ME – PhD Thesis Colloquium

Studies on Hydrogen-Enriched Methane Combustion in a Trapped Vortex Combustor

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May 7th, 2025 at 10.30 am

Venue: Conference Room, ME @ IISc

ABSTRACT

Among the conventional fossil fuel-based power generation technologies, gas turbines are one of the cleanest and most efficient options. Instead of coal in power plants, the use of natural gas-fired open-cycle gas turbines reduces specific carbon emissions by 25% to 50%. Enriching natural gas with hydrogen is a viable means of reducing carbon emissions even further . A trapped vortex combustor (TVC) is a relatively new concept which utilizes a physical cavity for stabilizing the flame leading to higher flame stability and lower emissions. The present work explores the feasibility of the TVC as a viable combustion device for hydrogen blended natural gas fuel using an optically-accessible high-pressure combustor test facility. In the first part of the study, non-reacting flow characterization is used to establish the baseline vortex dynamics in a model trapped-vortex combustor (TVC). Using acetone planar laser-induced fluorescence (PLIF) and particle image velocimetry measurements, the cavity vortex is shown to scale with the jet main stream momentum flux ratio (J).

In the second part of the study, methane–air combustion tests are conducted to assess baseline flame behavior. The methane flame, initiated in premixed mode, is observed to be anchored along the cavity shear layer near the Rich blow-out limit (RBO) and cavity walls as revealed by OH-PLIF imaging. Lean blow-out (LBO) and RBO limits were measured. As the equivalence ratio approached the lean limit, the flame began to oscillate and partially detached. High-speed chemiluminescence imaging and pressure signals capture this instability, with a low-frequency (~200 Hz) fluctuation growing near the LBO. Rayleigh index analysis of the pressure–heat-release oscillations showed positive feedback regions in the cavity during stable operation, which diminishes as the flame nears blow-out.

In the third part of the study, hydrogen-enriched methane blends are introduced, dramatically altering flame dynamics. Hydrogen addition up to 50% by volume is observed to extend the lean flammability limit of the TVC. The lean blow-out equivalence ratio was significantly lowered with hydrogen, enabling stable combustion in high-strain-rate regions that were nonflammable with pure methane. The hydrogen-enriched flame remained more compact and attached due to higher extinction strain rate. Emission sampling showed a marked drop in CO and unburned hydrocarbon emissions with hydrogen enrichment due to more complete combustion, while NOx emissions rose moderately with higher flame temperatures. Introduction of hydrogen fuel also resulted in the higher combustion efficiency. The tests were then carried out at higher pressures up to 5 bar. It was observed that the flame structure changed from corrugated flame regime to broken framelet regime. An important observation is that the TVC allows for ultra-lean operating conditions at which no thermo-acoustic instabilities are observed. In the final part of the study, 100% hydrogen operation (without any methane) in the TVC was successfully demonstrated. The pure hydrogen flame anchored predominantly as a diffusion flame stabilized by the cavity vortex – and exhibited extremely high reactivity. Overall, the current study successfully demonstrates the use of hydrogen-enriched methane fuel in a TVC, detailing the strategies to be adopted while also highlighting the improvement in performance obtained due to addition of hydrogen to the fuel.

ABOUT THE SPEAKER

Nikhil Verma is a PhD student in the Department of Mechanical Engineering at IISc Bengaluru. He completed his B.Tech. in Mechanical Engineering from ABES Engineering College, Ghaziabad, Uttar Pradesh, in 2017. He completed his Masters Degree from the Indian Institute of Space Science and Technology in 2019. He joined IISc as a PhD student in January, 2020. His research interests include Combustion, Airbreathing Propulsion, Rocket Propulsion, and High enthalpy flows.