Experimental rig to characterize combustor flow-fuel mixing for improvement of CFD tools

Turbomachinery and Heat Transfer Laboratory, Aerospace Engineering, Technion – Israel Institute of Technology

SK Karthick, Ian Jacobi, and Beni Cukurel

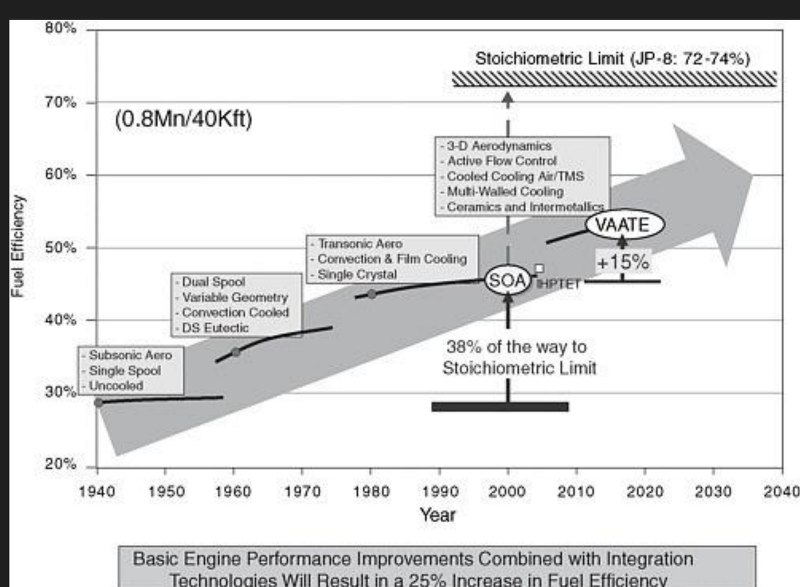
The 18th Israeli Symposium on Jet Engines and Gas Turbines

November 28, 2019, Technion – Haifa.

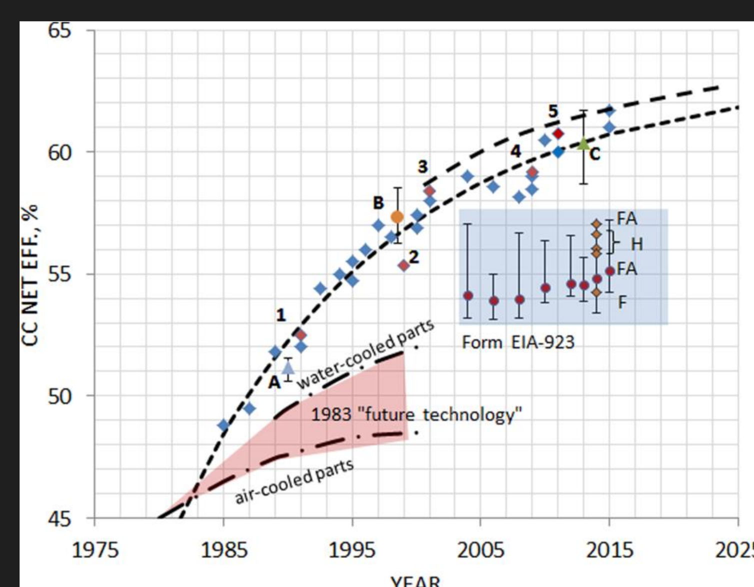
INTRODUCTION

New applications have generated new demands for competitive gas turbines,

- for high-speed vehicles where **flame stability** is of paramount importance
- in UAVs and other small vehicles, where increased **combustion efficiency** could lead to **smaller form factors** and **higher operational limits**
- in traditional vehicles where **overall efficiency** demands continue to increase



fuel efficiency achieved over years



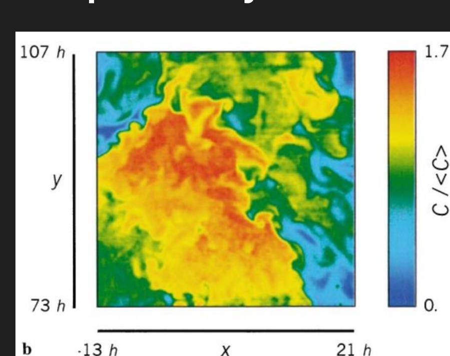
combustion chamber net efficiency achieved over years

MOTIVATION

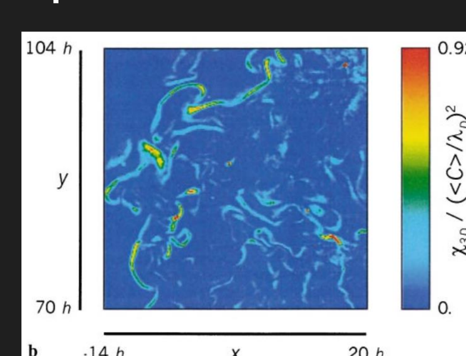
The key to designing and modeling the next generation of combustors is understanding the scalar mixing processes that occur inside them, and specifically the scalar dissipation.

Scalar dissipation | Scalar dissipation measures the magnitude of spatial variations in fuel concentration in non-premixed combustion modelling. The scalar dissipation defines the time and length-scales for turbulent mixing of combustion reactants, thus providing the key parameters for the design of mixing systems and the description of subsequent flames.

Images are from the experiments of Su & Clemens (1999)



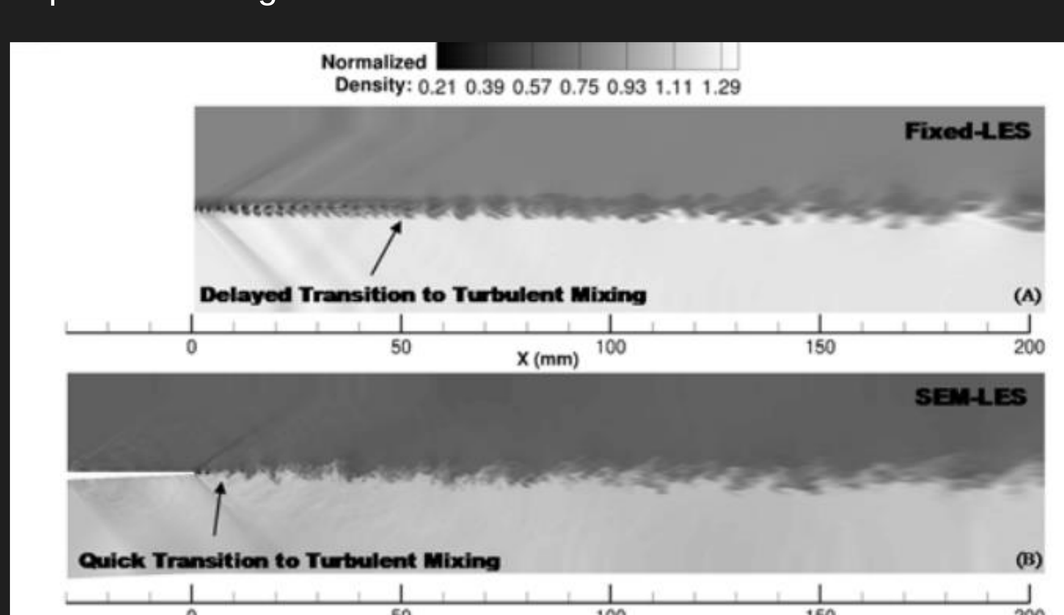
Scalar field



Scalar dissipation rate

Because the scalar dissipation rate is so important for determining combustion properties, efforts have been made to approximate its value, using (1) computations and (2) experiments.

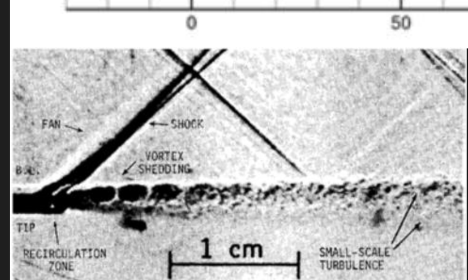
Many CFD schemes like DDES, LES, hybrid URANS have been used to estimate the scalar field. But, they do not actually solve for the fine-scale turbulence, and instead use models to represent the momentum mixing. So too, they do not solve for the fine-scale mixing, and instead use models that depend on fitting constants. The result is calculations that do not match experiments.



LES – knob position 1
(results are not so accurate)

LES – knob position 2
(results are close to experiments)
Mankbadi & Debonis (2017)

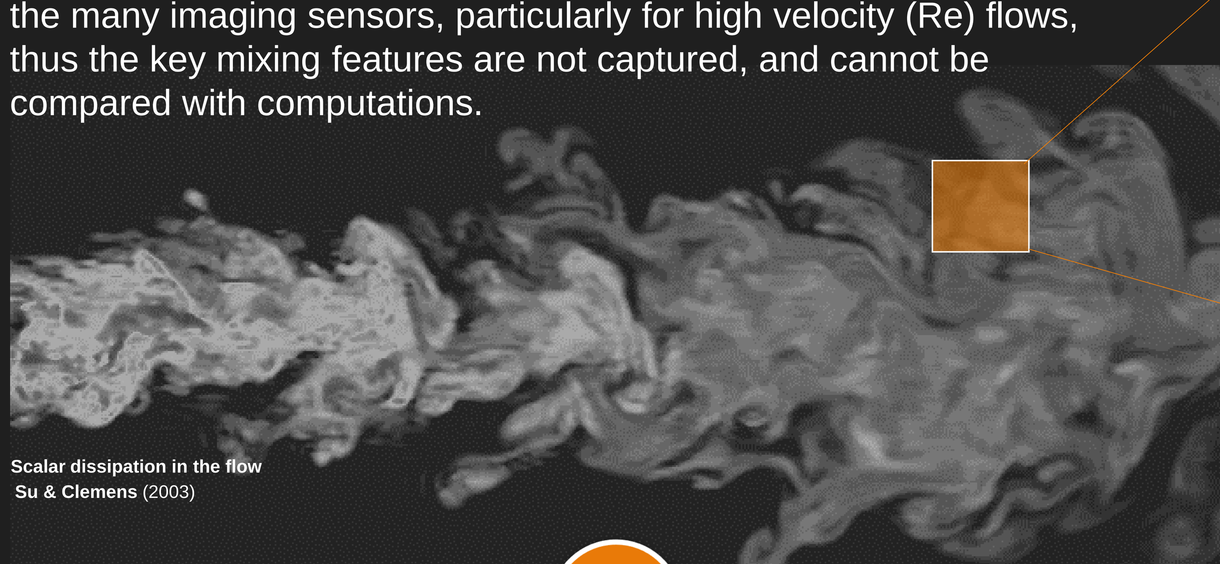
Experiments – Shadowgraph
(subsonic compressible mixing layer)
Papamoschou & Roshko (1988)



Example: A simple case study of subsonic compressible mixing layer generated across a supersonic and subsonic streams are considered. LES-k1 did not predict the turbulence, whereas LES-k2 predicted it. Still the values are slightly deviant from the experiments

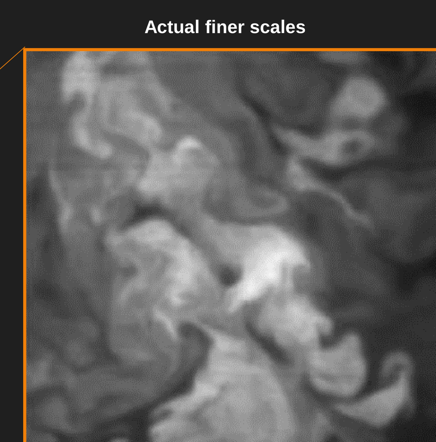
OBJECTIVES

Experiments of scalar mixing are challenging because the relevant scales (Batchelor scales) exceed the spatial resolution of the many imaging sensors, particularly for high velocity (Re) flows, thus the key mixing features are not captured, and cannot be compared with computations.

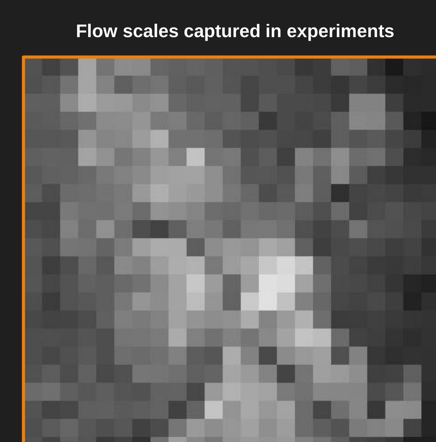


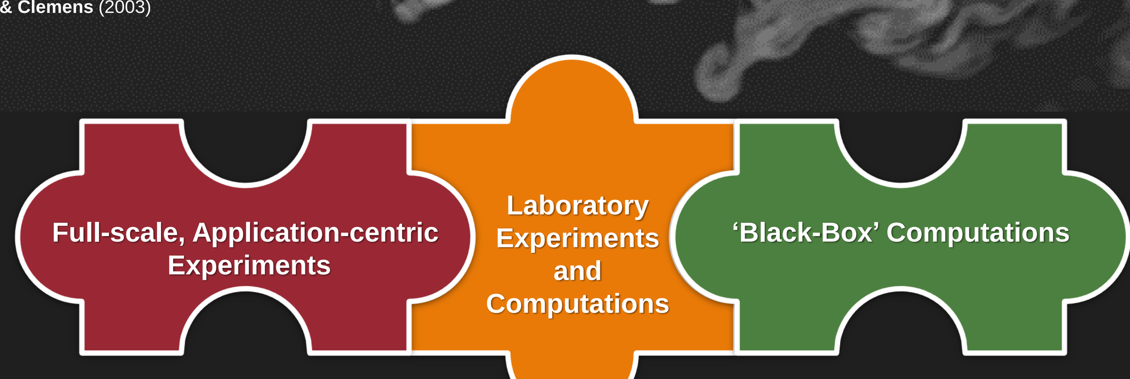
Scalar dissipation in the flow
Su & Clemens (2003)

Actual finer scales



Flow scales captured in experiments



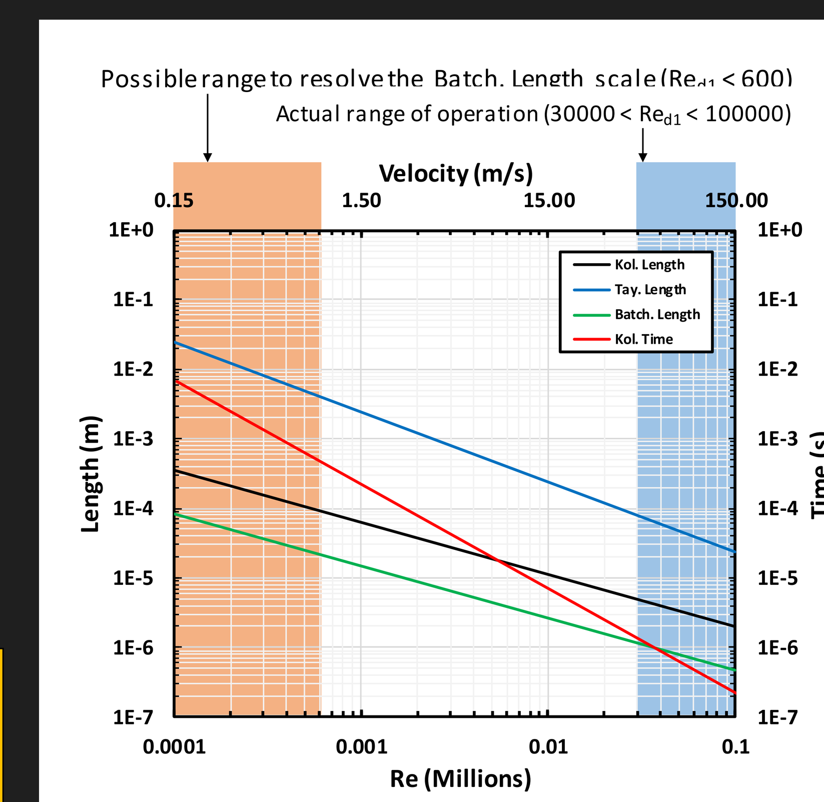


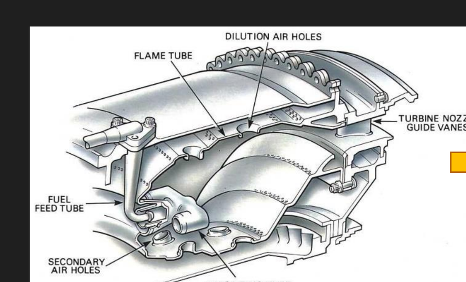
The proposed program of laboratory-scale experiments and accompanying computations will bridge the gap between the state of the art in 'black-box' scalar mixing computations and full-scale, application-specific experiments. By experimentally resolving the relevant mixing scales in simplified geometries, and contrasting the measurements with CFD, we will provide deep insight into the use and improvement of CFD tools for designing new combustors.

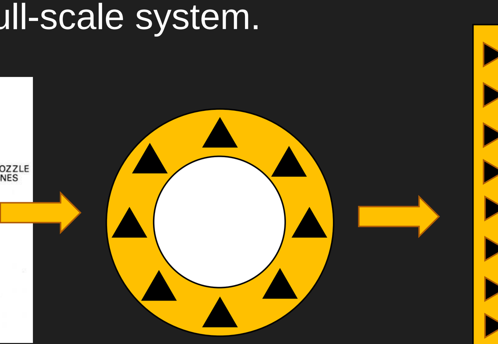
MODELING THE COMBUSTOR FLOW

- **To bridge the gap, we move from highly application specific geometries that are difficult to generalize, to more abstract combustors that capture the key physics**
- **To bridge the gap, we will study the flow over a range of flow regimes in which the scalar mixing can be fully resolved, in contrast to CFD modeling which requires tunable knobs**

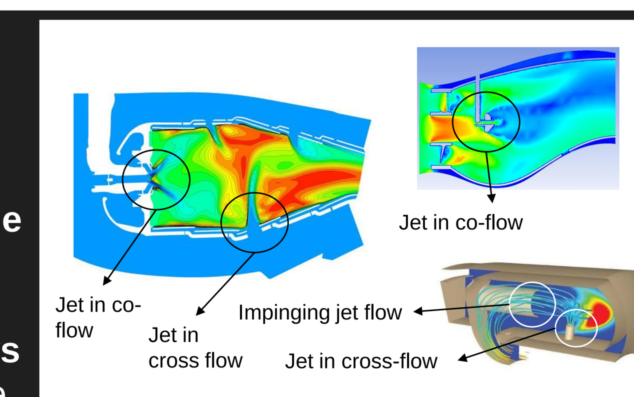
Unlike full-scale, application-specific combustors, the laboratory rig is designed to make high resolution scalar measurements easy. This means a simplified prism geometry, which was designed to faithfully capture the periodic regularity of the full-scale system.

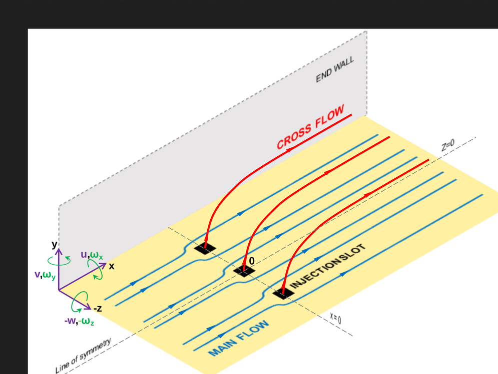






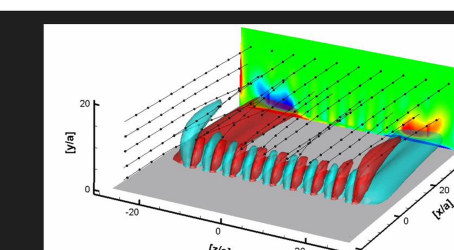
The experimental geometry is reduced in steps from the actual one
Can-combustor >> annular combustor (radial array) >> Linear array



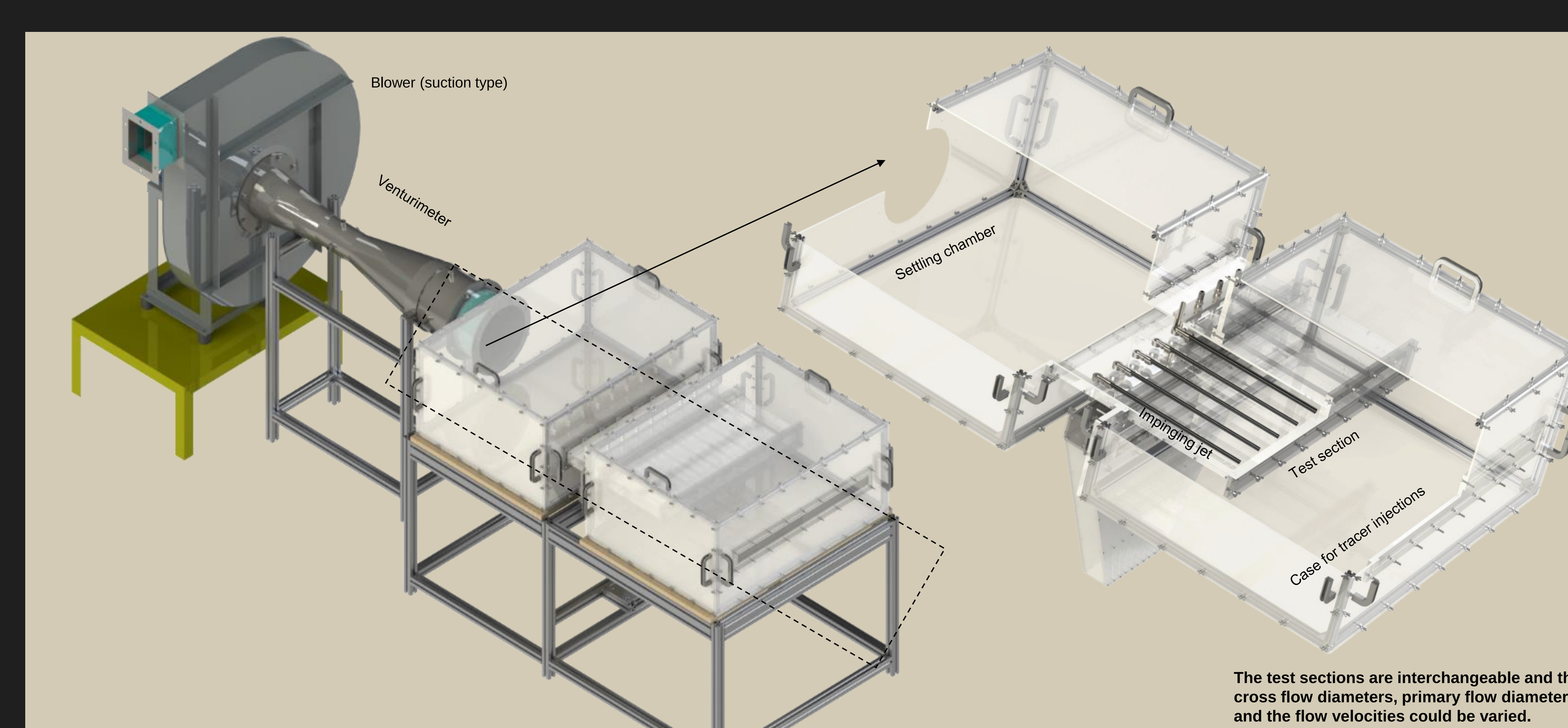


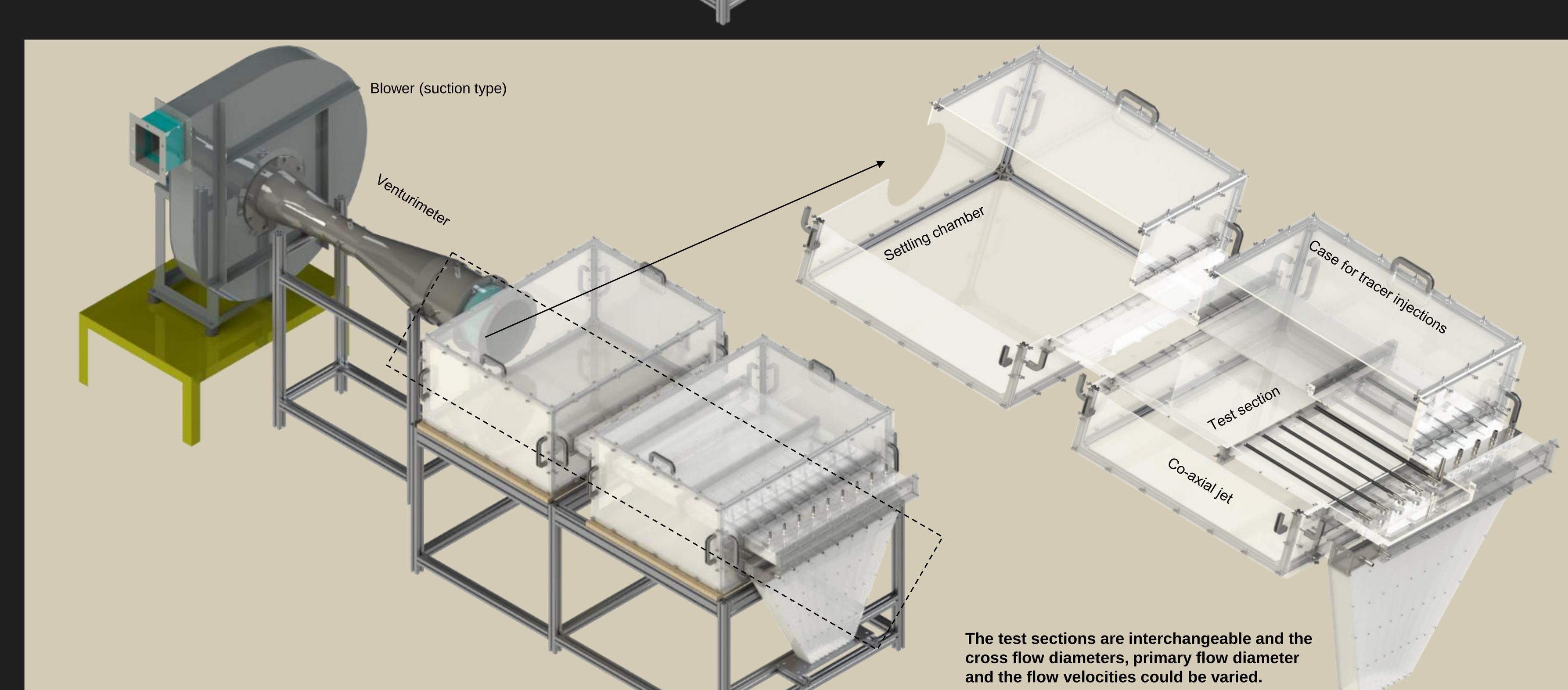
Challenges in realizing Linear Arrays
Effects of the wall Effects of array size

- Wall effects are **significant** in the module **close to wall**
- At least **9 modules are needed** so that the middle module is free from wall effects



EXPERIMENTAL TEST RIG





Careful experimental measurements of scalar mixing in a combustor will provide:

- a comprehensive database of high resolution mixing data for comparison with current and future CFD calculations
- The comparisons will also form the basis of new best-practice recommendations for the use and improvement of CFD codes, as well as
- cautionary guidance for potential CFD inadequacies.

APPLICABILITY AND LIMITATIONS

- **Geometric Abstraction |** The center modules of linear arrays have been shown in our simulations and other experiments (Bicen et al., 1988) to represent well the flow behavior in an actual annular system.

- **Cold (non-reacting) Operation |** A number of researchers have shown that the flow behavior of non-reacting flows can represent the behavior of reacting flows adequately under a variety of realistic operating conditions. In particular, the shear layer thickness and kinematic variables encountered in non-reacting and reacting flows vary only slightly (Hermanson & Dimotakis, 1988 and Tangirala et al., 1987, Schlegal & Ghoniem, 2014 and Adoua & Page, 2017). Moreover, because the flame is held far away from the zone of fluid interactions and is not confined around the axis like in the case of can-combustor, the reactive flow will closely represent the cold flow experiments (Brum & Samuelson, 1987).

Research Support by MAFAT Grant No. 4440847962