Supersonic combustion modeling based on OpenFOAM

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Supersonic combustion modelings conducted by the author's group based on OpenFOAM is present by introducing the recent modeling results. Two types of fuel, hydrogen and kerosene for the scramjet combustor were used in the modeling. As the detailed kinetic mechanisms for kerosene usually contain thousands of elementary reactions, the reduction work of kerosene mechanism conducted by the author's group is also introduced. As of this writing, the smallest skeletal kerosene mechanism has been reduced to have only 19 species and 53 reversible reactions. The influences of kinetic mechanisms, global equivalence ratios, inlet Mach number, geometric shape, and domain symmetry were analyzed based on high-fidelity modelings and available measurements. It is pointed out that with the advance of computational technology, modelings with both accurate descriptions of flow and chemistry are becoming an indispensable and promising approach for the study of supersonic combustion.

The modelings are performed by the compressible reacting flow solver AstroFoam, which is developed from the standard compressible flow solver rhoCentralFoam [18] distributed with the finite-volume (FV) unstructured CFD package OpenFOAM V3.0.1 [19]. The main development is the adding of a full species transport module with multi-component diffusion and turbulent combustion module. The OpenFOAM CFD package has been coupled with CHEMKIN II chemistry solving package [20] to accurately calculate the multicomponent thermophysical and transport properties, as well as SUPERTRAPP V3.1 package [21] to determine the non-ideal gas properties. The nonlinear inviscid convective fluxes in AstroFoam are evaluated by the semi-discrete central Kurganov-Tadmor (KT) scheme [22] inherited from rhoCentralFoam [18], which assumes a second-order numerical dissipation in resolving discontinuities (e.g., shock waves and rarefaction tips) yet a high computational efficiency due to its Riemann-free simplicity. The volume integration of the spatial gradient, divergence and Laplacian terms in the partial differential equations (PDEs) are discretized as the Gauss face integration, where the face values are interpolated by the third-order scale-selective discretization (SSD) scheme [23]. The time integration is advanced by the second-order Crank-Nicolson scheme [24]. The AstroFoam together with the original rhoCentralFoam solver was firstly validated for various frozen flows, including the canonical shock tube problem, forward step flow, hypersonic flow over a biconic, and supersonic jets [18, 25-31]. The solver is then applied to various scramjet combustor cases [32-37] to examine its accuracy and robustness in the modeling of complex supersonic combustions.

The typical working scope of scramjet combustors is Ma= 4-8 and H (altitude)= 16000-26000 m in the Ma-H map, most of which has been covered by the serial studies conducted by Yao et al. [43-50, 61, 65-71] as summarized in Table 1 and Figure 1. Three geometric types of supersonic combustors were modeled, including the traditional rectangular combustor, and two novel non-rectangular combustors: a round combustor and an elliptic combustor. The inlet Mach number ranges from 2.0 to 3.0, which correspond to the flight Ma numbers from 4.0 to 7.0. Fuel-lean and fuel-rich cases with global equivalence ratios from 0.6 to 1.4 were modeled for comparison. In a recent study [65], a kerosene-fueled supersonic combustion modeling based on 135.6 million cells was reported (Figure 2).

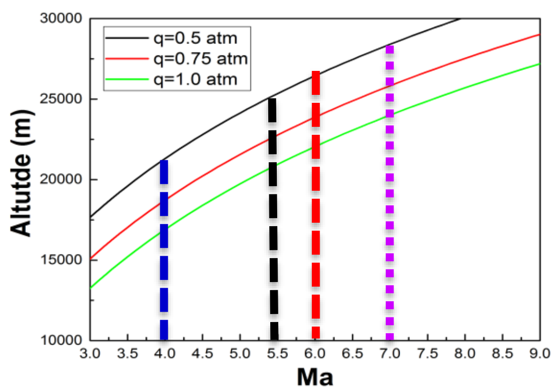
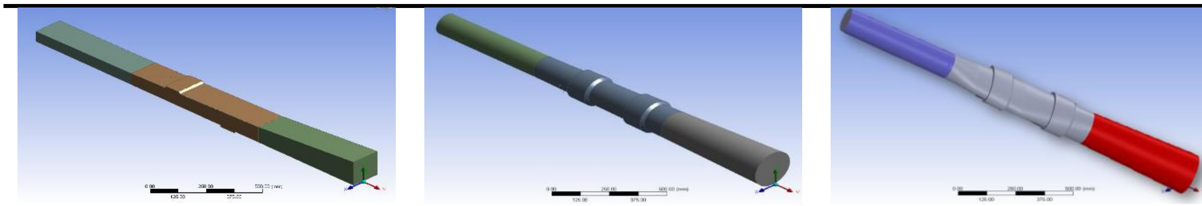


Figure 1. Working scope of modeled scramjet combustors

Table 1. Inlet Mach numbers and global equivalence ratios of modeled cases



Rectangular combustor		Round combustor			Elliptic combustor	
Ma=2.0	Ma=2.5	Ma=2.0	Ma=2.5	Ma=3.0	Ma=2.5	Ma=3.0
Φ=0.8	Φ=0.6	Φ=0.7	Φ=0.64	Φ=0.7	Φ=0.8	Φ=0.8
Φ=1.0	Φ=1.0		Φ=0.7	Φ=0.8		
Φ=1.2	Φ=1.2		Φ=0.8			
Φ=1.4						

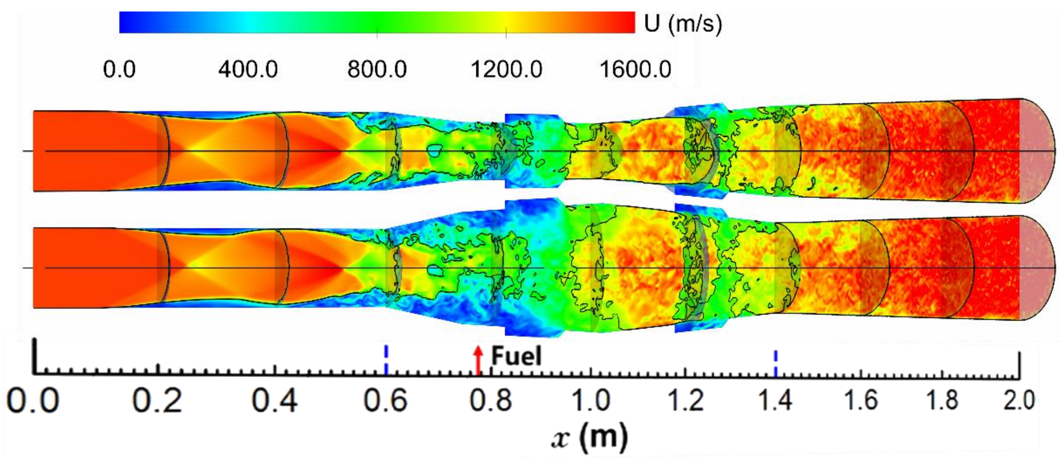


Figure 2. Supersonic combustion modeled by 135.6 million cells [65]