Computational fluid dynamics is used as a virtual wind tunnel to optimize the design of scramjet engines at up to Mach 6.5.

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Conventional jet engines use a turbine-driven compressor to compress air prior to combustion of fuel. The exhaust from the combustion drives the turbine and creates thrust from the nozzle to propel the plane. Ramjet engines replace the compressor with a specially shaped duct, open at the front, that uses the forward motion of the aircraft to compress air. No moving parts are required in a ramjet. Fuel is sprayed into the airstream, and the mixture is ignited. Combustion in a ramjet takes place at subsonic speeds, but the exhaust gas is accelerated to supersonic speeds. Ramjet engines can function only at above Mach 1 speeds, so the aircraft must reach this velocity through some other method of propulsion. The turboramjet engine uses a turbojet engine for subsonic and low supersonic flight as well as a ramjet engine for sustained cruise at high supersonic Mach numbers. Turboramjet-powered planes, such as the Concorde supersonic transport and Lockheed SR-71 Blackbird strategic reconnaissance aircraft, operate at up to Mach 3–4. A scramjet, or supersonic combustion ramjet, is similar to a ramjet, but combustion takes place at supersonic speeds. This allows the scramjet to achieve theoretical speeds of up to Mach 24, or 18,000 mph.
Researchers have been working on scramjet technology for over 50 years, but scramjets have achieved powered flight only very recently.

**SCRAMJET DESIGN CHALLENGES**

The scramjet comprises three basic components: Air is compressed and decelerated in the inlet, gaseous or liquid fuel is burned with atmospheric oxygen in the combustor to produce heat, and heated air is accelerated to produce thrust in the nozzle. While scramjets are conceptually simple, producing a working one requires
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overcoming extreme technical challenges. When flight speed exceeds Mach 5, the temperature of the air entering the combustor is so high that, if decelerated to subsonic speeds, any heat generated by combustion will result only in the dissociation of air; it will not produce thrust. Therefore, the air is decelerated to a Mach number typically between 2 and 2.5 prior to combustion.

When air enters the combustor, which is about 1 meter long, it travels at approximately 1.2 kilometers per second, so the fuel must be injected, mixed, ignited and burned within approximately 1 millisecond. The air is moving so fast horizontally that it is difficult to get the fuel to spread in the vertical and lateral directions. Some scramjet development teams are considering employing a gaseous fuel, such as hydrogen, because it will quickly mix with the air and burn. Others are pursuing the use of liquid fuels, such as kerosene, that are denser and require smaller fuel tanks. Liquid fuel must vaporize before it can burn, adding another time factor that increases the combustion challenge. The higher the Mach number at the combustor inlet, the more heat that can be added and the more power the engine can generate. However, higher Mach numbers also make it more difficult to maintain stable combustion.

Ground testing full-scale combustors is very difficult because of the challenge of mimicking speeds above Mach 5 at an altitude of up to 32.5 kilometers (20 miles). Scramjets are tested in high-enthalpy wind tunnels, and there are only a few that exist in the world. Testing scramjet engines requires on the order of 10 kilograms of air per second. This is normally accomplished through vitiation (removing the oxygen), compressing the air, injecting fuel, and burning it in the air to achieve the temperature and pressures needed for the experiment. This adds complications because vitiated air has different properties than atmospheric air, and extrapolation to flight conditions is difficult. Another problem is that scramjet combustors present a very hostile environment for instrumentation and measurement.

SCRAMJET SIMULATIONS
Researchers at the Indian Institute of Technology (IIT) Madras are working on the hypersonic technology demonstrator vehicle (HSTDV) for the Defence Research Lab. The HSTDV is an unmanned scramjet demonstration aircraft for hypersonic flight (Mach 6.5). Researchers first evaluated the ability of ANSYS Fluent to provide accurate design predictions for the HSTDV scramjet by simulating a scaled-down intake design for which wind tunnel results have been published in open literature. The simulation results captured

Scaled intake simulation results matched physical experiments. The intake has two components: a ramp on the bottom and a cowl on the top. For the intake shown in this figure, the cowl has been split into a hinged movable portion (front) and a fixed portion (back). The four cases correspond to different orientations of the front part of the cowl.
Simulation can predict important performance metrics.

Simulation of preliminary design of full-scale combustor

Simulation of full-scale combustor with particle tracking

CFD simulation of full-scale combustor with particle tracking

The intricate details shown in the physical test results, including impinging shock-induced separation and re-attachment of the boundary layer. Simulation accurately predicted operating conditions in which unstarted flow occurs, meaning that the pressure rise in the combustor is so high that enough air cannot be pushed through the inlet, extinguishing the flame. CFD also accurately predicted the pressure throughout the intake. A similar exercise was carried out for validating predictions of supersonic combustion of different fuels — both liquid and gaseous in model scramjet combustors. With the confidence gained from the validation study, IIT researchers moved to simulating the full-scale intake of the HSTDV. Simulation results showed the shock reflections as the incoming air hit the intake across the entire range of operating conditions, including different angles of attack.

Next, the IIT team used CFD to evaluate different injection schemes to optimize the design of the HSTDV scramjet combustor. The full-scale combustor calculations utilized a 2-million-cell mesh. These models use full 3-D, compressible, turbulent reacting flow and include very fine meshes with a mesh spacing of less than 0.1 mm with gradient-based adaption to fully resolve shocks. To model supersonic combustion of hydrogen, researchers used an eight-species, 37-reaction mechanism as well as short- and even single-step mechanisms. For ethylene fuel, they employed a nine-species, 20-reaction mechanism. For kerosene fuel, a single-step mechanism was used. The models incorporate one-equation Spalart–Allmaras and two-equation SST k-ω turbulence models. These are some of the first simulation results for a full-scale scramjet combustor to be reported in open literature. Because there are so few wind tunnels in the world capable of accommodating a full-scale scramjet combustor, CFD simulation is crucial to optimizing the design. The calculations, starting from scratch, took about four to five months of run time to converge to the desired level.

DESIGN OPTIMIZATION

The team used CFD to simulate a full combustor with five struts, each containing 22 injectors and using V-gutters for flame stabilization. The struts are staggered to map fuel across the entire cross...
Simulation of modified design of full-scale combustor

IIT researchers are using ANSYS Fluent software as a virtual wind tunnel.

section of the combustor. The simulation shows liquid droplets injected from the struts; particle tracking (DPM) is used to track their movement. The tracks disappear once the droplets have completely evaporated. CFD aided in evaluating different injection strategies with the goal of evaporating all of the fuel and mixing it as thoroughly as possible within the combustor. Simulation results showed that the initial designs released too much heat too quickly, so the next design candidate moved the struts downstream in the combustor. The best design achieved with simulation was able to load 95 percent of the combustor with kerosene. After the simulation was completed, a prototype of this design was built and tested, and the experimental results matched the simulation predictions within the measurement margin of error.

Simulations have been shown to predict the flow in model combustors quite well for different fuels and injection schemes. Simulation can predict important performance metrics, such as mixing and combustion efficiencies, degree of mixing and total pressure loss. As a result, IIT researchers are using ANSYS Fluent software as a virtual wind tunnel to evaluate preliminary designs and identify a small subset of designs for fabrication and testing while using much more expensive and time-consuming wind tunnel testing primarily to validate CFD results.

ADDITIONAL RESOURCES

USER-DEFINED FUNCTIONS FOR DISCRETE PHASE MODEL IN ANSYS FLUENT
ansys.com/81run

Validation study of full-scale combustor showed good correlation between simulation and experiments.