High fidelity numerical techniques for the development of supersonic/ hypersonic air-breathing vehicles @ Heat Transfer Lab, IIT Hyderabad

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The quest to travel faster than the speed of sound gave birth to the invention of supersonic and hypersonic vehicles. The demand for agile, high-performance and long-range next-generation supersonic/hypersonic vehicles is ever-growing. Design and development of contemporary supersonic/hypersonic aircraft, air defense systems, and re-entry vehicles rely on the comprehension of ubiquitous compressible turbulent flow over the surfaces of these vehicles. Airframe structures of these supersonic/hypersonic vehicles experience an enormous amount of drag and aerodynamic heating owing to the formation of bow shock ahead of the vehicle and dissipation of kinetic energy into internal energy on the vehicle surfaces. Experimental investigation of full-scale vehicle models is seldom carried out owing to the exorbitant cost of full-scale model testing. The aforementioned limitations of experimental investigations pave the way for computational fluid dynamics (CFD). With the advent of high fidelity numerical schemes viz., compact schemes and a marked increase in the computational resources (viz., high-performance computing facilities, parallelization of CFD codes viz., OpenFOAM) the usage of CFD as a design optimization tool become prominent.

The phenomena of shock train formation in a constant or nearly constant area duct are encountered in scramjet (supersonic combustion ramjet) engine isolator/channel. A Series of multiple shocks are established in the channel if the flow through the channel is subjected to back-pressure (i.e., Poutflow > Pinflow) arising due to combustion in the combustor.

We have carried out numerical investigations (by employing an in-house solver) to find a combination of inflow Mach number and the back-pressure ratio, for which the shock train is fully established in the isolator or, it is fully disgorged from the inlet forming subsonic conditions in the channel/isolator, as depicted in **Fig. 1** at different Mach numbers **(Ref. 1)**.

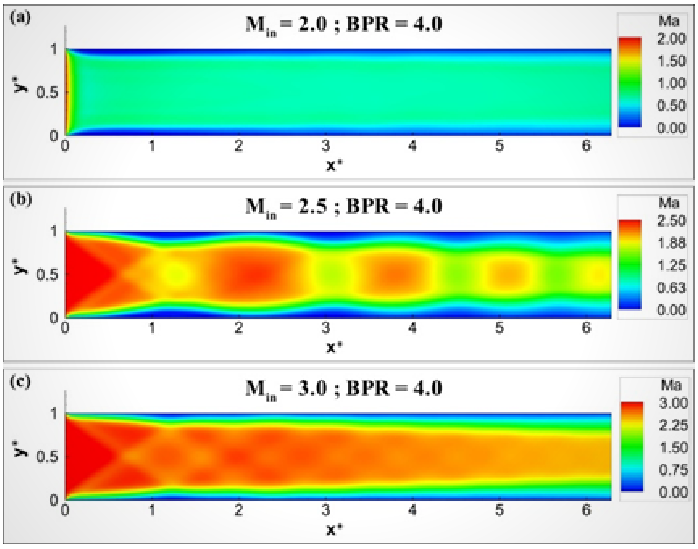

Fig. 1: Mach contours at different Mach numbers at Back Pressure Ratio equal to 4

Cavities in the scramjet engine combustor facilitate in establishing sustained combustion by retarding the supersonic flow, therefore, often referred to as flame holders. We have investigated the strength of the recirculation zones formed in the modified base rectangle and angle cavity-type flame holders. Here, we have modified the base rectangle and angle cavities by introducing intrusive and extrusive types of subcavites in the base cavities. Intrusive type **(see Fig. 2)** of subcavity can be preferred over an extrusive type of subcavity in the design of a cavity-type flame holder for scramjet engines for air-fuel mixing augmentation and efficient combustion **(Ref. 2)**.

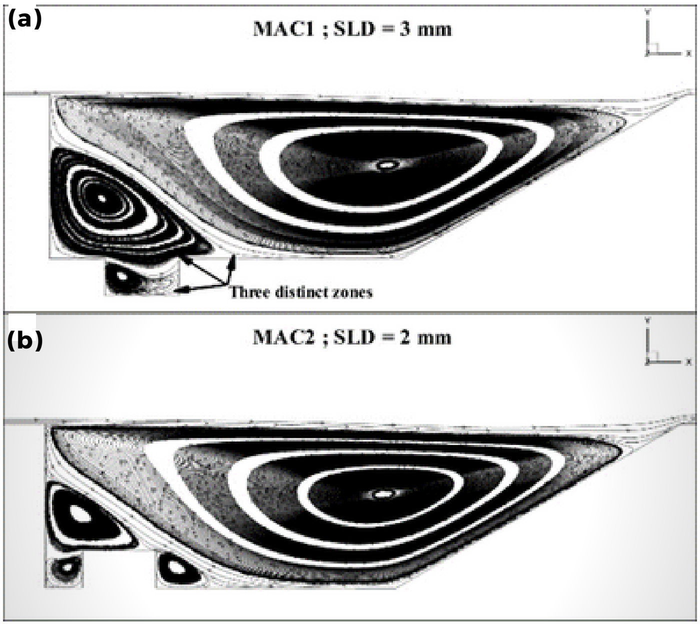

Fig. 2: Streamline contours at Mach 2: (a) Modified Angle Cavity1 (extrusive), and (b) Modified Angle Cavity2 (intrusive)

Shielding the dome-shaped forebody of the supersonic/hypersonic vehicles from severe aerodynamic drag and heating is an essential and challenging task for the designer. Because reducing the drag markedly increases the flight range, economizes the fuel usage, reduces the complexity of the propulsion system, and maximizes the gross takeoff weight [i.e., a 1% reduction in total drag can lead to 5 to 10% increment in payload carrying capacity **(Ref. 3)**]. We have explored the effectivity of different active [cold fluid injection] and passive [mechanical spike at different spike semi-cone angles (θ_S) and bump on the spike stem] techniques in mitigating the aerodynamic drag and heating. Correlations are proposed to estimate the aerodynamic drag and heating as a function of θ_S at different free-stream Mach numbers. Results also highlight that effectivity of the small bump **(see Fig. 3)** on the spike stem in reducing aerodynamic drag is equivalent to that of the cold fluid injection technique **(Ref. 4)**.

References:

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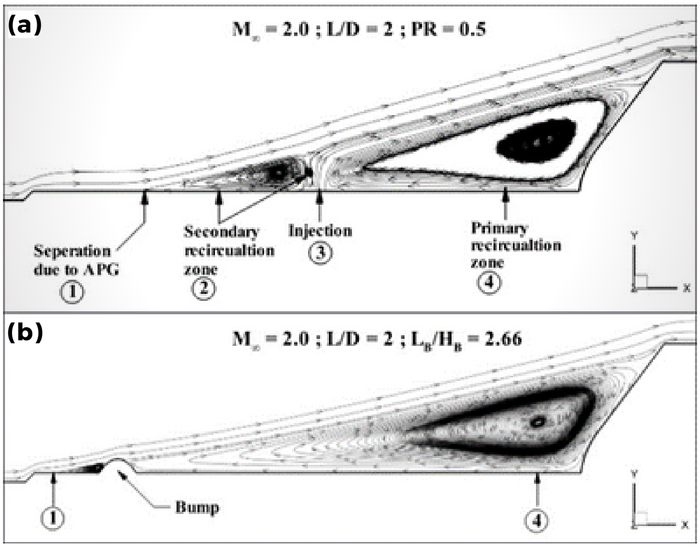

Fig. 3: Streamline contours at Mach 2: (a) spike with lateral injection, and (b) spike with a small bump on the stem

Multi-scale modeling of ductile fracture

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The genesis of macroscale damage in alloys lies in the microstructural inhomogeneities. The perceivable macro damage is usually initiated at much lower scales. The mechanisms leading to ductile failure are of fundamental interest in nuclear technologies, hypersonic applications, aerospace & defense sectors, sheet metal applications, ceramic matrix composites, additive manufacturing, biomedical implants, etc.

At the micro-mechanics lab, IIT Hyderabad, our group works on ductile failure mechanisms. For example, ductile failure of metal reinforcements embedded in ceramic matrix composites is one of the active areas of research. The ceramic matrix composites (CMC) are brittle in nature, particle strengthening is carried out in these materials to increase the ductility. Over several years, our team has developed and implemented advanced numerical techniques to understand the critical stages in ductile failure. The voids are the starting point for dimples commonly seen in the fractography images of the fractured ductile specimens. Hence, the stages in ductile failure can be broadly classified into void nucleation, growth, and coalescence.

A brief overview of the multi-scale model developed at our lab to understand cavitation instability is presented here. The developed model effectively captures the deformation mechanisms at different scales (macro to meso) and connects the scales using the state variables. From experimental literature, the dominant failure mechanisms observed in CMCs are ductile failure of the metal reinforcement, cracking of brittle matrix, and de-cohesion of the matrix and reinforcement. Out of these failure modes, ductile failure of the metal reinforcements is the dominant failure mechanism.

Ductile failure of the metal reinforcement, its influence on the overall mechanical properties of CMCs is quite challenging due to the complex interplay between anisotropy of the metal reinforcement, configurational defects (such as cracks), and material constraints experienced by the reinforcement. In CMCs, when the crack advances, two possible scenarios are encountered: crack circumventing the reinforcement and crack bridging the reinforcement.

When the interface between the particle and matrix is weaker, de-cohesion of interface and partial matrix cracking is observed. While the interface between the particle and matrix is stronger, crack bridging phenomena are predominantly observed (see Fig. 1). All these failure mechanism results in a significant increase in fracture energy of the CMCs.

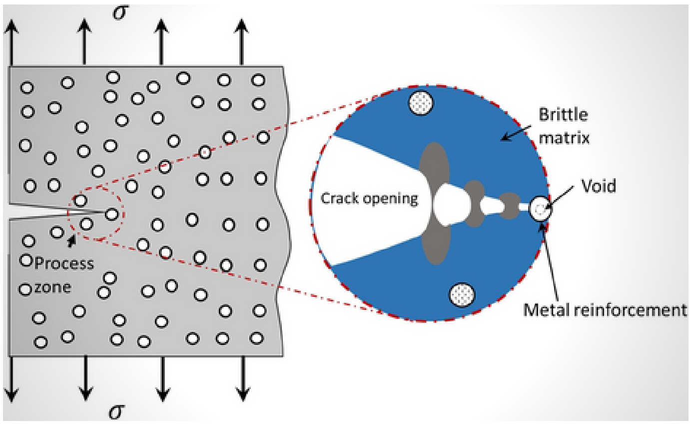

Fig. 1: A schematic of fracture in brittle matrix composite with reinforcement

In the latter scenario, fracture energy is solely due to cavitation. While in the former scenario, the observed fracture energy is partially from the cavitation, interface de-bonding, and matrix cracking. Instabilities such as exponential void expansion at certain constant remote strain are observed during cavitation. The critical stress corresponding to this cavitation instability is of interest in understanding void nucleation. Further, material anisotropy greatly influences critical stress. Earlier estimates of critical stress were based on isotropic phenomenological models. To address this, in our group, we have conducted a systematic approach to arrive at the limits of cavitation instability using mechanistic approaches based on crystal plasticity framework.