COLLEGE OF ENGINEERING
AEROSPACE ENGINEERING
UNIVERSITY OF MICHIGAN

A Joint Experimental/Computational Study of Non-idealities in Practical Rotating Detonation Engines

PI: Mirko Gamba

Co-I: Venkat Raman

Fabian Chacon, James Duvall, Alex Feleo
Takuma Sato, and Supraj Prakash

Department of Aerospace Engineering
University of Michigan

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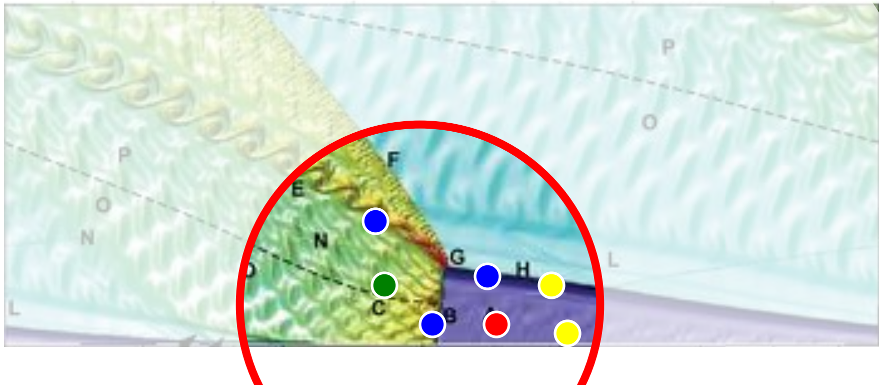
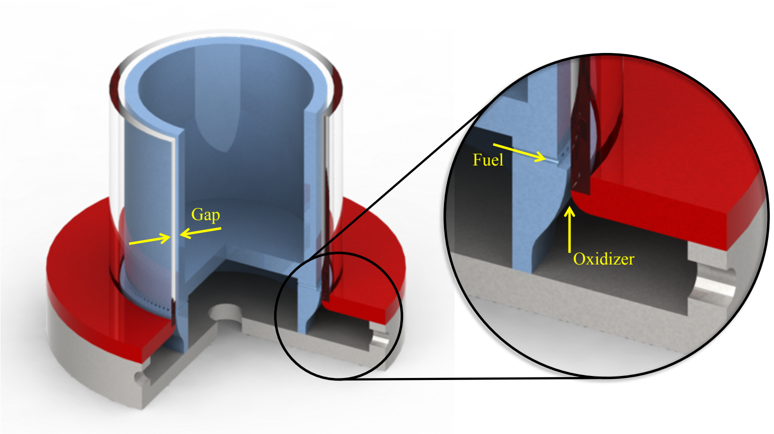
Outline

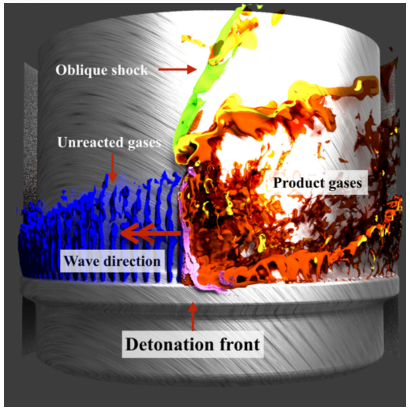
- Introduction to the problem and general approach
- Experimental activities
- Computational activities

Overarching goal:
investigate non-idealities and their link to loss of pressure gain



- Detonation non-idealities
  - Incomplete fuel/air mixing
  - Fuel/air charge stratification
  - Mixture leakage (incomplete heat release)
  - Parasitic combustion:
    - Premature ignition (e.g., burnt/unburnt interface)
    - Stabilization of deflagration (flame)
  - Detonation-induced flow instabilities
    - Richtmyer-Meshkov (R-M) instability
    - Kelvin-Helmholtz (K-H) instability
- They lead to loss in pressure gain
  - Linked to loss of detonation propagation
- Additional losses exist during flow expansion
  - Secondary shock and (multiple) oblique shock
  - Flow instabilities (e.g., K-H instability)
  - Mixture leakage through burn/unburnt interface





From: (top) Nordeen et al., AIAA 2011-0803

Overarching objectives of the project

- **Objective 1:**
  Develop canonical and operational RDE configurations, as well as imaging-based laser diagnostics for understanding fuel stratification, leakage, parasitic combustion and detonation structure under non-ideal conditions in RDEs.

- **Objective 2:**
  Develop a comprehensive picture of the fundamental physics governing non-idealities and how they impact RDE performance and operability from both experiments and simulations.

- **Objective 3:**
  Develop detailed computational tools (DNS and LES) for studying detonation wave propagation processes in RDEs.

Outcomes

- **Outcome 1:**
  Identify the sources and properties of non-idealities in RDEs, their contribution to loss in pressure gain, and potential design limitations

- **Outcome 2:**
  Detailed experimental tools and measurements (databases) about fundamental aspects of RDEs will become available to the RDE design community.
  - We have established collaborations with industrial partners

- **Outcome 3:**
  Detailed computational tools (DNS/LES) as well as combustion models with detailed chemistry for pressure gain combustion will be made available to the RDE design community.
  - e.g., openFoam development of RDE modeling
  - e.g., transfer of detonation computational models partners

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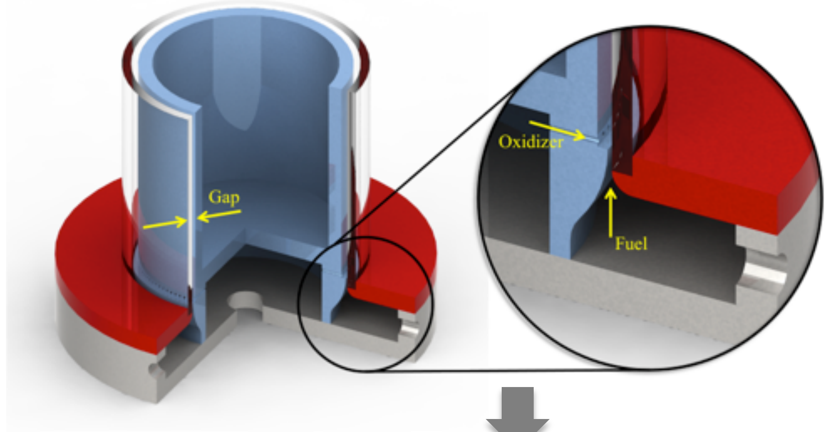
What has been achieved: experimental activities

- **RDE test facility:** Hierarchy of experiment systems
  - Injector sector (unwrapped) for simple flowfield visualization
  - Modular RDE to investigate operation
  - Race track (optical) RDE to conduct flowfield measurements using laser-diagnostics
- **Design and analysis of canonical injection schemes**
  - We considered three canonical configurations
  - Specifically focused on an axial air inlet configuration
- **Identification of secondary combustion as a limiting factor**
  - Parasitic combustion
  - Commensal combustion
  - Their effects on detonation properties
- **Diagnostics and tools for diagnostics for RDEs**
  - Race track RDE enables convenient laser diagnostics in realistic RDE flowfield
  - OH PLIF in RDE flows
  - Emission measurements to identify secondary combustion

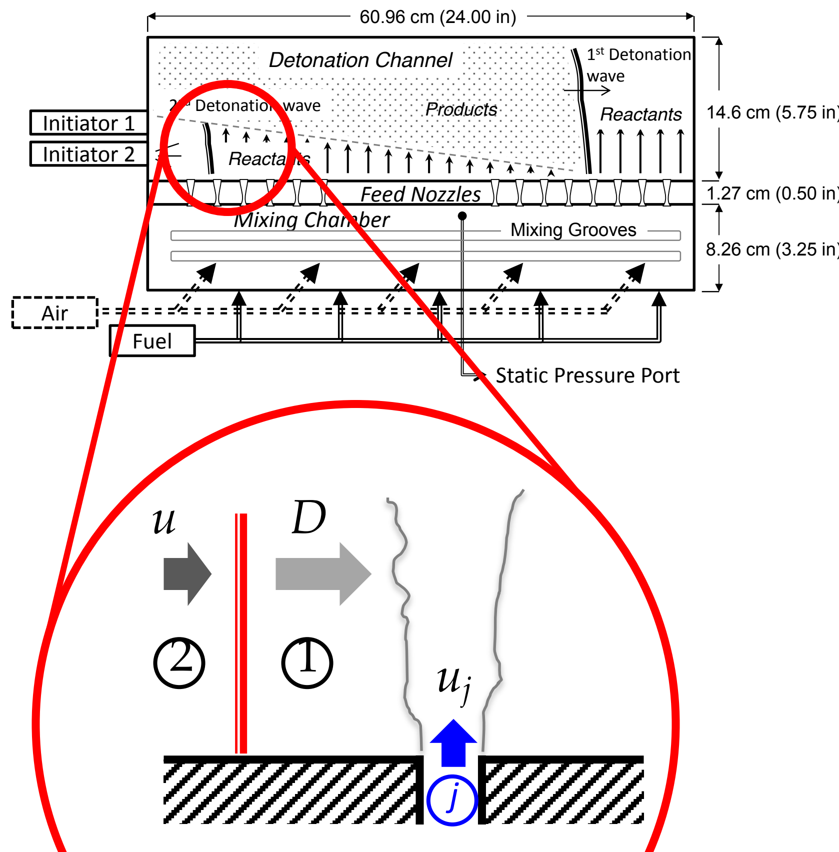
Experimental multi-level approach

RDE full system:
- Link between mixing/secondary combustion and performance



Linearized analogue (race track RDE):
- Detonation and flowfield structure
- Application of laser diagnostics

Single or multiple injectors:
- Mixing studies
- Shock-induced mixing



Complete physics

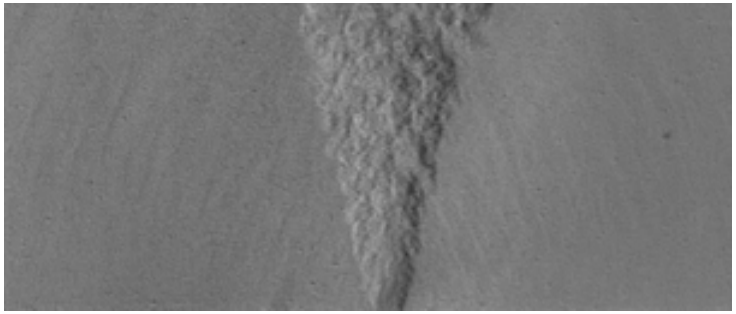
Hierarchy

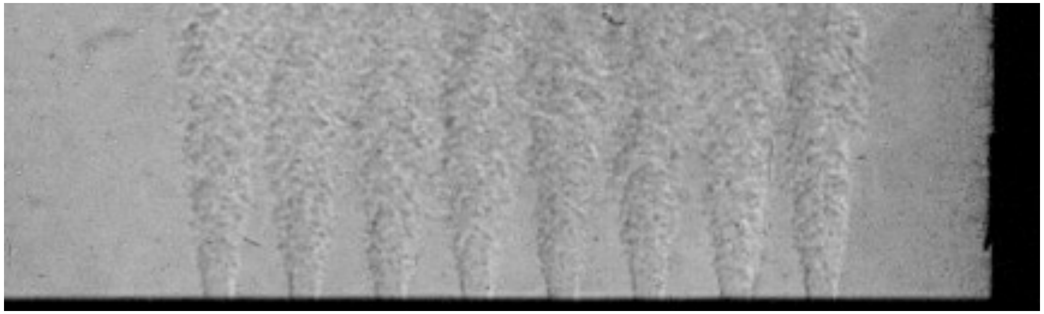
Reduced physics

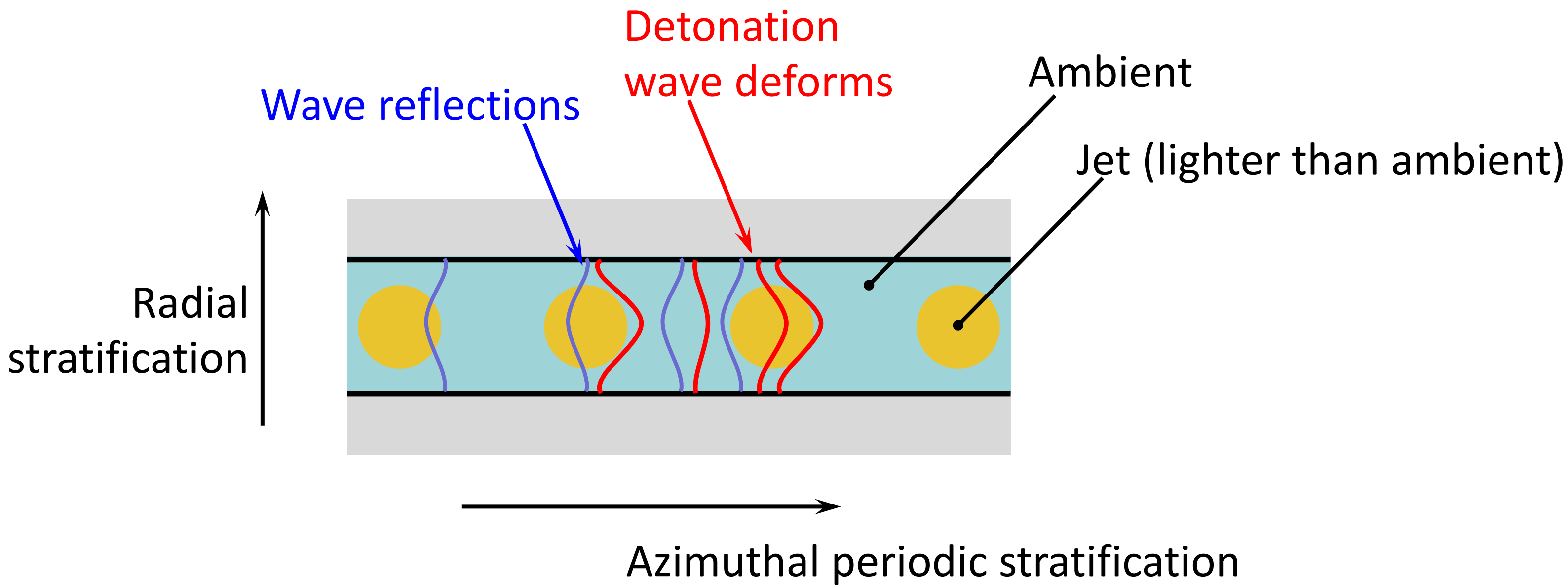
SHOCK/STRATIFICATION INTERACTION AND SHOCK INDUCED MIXING

Initial understanding of jet/shock interaction

- Different portions of the shock move at different speeds
- Shock wave is deformed by radial stratification
- Generation of counter-propagating waves (compression / expansions)
- Depends on density and speed of sound ratios

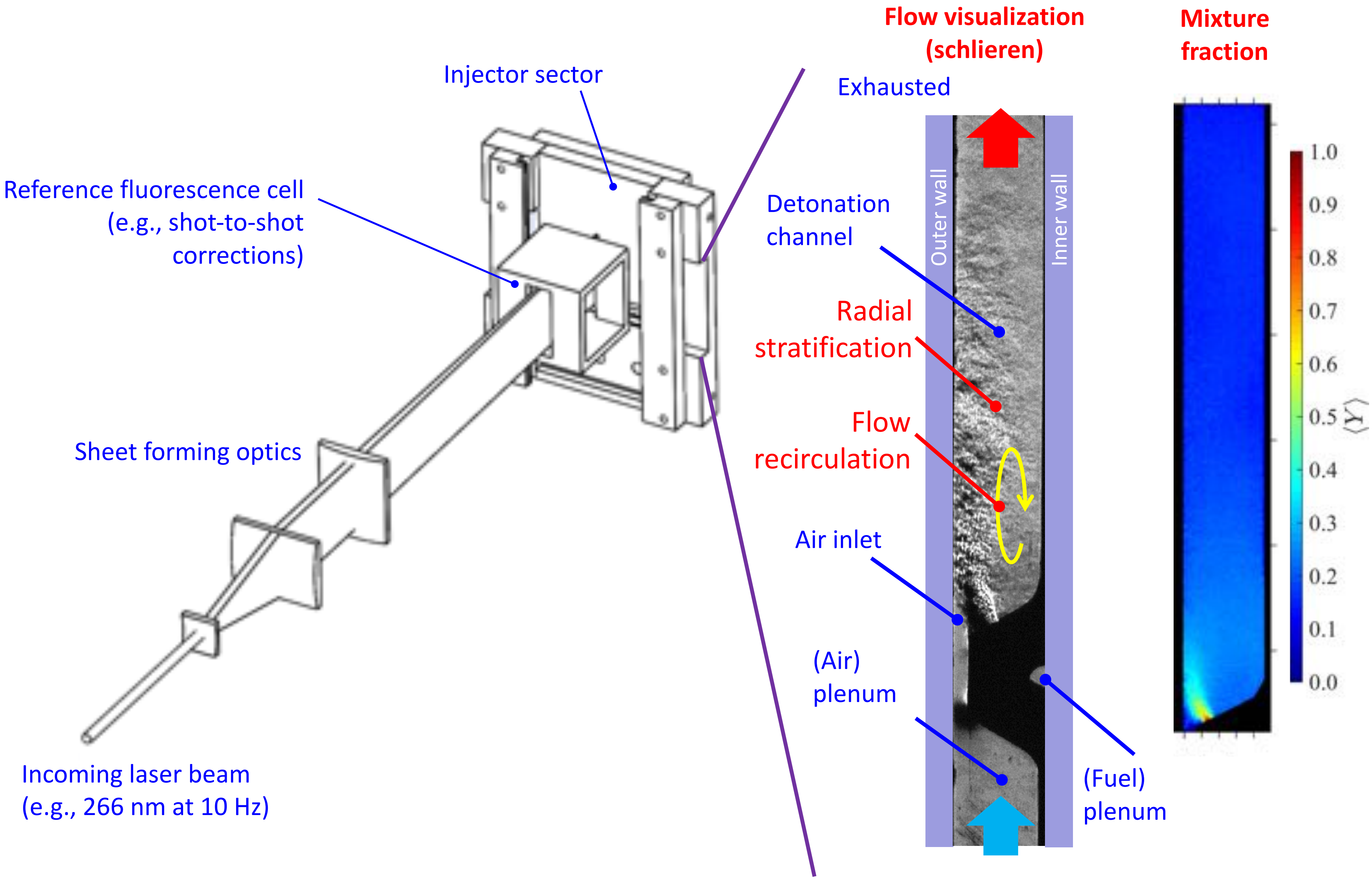






MIXING MEASUREMENTS IN INJECTOR SECTOR

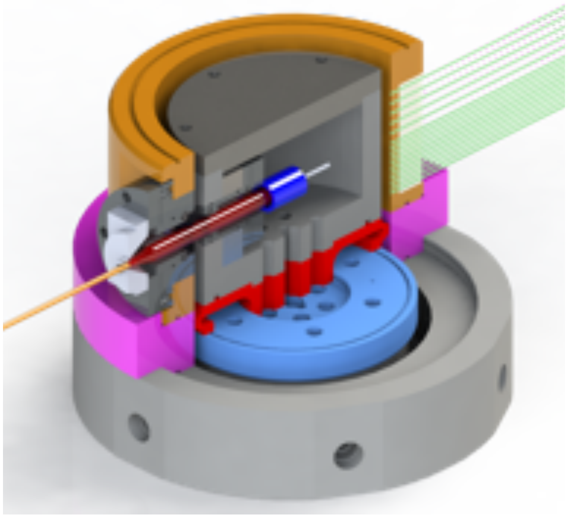
Injector sector subassembly for mixing studies

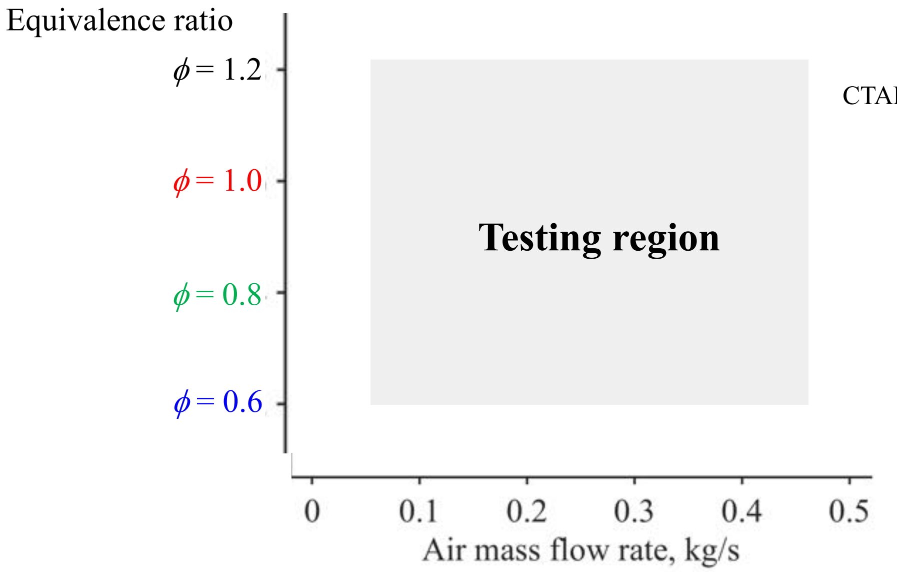


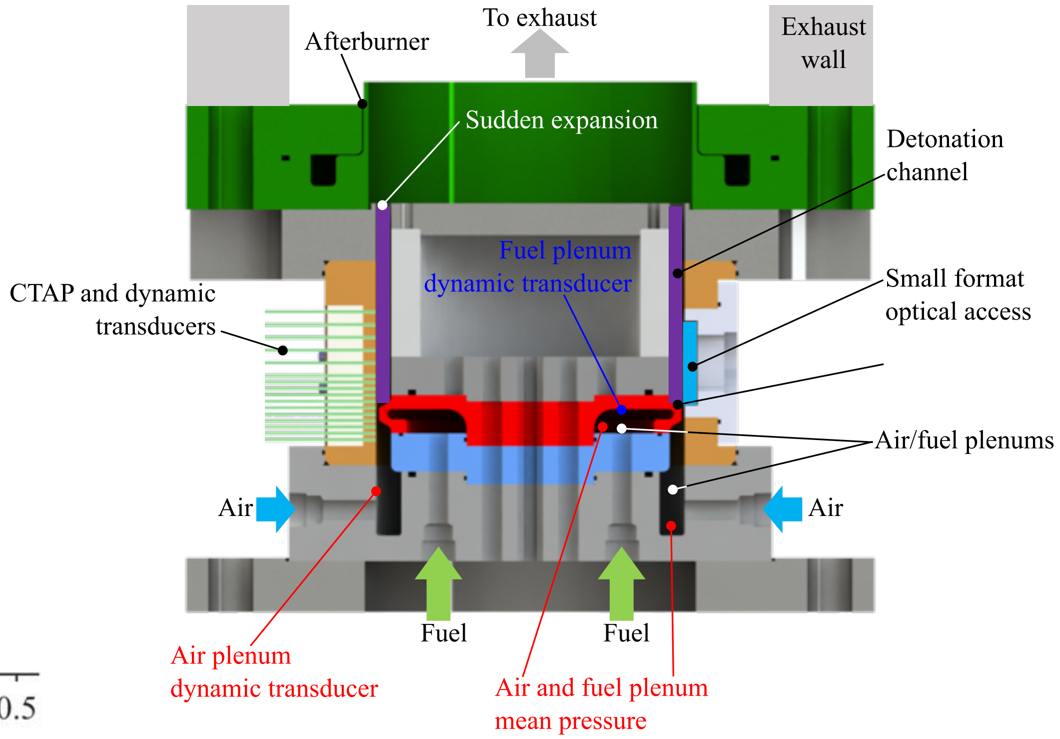
INVESTIGATE OPERATION WITH DIFFERENT INJECTION CONFIGURATIONS (FLOWFIELD STRUCTURE, MIXING PROFILE, ETC.)

6” diameter round RDE

- **Modular configuration in its geometry and operation**
  - Allows for parametric studies for (e.g., geometric scaling , dynamics studies)
- **Multiple injection schemes:**
  - Axial air inlet
  - Radial air inlet
  - Discrete injection

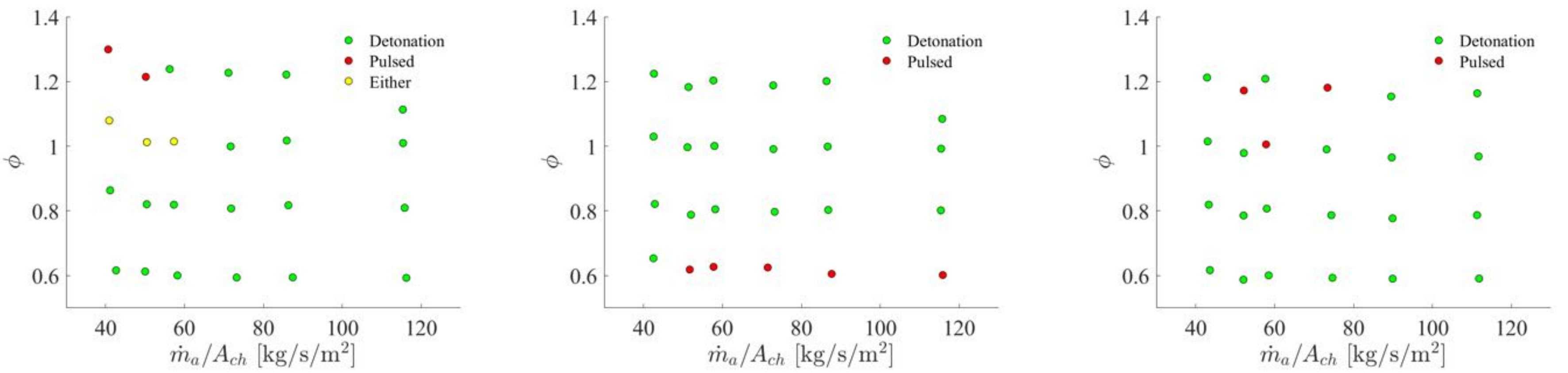


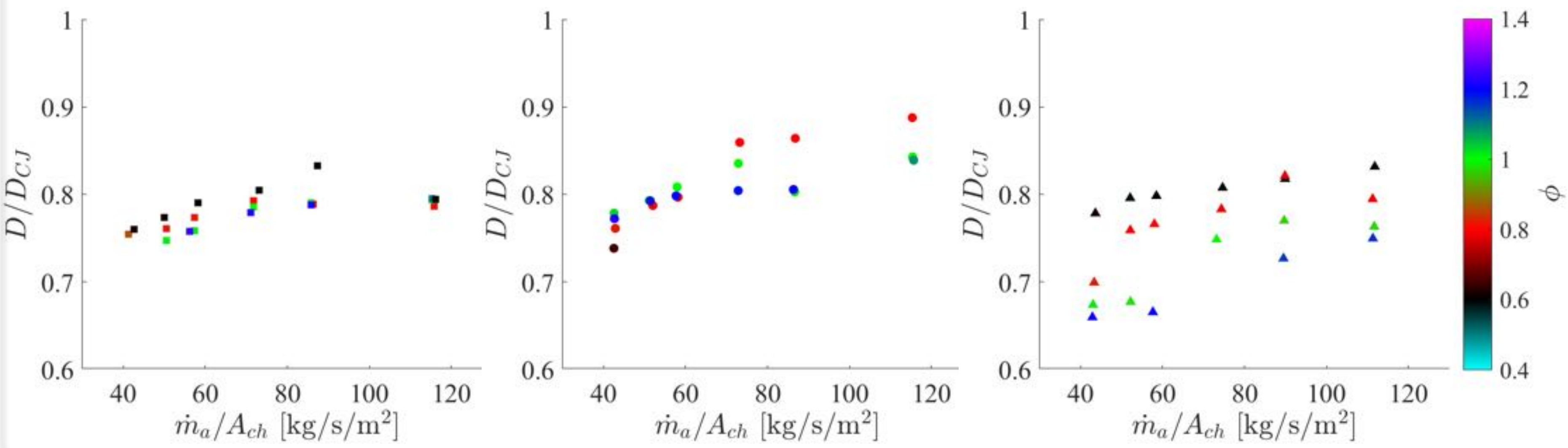




Characterization of the operation of RDEs with different injection

Axial | Radial | Discrete





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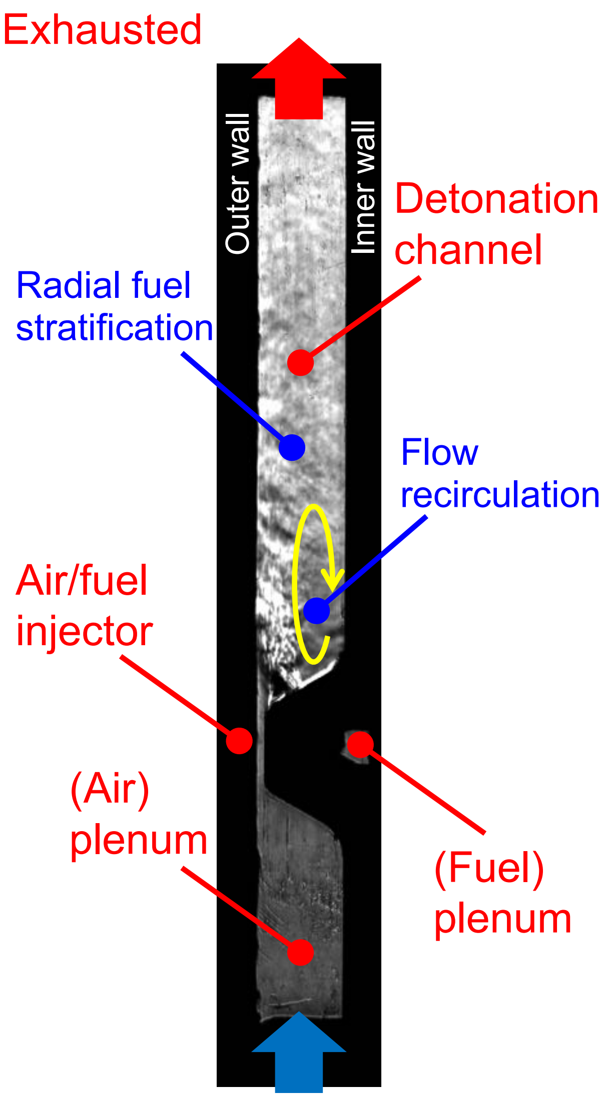
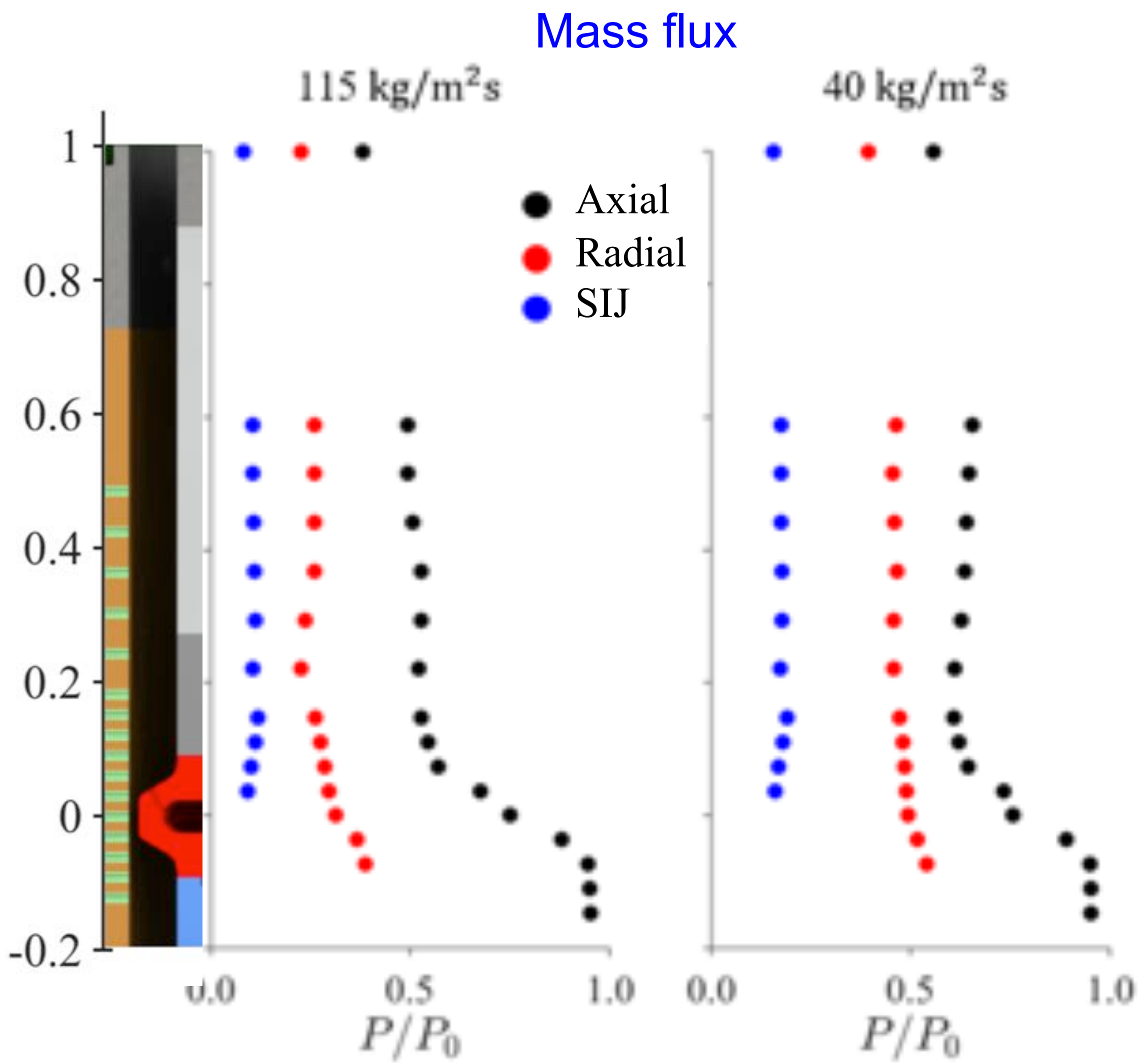
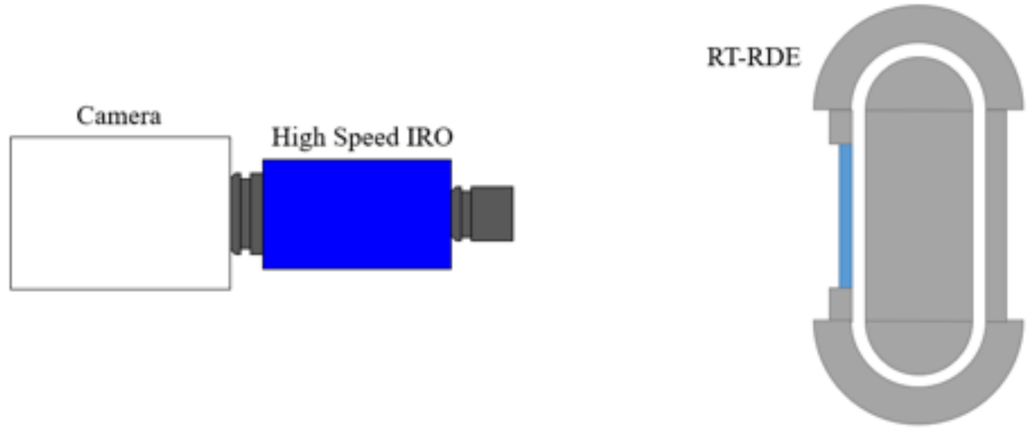




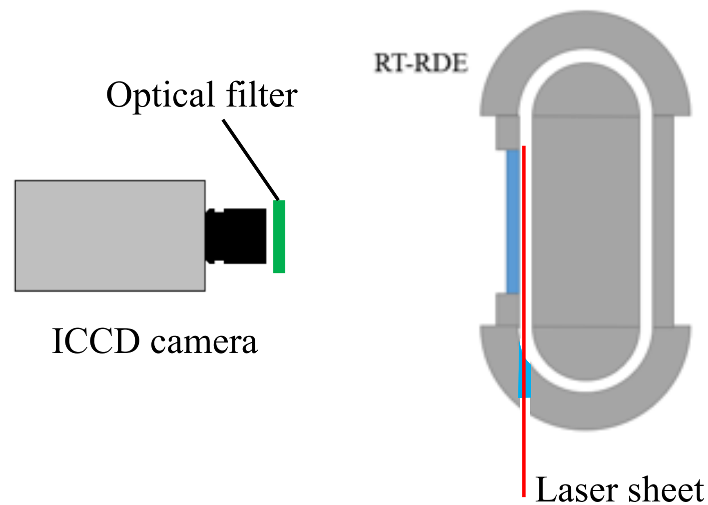
INVESTIGATE SECONDARY COMBUSTION IN RACETRACK AND ROUND RDE

Visualization methods

- **High-speed OH* chemiluminescence:**
  - Imaging near 310 nm
  - 2 μs exposure with moderate gain
  - Rate: 80 kHz
  - Used to visualize low intensity combustion events

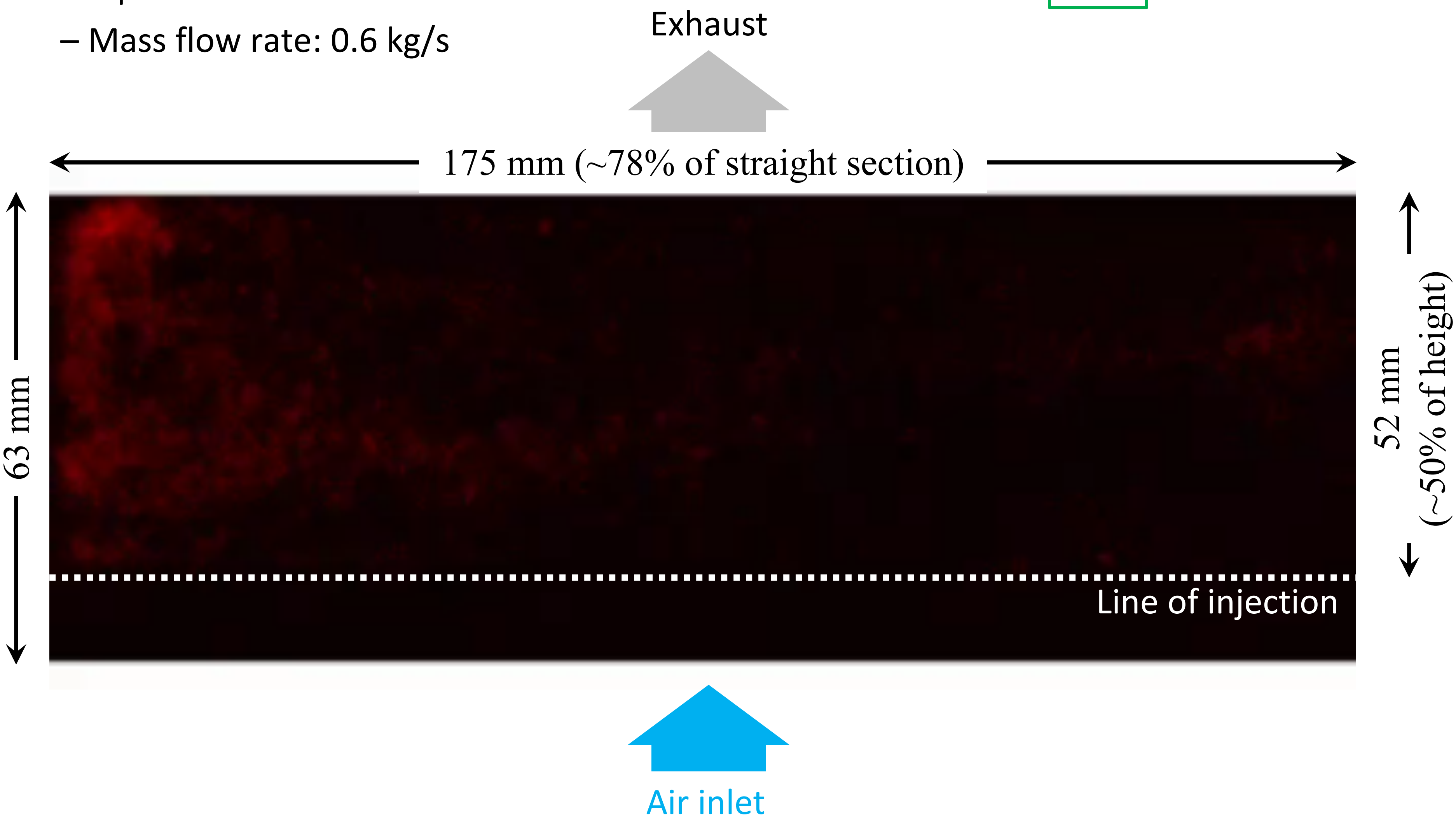


- **OH planar laser-induced fluorescence:**
  - $A^2\Sigma^+ \leftarrow X^2\Pi(v'=1, v''=0)$
  - Excitation of $Q_1(9)$ and $Q_2(8)$ near 284 nm
  - Collection at 310 ± 10 nm
  - Low speed acquisition produces a series of single-shot uncorrelated images



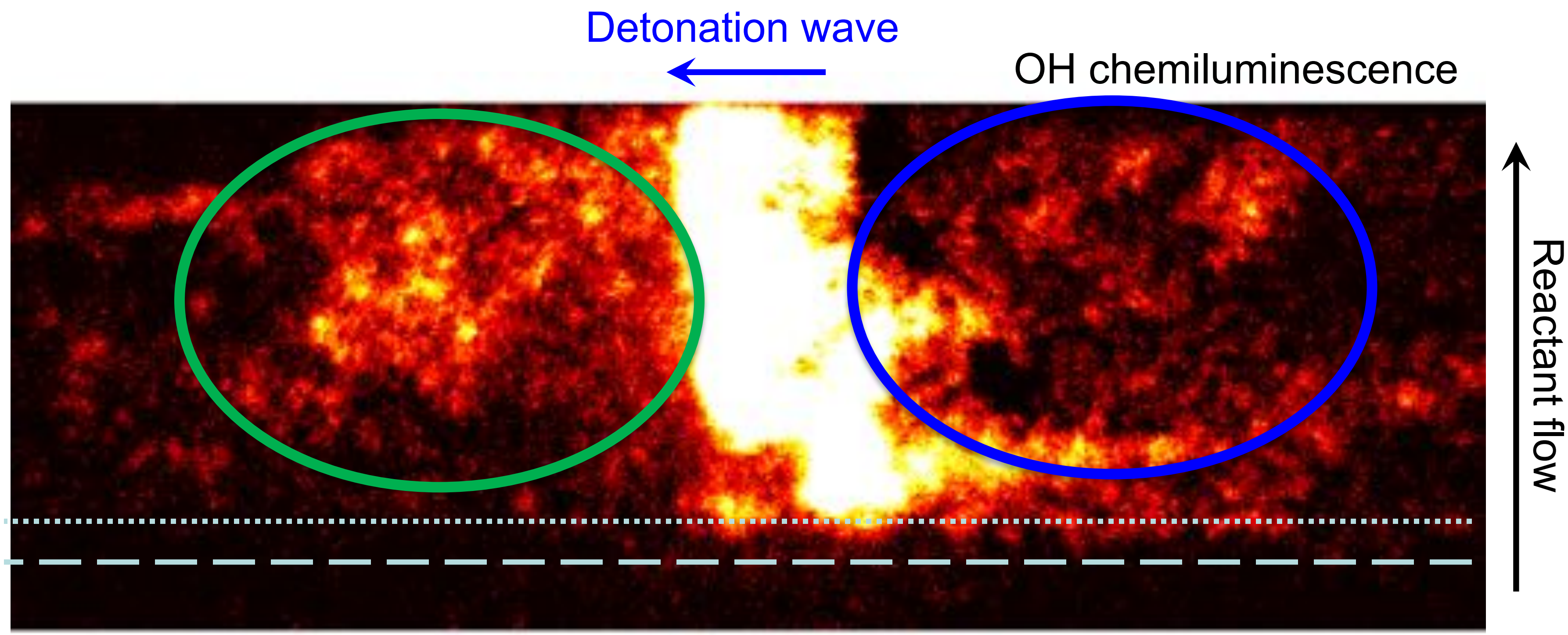
Exploring parasitic combustion with the RT-RDE (1)

- Operation conditions:
  - Fuel: Hydrogen
  - Equivalence ratio: 1.3
  - Mass flow rate: 0.6 kg/s



RDE Biology: Parasitic vs. Commensal Combustion

- We can now differentiate between *two types of secondary combustion* based on their *impact on the detonation wave*.



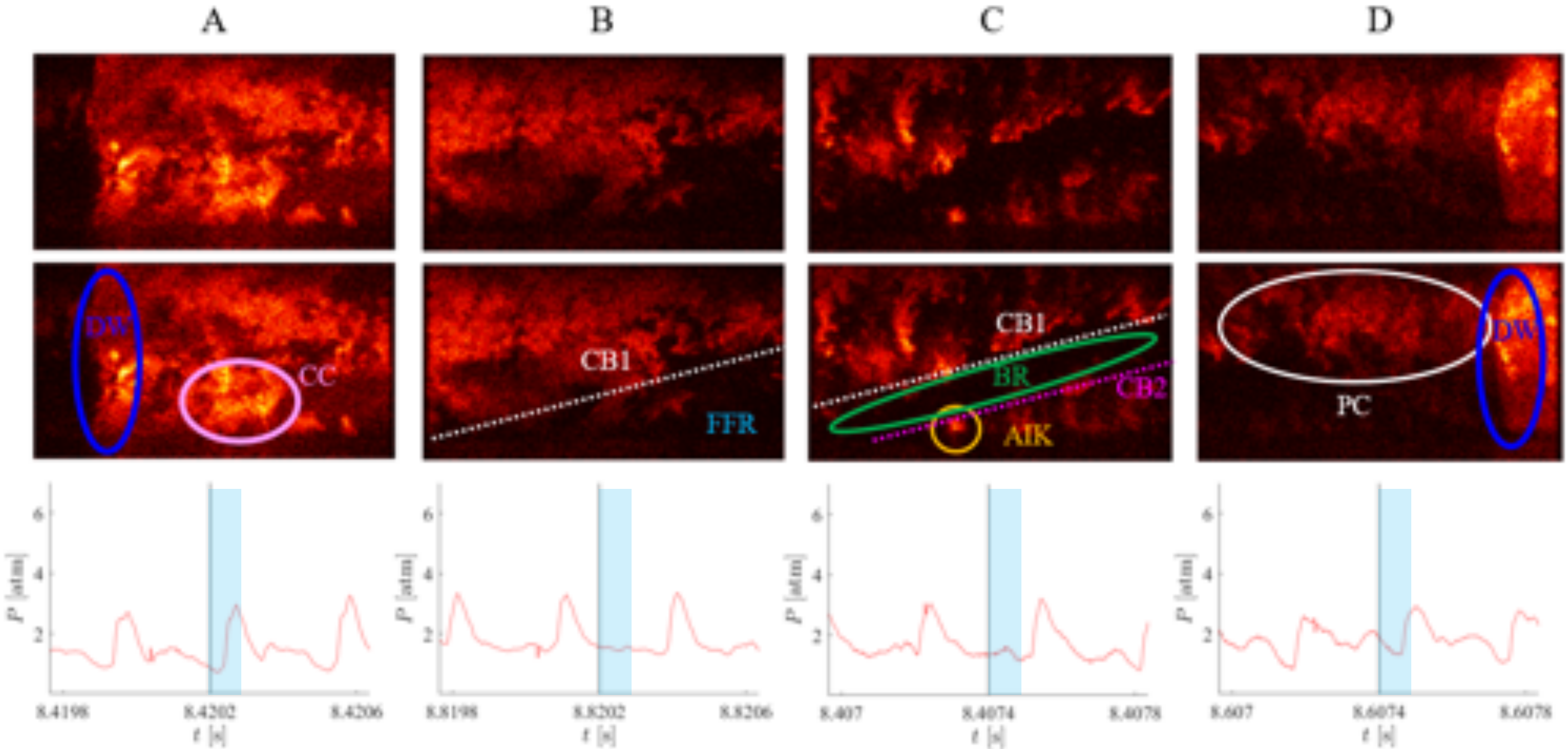
Parasitic combustion

- Combustion before arrival of wave
- Heat released before the detonation wave does not support it
- Mixture is heated and vitiated

Commensal combustion

- Combustion trailing the wave
- Heat released after the detonation wave does no have an impact on it
- Consequence of mixture leakage

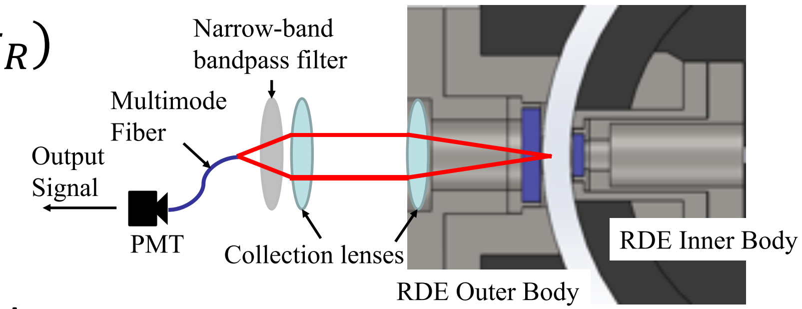
OH distribution from pseudo-series

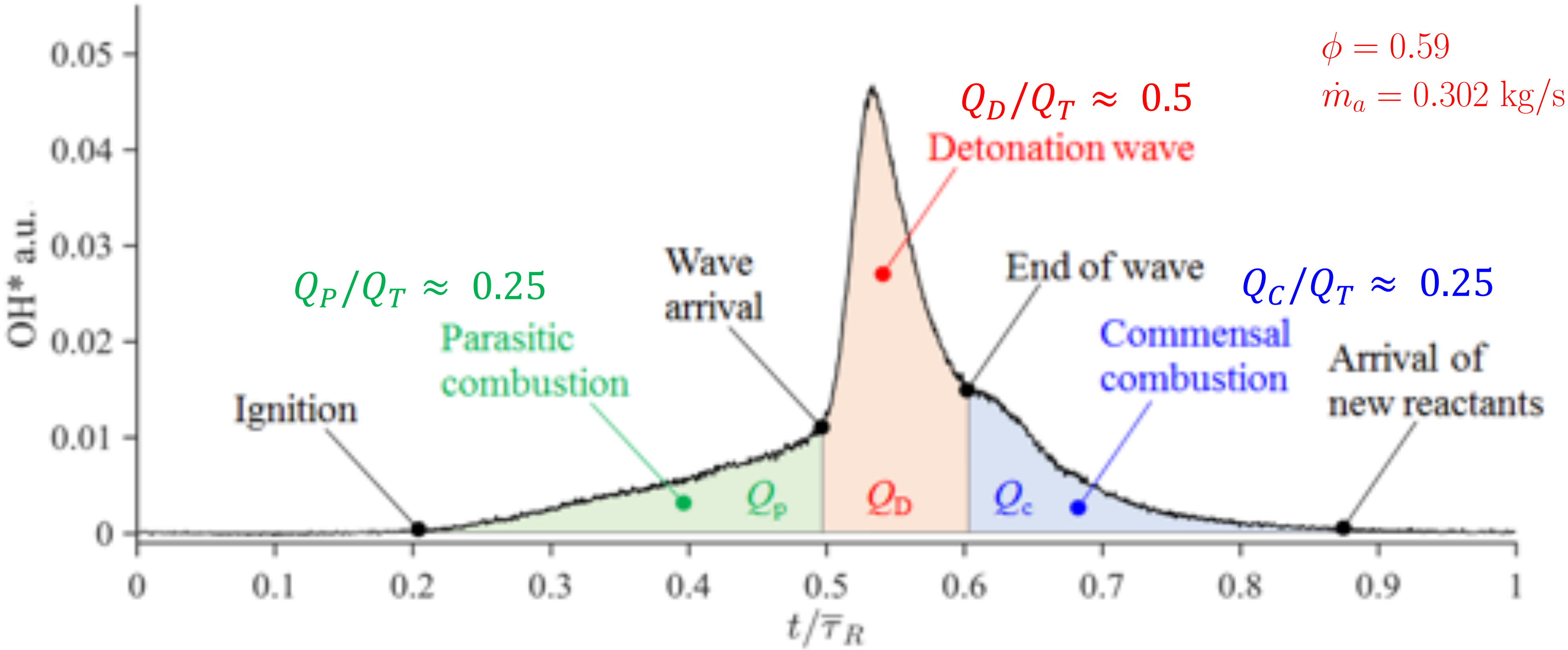


- Detonation wave (DW)
- Non uniform structures present in wake of the detonation
- Contact burns 1 and 2 (CB1) and (CB2)
- Buffer region (BR)
  - Increased resolution shows significant dark band
- Auto ignition kernels (AIK)
- Parasitic and commensal Combustion (PC) and (CC)
  - Commensal is not easily distinguished as in OH* chemiluminescence

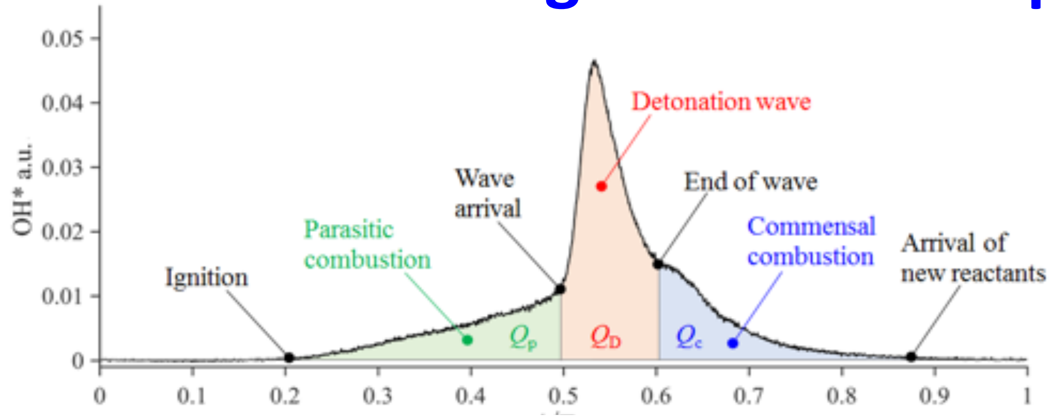
Representative Cycle of OH* Emission

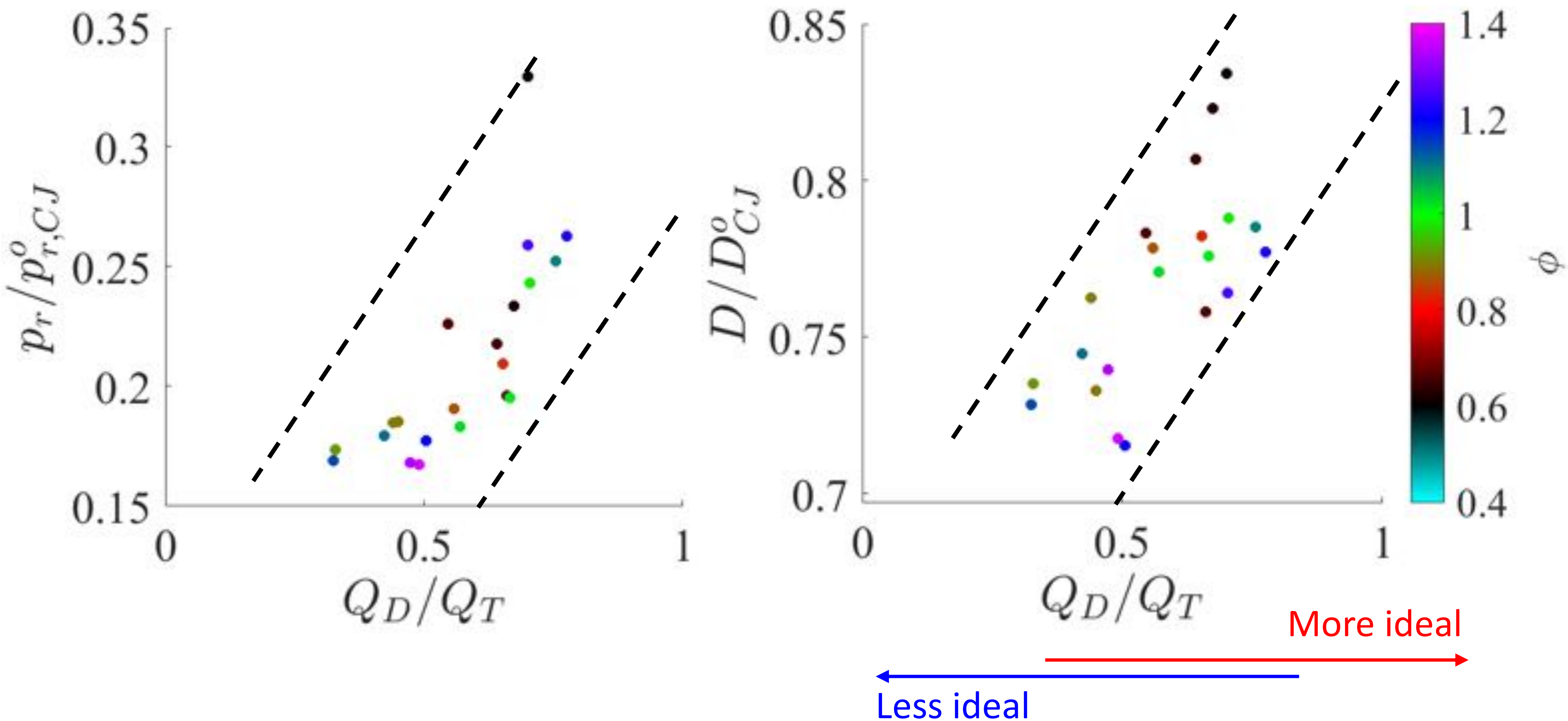
- Constructed from phase averaging across cycles
- Time normalized by average rotational time $(\overline{\tau}_R)$
- Regions are arbitrarily chosen based on prominent points of change
  - Work is being done to better identify the regions
- Define Q_T as total heat release observed in circle
  - Not total heat release of chemical reactions





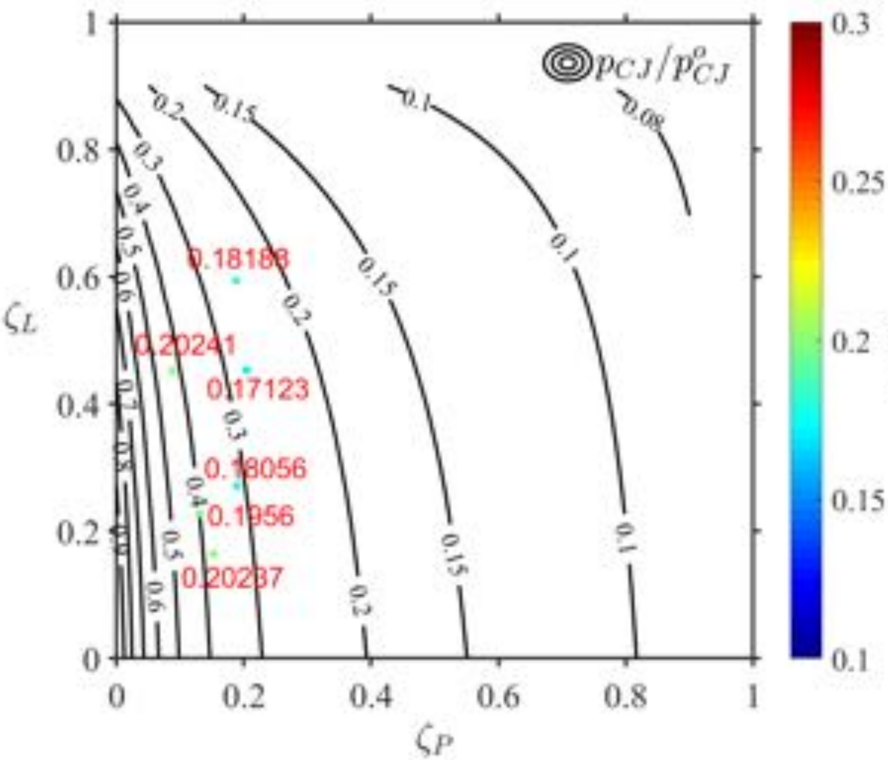
Secondary combustion changes detonation properties





Effect on detonation properties and practical RDE operation

Fraction leaking through

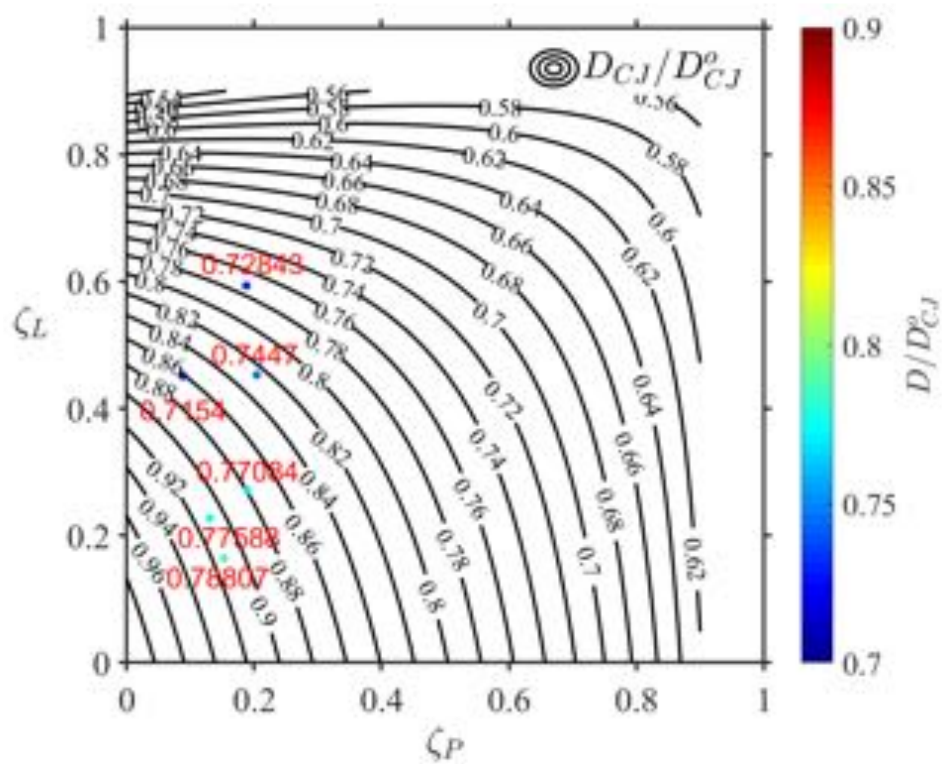


Fraction of mixture pre-burning

Data in a neighborhood of $\phi = 1$

- Detonation speed and pressure reduced with secondary combustion
  - Strong effect by parasitic combustion
  - Somewhat less affected by commensal

- Limited agreement, even on trends
- Limitations on:
  - OH* vs heat release correlation
  - Pressure measurements
  - Model still missing phenomena



Lessons learnt

- **Reacting flowfield is a detonating field mixed with secondary combustion regions**
  - Wide spread parasitic combustion is observed
  - Buffer region made of either pure fuel or air, depends on relative response
  - Commensal combustion caused my mixture leakage
- **Detonation properties are reduced by parasitic combustion and mixture leakage**
  - Secondary combustion reduces peak pressure and speed
  - Counter propagating waves increases secondary combustion
  - Practical RDEs may operates with a significant fraction of fill region consumed away from detonation wave
- **Even if parasitic combustion does not occur, entrainment of post-detonation gases into fresh mixture (vitiation or EGR effect) has a similar effect of parasitic combustion**
  - Vitiation significantly alters wave properties

Outline

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- Experimental activities
- Computational activities

Understanding Detonation Structure in Canonical Flows

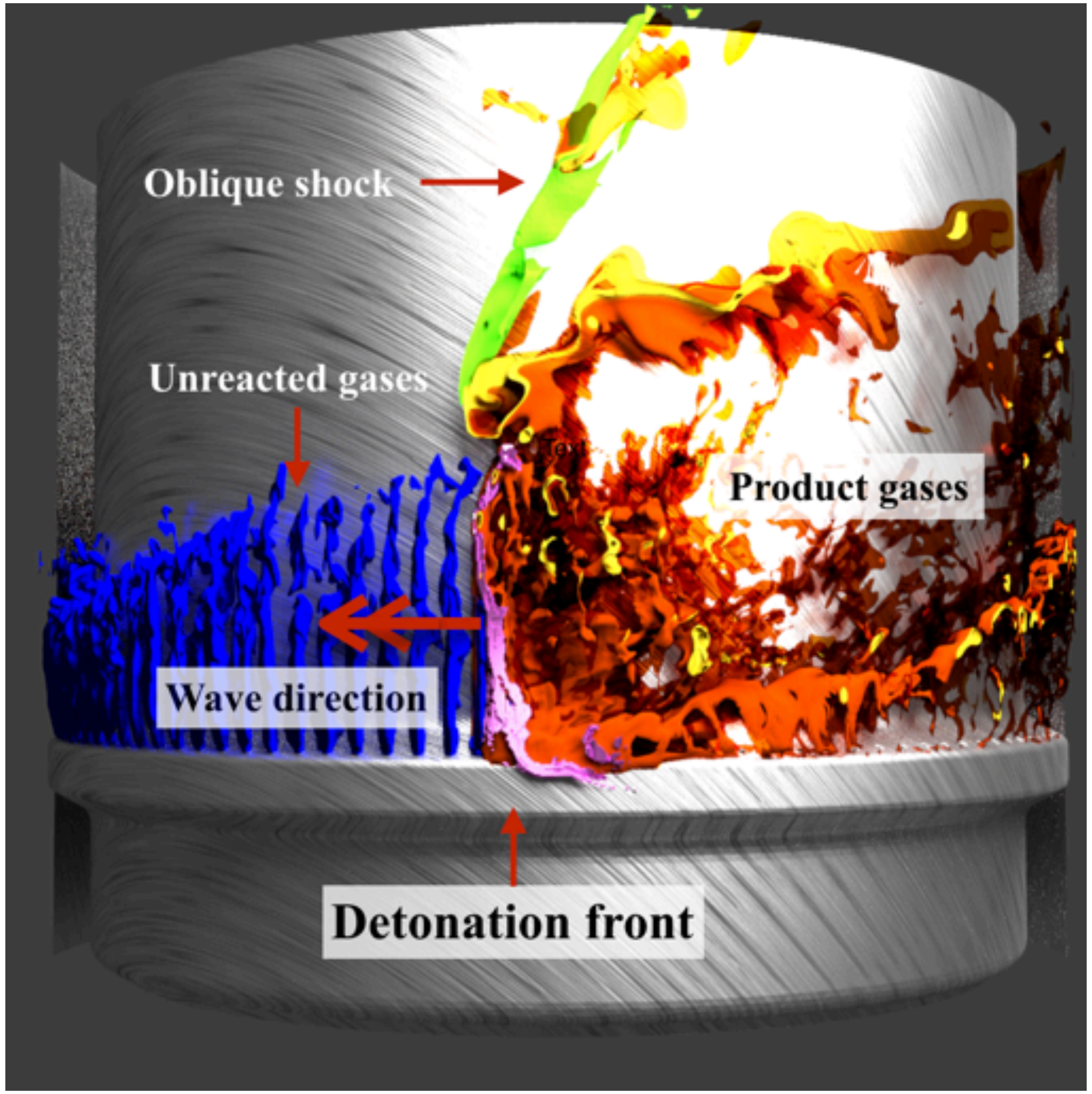
Supraj Prakash, Venkat Raman

University of Michigan, Ann Arbor
Department of Aerospace Engineering

APCL

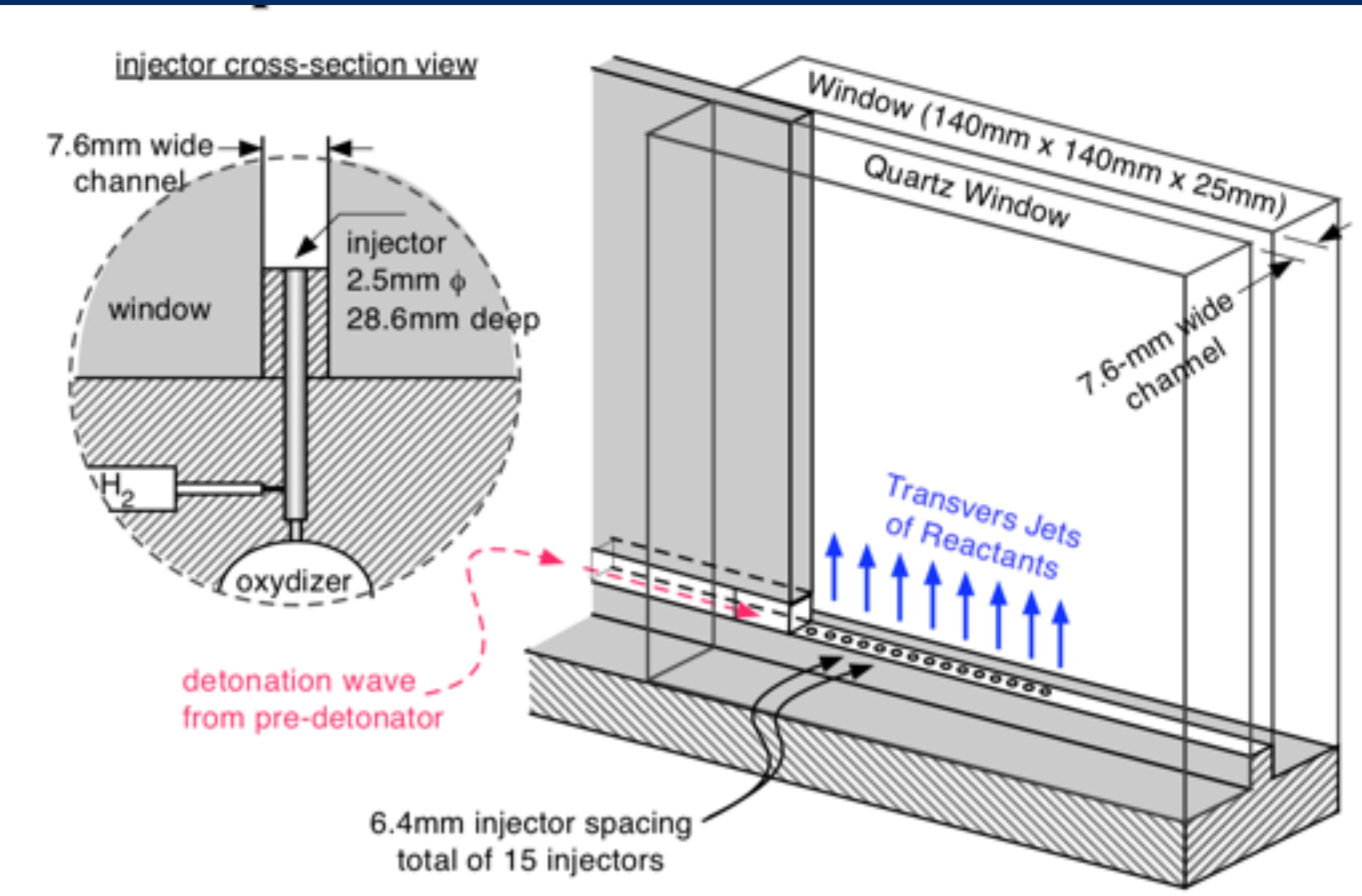
Effect of Fuel Stratification

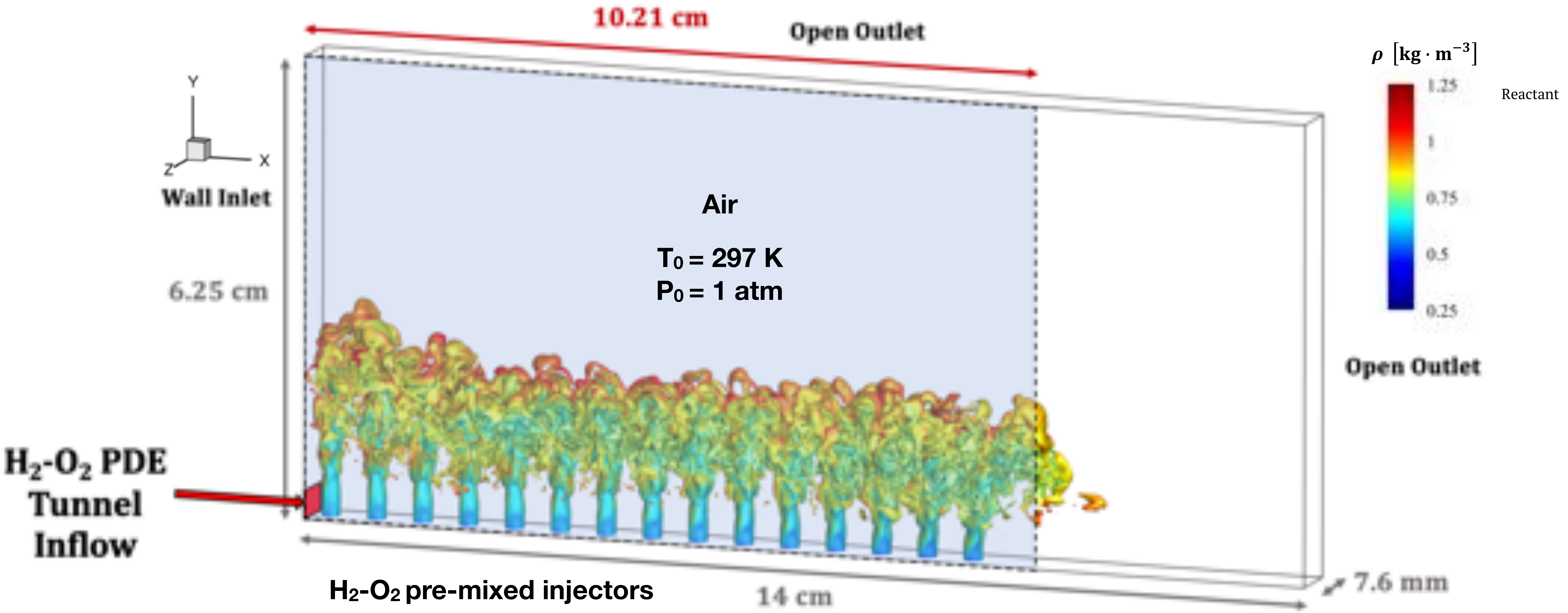
- **Fuel-air mixing not complete before wave arrives**
  - ➡ Strong spatial variations in equivalence ratio
- **What is the effect of such variations**
  - ➡ Structure of detonations in stratified mixtures



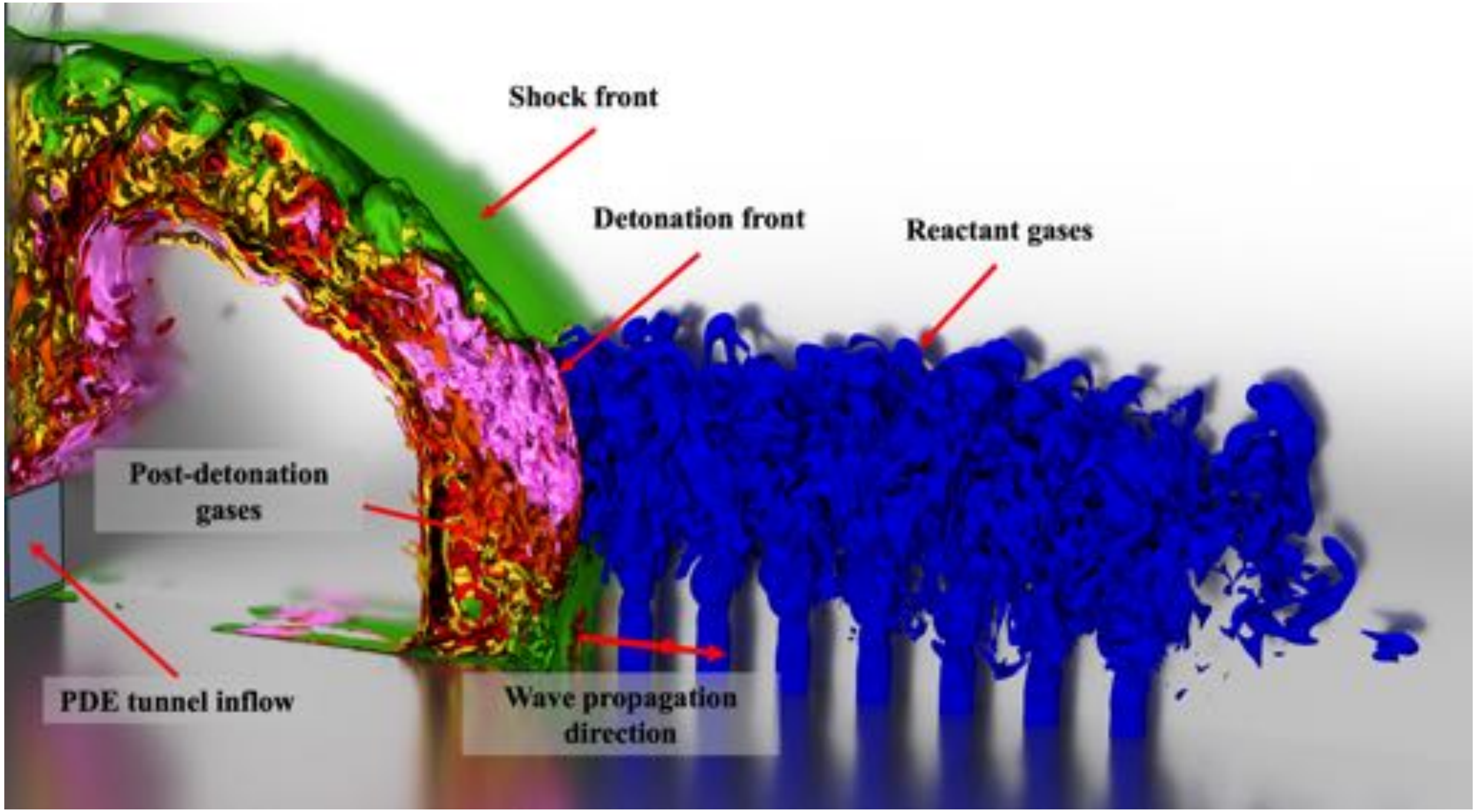
LMDE Configuration

- **Canonical RDE geometry**
  - ➡ 15 premixed injectors of 2.5 mm diameter
  - ➡ 6.4 mm center-to-center spacing
  - ➡ Pulse detonation engine (PDE) inflow





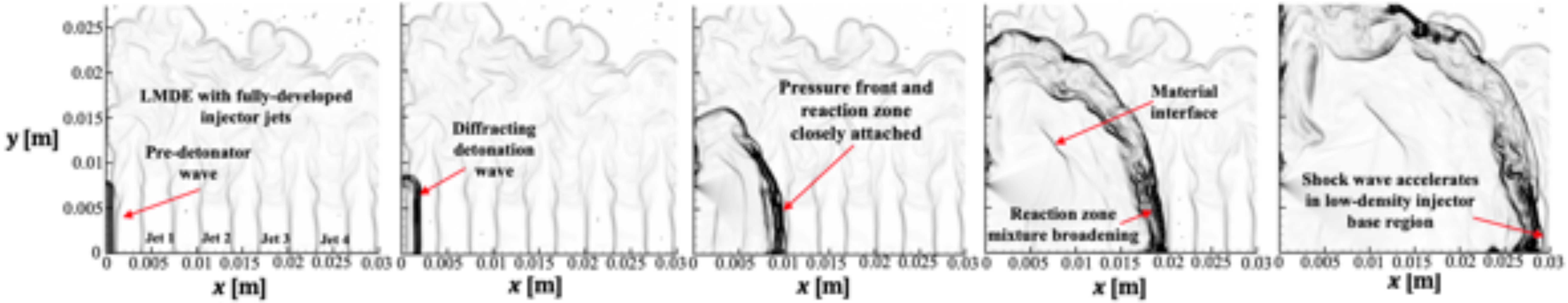
Detonation Structure



Detonation Wave Behavior in LMDE

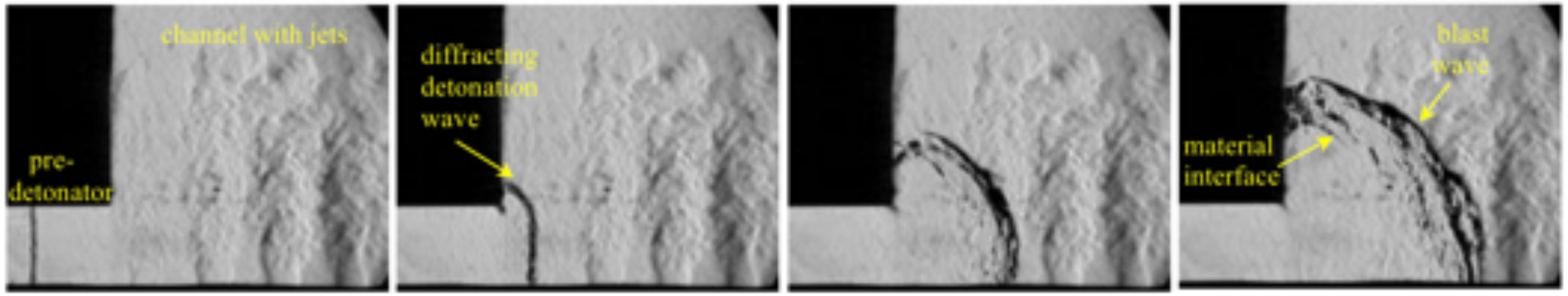
- **3D detonation wave consists of complex reaction zone**
  - ➡ Broadening reaction zone with detonation to deflagration regions
  - ➡ Turbulent mixing of post-detonation and intermediary gases behind triple points

Numerical Schlieren



(a) τ_0 (b) $\tau_0 + 0.5\ \mu s$ (c) $\tau_0 + 4\ \mu s$ (d) $\tau_0 + 8\ \mu s$ (e) $\tau_0 + 12\ \mu s$

Experimental Results

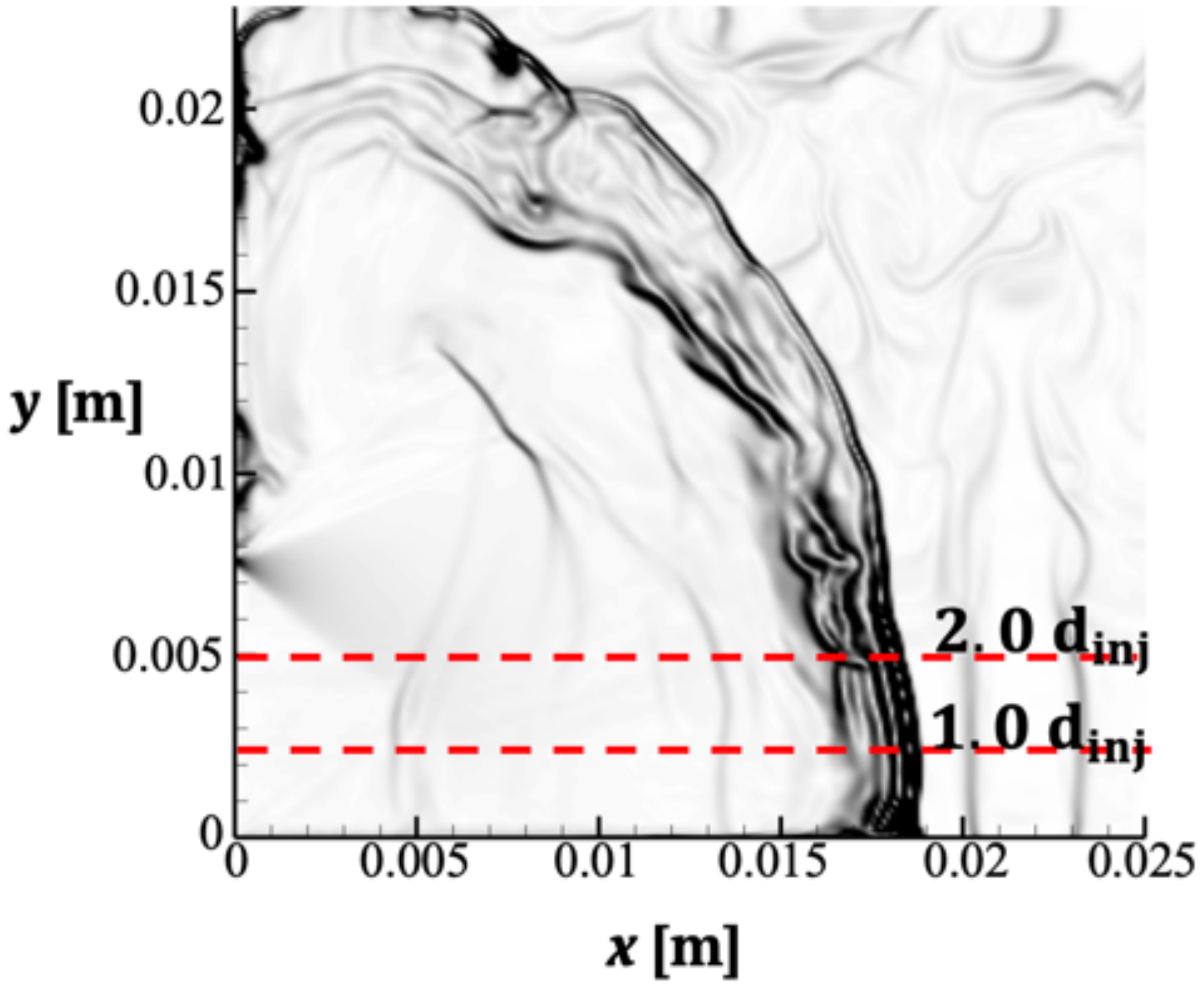


(a) τ_0 (b) τ_0+4μs (c) τ_0+8μs (d) τ_0+12μs

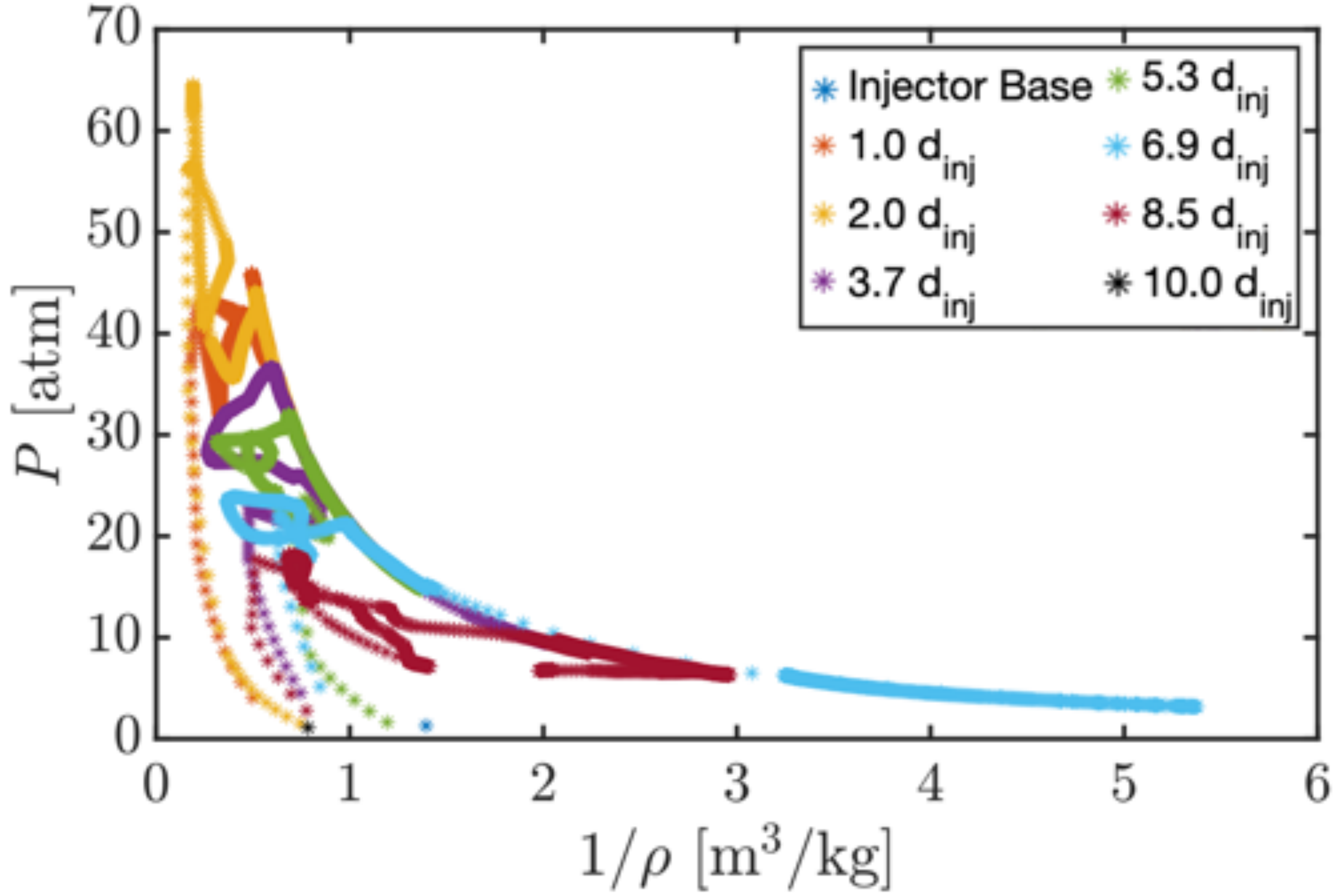
Numerical results closely resemble experimental detonation behavior

Detonation Analysis

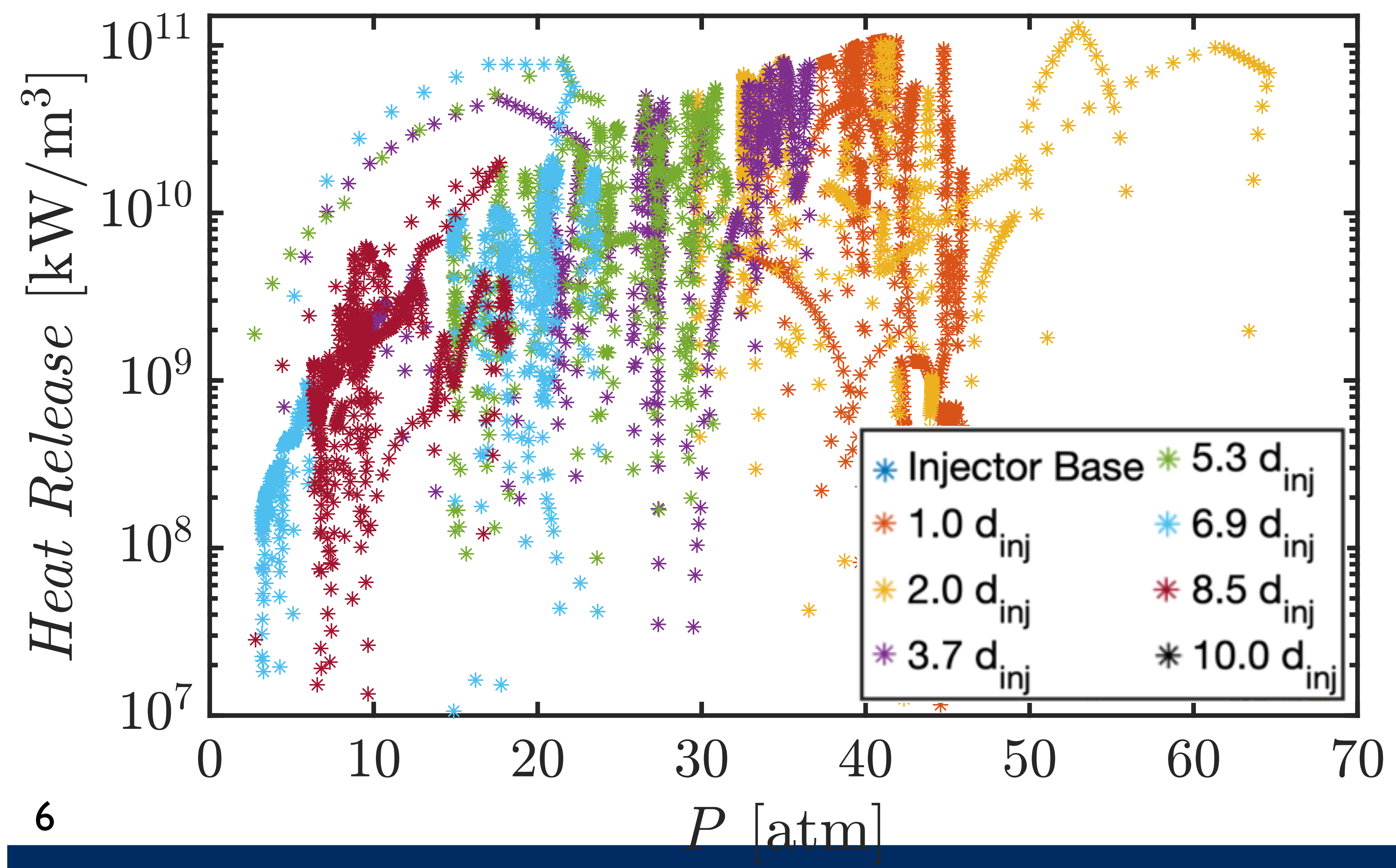
- **Strong detonation at twice jet diameter**
- **Transition to deflagration at 5.3-6.9 injector diameters from ba**
  - ➡ Heat release local maxima in deflagration region
- **Peak heat release at von Neumann pressure of H_2-O_2 detonatio**
  - ➡ Local maxima at ~42 atm - von Neumann condition
  - ➡ Additional peaks correspond to triple point collisions



Rankine Hugoniot Relation



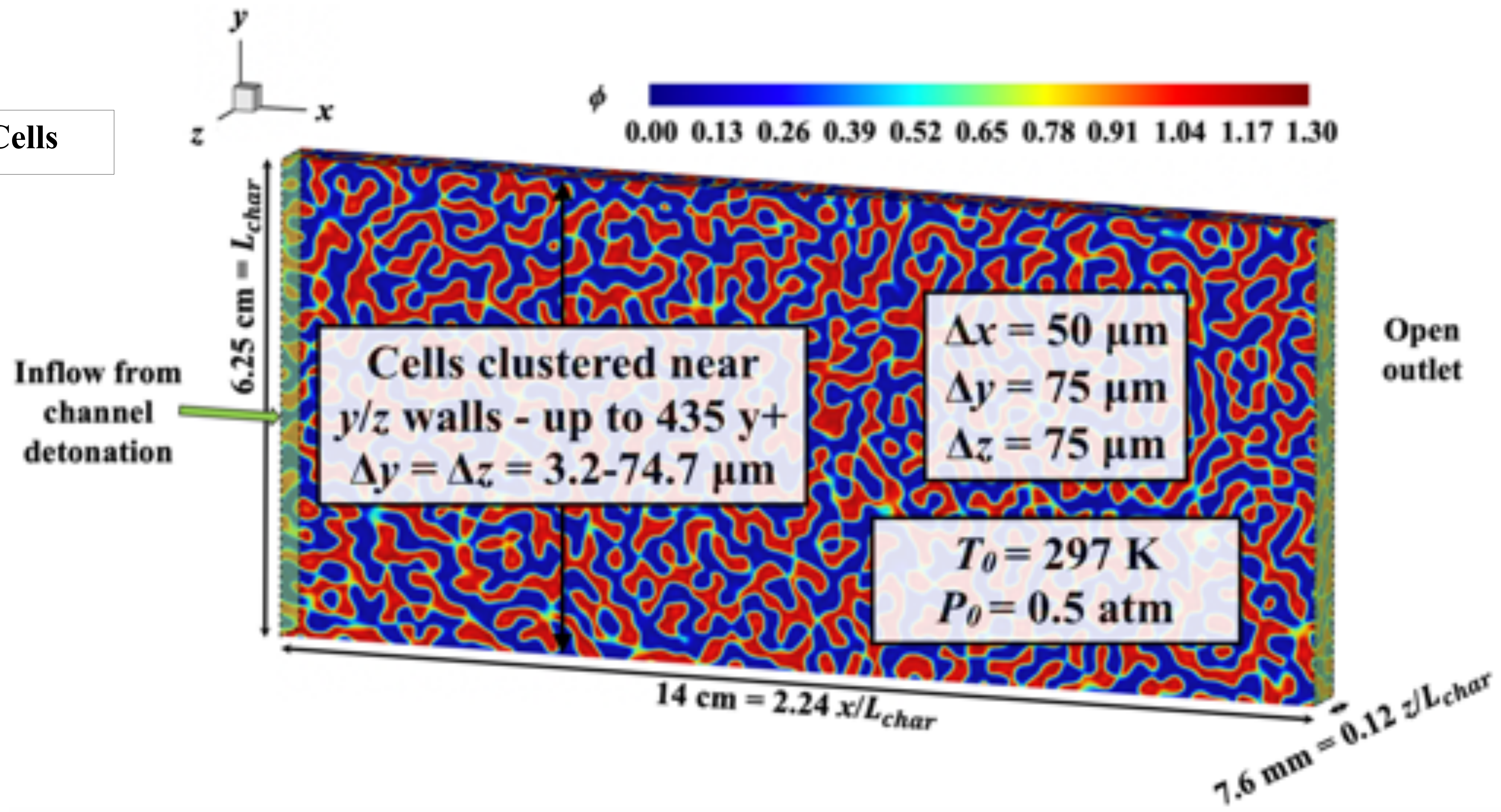
Heat Release per Unit Volume Relation

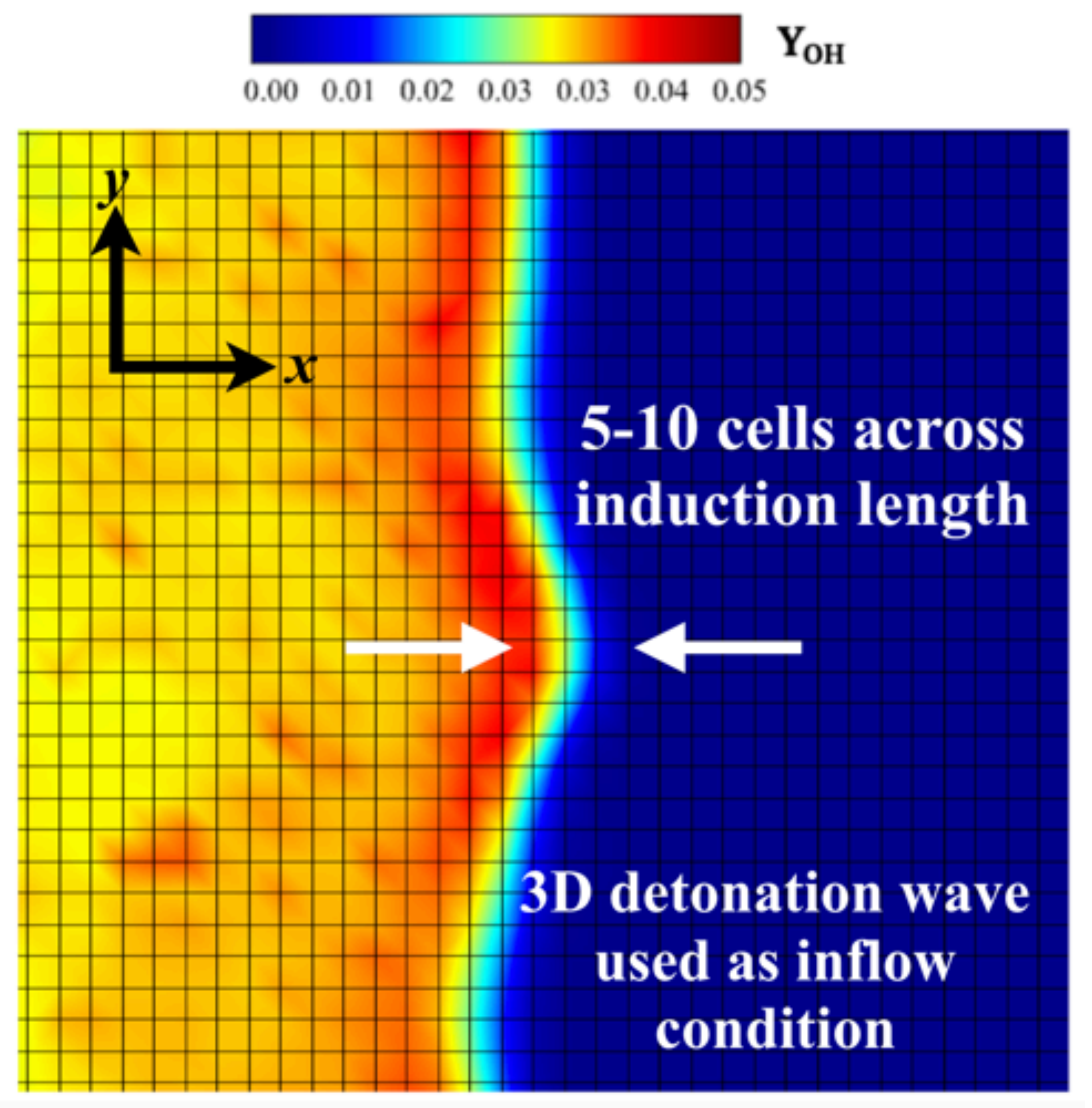


Computational Approach

- **Canonical geometry**
  - → Confined channel with open outlet
  - → 14 cm by 6.25 cm by 7.6 mm channel – RDE annulu

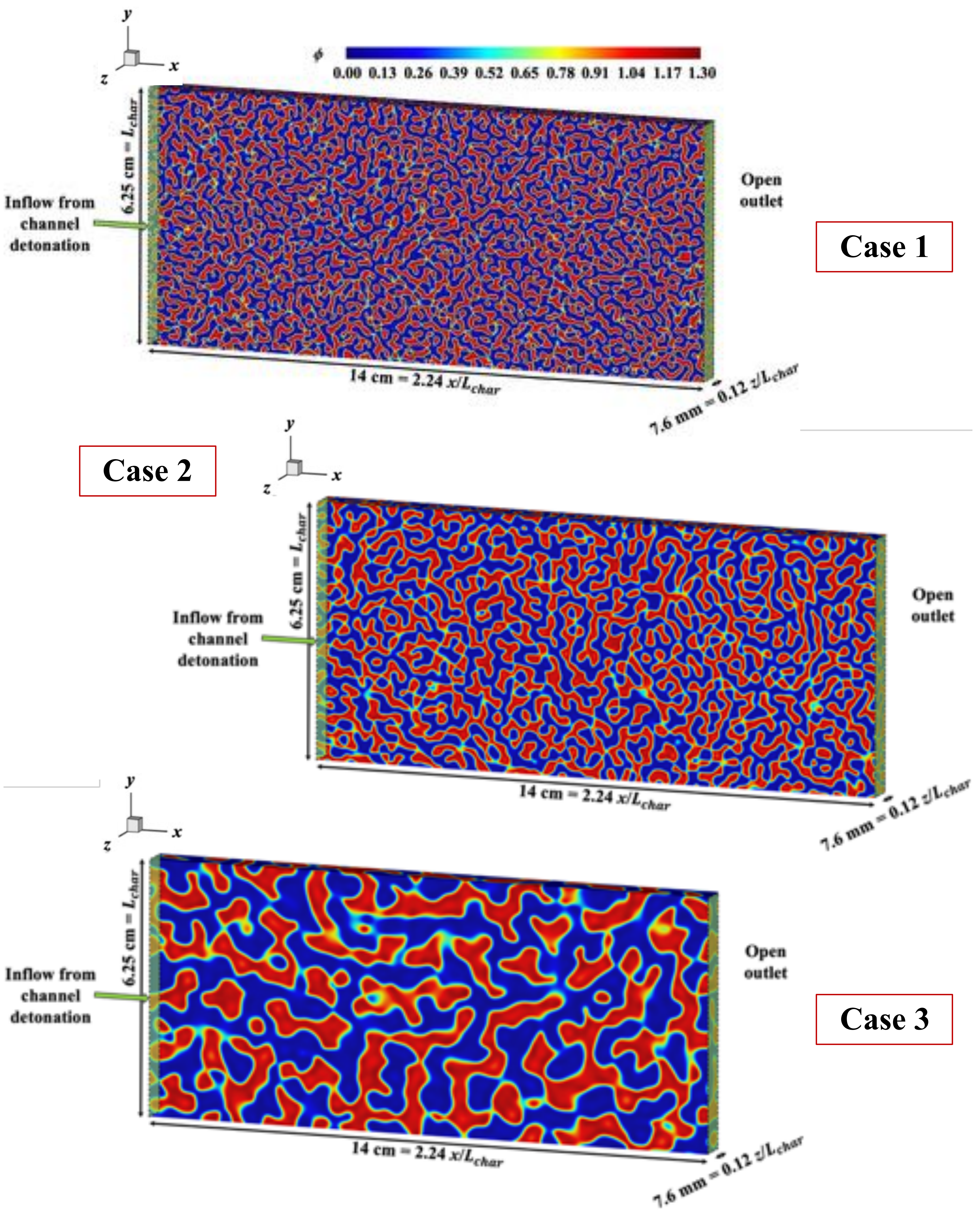
320M Cells



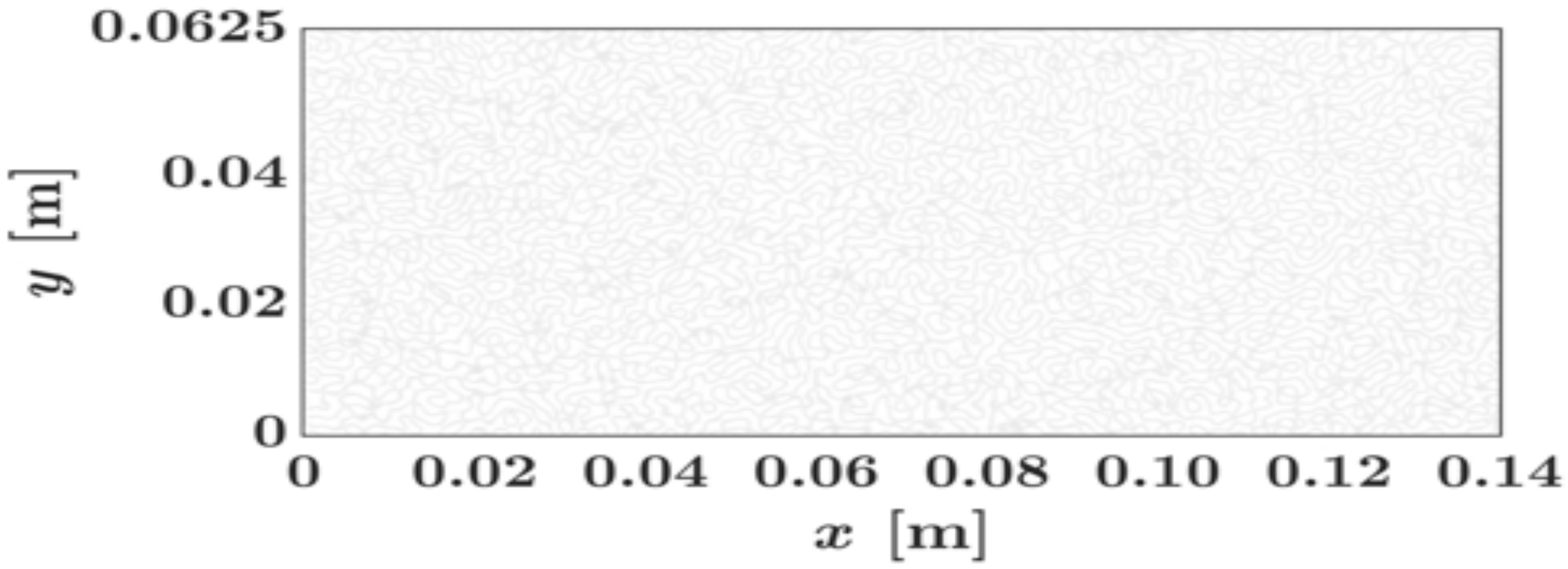


Fuel-Oxidizer Distribution

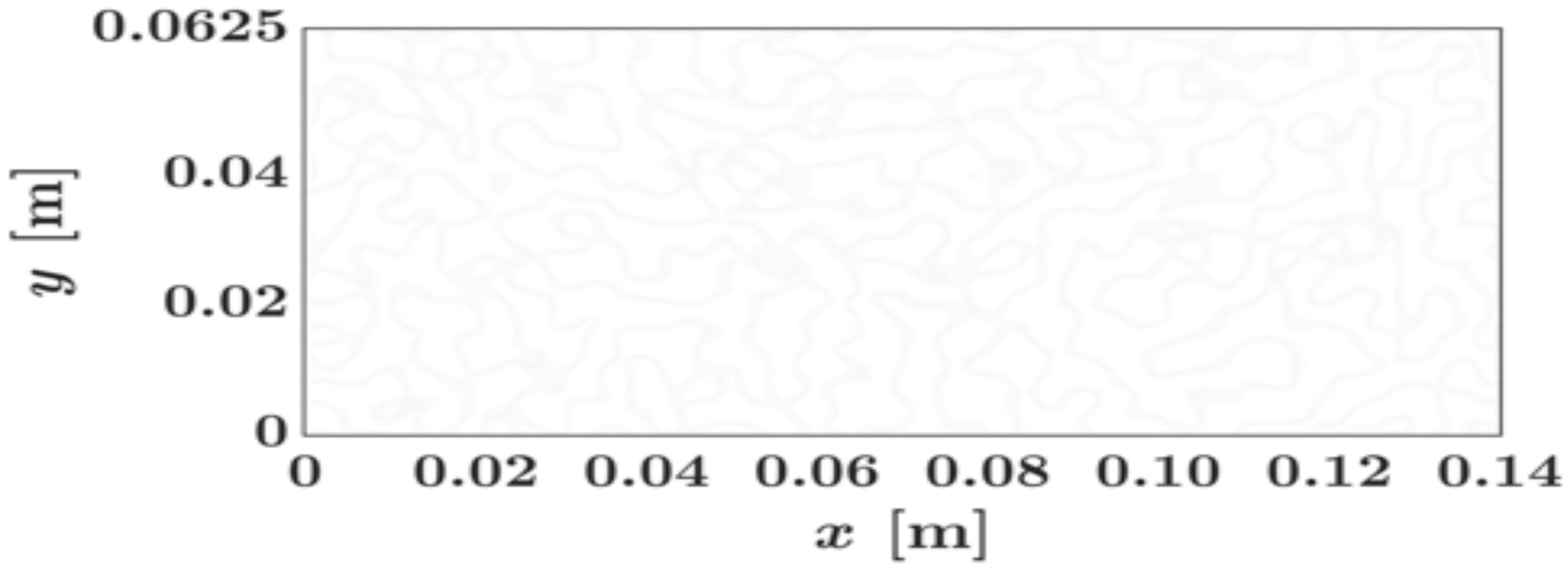
- **Fuel equivalence ratio:** $\phi = \{0, 1.3\}$
- **Scalar field is attributed to fuel mole fraction**
  - → Remaining species and density computed
- **Want to conserve statistics among cases**
  - → Total fuel mass $\chi_{H_2} = \{0, 0.353\}$
  - → Mean, variance, and standard deviation of
- **3 different stratification length scales**
  - → Vary ϕ → preserve Fourier coefficients
  - → Integral length scales: $\Psi(k, \mathbf{0})$
    - → Case 1: 0.581 mm → $k_s/dk = 30$
    - → Case 2: 0.894 mm → $k_s/dk = 20$
    - → Case 3: 1.854 mm → $k_s/dk = 10$



Numerical Schlieren



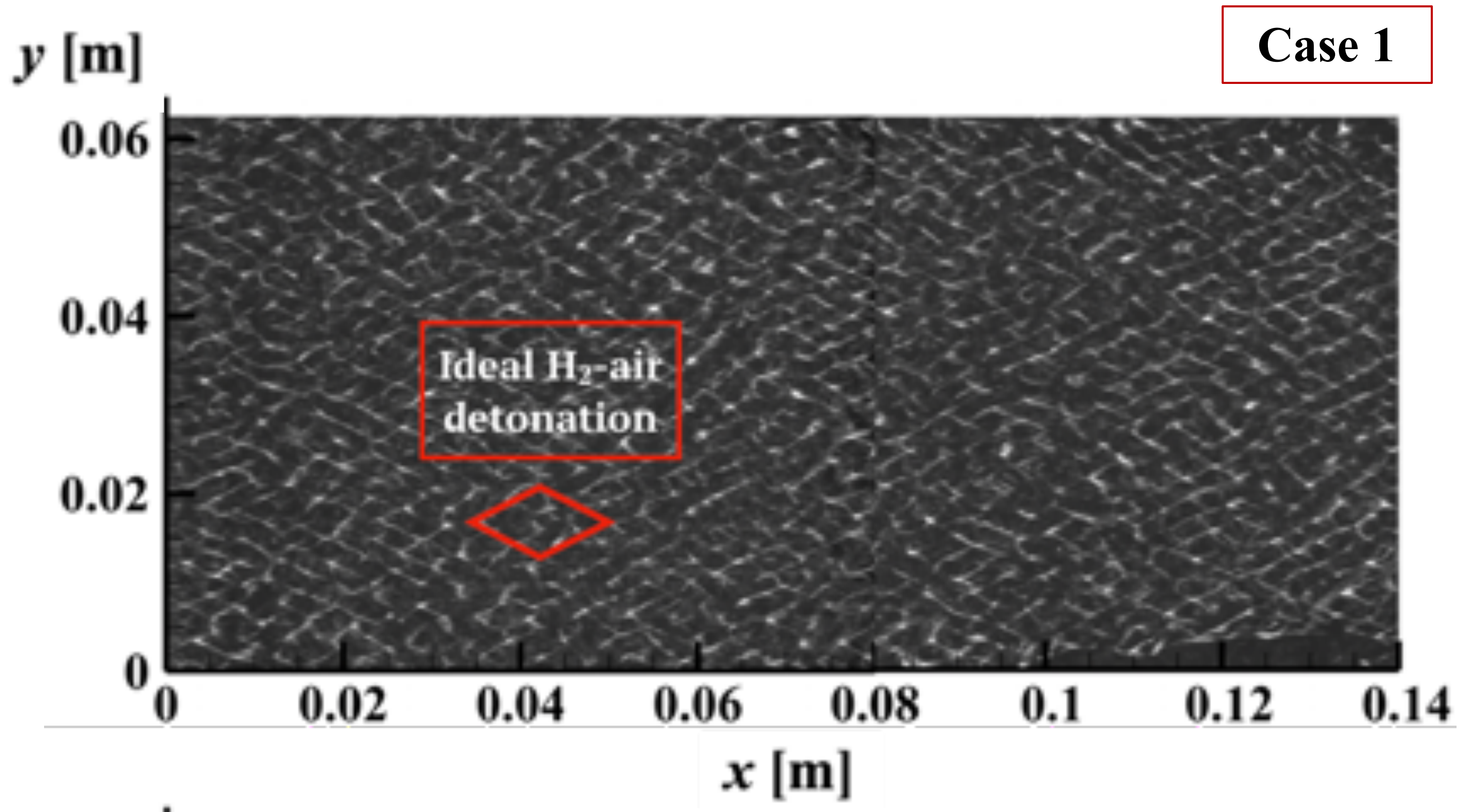
Case 1
Small
Stratification
Length Scale



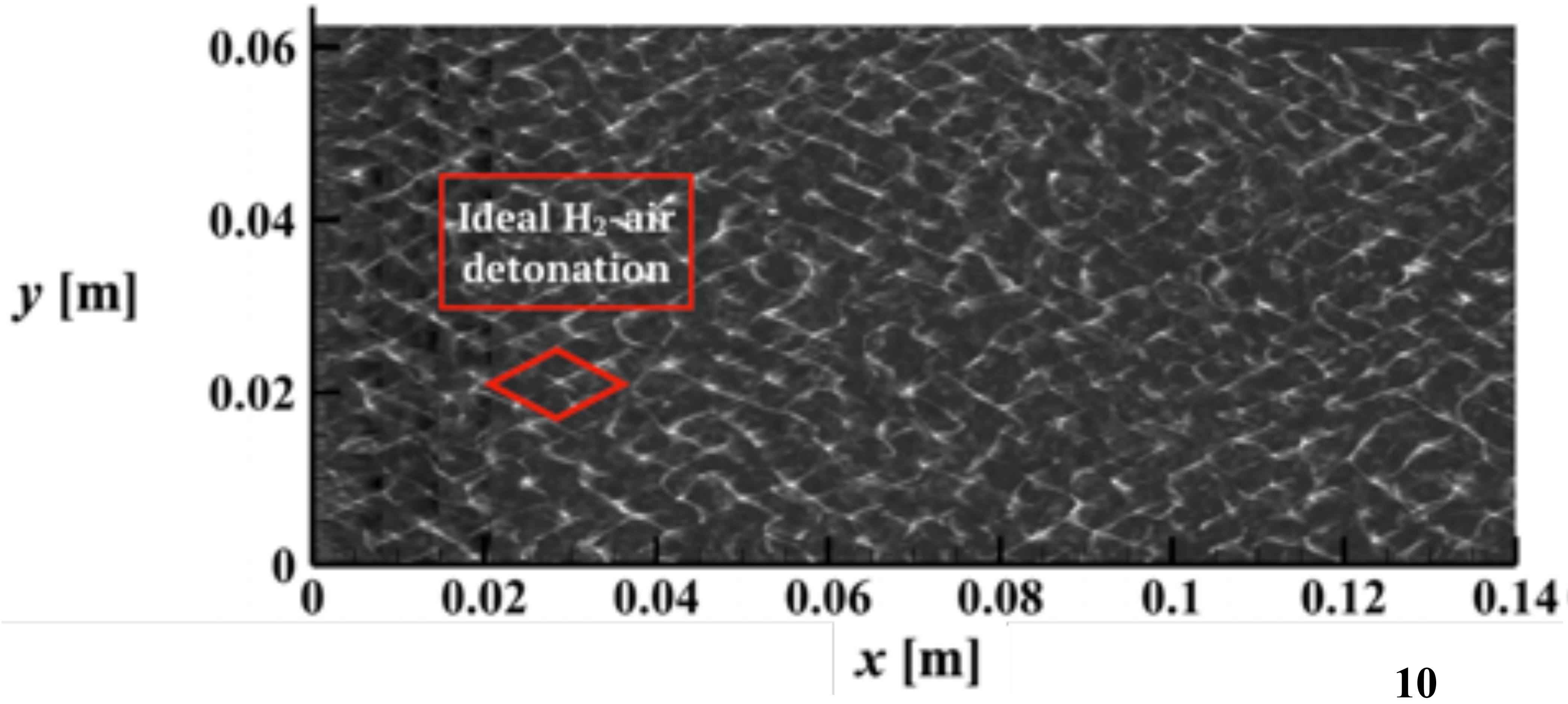
Case 3
Large
Stratification
Length Scale

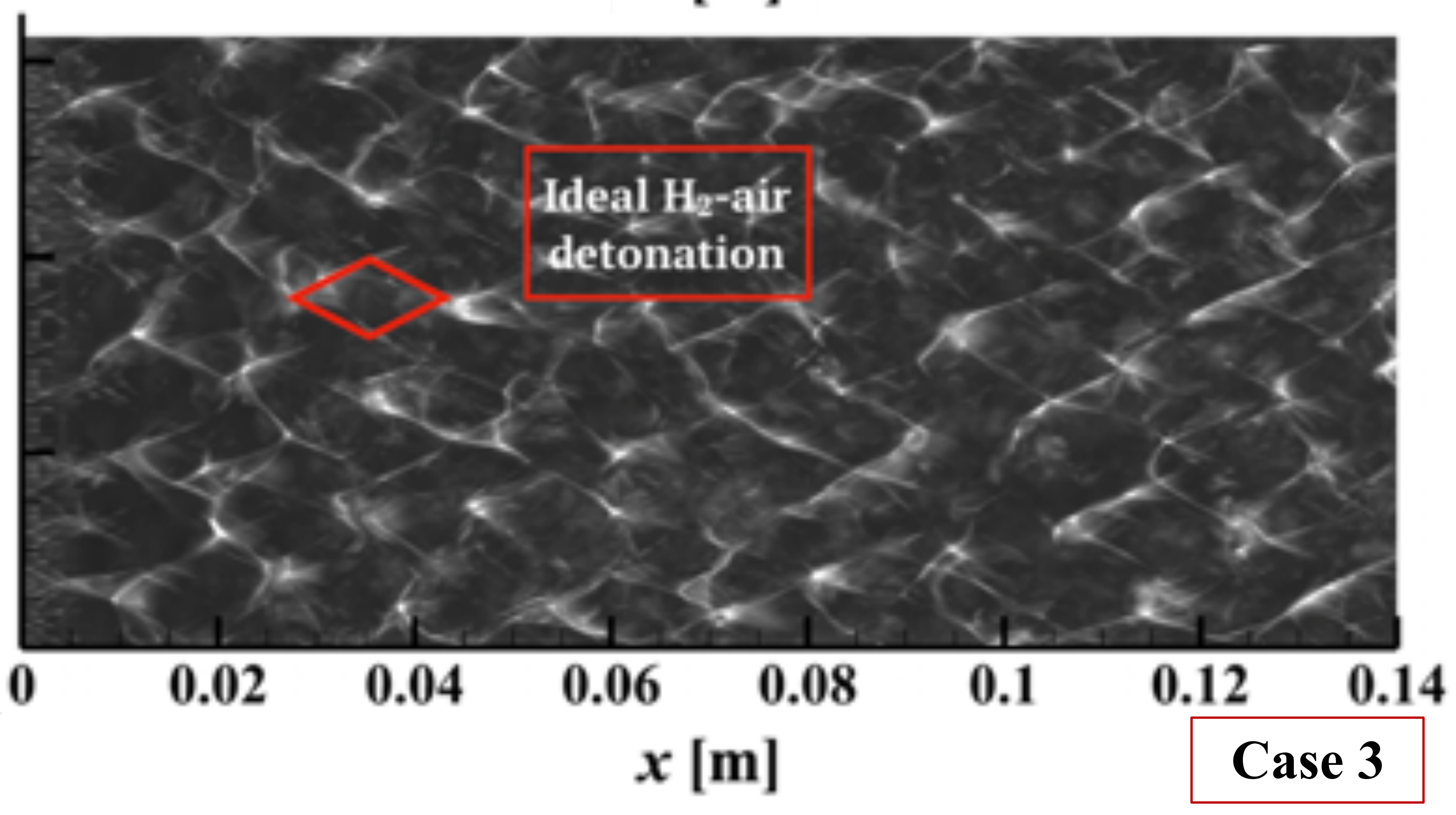
Detonation Cell Structures

- **Fuel patch locations and density irregularities result in staggered detonation cells**
- **Stratification length scale directly affects detonation cell structure and size**



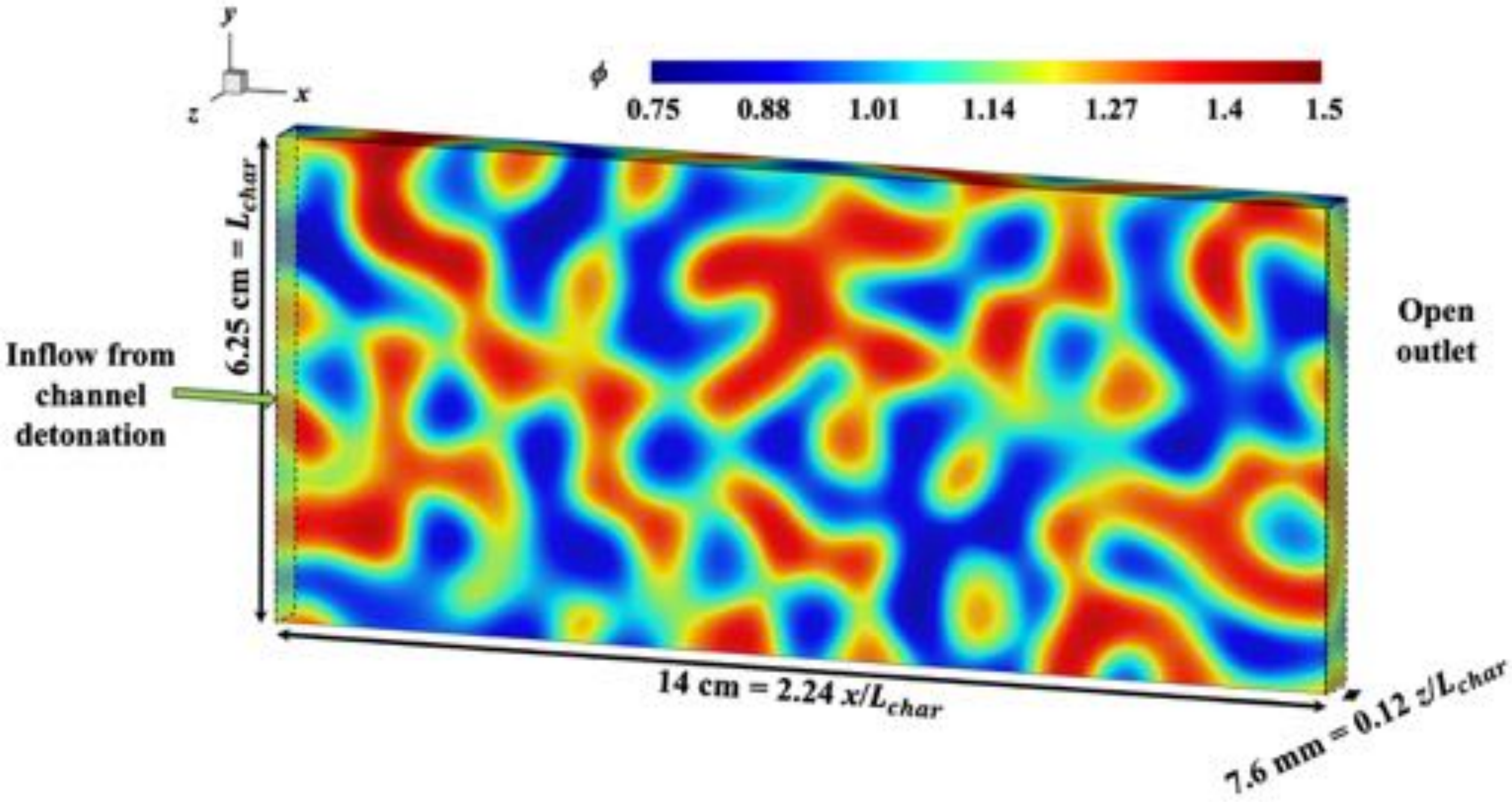
Fuel spatial distribution can alter effective cell size





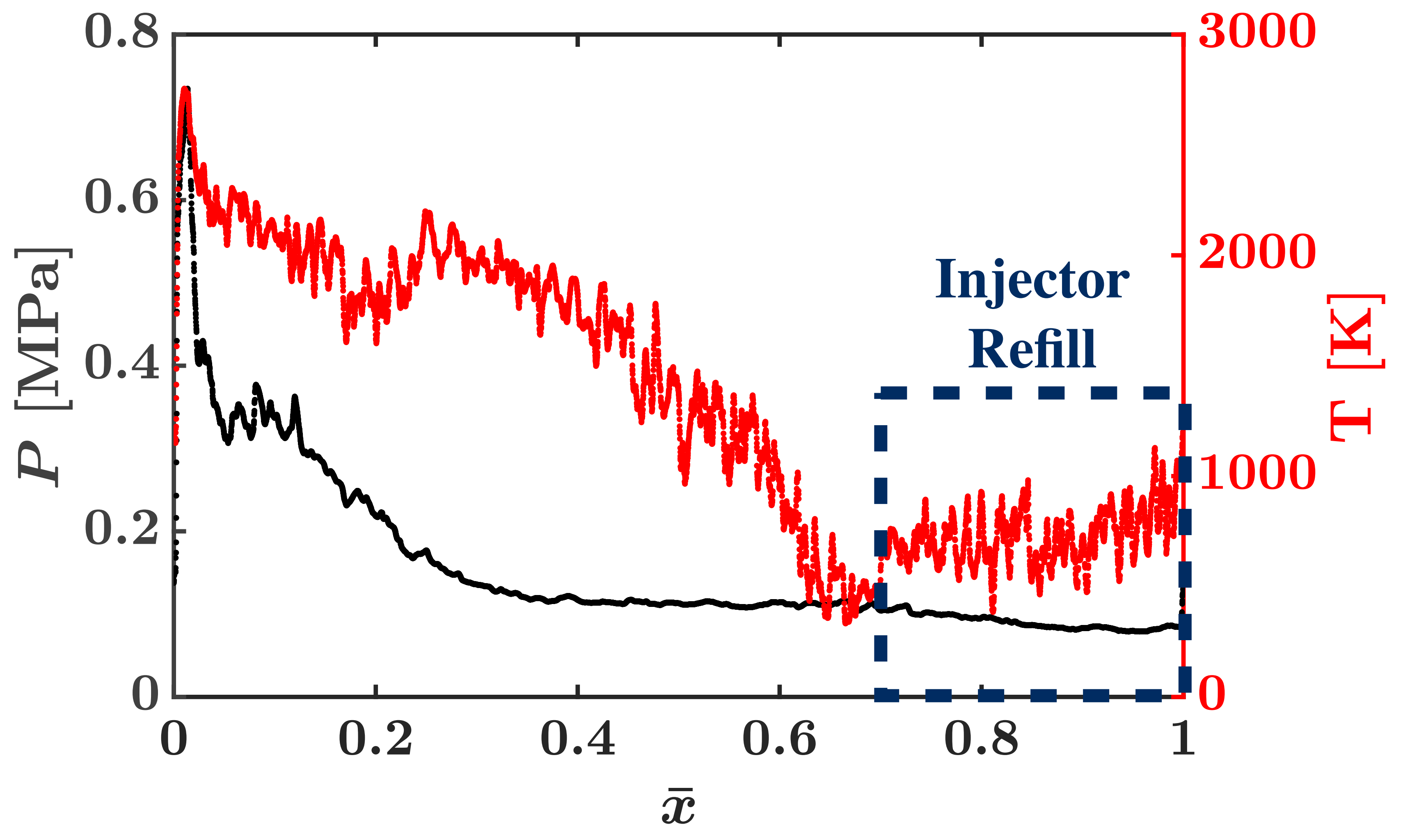
Case 2

Baseline Case

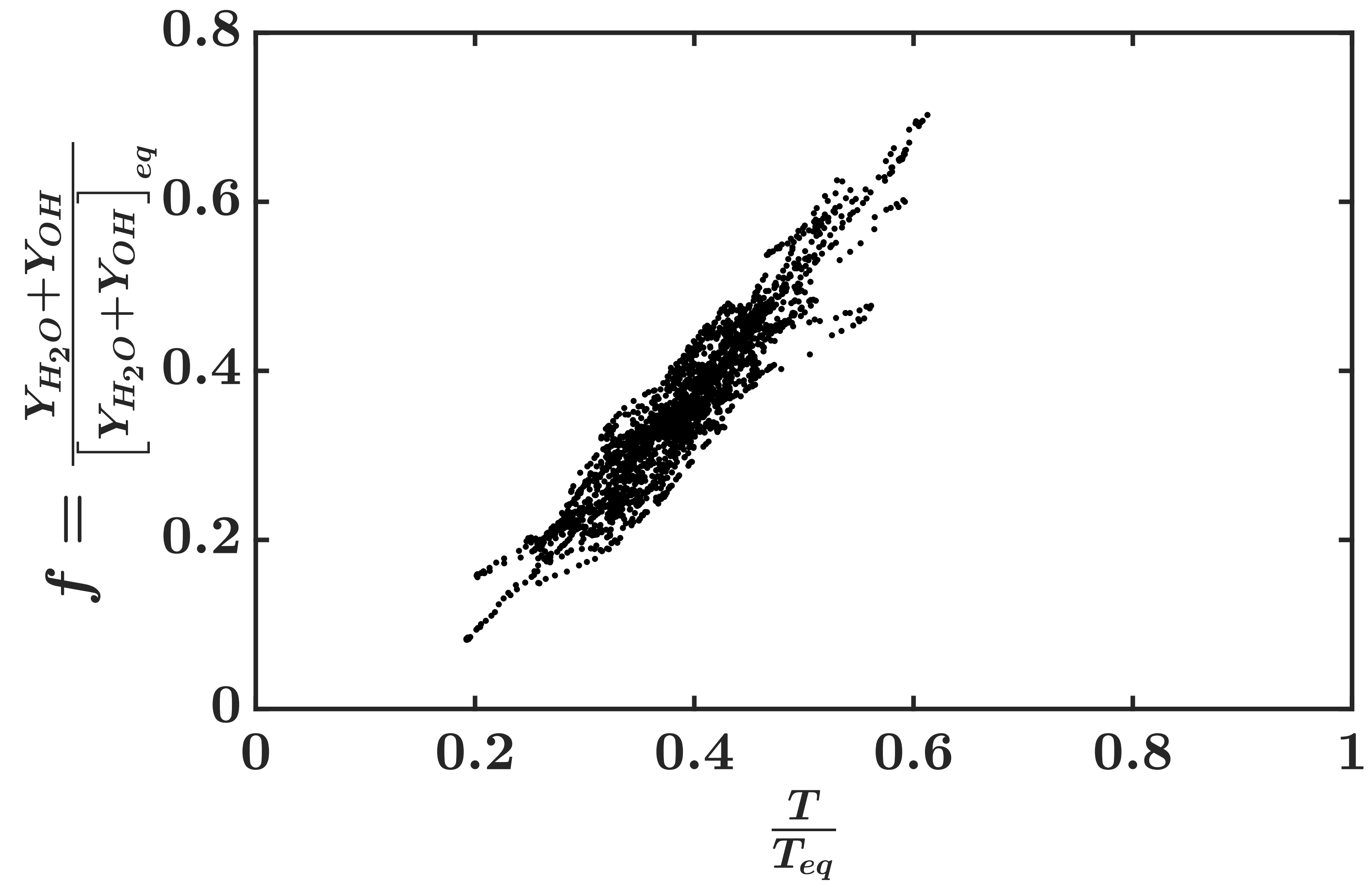


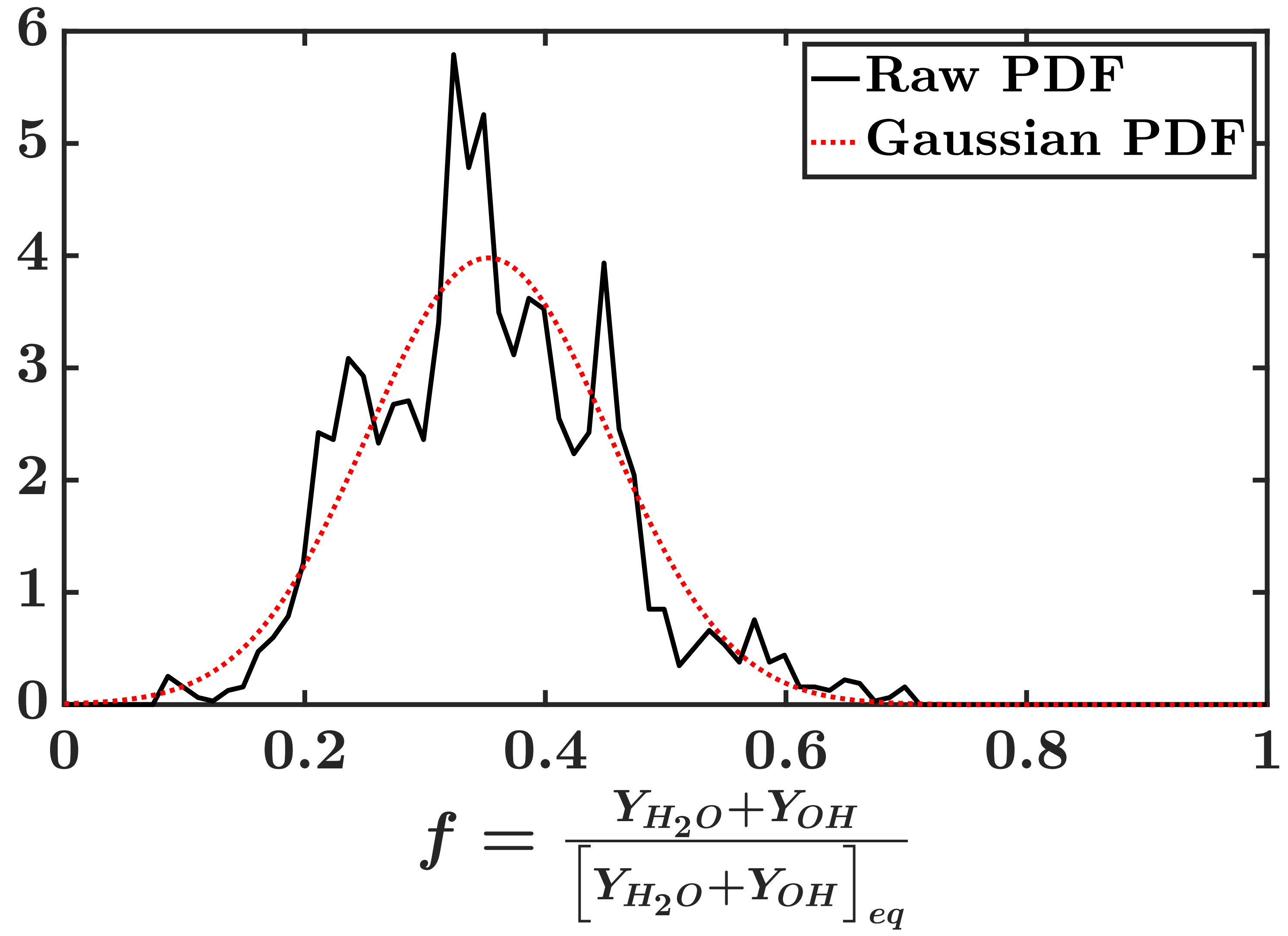
Preburning Ratio

- **Preburning ratio - a metric to describe level of local mixedness with burnt gas mixtures**
  - ➡ $$f = \frac{Y_{H_2O} + Y_{OH}}{[Y_{H_2O} + Y_{OH}]_{eq}}$$

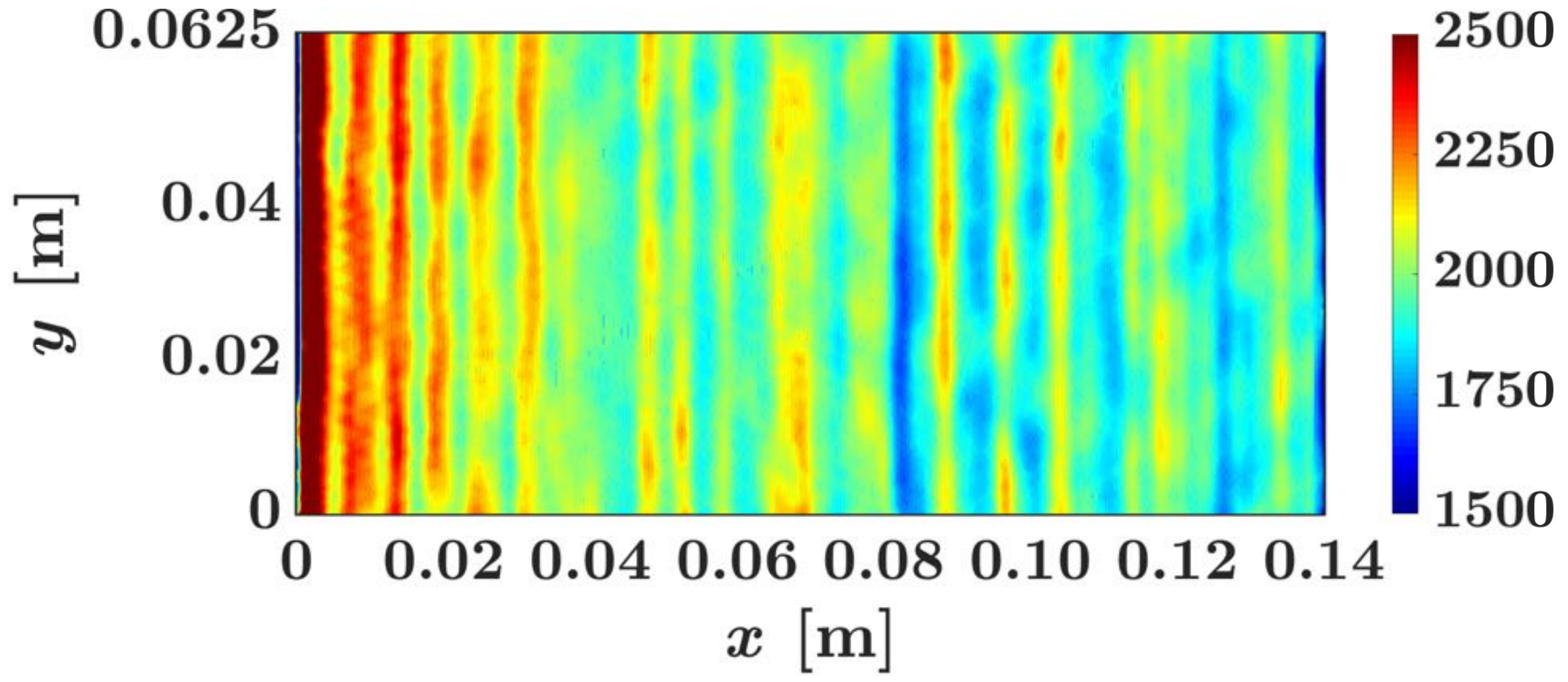


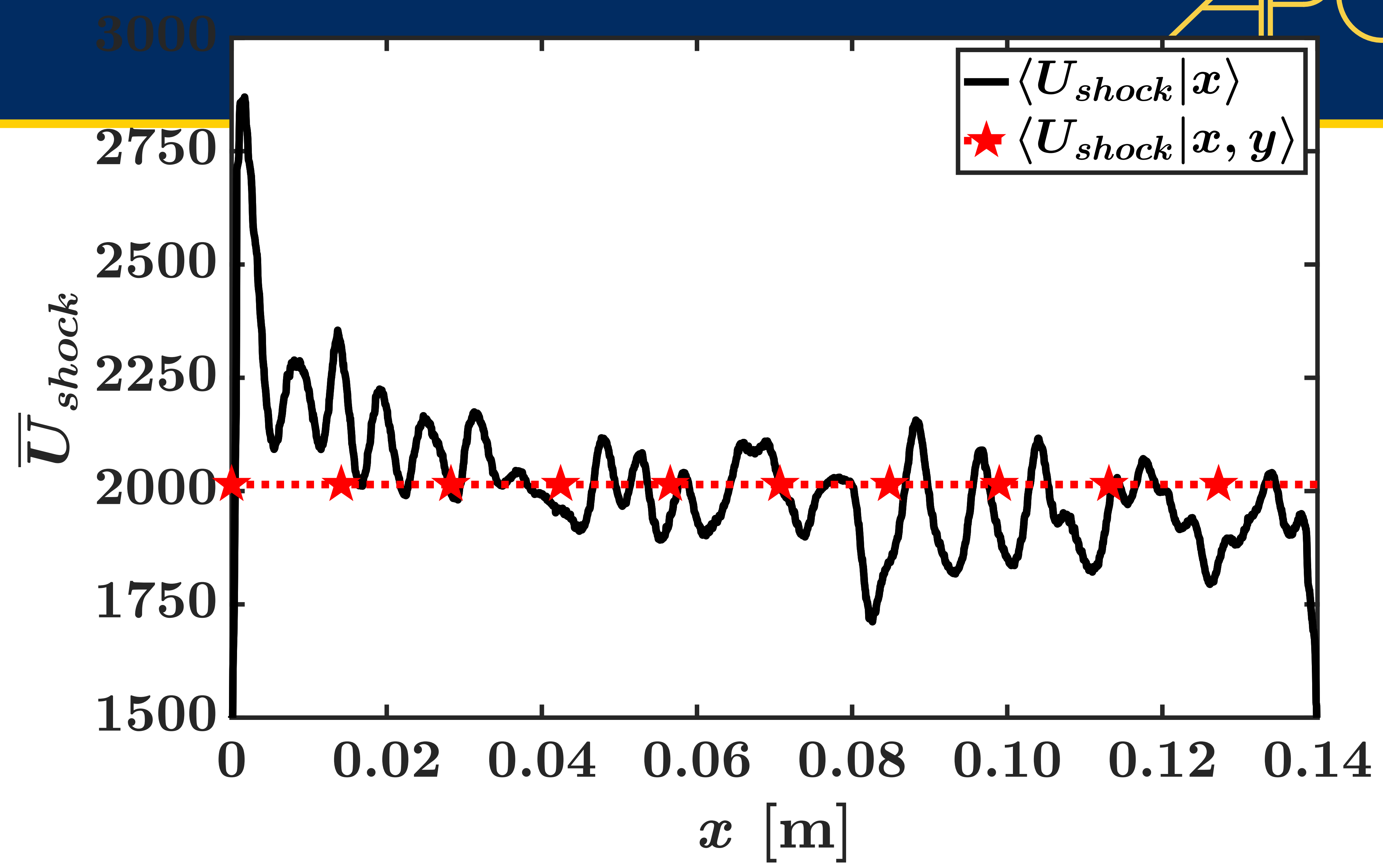
- **Extracted from full-scale RDE simulations - H_2/air axial inlet simulations**
  - ➡ Preburning region
  - ➡ $\bar{x} = \{0.7, 1\}$
  - ➡ Variation in x
  - ➡ Homogeneous in y/z
- **$\mu = 0.3526$**
- **$\sigma = 0.1002$**

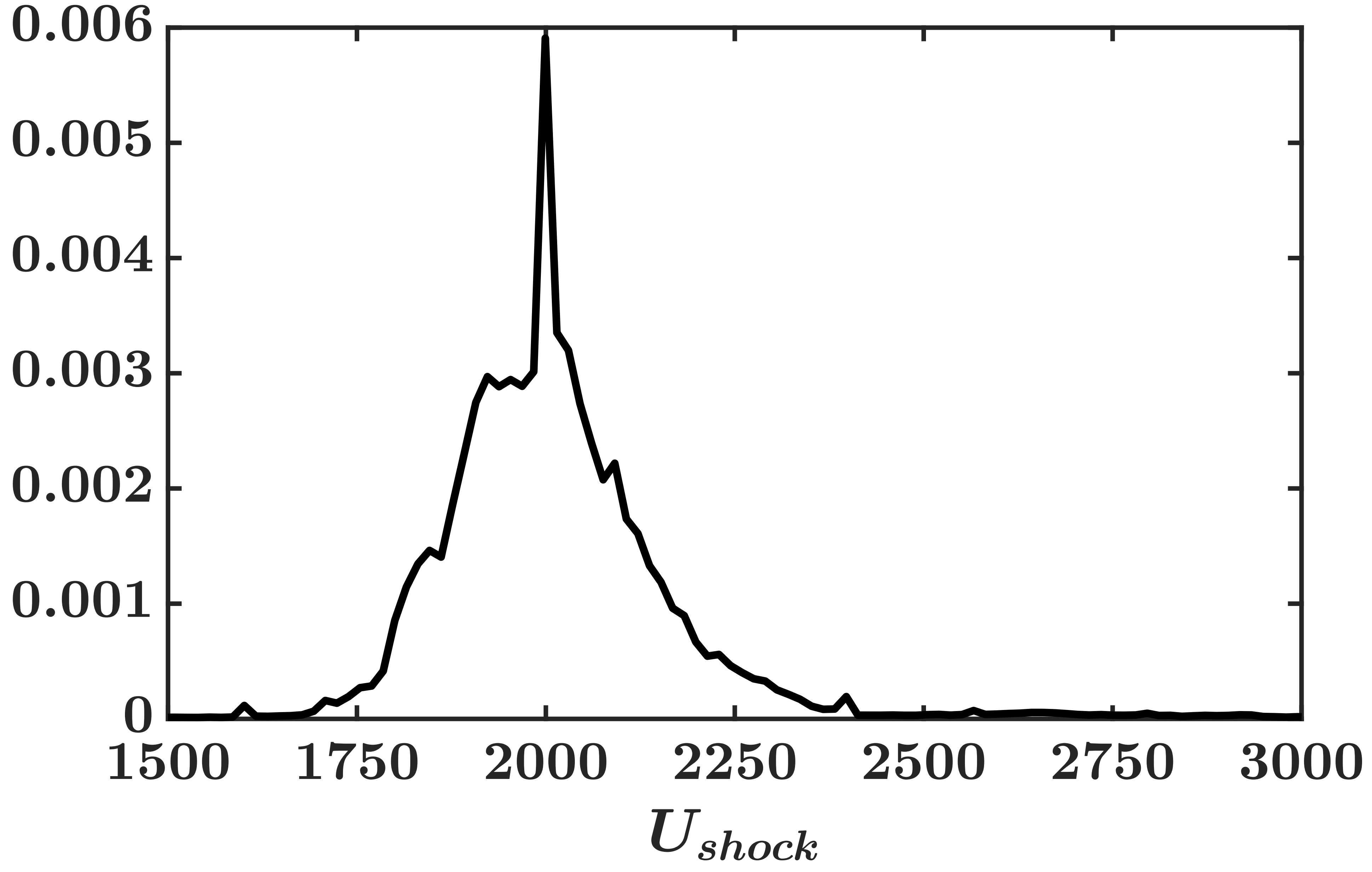




Shock Velocity

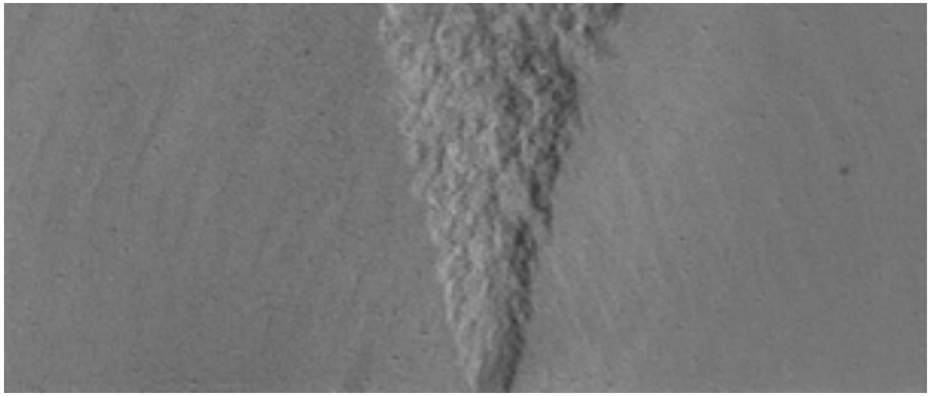






Conclusions

- **Detonations in non-premixed discrete injectors is vastly different from ideal premixed systems**
- **Thicker detonation wave**
  - ➡ Detached reaction front
  - ➡ Complex internal wave structure
  - ➡ Variations in propagation speed
- **Pre-burning and stratification**
  - ➡ Can reduce speeds by 50%
  - ➡ Results in vorticity generation behind the wave that increases fuel oxidation



Questions?