Computational and Experimental Analysis of Hot-Surface Ignition of Fuel Sprays in Aircraft Compartment Fires

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Compartment fires pose substantial industrial fire risks. Enclosed spaces better retain heat and combustion products, which increase fire intensity. Particularly in the automotive, aerospace, chemical, and petroleum industries, transportation of pressurized, flammable liquids next to high-temperature components may make leaks onto a hot surface possible, triggering liquid fuel ignition. In aircraft, accidental hot surface ignition may occur when fuel, hydraulic fluid, or oil transported to the engine leaks, impinging on nearby hot surfaces. In these environments, the highly coupled and transient phenomena comprising hot surface ignition—including spray/wall/flow interactions—are not well understood. To this end, a joint computational and experimental effort is undertaken to characterize compartment-fire ignition scenarios.

We have developed computational modeling tools that consist of detailed high-fidelity simulations and low-order models to facilitate parametric studies of the hot surface ignition limits. We found these limits to shift to higher wall temperatures and richer equivalence ratios with increasing strain rate. The post-ignition steady-state behavior was also analyzed parametrically, demonstrating different flame stabilization regimes. The resulting wall heat flux exhibited large, non-monotonic variations across regimes. High-fidelity three-dimensional simulations of hot surface ignition of fuel sprays were conducted to analyze the multiphase reacting flow physics, including spray-wall interactions. We demonstrate that the transient peak in wall heat flux and ensuing flame dynamics are strongly dependent on the wall temperature due to its effect on the ignition delay time and associated fuel vapor build-up.

Complementing these computational investigations, we have initiated activities to design a novel hot surface ignition apparatus that will provide transient data for simulation validation and further analysis. An engine nacelle-like compartment at ambient pressure with forced ventilation will be used to represent the geometry and conditions experienced in an aircraft. The platform's flexibility and modularity will enable exploration of parametric dependencies, including spray-angle variations, and the geometry's rotation will allow examination of buoyancy effects. Instrumentation including thermometry, planar laser-induced fluorescence, phase-doppler particle analysis, and high-speed imaging will permit key variables like heat flux, wall temperature, reaction progress, spray characteristics, and the velocity field to be measured and compared to results from computational studies. Ultimately, this combined computational-experimental analysis of hot surface ignition will yield new insight into the phenomenon, furthering understanding of compartment fire evolution in aircraft and informing the implementation of appropriate safety measures and compartment fire certification.