Minimizing Fuel-Oxidizer Mixture Inhomogeneities in Rotating Detonation Engines

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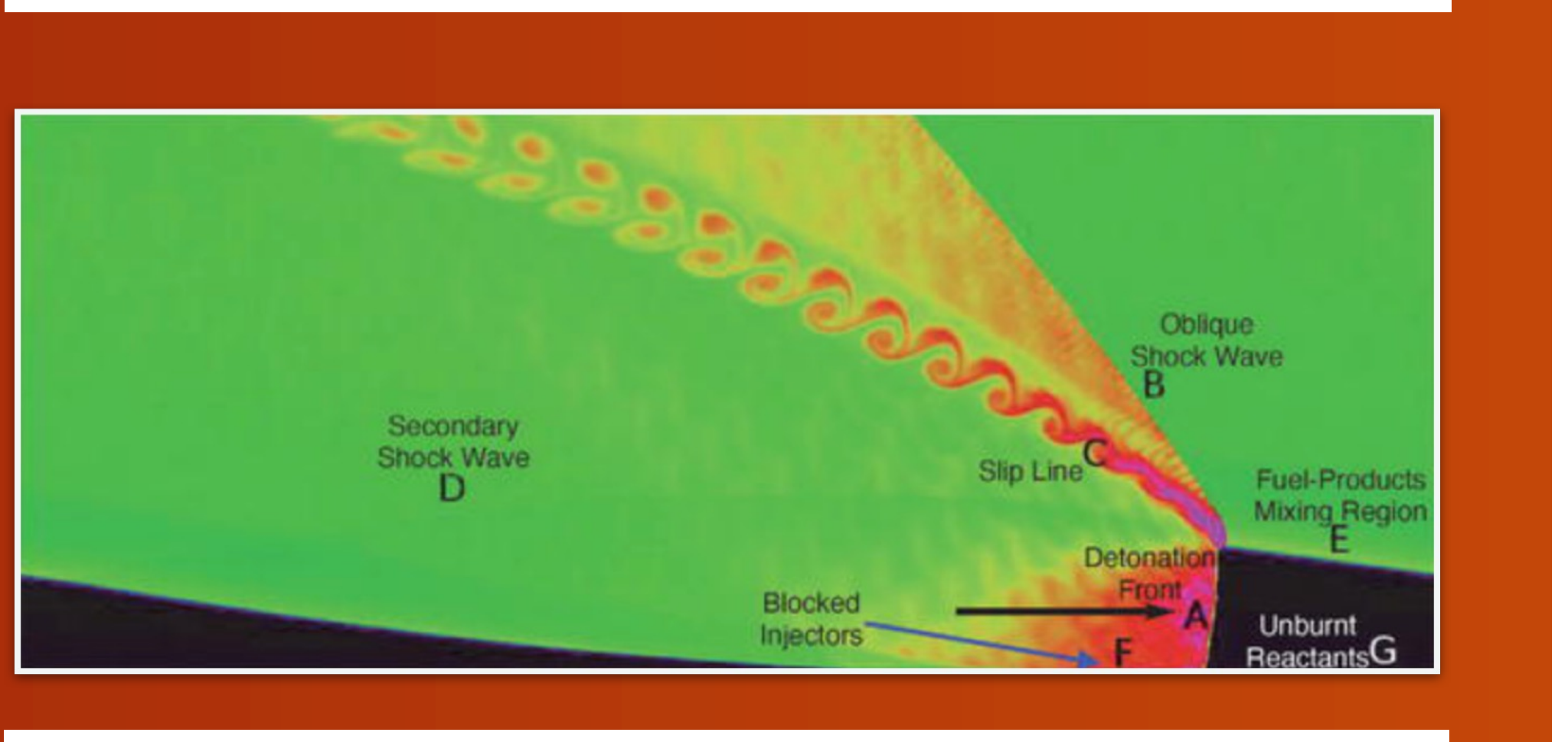
Background

- The rotating detonation engine (RDE) is deemed as one of the most **promising and interesting areas of propulsion research.**
  - The RDE is a pressure-gain propulsion system that utilizes rotating detonation waves to compress and ignite a mixture of injected fuel and oxidizer for powerful levels of propulsive thrust (Shaw et al., 2019).
- Detonative combustion is experimental, yet introduces the prospect of **low-complexity**, **compact**, and **highly efficient** propulsion.
- In engines with premixed injected fuel mixtures, the flashback effect occurs, which interrupts the fuel-air injection process.
  - Due to concerns with flashback, fuel-air injection is separated.
- The **uneven, unstable, and turbulent flow field** of the separated injected material **can decrease and disrupt engine and detonation wave efficiency.**
- More work is required to optimize injection for **maximized fuel-oxidizer mixture homogeneity.**



The Flashback Effect: The process of a propagating detonation wave interrupting the injection of fuel mixture material. Figure from (Schwer 2010).

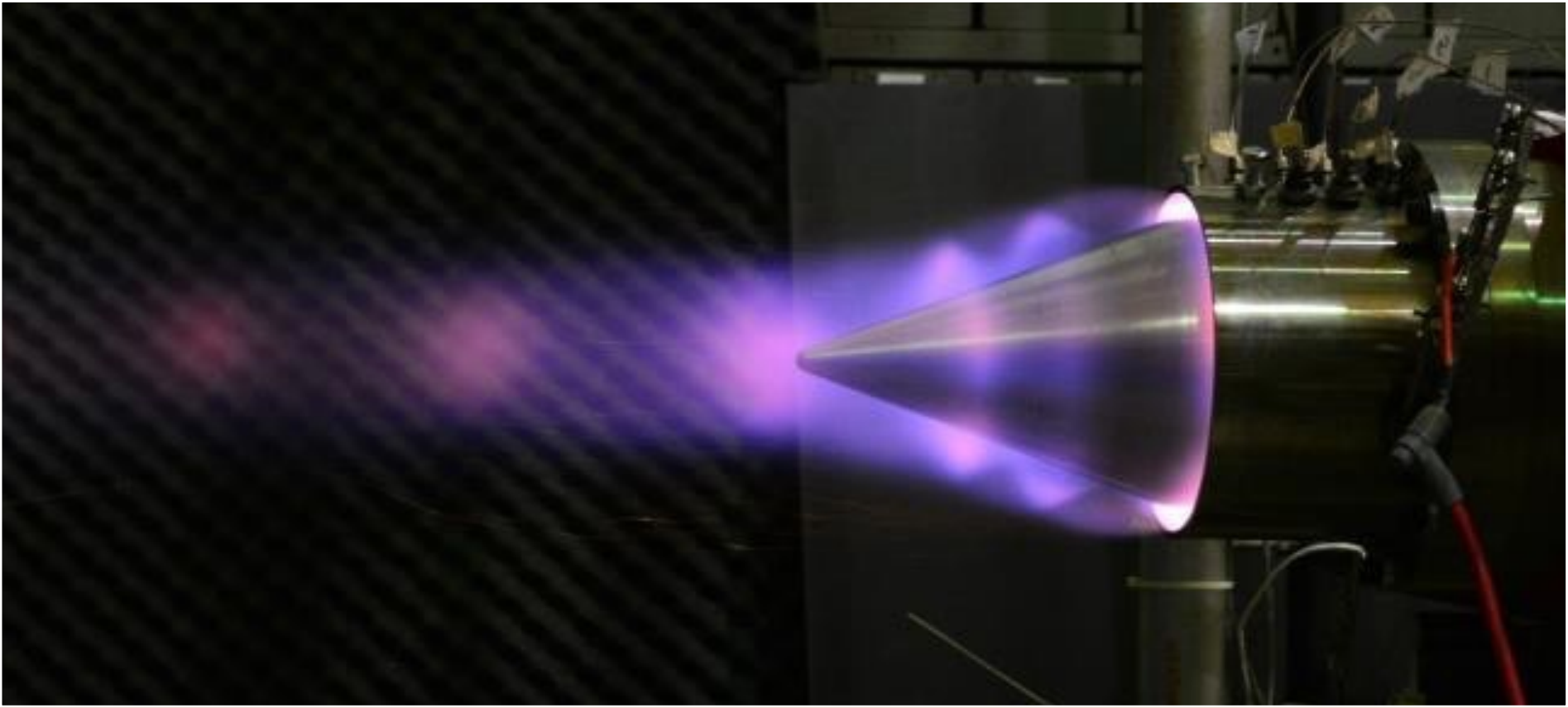
Source: https://cdnintech.com/media/chapter/70511/1512345123/media/F5.png

Problem Statement

- Non-premixed fuel and oxidizer injection in rotating detonation engines produces **structural mixture inhomogeneities that negatively impact the engine's** propulsive, thermal, and detonative efficiency and control.

Project Aims

- This project aims to develop a strategy for injecting air and fuel from separate injectors with the goal of **reducing uneven mixture distribution** within the engine's detonation channel.



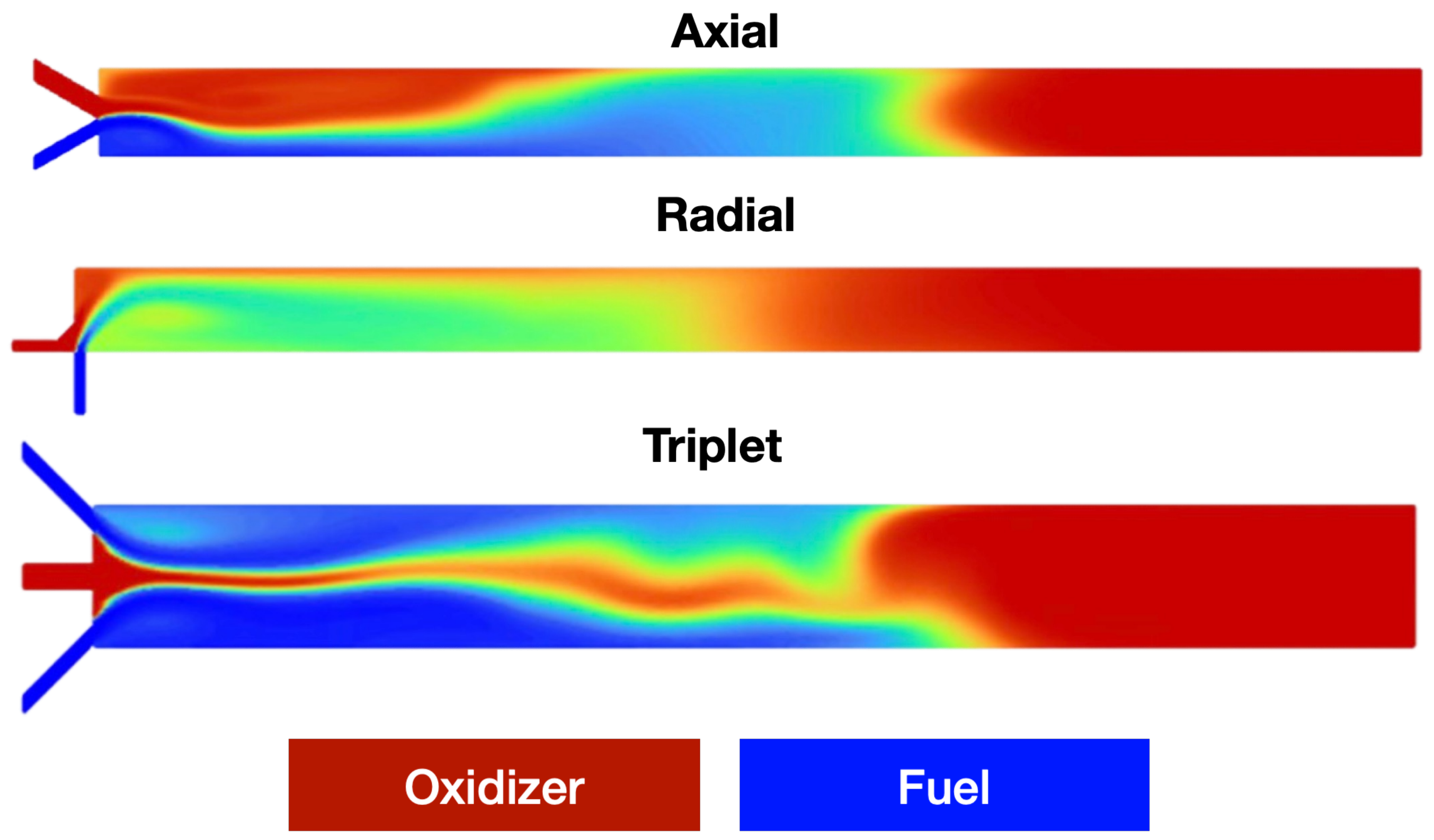
The Rotating Detonation Engine: Experimental RDE from the Air Force Research Laboratory.

Source: https://afresearchlab.com/wp-content/uploads/2023/02/rde_image7.jpg

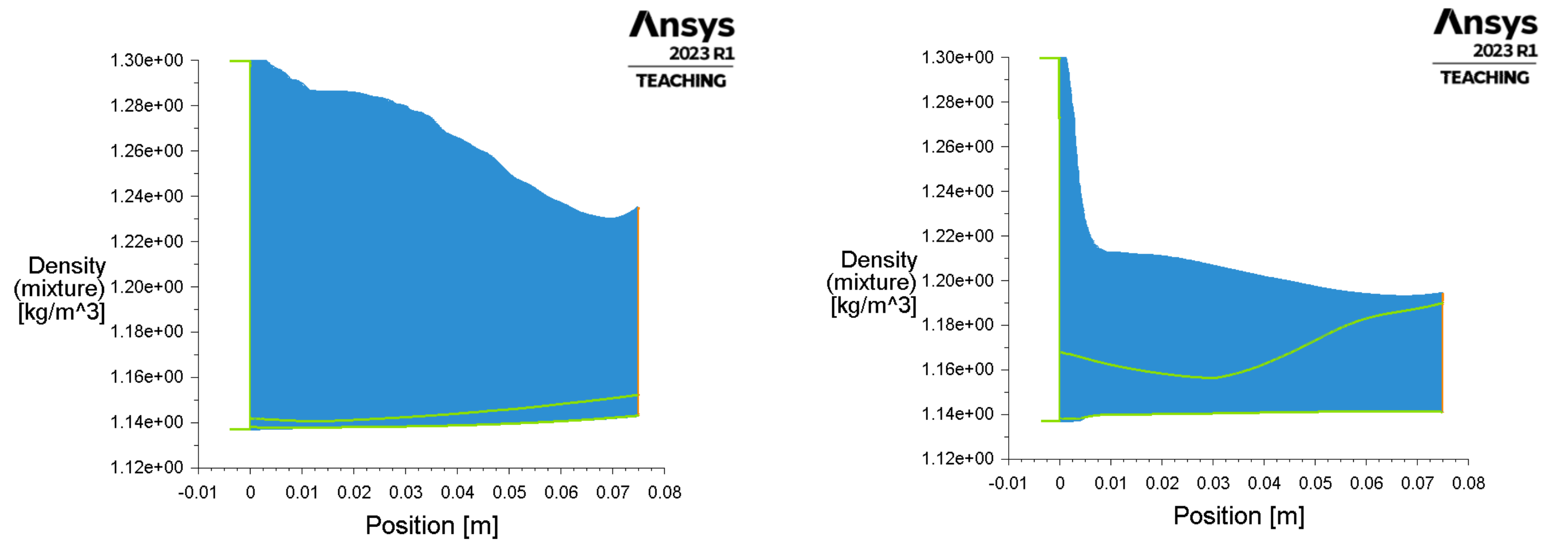
Main Takeaway

Through the iterative adjustment of injection-specific variables within a 2-D computational domain, an effective solution to structural inhomogeneities in RDE fuel-oxidizer mixtures can be developed.

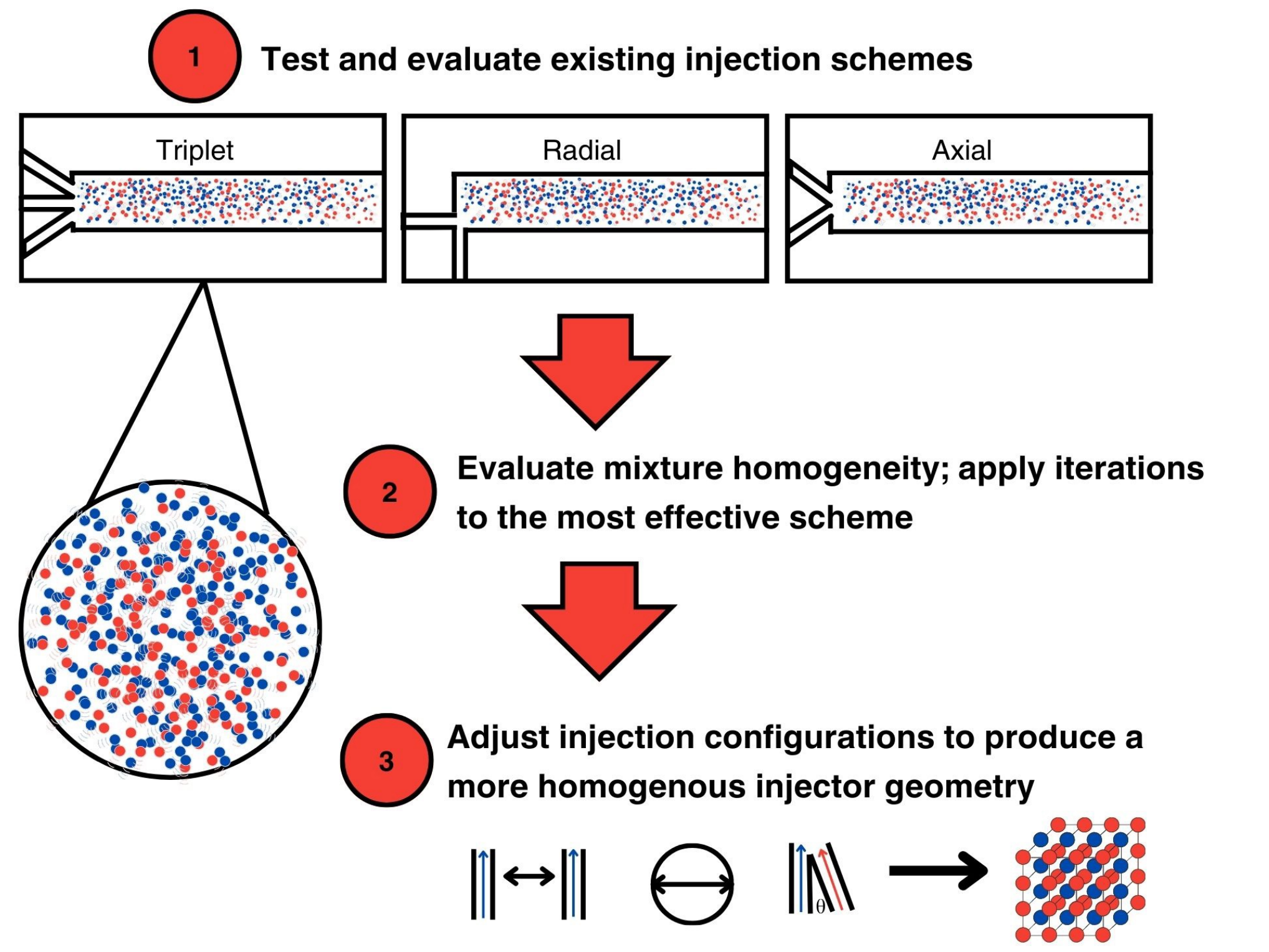
Results



	Axial	Radial	Triplet	Iterated Triplet
densityFactor Deviation	0.034	0.057	0.015	0.00848
Volume Fraction equivalence (%)	2.1	0	97.71	98.04



Methodology



1. Test and evaluate existing injection schemes
2. Evaluate mixture homogeneity; apply iterations to the most effective scheme
3. Adjust injection configurations to produce a more homogenous injector geometry

Simulation Specifics:

- Each 2-dimensional existing configuration was tested in a transient-state, turbulent flow model in Ansys Fluent
  - **Consistent parameters:** mesh size, oxidizer, timeframe
  - **Inconsistent parameters:** chamber/injector geometry, fuel, mass flow rate
- A k-epsilon solver was used to evaluate particle turbulent flow characteristics after 750ms of injection.
- Schemes were modeled using existing design parameters (Goto et al., 2019; Koo et al., 2023; Bennewitz et al., 2023).

Homogeneity Quantifications Methods

Volume Fraction Variance

- Evaluates injector-to-outlet variance in volume fraction (averaged fraction of each phase in multi-phase model).

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SAMPLE: OXYGEN PHASE FRACTION FORMULA

p1Inlet = ave(Phase1.Volume Fraction)@inlet_2

p1outlet = ave(Phase1.Volume Fraction)@outlet
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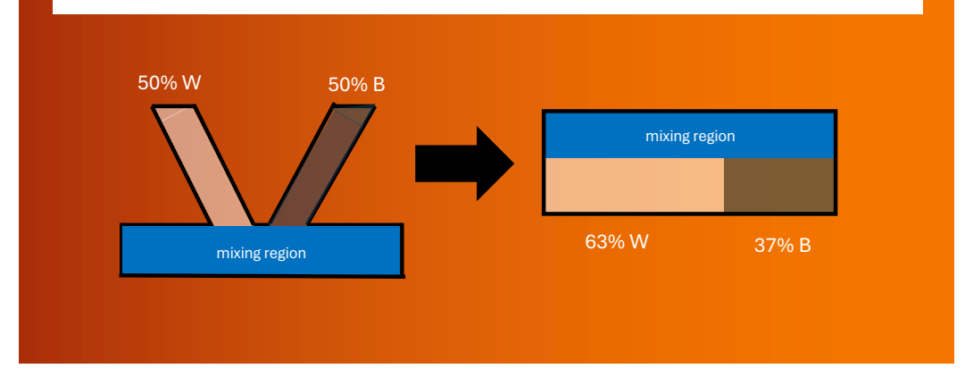
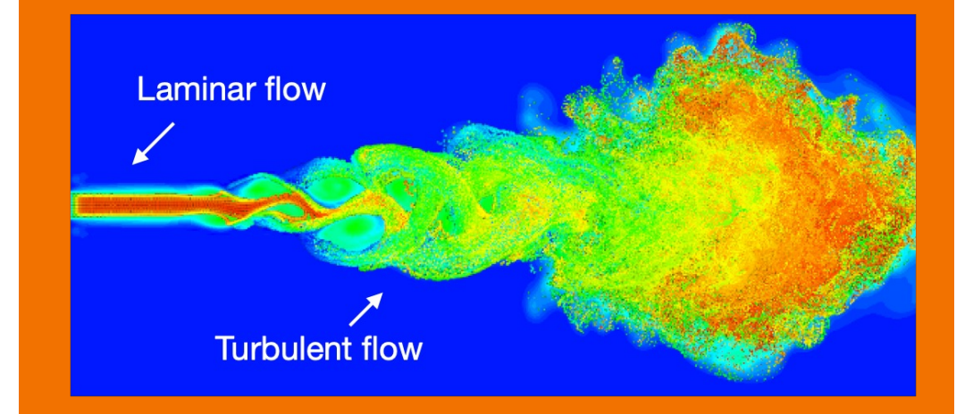


Turbulent Kinetic Energy

- Turbulent kinetic energy, as a diffusivity parameter, is supplied by non-laminar fluid flow, which fuels mixture homogenization.



Laminar to turbulent flow in a jet engine. Source:https://mriquestions.com/uploads/3/4/5/7/34572113/4018448_orig.png

densityFactor Deviation

- Compares averaged density values at inlet to through-chamber density values.
- Equivalence is quantified by a density factor ratio closest to 1.

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SAMPLE: density changes from inlet to chamber body:

densityInlet = (ave(Density)@inlet_1 + ave(Density)@inlet_2 +
ave(Density)@inlet_3)/3

densitySurfaceBody = ave(Density)@surface_body

densityFactor = densityInlet/densitySurfaceBody

Lowest deviation from 1: highest level of homogeneity
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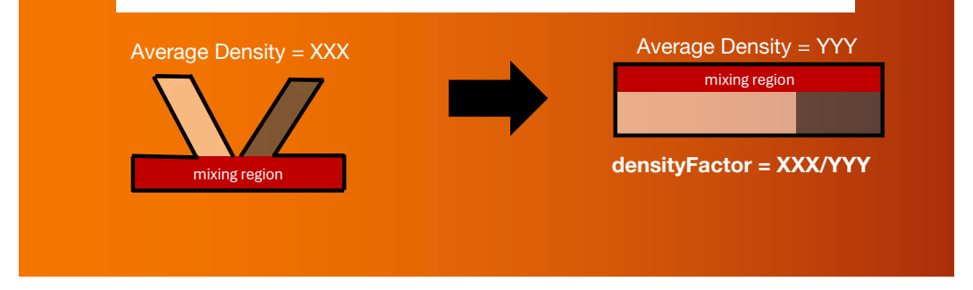
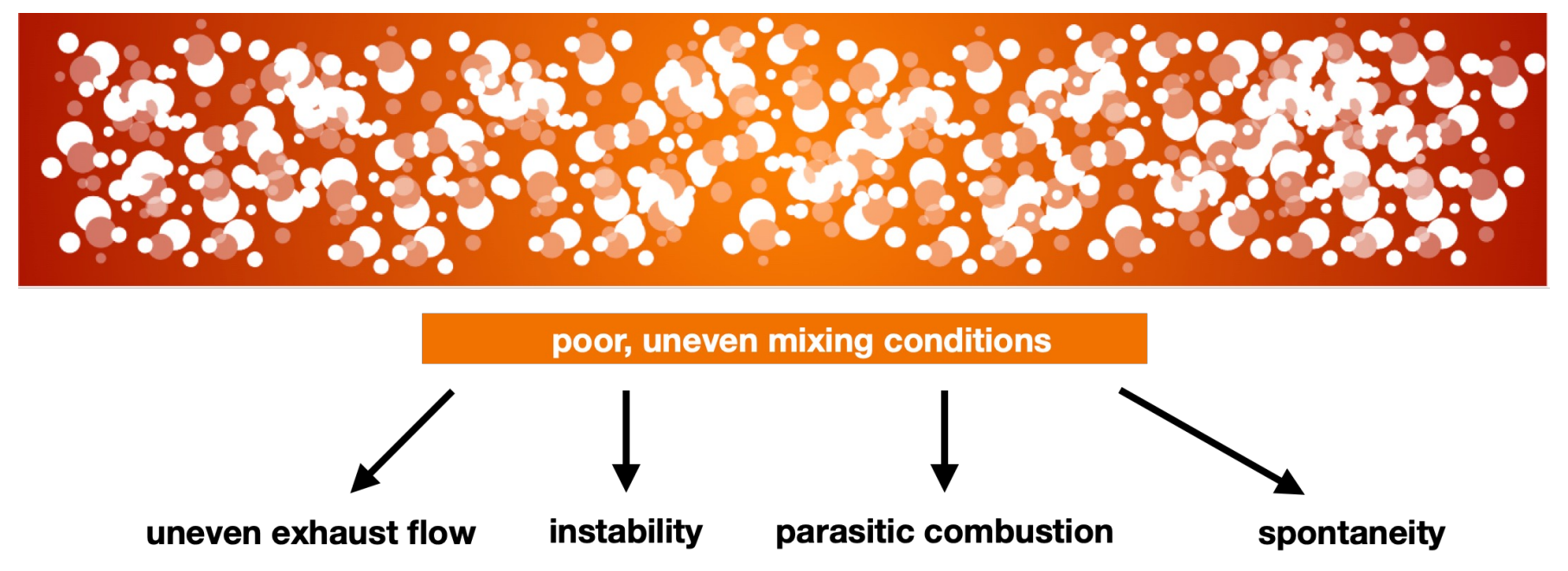


Novel Approach

Inhomogeneous Fuel Mixtures



poor, uneven mixing conditions

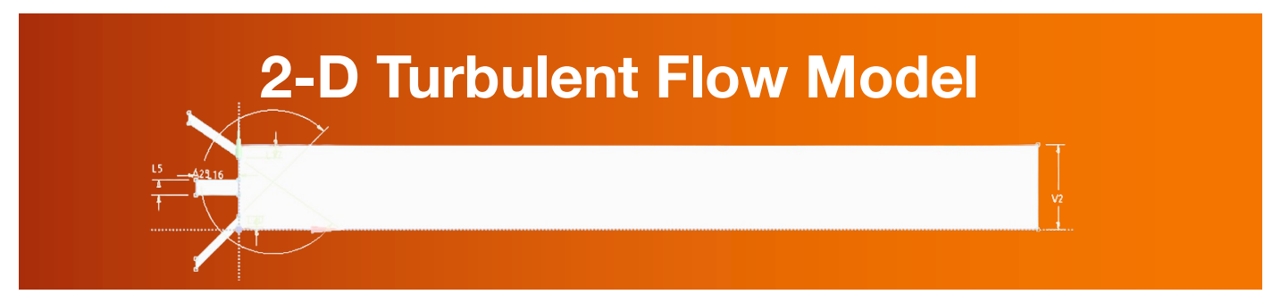
uneven exhaust flow

instability

parasitic combustion

spontaneity

2-D Turbulent Flow Model



Quantitative Homogeneity Comparison

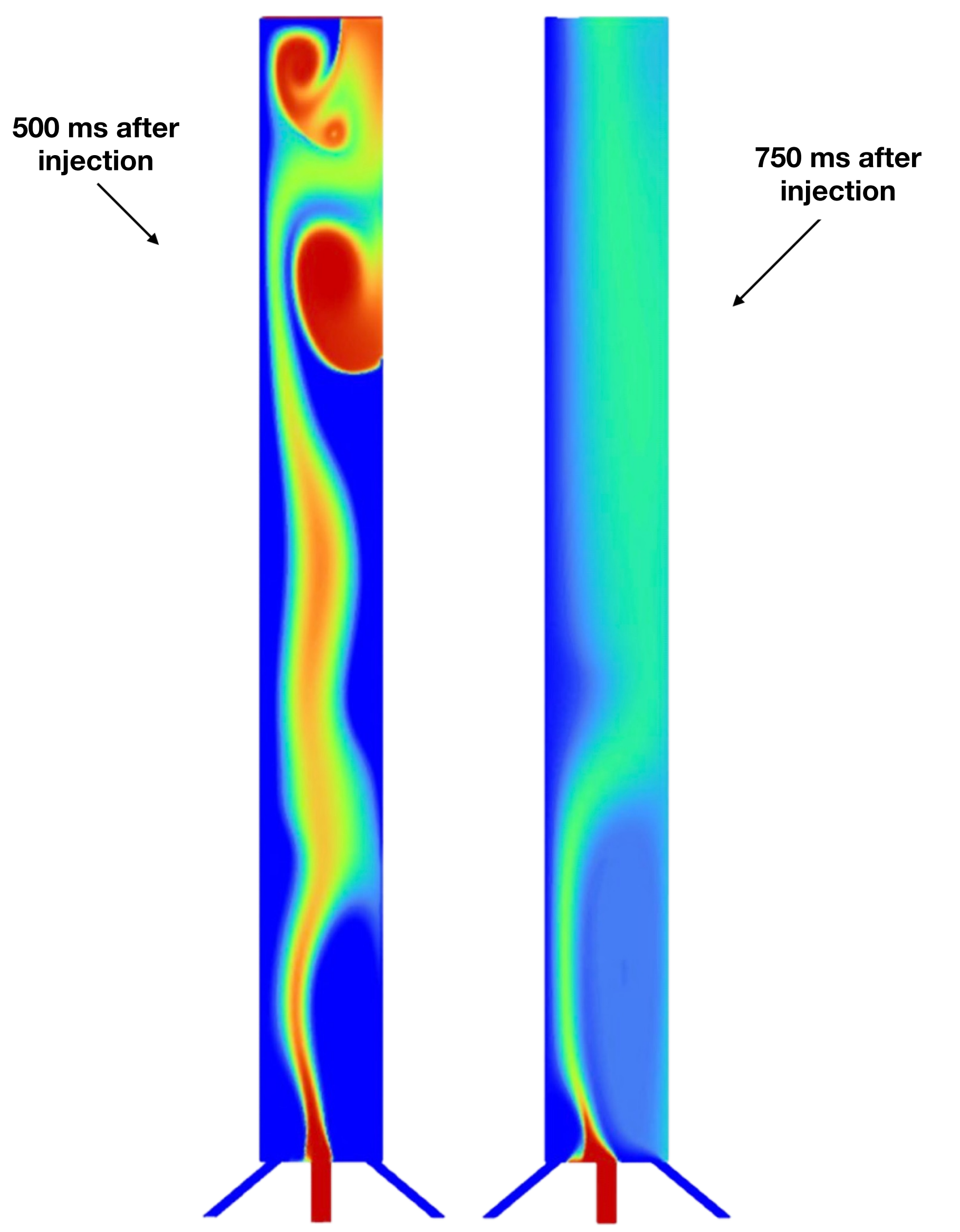
Using the densityFactor attribute to determine effective schemes

Iterative Design Enhancement

Approaching complex fluid mechanics with simplified iterative process

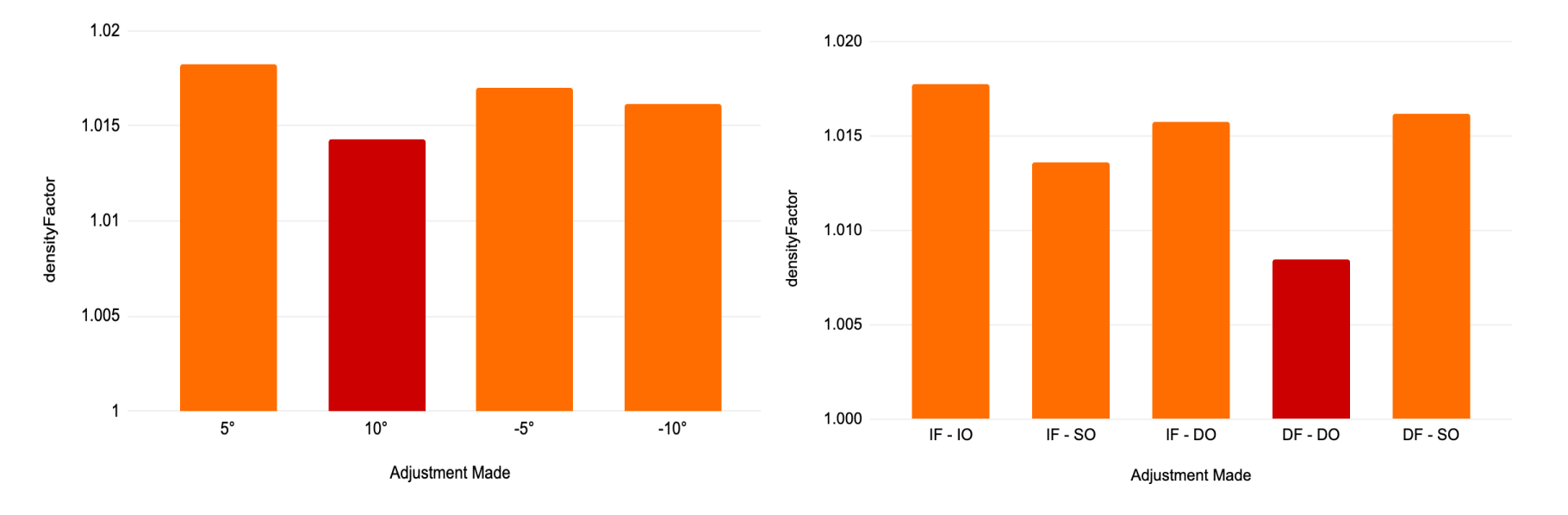
All images, graphs, and charts created by the student researcher unless otherwise noted.

Post-Iteration Analysis



10-Iteration Cycle

- Homogeneity level improvements based on densityFactor attribute.
- 10-degree angle addition to outer fuel injectors and tighter injector diameters improved overall homogeneity by 2.3%, a 6.3% improvement from previous injector configurations.
- Reached homogeneity level of 99.2% after iterations.



Conclusions & Next Steps

- This work **improves existing effective RDE injection methods by 2.3%.**
- Establishes a **new method for improving** simple in-chamber **mixture homogeneity.**
- This work may be applied to fluid injection in ventilation, defense, and rocketry.
- **Next steps:**
  - validate and improve computational model
  - decrease mesh size for more precise results
  - pursue physical experimentation with improved injector schemes

Vocabulary

- **Detonation**
  - High-pressure, rapid combustion reaction involving an accelerating shock wave front.
- **Homogeneity**
  - Level of evenness, or even distribution of a mixture.
- **Pressure-Gain Combustion (PGC)**
  - Pressure increase produced by gas expansion.
- **Propagation**
  - Transmission or advancement of a material.
- **Computational Fluid Dynamics (CFD)**
  - Computer-aided predictions of fluid-flow.