Going with the hypersonic flow

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Argonne scientists are helping to solve the challenge of hypersonic flight by unraveling the complexities of combustion, which will propel aircraft to those speeds. Credit: Shutterstock / Andrey Yurlov

"Unless you're trying to get to space or blow something up, there's nothing moving at hypersonic speeds," said Alan Kastengren.

Not much at the moment, anyway. But the world's largest militaries are busy developing aircraft and weapons that meet or exceed speeds of Mach 5, the low end of the hypersonic boundary.

The United States' hypersonics program, for example, recently was reinvigorated, by both the threat of being surpassed by rival nations and increased investment by the U.S. Department of Defense to accelerate new innovations, including hypersonic technology.

Among the major difficulties in achieving successful hypersonic flight is getting the right fuel-air mixture required for effective combustion. Kastengren, a physicist at the U.S. Department of Energy's (DOE) Argonne National Laboratory, is an expert in complex flow who has taken up the challenge of hypersonic combustion.

Using the powerful X-ray resources at Argonne's Advanced Photon Source (APS), a DOE Office of Science User Facility, he hopes to obtain a more accurate picture of the dynamics occurring within clouds of fuel droplets generated by the minute and detailed geometry of supersonic combustor spray nozzles, the type used in supersonic combustion ramjet, or "scramjet," engines for hypersonic flight.

"X-rays are able to penetrate through that cloud and measure what's going on very quantitatively," said Kastengren. "We can do it at high speeds and we can do it with high precision because we have one of the world's largest and brightest hard X-ray sources."

Obeying the speed limit

For the past 12 years, Kastengren has been busy taking detailed X-ray measurements of automotive fuel injection systems, mainly for cars and trucks, vehicles that more often than not must obey a well-defined—if sometimes ignored—speed limit. As his research has advanced, so too have the vehicles, with speed limits defined only by engineering terms like Mach, supersonic and hypersonic.

In 2008, his group leader, senior physicist Jin Wang, received funding to build a separate beamline on the synchrotron at the APS, mainly to observe X-ray absorption in fuels. Part of Kastengren's job entailed securing new users from outside of Argonne, whose projects went well beyond traditional fuel injection.

These included members of the aerospace community, who were studying liquid rocket and scramjet injectors, as well as fuel-air mixing applications.

Inadvertently, his earlier work prepared Kastengren for this most recent project studying supersonic combustion in hypersonic vehicles.

In mid-2016, Kastengren received Argonne funding to pursue the development of a science portfolio in this area, work for which he was already garnering the attention of such potential sponsors as the Air Force Research Laboratory (AFRL) and the Air Force Office of Scientific Research, both of which are investigating complex flows in hypersonic and liquid rocket propulsion.

Because the concept has a number of unique applications for the national security community, Kastengren's project became a part of Argonne's National Security Programs (NSP), whose purpose it is to apply Argonne's world-class resources toward solving the nation's toughest security issues.

"There are many facilities around the country doing this kind of research, but none can make the types of measurements performed at the APS," said NSP Director Keith Bradley. "We bring unique experimental capabilities to this problem, and we think Alan's work could be an early growth opportunity."

Lighting a match in a hurricane

The APS, considered the brightest hard X-ray synchrotron in the Western Hemisphere, can conduct science in regions that are difficult to observe and measure, which is particularly instrumental in understanding how combustion processes work. One key advantage, for example, is the ability to peer inside metal objects that are otherwise opaque, such as injectors.

And because its X-ray beams are so bright, the APS allows for a more accurate accounting of dynamic processes that require much higher speeds and resolutions to capture. It also has as a major advantage, its association with Argonne, a laboratory well known for its integrative work on fundamental materials science and combustion chemistry, as well as practical problems in combustion.

Interest in Kastengren's project falls in line with the Department of Defense's recent thrust to make hypersonics a top priority, as both an offensive mechanism and a defensive strategy. In jets and missiles, this means the ability to fly at Mach 5—five times the speed of sound—or faster, allowing them to out-maneuver adversaries and defy enemy air defenses.

Such aircraft use scramjets, which rely on oxygen pulled from the atmosphere rather than from traditional, bulky onboard oxygen tanks. This makes for a lighter, faster vehicle, but a much more intense flow picture.

The word "notorious" often shows up in proposals related to studies of hypersonic flows, as in they are notoriously difficult to study. Having worked with researchers developing scramjet engines for hypersonic vehicles, Kastengren understands some of the challenges.

Among the larger problems, air moves supersonically through the engine, relative to the vehicle, and researchers must precisely determine how the fuel and air can mix together quickly and safely. Diagnostics near the injection point are particularly prickly, as the merging liquid and supersonic crossflow form a complex, coupled flowfield.

It's akin to lighting a match in a hurricane, said Kastengren.

Breaching supersonic barriers

Despite these particular intricacies, mixing fuel and air remains a basic problem, one that the APS is well-equipped to handle, and one for which X-rays are well-suited. As a diagnostic tool, the APS can provide the quantitative data needed for computational modeling.

Recent measurements conducted at the APS already have demonstrated the X-ray technique's effective, quantitative capabilities in a range of challenging flowfields, such as liquid rocket injectors. Collaborating with the AFRL, Kastengren plans to use similar X-ray diagnostics to probe the mixing of a liquid jet into a Mach 2 supersonic crossflow.

First-ever data derived from supersonic jet-in-crossflow measurements will act as a critical benchmark in validating computational models of scramjet fuel-air mixing, leading to improved performance of scramjet combustors and other combustion devices.

"We have great capabilities at the beamline that position us to make unique contributions," said Bradley. "And as we continue to unravel the mysteries of advanced propulsion, we will discover additional capabilities that will render even greater insights."

But for now, the challenges that hypersonics presents are helping Kastengren, Argonne and the APS define their place in the scramjet community, and establish the criticality of their integrated capabilities in solving those problems.

Provided by Argonne National Laboratory

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