Women in Aerospace Symposium
MIT, Cambridge, Mass.
May 24-26, 2016

Experimental study of soot aerosol formation in swirl-stabilized flames of alternative aviation fuels on a path to sustainable aviation

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Abstract

Particulate matter (soot aerosol or carbon black) emissions from combustion systems have adverse effects on human health and the environment. Soot is a major contributor to the total radiation heat loss in propulsion systems. Soot aerosols in the atmosphere have significant positive radiative forcing that contributes to global warming because of strong absorption of sunlight by soot. As compared to CO_2, soot has a shorter lifetime in the atmosphere, and thus reducing soot emissions has become an effective short-term mitigation approach to cope with climate change. The mechanisms of soot formation and oxidation in propulsion systems are, however, not yet fully understood. To improve our air quality and public health, a better insight into how soot forms, grows and oxidizes in a combustor is necessary.

In aviation gas turbine engines, flames are often operated under turbulent non-premixed condition. Non-premixed combustion takes place when fuel and oxidizer are introduced to the combustor separately. The chemical reactions are controlled by the rate of mixing of the reactants. Non-premixed flames are shown to be less sensitive to the thermo-acoustic instability in the combustors than their premixed counterparts. However, soot formation is an artefact of non-premixed combustion in propulsion systems, and several novel combustion technologies have been developed to reduce its formation. Swirl-stabilized combustion concepts are extensively used in aircraft engines as it provides good mixing in a relatively compact volume. The swirl-stabilized flame features a recirculation zone along the centerline of the burner. This recirculation flow brings the hot products back to the root of the flame, and enhances the mixing with cold reactants resulting in a continuous ignition and flame stabilization.

To date, most experimental studies aiming to understand soot formation in turbulent flames have been confined to relatively simple configurations which may not be able to capture the essential features of the combustion chambers in propulsion systems. The soot particles are difficult to track in turbulent flames due to high intermittency levels and short residence times. With the advent of the advanced laser technology, laser-based combustion and flow field diagnostics are able to probe the complex turbulent reacting flows with soot particles. In our laboratory, a model gas turbine swirl combustor with good optical access is used to produce various turbulent flames of liquid and gaseous fuels. Several laser-based combustion diagnostics are used; namely, laser-induced incandescence (LII) for measuring soot concentration and particle size, stereoscopic particle image velocimetry (Stereo-PIV) for mapping 3D velocity field in the swirling flows, laser diffraction particle sizing technique for quantifying fuel droplet size and filtered Rayleigh scattering (FRS) for measuring the temperature field.

Adoption of biofuels into aviation is a promising option for reducing particulate matter emissions. Among all, alcohols have received considerable attention in recent years due to its renewable bio-based resources and simple production. Some alcohols have already been used as an additive in ground transportation and their application to the aviation field requires further research and development. Though several studies have been carried out on alternative fuels in simple laminar flames and in diesel engines, not much data are available on the effect of flow field structure on soot processes in swirl-stabilized burners. By examining the soot characteristics in spray combustion fueled by alcohols, alcohol-derived biojets and hydrocarbon mixtures, significant steps towards clean gas turbine combustion can be taken.

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