Introduction

Pre-chamber jet ignition is a useful approach for lean, low-NOx combustion, and used in natural gas IC engines [2], pulse detonated engines [3], and more recently, in wave rotor combustors (WRC) [1]. Combustion initiated by hot jet ignition is a complex phenomenon which includes jet penetration and mixing, ignition of relatively cold combustible mixture, vortex generation, shock-wave propagation and their interactions. Shock interaction with the density gradients and the resulting baroclinic vorticity accelerates the initial ignition. This can be a means for faster combustion in the WRC, as the vorticity increases mixing, flame surface area, and turbulence, which can all contribute to increased heat release rate. The WRC consists of an array of channels arranged around the axis of a cylindrical drum. When used as a novel combustor in gas turbine engines, the WRC can reduce fuel consumption rate, greenhouse gas emissions, and required engine air flow sizing by up to 20% based on thermodynamics.

Model Features

- Pre-chamber pressure: 6 bar or 2 bar
- Pre-chamber temperature: 2640 K (post-burn, calculated from thermochemical equilibrium)
- Pre-chamber fuel: equi-molar CH₄-H₂ blend
- Pre-chamber gas equivalence ratio: Φ=1.1
- CVC chamber pressure: 1 bar
- CVC chamber temperature: 300 K
- CVC chamber fuel: 30:70 molar CH₄-H₂ blend
- CVC chamber gas equivalence ratio: Φ=1.0
- Computational code: CONVERGE CFD
- Flow solver, turbulence & kinetics modeling:
  - Coupled solver, RNG k-ε RANS, SAGE chemistry
  - Reaction mechanism: DRM19
- Efficient computational modeling:
  1) Multi-zone Modeling.
  2) Adaptive Mesh Refinement (AMR)

Flame Surface Area & HRR

- 6 bar pre-chamber pressure: Right after the fast-slow interaction at around 2.4 ms, the leading flame surface area reaches maximum value, about 16 times the channel cross sectional area.
- 2 bar pre-chamber pressure: The shock wave does not affect the flame in terms of SFI or flame corrugation, linear relation between flame surface area and heat release rate (HRR).

Flame Propagation

- Gas motion inside CVC chamber caused by pre-chamber pressure and CVC combustion.
- Fast deflagration flame propagation must be distinguished from gas motion.
- First shock-flame interaction (SFI) at around 1.6 ms and second SFI at around 2.2 ms.

Flame Surface Area

Fig 1: Schematic of wave rotor combustor (courtesy Rolls-Royce)

Research Setup

Pre-chamber CVC chamber Camera

Fig 2: Experimental apparatus of traversing jet ignition rig at IUPUI

Fig 3: 3D Geometry for the numerical study of traversing jet ignition

In the laboratory pre-chamber, a richer mixture is ignited using a spark. The partially combusted gas is injected through a converging nozzle, which traverses the CVC chamber and ignites its lean mixture. This reproduces WRC ignition jet behavior, where reactive hot gas from a combusted channel traverses a fresh channel.

Summary & References

Shock wave interaction with the flame can quickly increase flame surface area when the pre-chamber pressure is large, especially on its second pass coming from the hot side. However, even with lower pre-chamber pressure, there is eventual increase in flame surface area and corresponding increase in heat release rate.