Validation of an Implicit Density-Based Solver for Supersonic Combustion

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A novel solver for chemically reacting flows has been developed within the open-source CFD framework OpenFOAM. This solver is based on a fast implicit finite volume lower-upper symmetric Gauss-Seidel (LU-SGS) algorithm to solve the fully coupled Navier-Stokes and species transport equations efficiently. It is specifically tailored for a wide range of reactive flows, from subsonic to supersonic. It targets applications such as turbomachinery and propulsion system development, supersonic hydrogen combustion, pressure gain combustion, and supersonic steam cracking processes.

The solver's capabilities are demonstrated through simulations of a supersonic combustor with a strut-based hydrogen injection system, where the non-premixed flame stabilizes in the wake of the strut. Validation is performed through qualitative and quantitative comparisons with experimental data and prior CFD studies [1,2].

In the first phase, steady-state RANS simulations are performed for reacting and non-reacting flows, using four different mesh refinements. These simulations closely match experimental data regarding pressure, temperature, and velocity. However, steady-state RANS cannot capture the unsteady behavior that strongly influences the flow dynamics. For instance, recirculation regions form behind the strut, trapping hydrogen and affecting fuel distribution. The high turbulence generated by under-expanded hydrogen jets and shear layer instabilities significantly enhances mixing between the hydrogen and incoming air. This turbulence-driven mixing, strongly linked to the unsteady nature of the shear layer, plays a critical role in stabilizing the flame downstream of the strut.

To capture these unsteady effects and gain deeper insights, Large Eddy Simulations (LES) are conducted for both reactive and non-reactive flows. LES provides detailed characterization of velocity fluctuations, turbulence-chemistry interactions, flame structures, and combustion stabilization dynamics. The simulations also capture oscillatory behaviors of the recirculation zones, offering valuable information on the transient features of the flow.

The developed solver is a robust and efficient tool for simulating complex supersonic reacting flows. Its ability to capture detailed flow physics and turbulence-chemistry interactions, especially when using LES, highlights its potential for advancing the design and analysis of high-speed combustion systems.

References

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