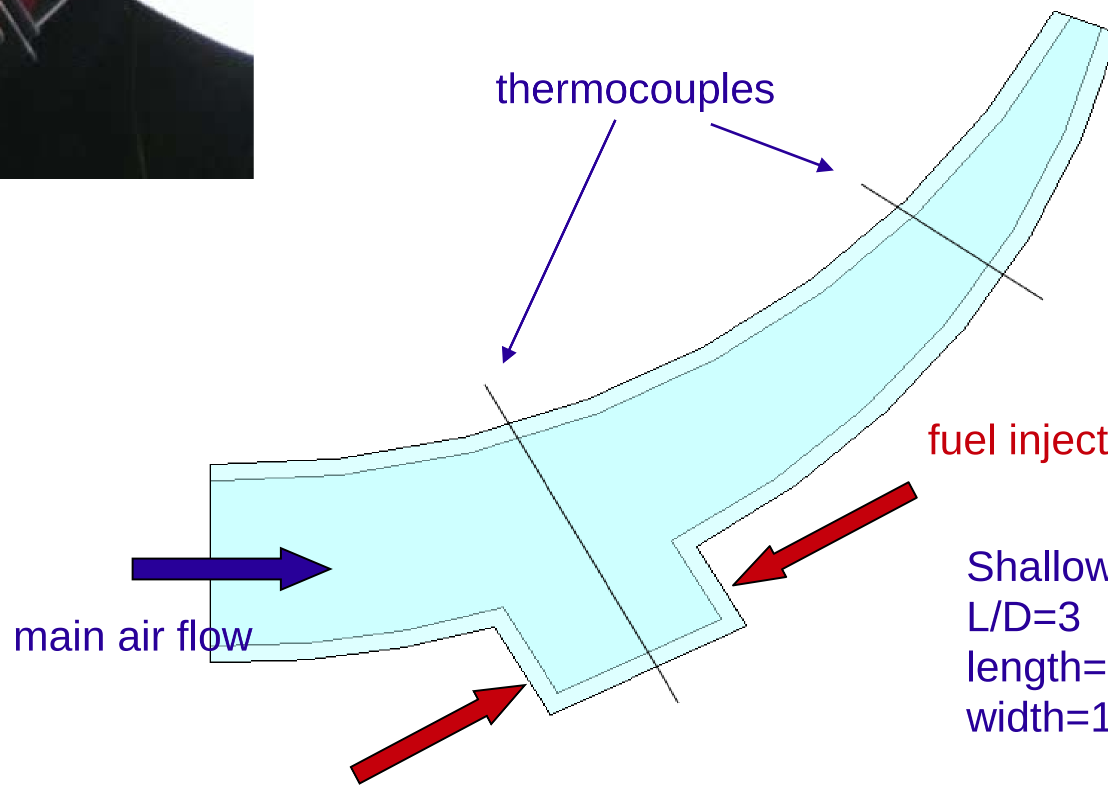
pressure side
of vane
U1
U2
suction side
of vane
y
x



2747.96
2435.71
2123.47
1811.22
1498.98
1186.73
874.49
562.245
250
flame
500
0
-500
-1000
-1500
0
500
1000
1500

Experimental Test Section

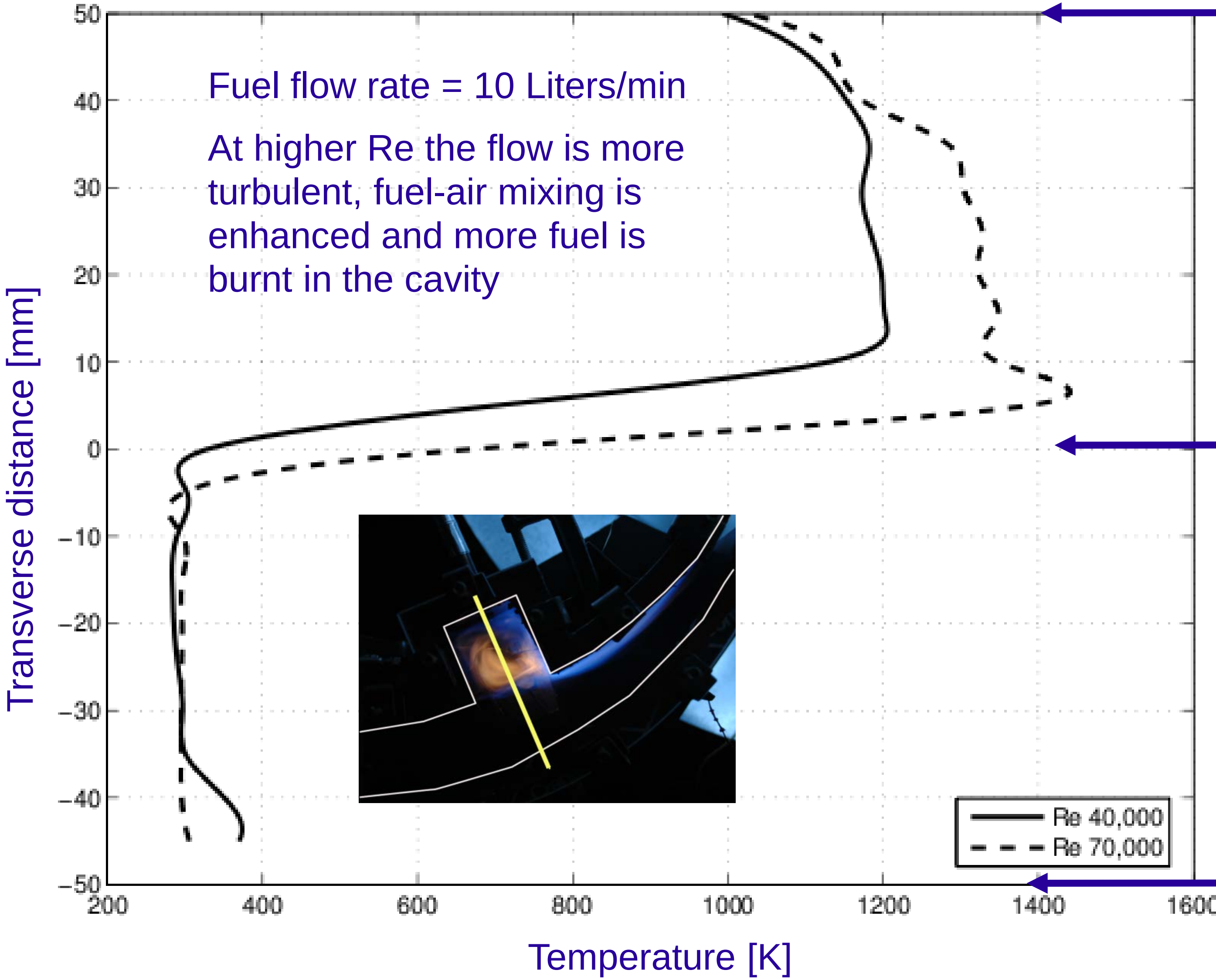




- Cavity on the inner and outer curvature
- Two aspect ratios: L/D=1 and L/D=3

Shallow cavity:
L/D=3
length=5cm
width=10cm

Temperature measurements

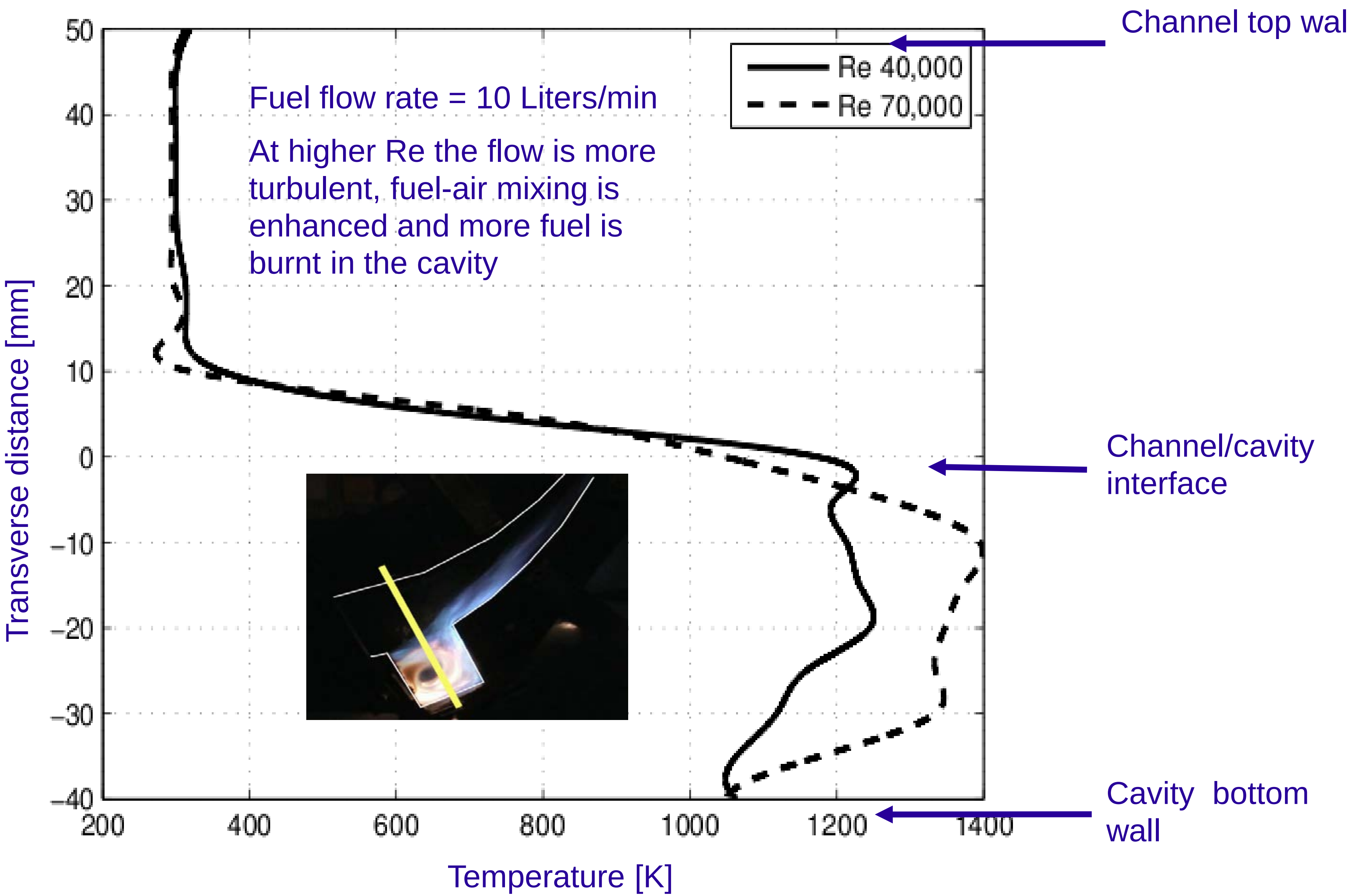


Cavity top wall

Channel/cavity interface

Channel bottom wall

Temperature measurements

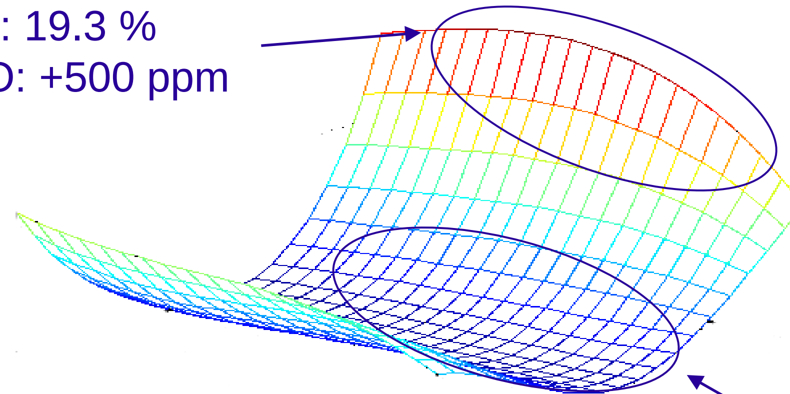


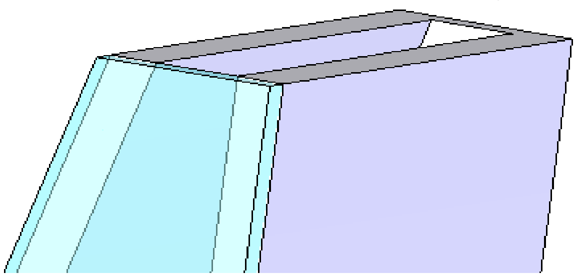
Temperature measurements

The flame is along the two side walls of the cavity.

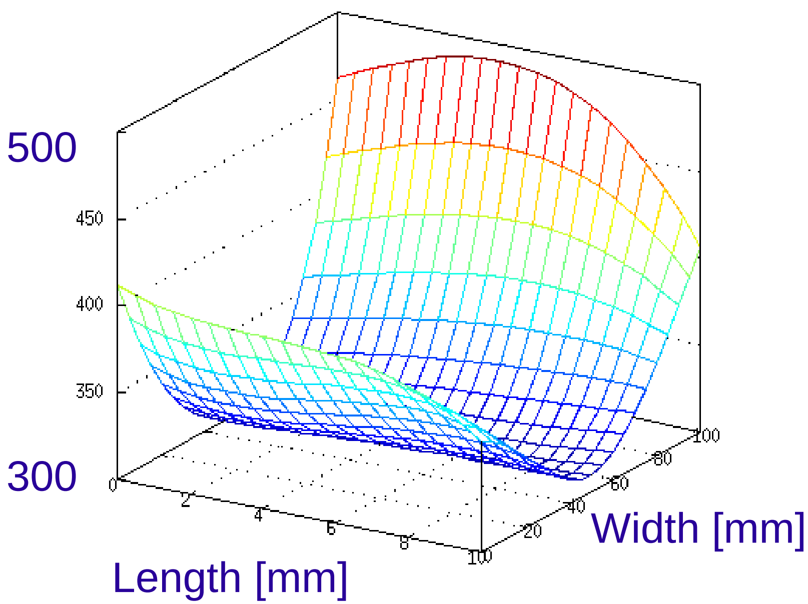
The flame is not symmetric due to the presence of the pyrex window.

O_2: 19.3 %
CO: +500 ppm



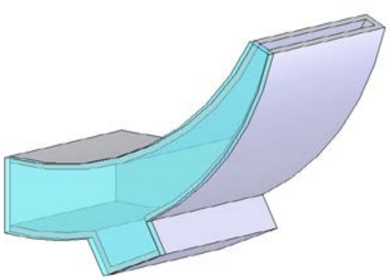


O_2: 20.9 %
CO: 10 ppm



Condition:

- Shallow cavity
- Counterflow injection
- Air: Re 70,000
- Fuel: 10 Liters/min



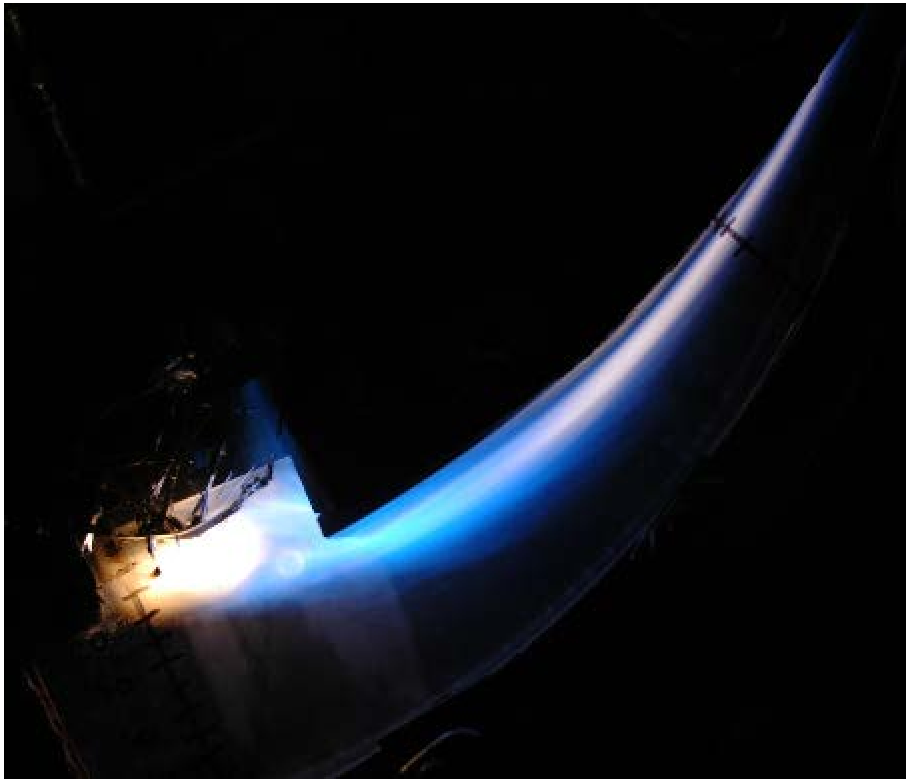
Experimental Observations

Combustion with liquid fuel (heptane):

Combustion stable at Re 40,000 and 70,000 only if the shallow cavity is used.

With a deep cavity the mixing is not sufficient and the heptane droplet evaporation doesn’t occur as efficiently.

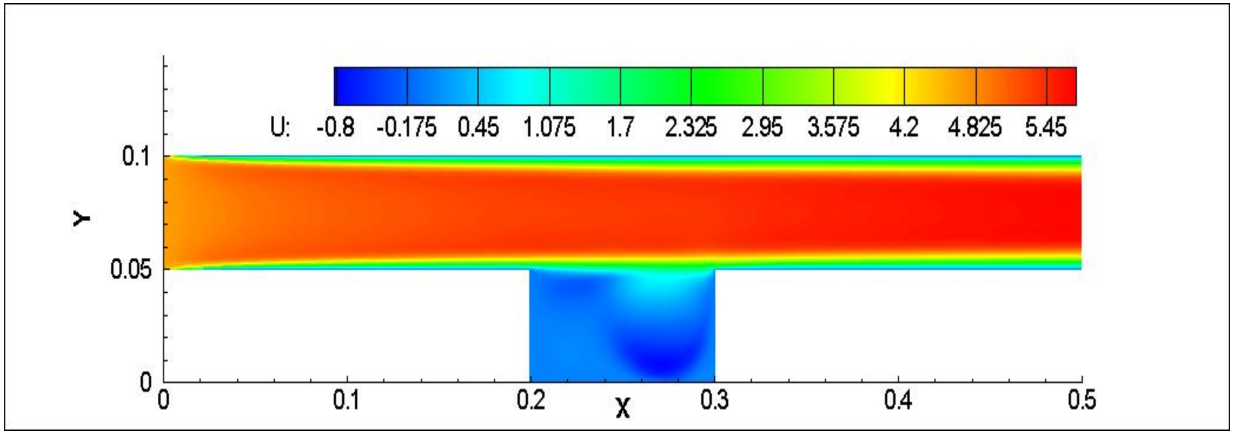
Fuel, and therefore the flame, penetrate farther into the main stream with liquid injection.



Recent DNS Studies

- Background and Motivation
- Numerical method
  - OpenFOAM
- 2D unsteady results
  - Effects of injection configuration
- 3D unsteady results
  - Mesh
  - Effects of injection configuration
- Conclusions
- Future Work

Cavity and injection stability



Re = 2000, no injection, steady

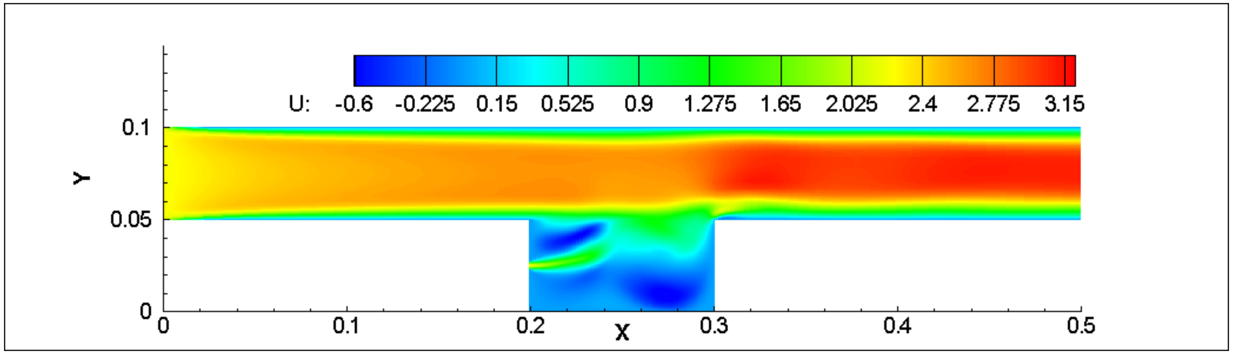
<u>No cavity</u>

•Steady at Re = 10^5

<u>Cavity without injection</u>

•Steady at Re = 2000

•Unsteady at Re = 3000



Re = 950, 10% mass injection, unsteady

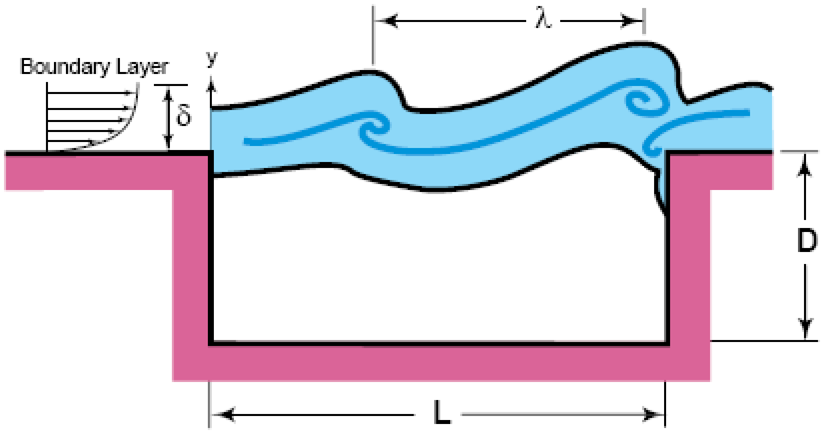
<u>Cavity with injection</u>

•Steady at Re = 900

•Unsteady at Re = 950

•Injection into quiescent field is steady at Re = 1000

Rossiter Modes



$$St_n = \frac{fL}{U} = \frac{n - C}{\xi + 1/\kappa}$$

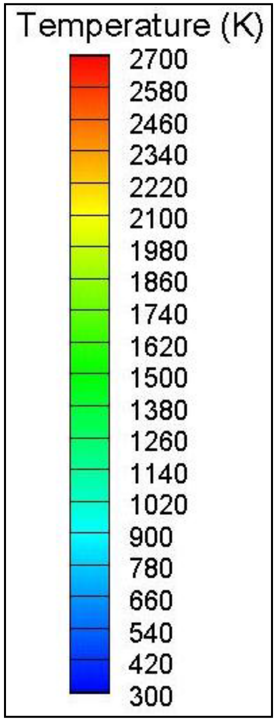
κ = Ratio of shear layer to freestream velocity

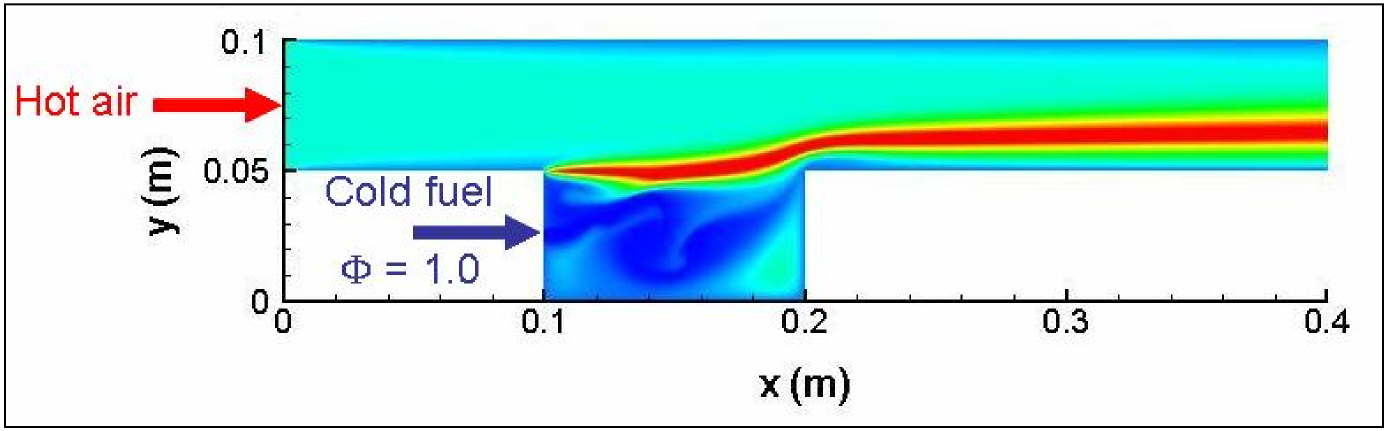
C = Correction factor ≈ 0.2

$$\xi = \frac{M}{\sqrt{1 + \frac{\gamma - 1}{2} M^2}}$$

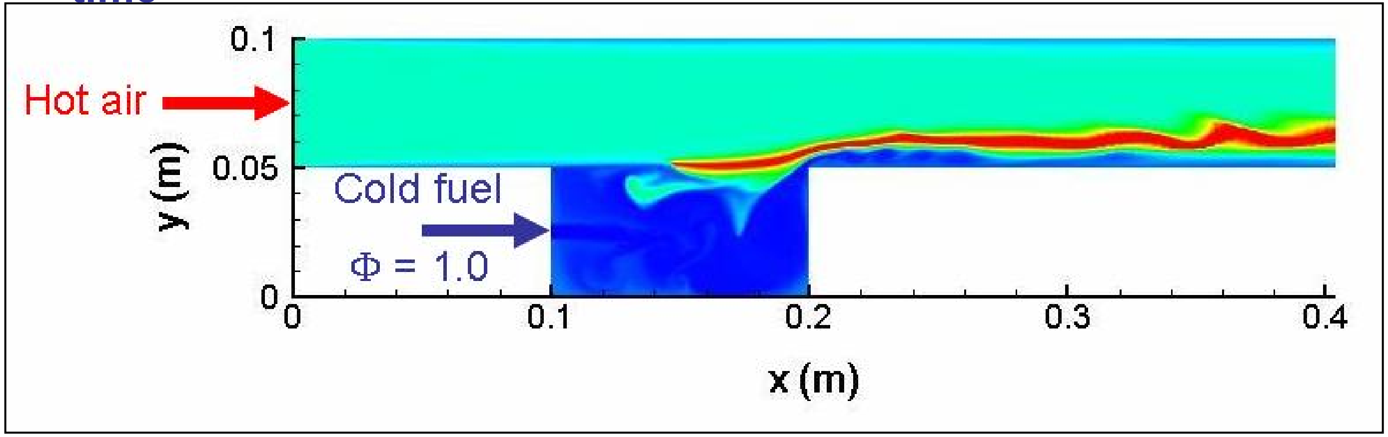
- Rossiter modes occur only for cold flow without injection in deep cavities. These modes are not seen with injection into cavity, shallow cavities, and / or reacting flow

Effect of Reynolds Number



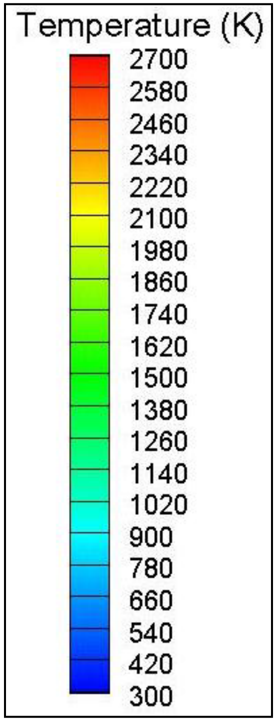


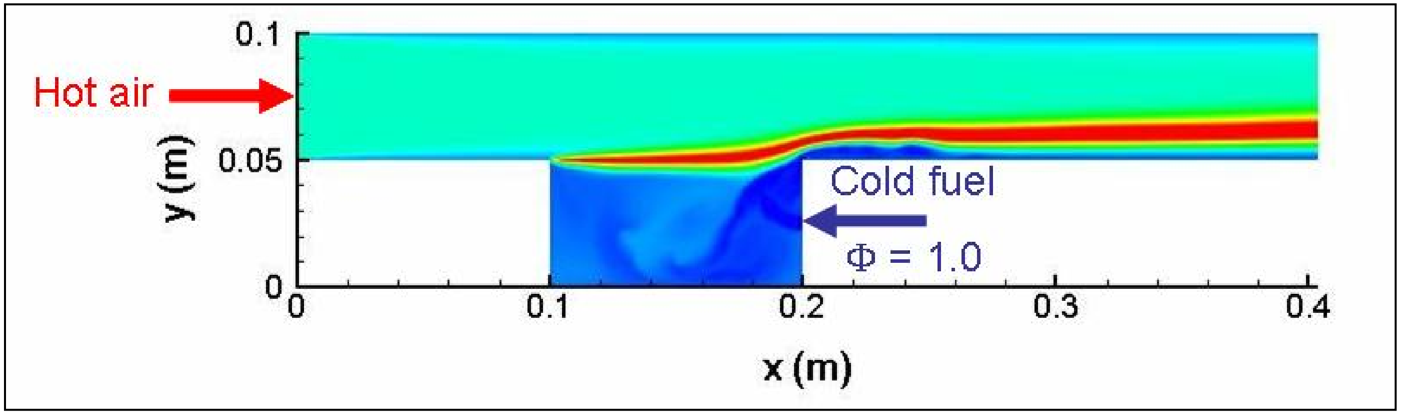
- Inlet Reynolds number = 500
- 6% increase in amount of fuel burned due to increased residence time



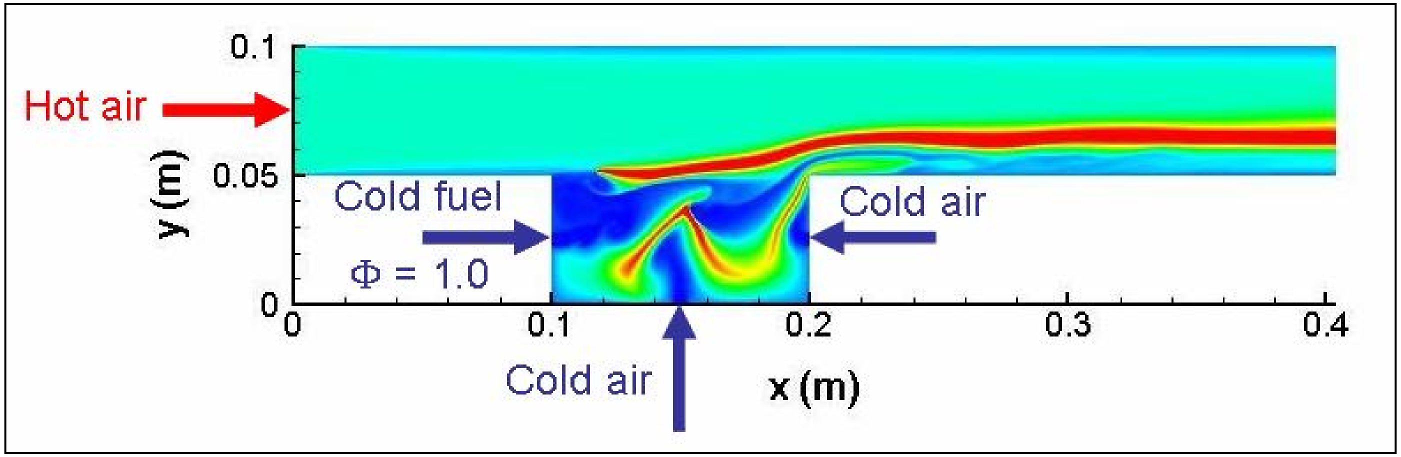
- Inlet Reynolds number = 2000
- Flame becomes unsteady
- 91% increase in amount of fuel burned due to turbulent mixing

Effect of Injection Configuration





- Inlet Reynolds number = 1000 with downstream injection
- 30% decrease in amount of fuel burned



- Inlet Reynolds number = 1000 with extra air injection into cavity
- Second flame produced
- 9% increase in amount of fuel burned

OpenFOAM

- Open source C++ libraries for CFD
- Top-level code is a direct representation of the equations. Continuum formulation is input without stating difference form.

$$\frac{\partial(\rho U)}{\partial t} + \nabla \bullet (\rho U U) - \nabla \bullet (\mu \nabla U) = -\nabla p$$ becomes:

```
solve ( fvm::ddt(rho, U) + fvm::div(phi, U) -
fvm::laplacian(mu, U) == - fvc::grad(p) );
```

- Uses **`reactingFoam`** solver with one-step reaction:

$$C_7H_{16} + 11(O_2 + 3.76N_2) \longrightarrow 7CO_2 + 8H_2O + 41.36N_2$$

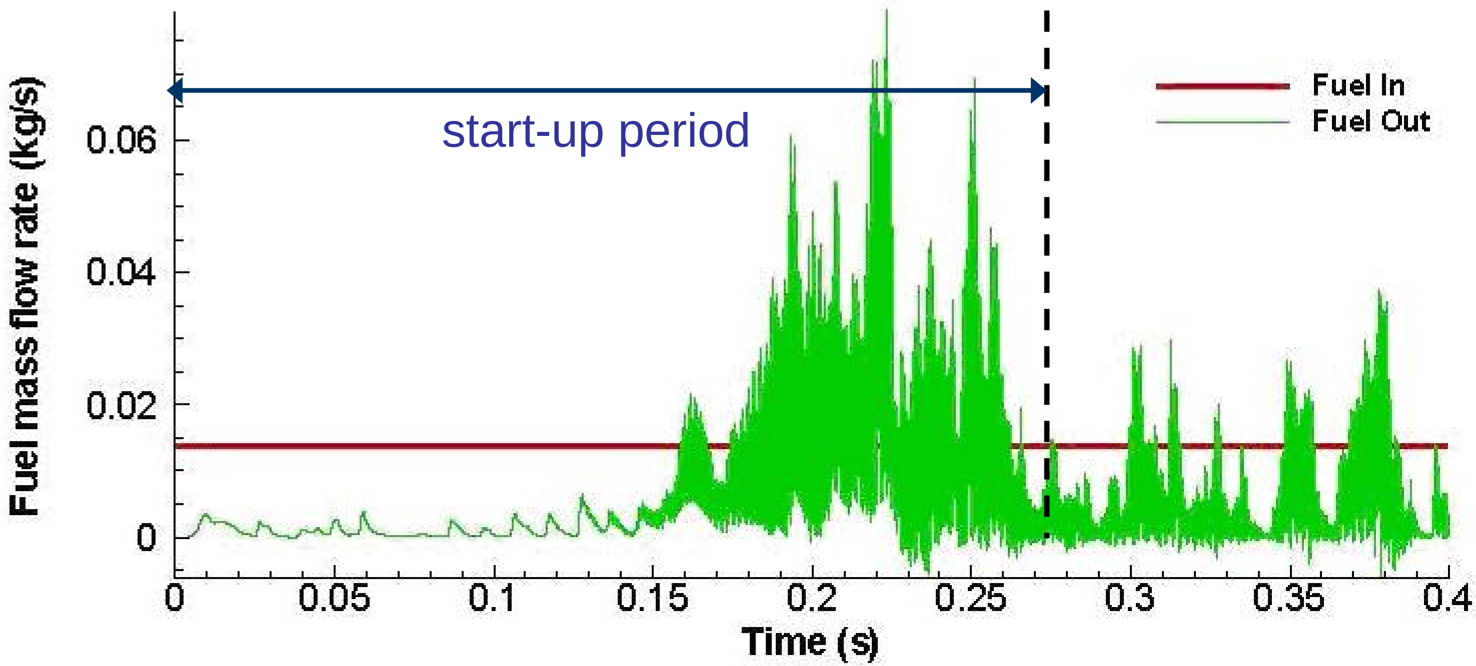
- Westbrook-Dryer chemical kinetics rate:

$$\dot{\omega}_F = -A\rho^{a+b} Y_F^a Y_O^b e^{-E_a / R_u T}$$

Burning Efficiency

$$\eta_c = \frac{1}{T}\int_{t_0}^{t_0+T} \frac{\dot{m}_{F,in} - \dot{m}_{F,out}}{\dot{m}_{F,in}}\,dt$$

where $\dot{m}_F$ is the fuel mass flow rate into or out of the system



Fuel mass flow rates for a cavity with *L/D* = 2.0 at *Re* = 5000.

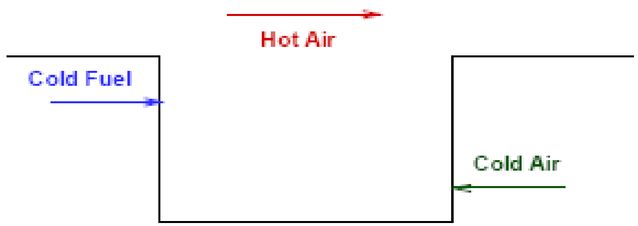
Mixedness

- Mixedness is defined locally as: $M = 1 + \dfrac{\left(y_C - y_{C,m}\right)\left(y_N - y_{N,m}\right)}{m^2}$
  - y_i is a modified mass fraction: $y_i = \dfrac{Y_i}{Y_C + Y_N}$
    - Y_C = mass fraction of carbon atoms
    - Y_N = mass fraction of nitrogen atoms
    - $y_C + y_N = 1$
  - $y_{i,m}$ is the perfectly mixed modified mass fraction of element *i*
  - *m* is used to enforce a mixedness of zero if completely unmixed for either Y_N or Y_C approaching zero:

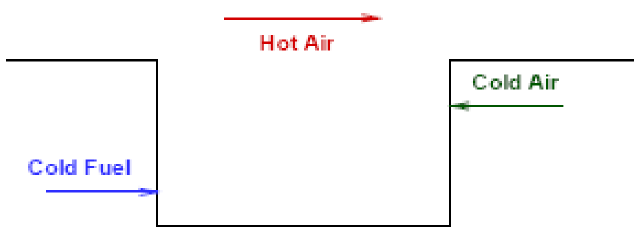
$$m = \begin{cases} y_{C,m}, & Y_C < Y_{C,m} \\ y_{N,m}, & Y_C > Y_{C,m} \end{cases}$$

Injection Configurations

- Vitiated air in channel (50% combustion products)
- 25% overall equivalence ratio
- 3 configurations with additional air injection



(a) Reinforcing

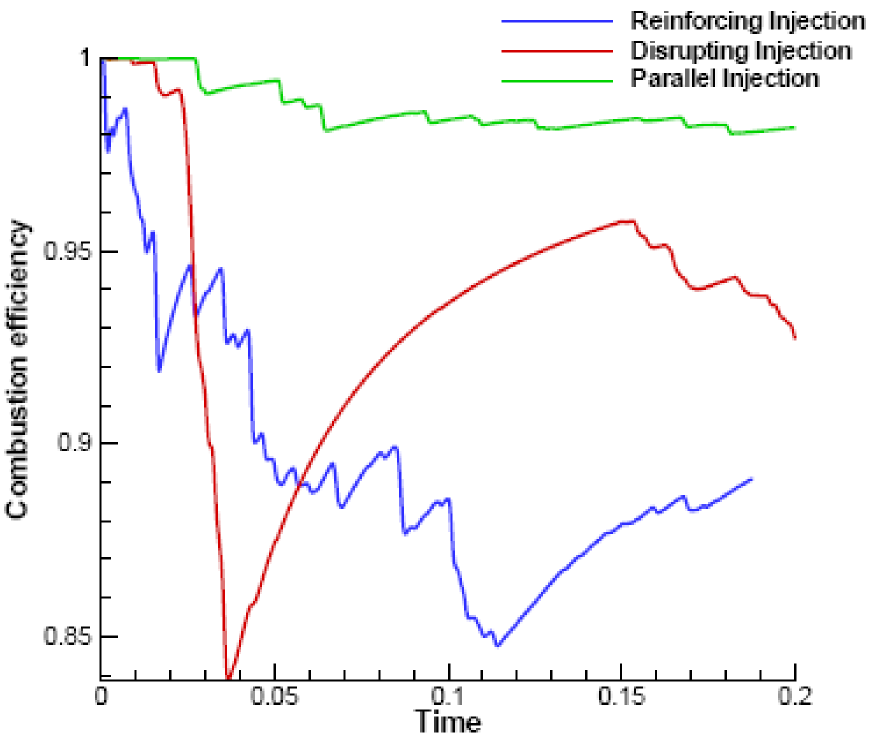


(b) Disrupting

(c) Parallel

Comparison of 2D Injection Configurations

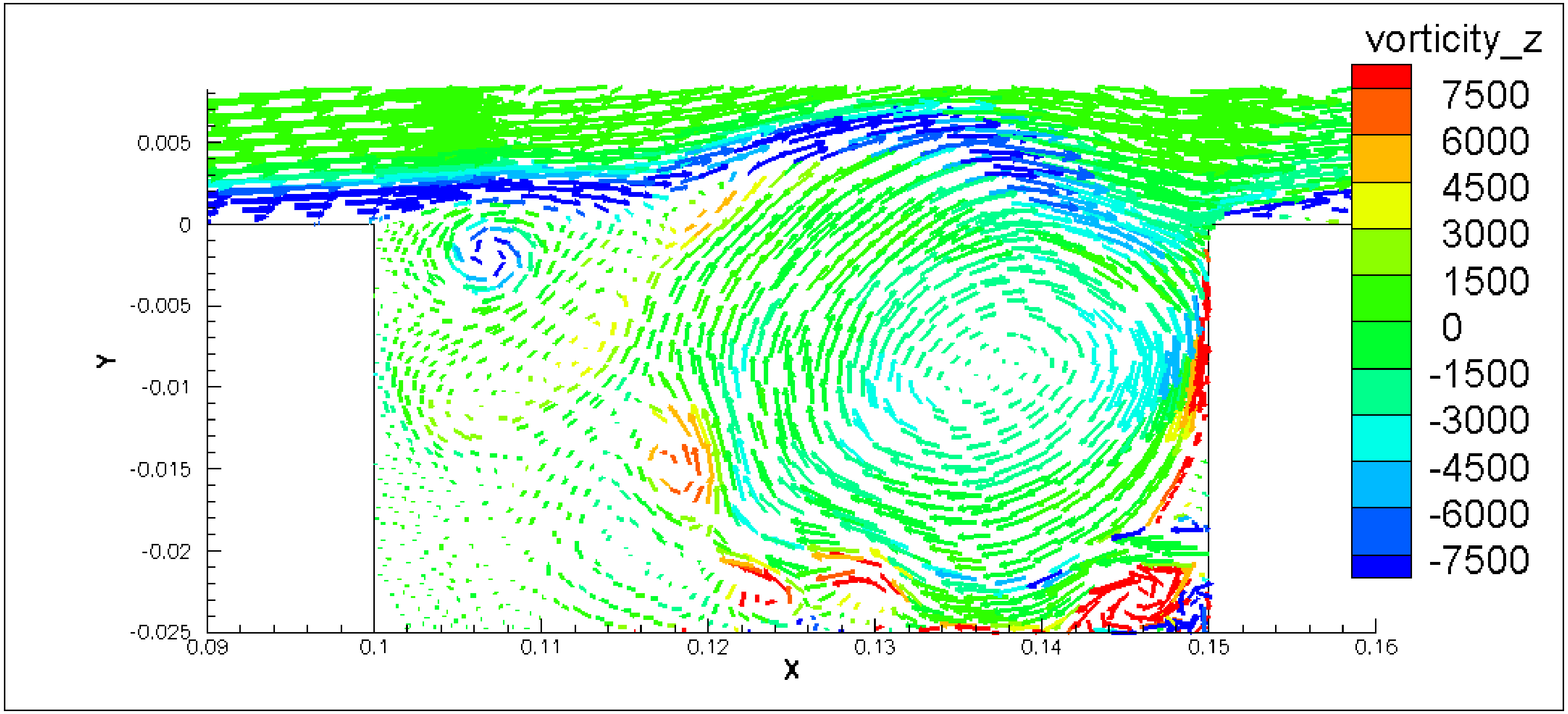
- 2:1 aspect ratio cavity at *Re* = 10000
  - Parallel injection has highest burning efficiency in 2D representation
  - Efficiency not converged after 0.2s or 12 channel residence times



Combustion efficiency for different 2D injection configurations

2D Reacting with Reinforcing Injection

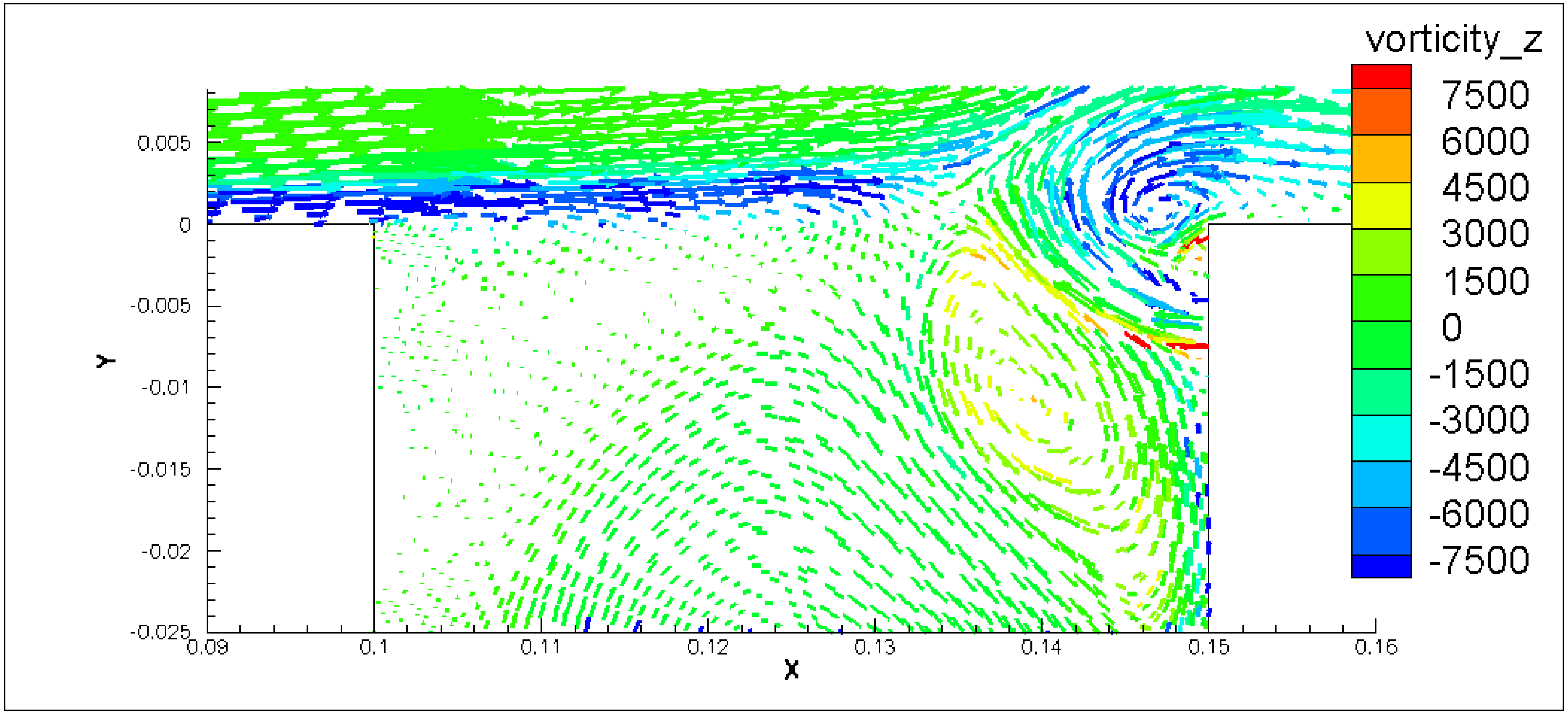
- Lowest burning efficiency
- Large vortices are nearly stationary



Velocity vectors and vorticity contours at Re = 10000

2D Reacting with Disrupting Injection

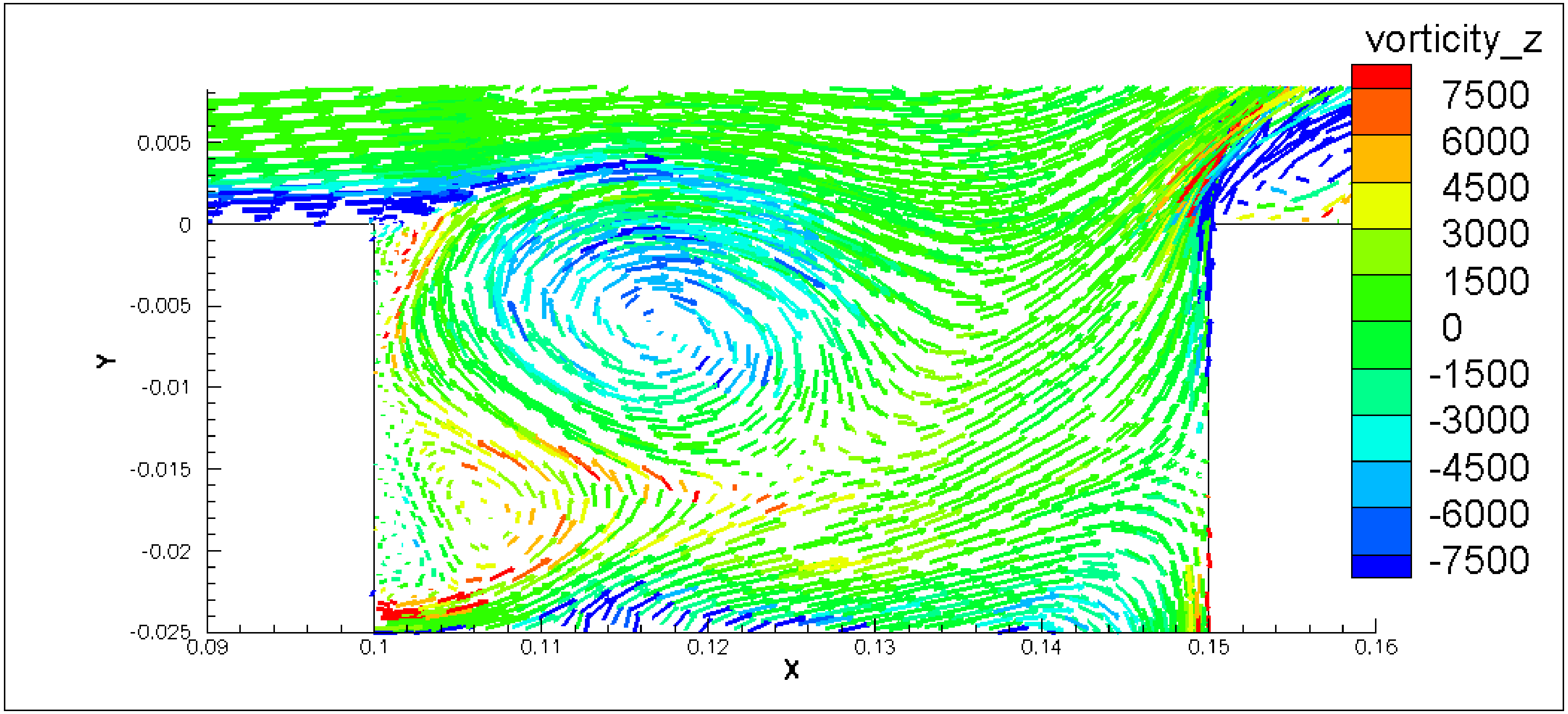
- Medium burning efficiency
- Large vortices are nearly stationary



Velocity vectors and vorticity contours at Re = 10000

2D Reacting with Parallel Injection

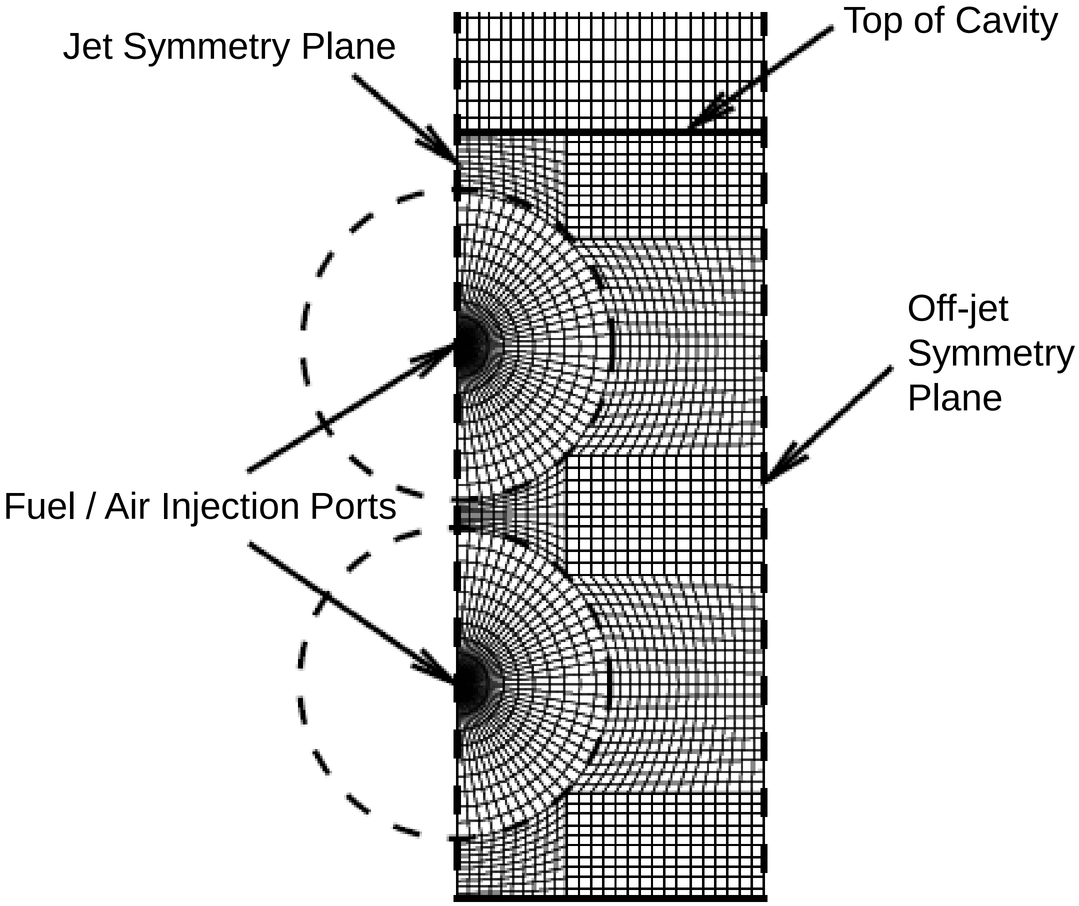
- Highest burning efficiency
- Much greater vortex interaction



Velocity vectors and vorticity contours at Re = 10000

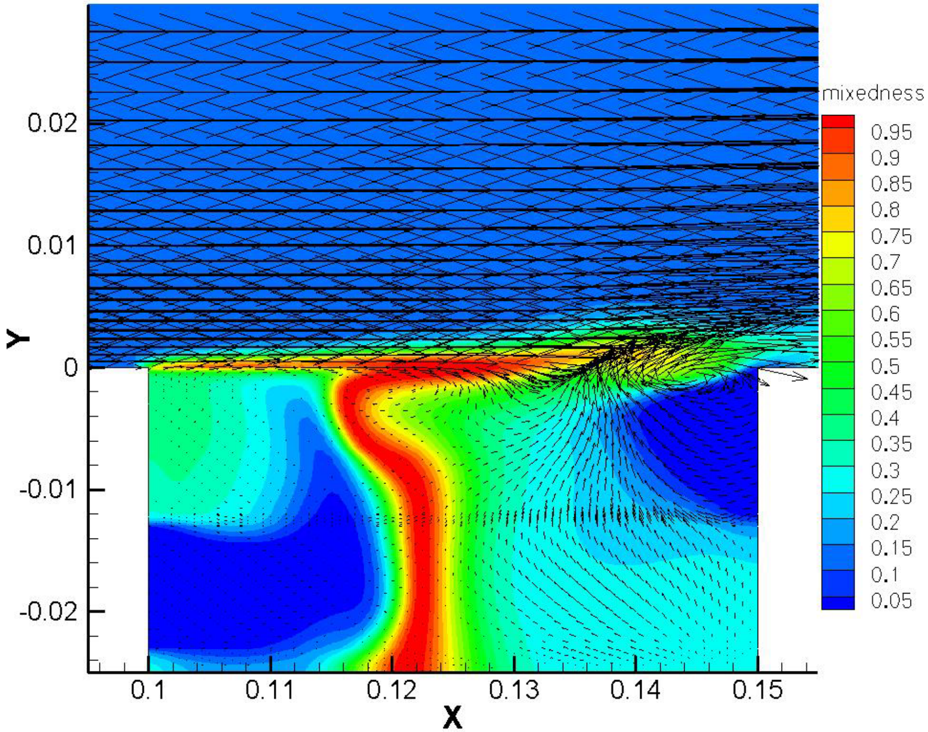
3D Mesh

- Symmetry planes used for efficient calculations
- Models periodic array of injectors
- Jet size increased for greater mesh resolution

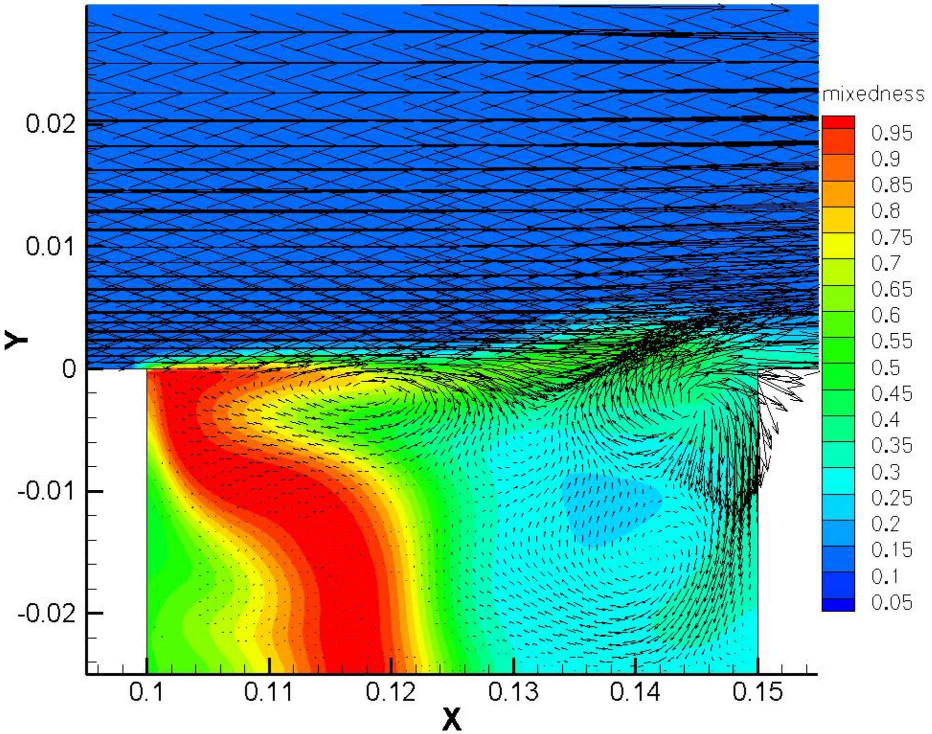


3D Reacting with Disrupting Injection

- Slices through cavity at *Re* = 10000
  - Mixedness contours and velocity vectors shown



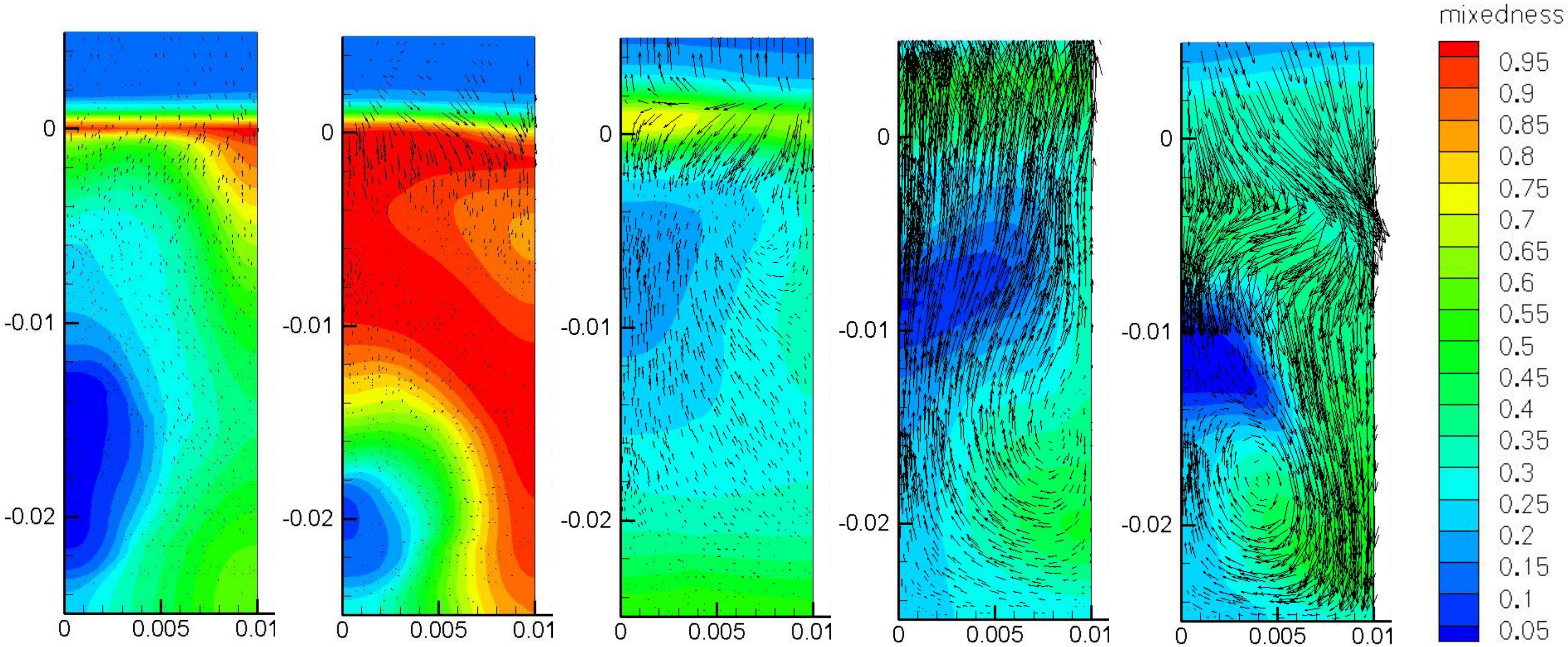
Jet symmetry plane



Off-jet symmetry plane

3D Reacting with Disrupting Injection

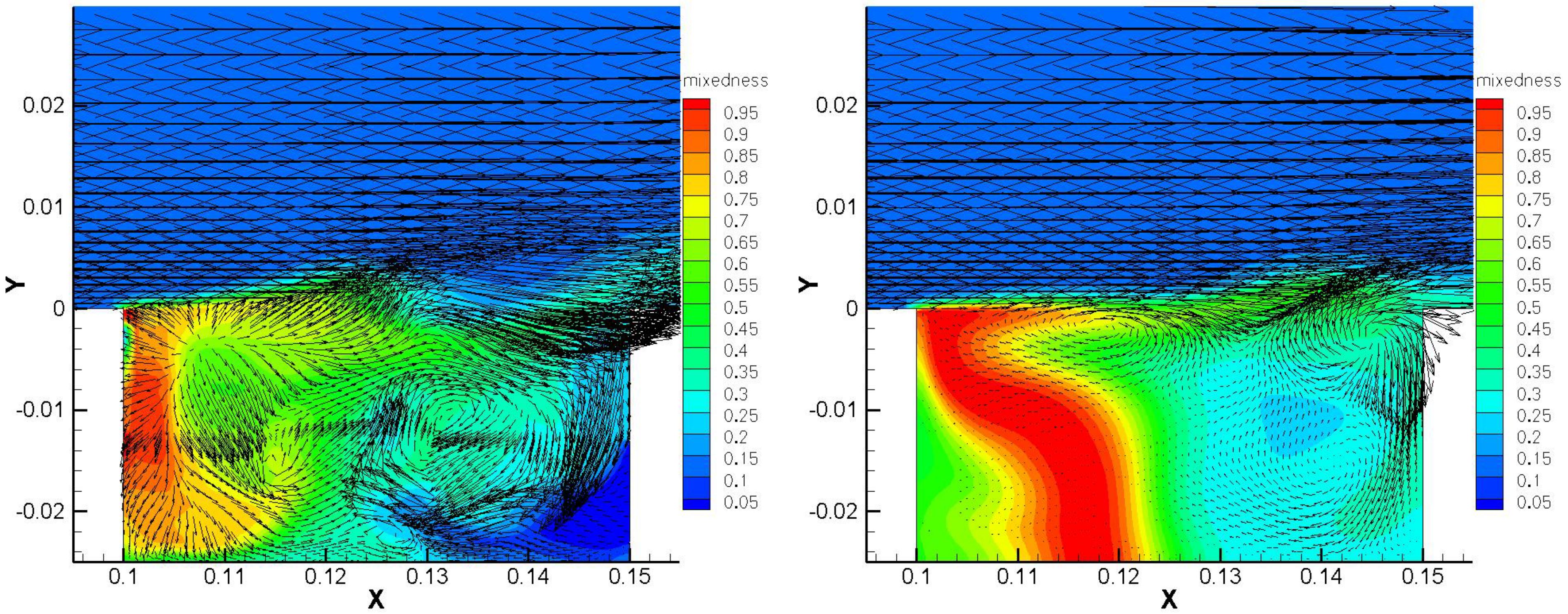
- Slices along cavity width at *Re* = 10000
  - Mixedness contours and velocity vectors shown



a) x = 0.105 **b) x = 0.115** **c) x = 0.125** **d) x = 0.135** **e) x = 0.145**

3D Reacting with Reinforcing Injection

- Slices through cavity at *Re* = 10000
  - Mixedness contours and velocity vectors shown

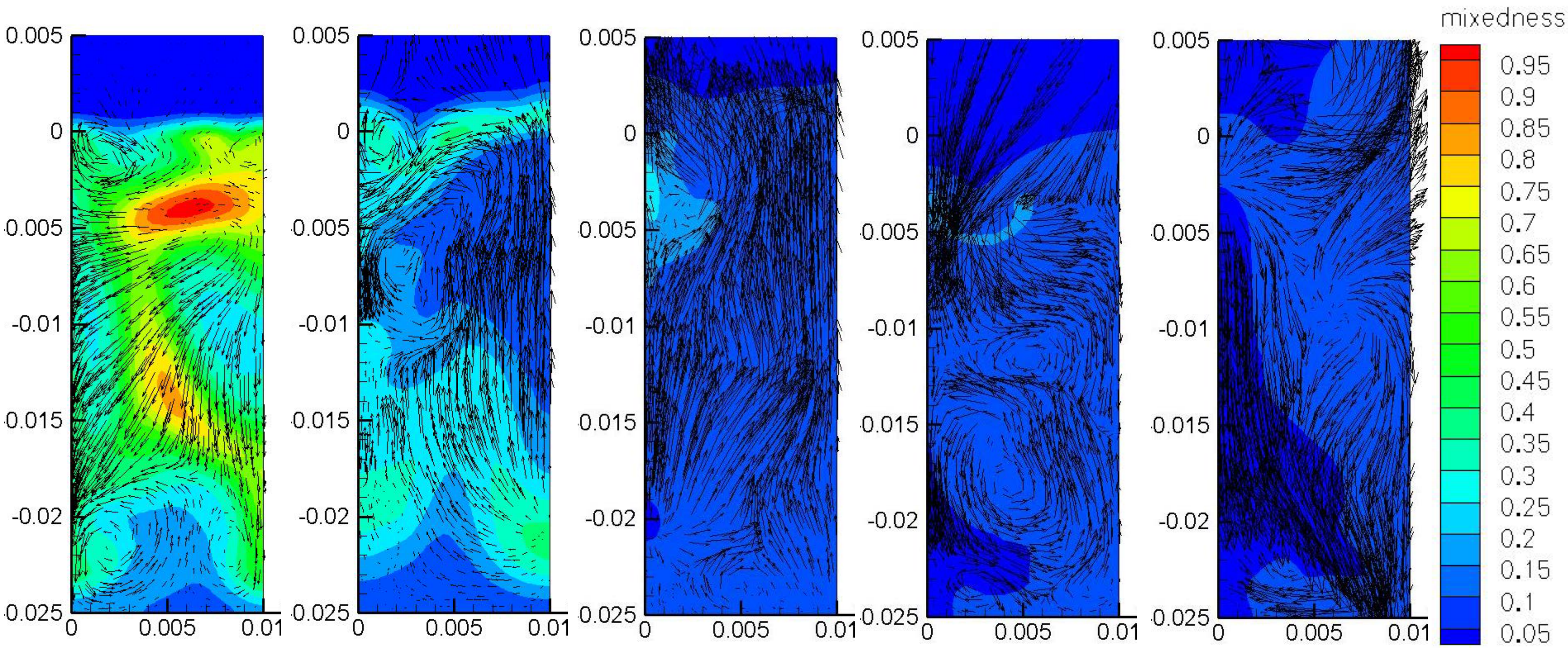


Jet symmetry plane

Off-jet symmetry plane

3D Reacting with Reinforcing Injection

- Slices along cavity width at *Re* = 10000
  - Mixedness contours and velocity vectors shown



a) x = 0.105 **b) x = 0.115** **c) x = 0.125** **d) x = 0.135** **e) x = 0.145**

Conclusions

- 2D results show:
  - Higher efficiency for parallel injection than for reinforcing or disrupting
  - Reinforcing and disrupting injection configurations create almost stationary vortices
  - Parallel injection significantly increases vortex interaction
- 3D results show:
  - 3D effects are significant
  - Reinforcing injection causes higher velocities in the cavity than disrupting injection
  - Disrupting injection creates a well-defined area of very high mixedness
  - Reinforcing injection creates a larger zone of relatively high mixedness

Future work

- Work already begun:
  - Improved 3D mesh
  - Curving channels
  - Converging channels
- Possible future improvements:
  - Liquid fuels
  - Turbulence modeling for higher Reynolds numbers

Thank You!