Keeping the **Space Race** from Heating Up

Coupled multiphysics simulation saves hundreds of thousands of payload-equivalent dollars per launch for SpaceX.

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Second demo flight of the SpaceX Falcon 1 launch vehicle

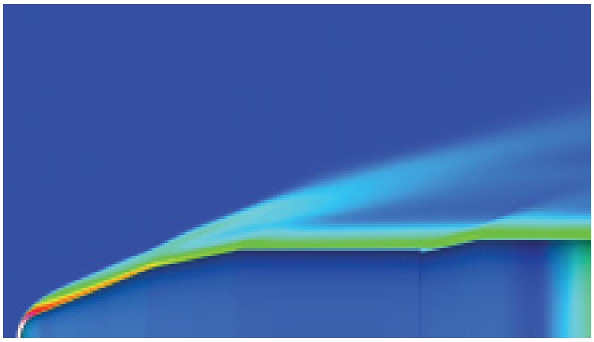
Space Exploration Technologies (SpaceX), a privately funded rocket venture founded by entrepreneur Elon Musk, is developing its Falcon family of launch vehicles from the ground up. SpaceX aims to change the paradigm of space flight by introducing a family of launch vehicles that will ultimately reduce the cost of space access by a factor of ten. As designers of the first launch vehicle developed entirely in the 21st century, Falcon engineers have the opportunity to take advantage of the latest design and analysis technologies.

One area of concern for the engineering design team was the amount of thermal insulation required to protect the payload and sensitive internal equipment from heat generated by high-speed atmospheric flight. Thermal insulation is required to protect the vehicle's metallic skin, in addition to sensitive electronic equipment that can malfunction at high temperatures. At higher temperatures, metals can lose critical structural performance as their material properties change. During the first demonstration flight, engineers erred on the side of safety by installing a conservative amount of thermal insulation. Optimizing the amount of insulation used for future flights is vital because every pound of excess insulation reduces the payload of the vehicle.

To optimize the insulation prior to the second demonstration flight, a simulation that integrated computational fluid dynamics (CFD) and finite element analysis (FEA) was performed to calculate surface and body temperatures expected during the flight. The main challenge of the coupled simulation was passing the heat loading for the surface of the launch vehicle, calculated by the CFD code, to the ANSYS Mechanical FEA model for structural and thermal analysis, and then passing the skin temperatures calculated by the FEA code back to the CFD analysis.

The temperature distribution on the launch vehicle throughout the entire flight was determined to ensure that sensors, instruments, propellant lines and other critical components were maintained at safe temperatures. Launch vehicle aerodynamics are uniquely challenging because there is no cruise condition. Instead, the conditions change continually and rapidly during the critical few minutes in which the rocket moves from sea level to the near-vacuum conditions at the edge of the atmosphere. The maximum heat transfer typically occurs high in the atmosphere when the speed of the launch

The Falcon 1 launch vehicle

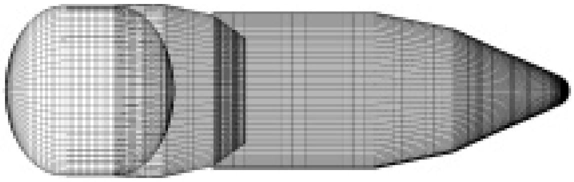


CFD contours demonstrate the heat load on the surface of the launch vehicle 152 seconds into the flight.

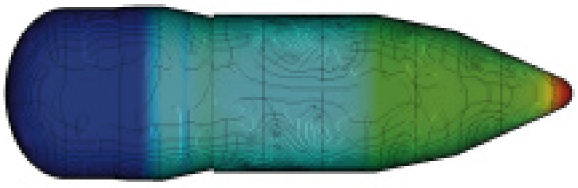
vehicle is very high and the density of air is very low. Heat transfer typically drops off to a much smaller value as the launch vehicle approaches its designated orbit.

With conditions changing so quickly during the atmospheric flight, multiple iterations of the simulation were required to capture the physics. Each of these iterations required both a fluid simulation of the air around the launch vehicle and a structural/thermal simulation of the launch vehicle itself. Since each code is dependent upon the results of the other, a series of iterations must be performed at each time step in order to converge to an accurate solution. Finally, since the amount of thermal insulation used also affects the heat transfer in the launch vehicle and the resulting vehicle skin temperatures, multiple repetitions of the entire simulation were required to examine the effect of varying the amount of insulation used.

SpaceX engineers used a CFD code designed for the high Mach numbers experienced during the launch vehicle's flight through the earth's atmosphere. The CFD code was used to calculate the increase in vehicle skin temperature that occurs due to the interaction between the vehicle body and the air through which it passes. The values for heat loading on the skin that are produced by the CFD code were then used as inputs for the ANSYS Mechanical simulation. This structural/thermal analysis then modeled the dissipation of the heat into the insulation and launch vehicle, which resulted in a new set of values for skin temperatures. These temperatures were then mapped back to the CFD simulation and the two codes run sequentially until they converged, such that the CFD results for heat loading were consistent with the skin temperatures determined by the structural/thermal code.



FEA mesh created for the Falcon 1



These contours represent the initial skin temperatures used for FEA simulation of the Falcon 1 launch vehicle.

SpaceX engineers developed a Matlab® routine, which automatically controlled the analysis by generating the appropriate input files for each code. These inputs included the correct atmospheric conditions and insulation amounts, in addition to mapping the results from each code to the other. The ANSYS Mechanical parametric design language (APDL) greatly simplified automation of the simulation process by providing a computer-aided design-based (CAD) application programming interface that enabled the integration code, in this case Matlab, to draw the model with a fraction of the number of commands — the launch vehicle model was defined with just a few lines of code. Using APDL, engineers were also able to create layered shell elements to represent the various layers of the skin of the launch vehicle, reducing solution time as compared to using solid elements.

After SpaceX engineers automated the process of running thousands of iterations, the minimum amount of insulation that would protect the launch vehicle was calculated to be approximately 50 pounds less than the amount used in the first demonstration flight. The temperature measurements taken during the second demonstration flight in March 2007 closely matched those predicted by the simulation, demonstrating that the reduced insulation performed as expected and within the requirements of the design.

As a result of simulation, the reduction in insulation weight makes it possible to increase the payload capacity of future Falcon 1 missions. With a number of launches scheduled over the next few years for the Falcon 1, and the larger Falcon 9 as well, SpaceX can now expand its range of potential customers and increase revenue on a payload mass equivalent basis. ■