Interaction of acoustics and combustion in rocket engines

Dr Justin Hardi and the Combustion Instabilities Group at the DLR Institute of Space Propulsion in Lampoldshausen have focused their studies on improving the understanding of the thermoacoustic processes in liquid rocket engines for over one and a half decades. As rocket engines operate at extremely high temperatures and pressures, being able to observe the combustion phenomena poses a huge challenge. Pushing sophisticated high-speed imaging techniques to their limits, the team can visualise thermoacoustic phenomena in liquid propellant rocket engines. Their research not only deepens our understanding of flame-acoustic interactions but also aims to prevent combustion instabilities.

Combustion instability is a high priority problem in the construction of rocket engines. Particularly dangerous high frequency (HF) combustion instabilities in rocket propulsion can lead to massive damage of the combustion chamber and surrounding components. Indeed, this was an issue for the later stages of development and testing of the Aestus engines, which contributed to the rise of Franco-German research programme Rocket Engine Stability iniTiative (REST), aimed at better understanding instability phenomena. Participating in the REST programme, Dr Hardi who heads the Combustion Instabilities Group at the DLR Institute of Space Propulsion investigates the thermoacoustic phenomena in liquid propellant rocket engines. Dr Hardi and his team specialise in visualising combustion instabilities. Their primary experimental approach is to observe these phenomena under realistic conditions. Not the simplest task: rocket engines run with extremely high energy densities, thus rendering it nearly impossible to place instruments into the flow. The team sometimes manages to get thermocouples close to the flame while having them survive a test run, but when traversing the flow, 1 mm distance can mean the difference between 45 and 3600 K, and rocket flames are extremely turbulent, so it's difficult to predict where/if such instrumentation will survive.

The teams' study of thermoacoustic interactions involves the investigation of events accompanying unstable operational modes of a rocket engine. Heat release oscillations arising from flame fluctuations affect the combustion chamber acoustics. The combustion process can drive acoustic oscillations to very high amplitudes which increases the transfer of heat to the inner surfaces of the combustion chamber. The engine itself can burn from the inside out, ending in disaster. The same thermoacoustic process is recreated with the use of robust experimental research combustors. In carefully controlled conditions, researchers

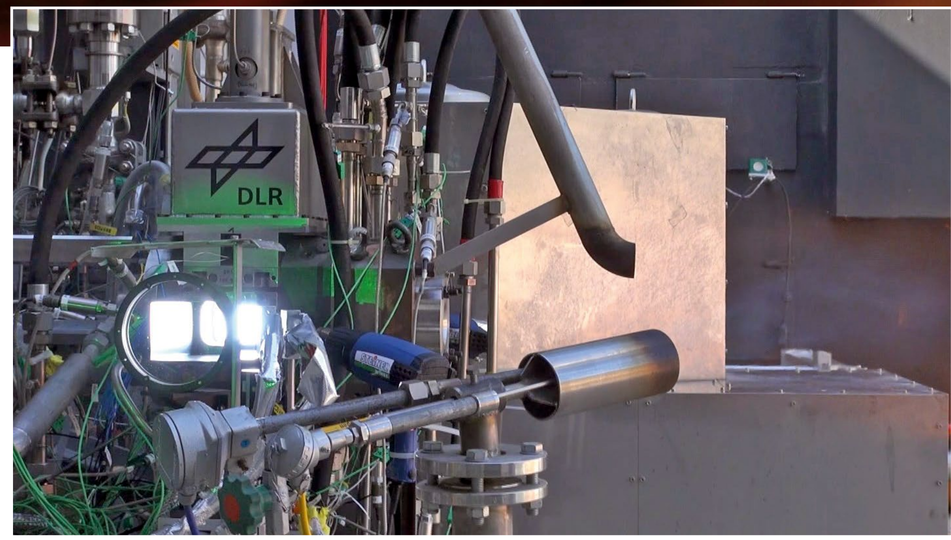
The team are pushing the boundaries of what is possible for visualising dynamic processes in rocket engines

A view through the nozzle to the faceplate and injectors of the experimental combustor model 'H' (abbreviated as 'BKH'). The optical access windows can be seen either side of the central injectors.

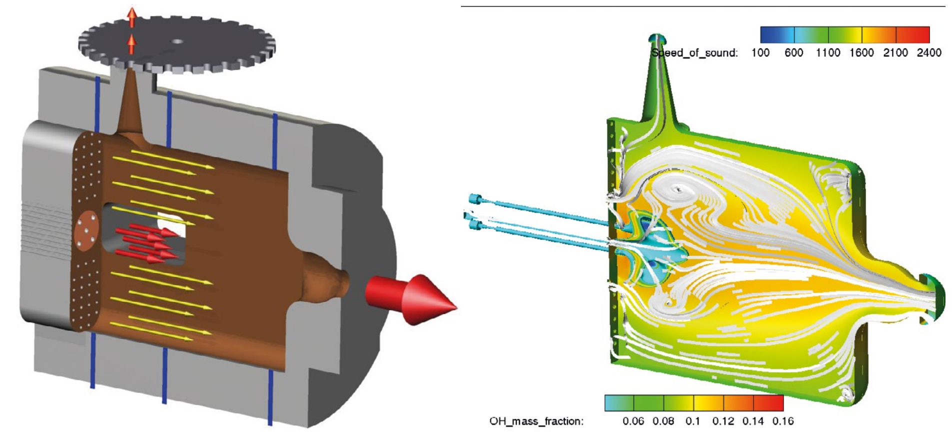
can observe the response of flames to acoustic disturbances for a wide range of artificially forced or self-excited acoustic amplitudes. Experimental combustors imitate conditions present in real rocket engines, with combustion chamber pressures up to 80 atmospheres and temperatures up to 3600 K, but importantly researchers have visual access to the chamber for their optical diagnostics.

PUSHING BOUNDARIES

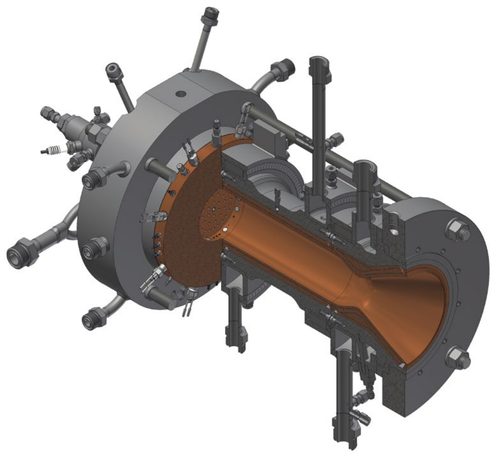
The team runs their experiments with the help of the capable test bench team at the P8 test facility, DLR Lampoldshausen. The facility is not only powerful enough to realise conditions representative of real engines, but can regulate propellant supply with high precision and fast reaction times. This allows test sequences to be performed with 12 or more combinations of varying operating parameters, and with excellent test-to-test repeatability. High-speed cameras register the processes in the combustion chamber and have captured images at impressive rates: up to 60,000 frames per second. Back-lit shadowgraph imaging allows visualisation of the movement of dense liquid oxygen within the core of the flame. A second camera collects flame luminosity in the UV. The pictures are analysed to identify coherent structures and motion in response to the local acoustic field, which is reconstructed



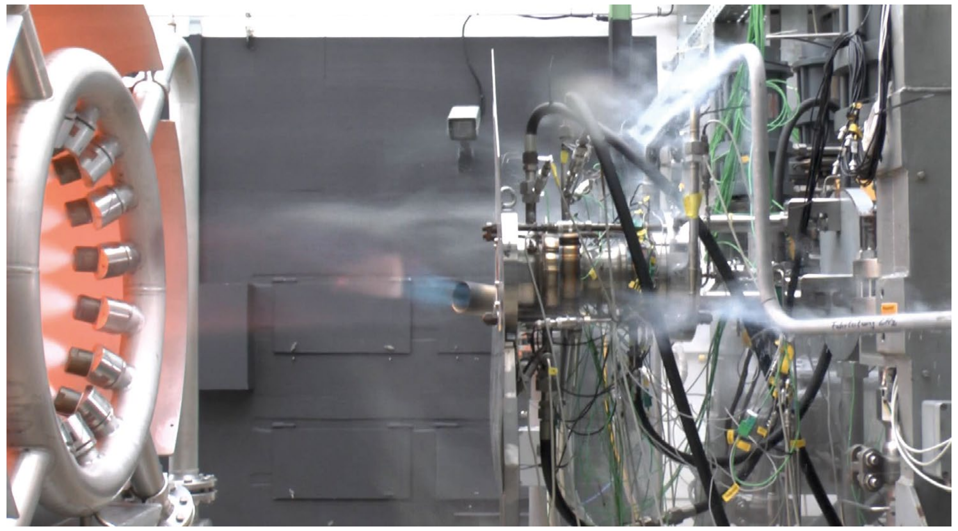
BKH during a test at the P8 test facility, with siren forcing of the internal combustor acoustics and high-speed imaging of the flame response through the windows in the side walls.



A conceptual illustration of the inside of the BKH experimental combustor with a rectangular cross-section, siren in the upper wall for acoustic forcing, and optical access windows. On the right is a numerical simulation of the cryogenic flames and flow field inside BKH. This kind of result is compared to experimental data from BKH to validate the simulation method.



A conceptual illustration of the inside of the experimental combustor model 'D' ('BKD' for short). BKD is a conventional, cylindrical thrust chamber and experiences self-excited combustion instabilities



BKD during a test at the P8 test facility, where self-excited flame dynamics are measured with fibre-optical probes. A modified version of BKD with an optical access window is currently in testing.

throughout the chamber from distributed sensor measurements. Advances in data analysis methods allow ever increasing depth of detail to be extracted from the measurements. Parallel numerical modelling, both in-house and from external partners, has improved the interpretation of the results immensely. By pushing the boundaries of what is possible for visualising dynamic processes, the team are providing the foundation for creating tools which will reduce the need for expensive ground testing of future rocket engines. From a practical standpoint, it is often crucial to analyse the combustion processes occurring within certain types of engines. Careful study of such processes then gives rise to specific combustion chamber designs; properly designed control of combustion allows one to, for example, rule out excessive pressure fluctuations while at the same time maintaining sufficiently rapid and efficient fuel burning.

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INJECTION CONDITIONS INFLUENCE ACOUSTIC MODES

One particular aim of the teams' research is to examine the behaviour of the cryogenic spray flames when experiencing self-excited instabilities. The experimental setup reflects common features of frequently used types of liquid propellant rocket engines. Combustion instabilities have long been known to adversely affect the proper functioning of liquid rocket engines, at times leading to sudden catastrophic failures. Famous examples include the catastrophic in-flight loss of the second launch of the Ariane family of rockets in 1980, caused by the occurrence of instabilities in one of its Viking engines during first stage burn.

The team's findings include the elucidation of mechanisms responsible for combustion instabilities hypothesised in the 1960s but which could not be measured and therefore proven until now. With their extensive and deliberate application of conventional sensors and optical diagnostics they could demonstrate how injection conditions influence the acoustic modes in the combustion chamber. During operation, combustion chamber, manifold, and injector volumes of the rocket engine start to resonate with different frequencies, which can lead to the combustion instability. The hydrogen temperature in particular significantly affects the combustion chamber frequencies. By varying the hydrogen injection temperature, researchers were able to reproduce the instabilities. A significant finding is that the dependency can lead to coupling with injector acoustics. The team also show that both the combustion chamber and injector acoustics influence the flame dynamics. These two aspects could until now be hypothesised but not directly measured in rocket engines, as the team has managed with its diagnostic techniques. This has a huge impact: allowing the motion and the size of the flame to be predicted for a wide range of excitation amplitudes.

CHALLENGING THE STATUS QUO

The team's findings challenge the historical, widely held view that low hydrogen injection temperatures are always responsible for instability. They show experimentally that the combustor can be stable at low but unstable at high hydrogen temperatures.

The future looks bright. Not only are Dr Hardi and the Combustion Instabilities Group providing international partners and the industry with valuable knowledge, outcomes from their ongoing research include invaluable data sets for modellers attempting to predict instabilities numerically. Dr Hardi's on-going research and future plans include further examination of the temperature-instability relationship and ultimately, through sophisticated modelling, the prevention of combustion instabilities at the design stage.

Q&A

What is the most challenging problem that you are currently trying to solve?

While our visualisation data is extremely valuable for validating numerical modelling of rocket flame dynamics, it is not directly compatible with the results typically produced by such simulations. For example, the flame luminosity captured by our camera cannot be easily related to the chemiluminescence of a particular reacting species whose concentration is estimated in a CFD simulation. We are working on ways to interface our experimental data with numerical results, both our own and those of partners, so that they can be compared more directly and provide quantitative validation of the models.

What do you think will be the fuel of future space rockets?

Methane is currently very popular as a potential fuel for future launchers. Theoretically, it has some economic advantages over other high-performance propellants like hydrogen – the current staple in Europe. All over the world, teams are studying methane as a fuel and developing engines to demonstrate its performance. We are also shifting our research focus accordingly to support the European efforts.

Will the models you're developing completely eliminate the possibility of catastrophes during the rocket launch?

Conventional methods of preventing combustion instabilities in flight are mature to the point that we rarely see them cause a failure these days. The problem is that these methods are largely based on trial and error, and therefore represent an immense cost to engine development programmes. The predictive capabilities of models are currently not good enough to ensure stability at the design stage, but any improvement would result in reduced testing requirements and therefore development costs. We support the gradual improvement of the models with our experiments and numerical tools.

What is the most interesting part of your research?

Test firing rocket combustors! The adrenaline rush in the seconds before ignition where we are about to release 90 MW of thermal power in a small tube… with a window in it! And the results are also spectacular. I am always fascinated by the behaviour of liquid oxygen jets as they break up and are consumed in the surrounding flame, and how they react to the acoustic waves we send through them. Watching replays of our high-speed imaging of these processes is mesmerising!

How does your work integrate with the work of rocket engine designers?

I see our role as to fill the rocket engine designer's textbook with information they can use to make design decisions. We work closely with industry to make sure they have that information as soon as possible, and we are available to consult when anomalies arise during engine development.

Detail

RESEARCH OBJECTIVES

Dr Hardi's research explores thermoacoustic instabilities in cryogenic rocket engines. His team specialises in visualising thermoacoustic phenomena with the aim of examining the participating dynamic processes under realistic conditions.

FUNDING

- The German Aerospace Center (DLR)
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COLLABORATORS

Members of REST:
ArianeGroup, Ottobrunn; ArianeGroup, Vernon; EM2C, CentraleSupélec, Paris; DLR Institute of Aerodynamics and Flow Technology, Göttingen; CNES; CNRS; CORIA; IMFT; ONERA; Technical University of Munich

Other collaborators:
JAXA; The University of Adelaide; The University of Rome (La Sapienza); Universität der Bundeswehr München; ETH Zurich

BIO

Justin Hardi graduated with a double degree in Aerospace Engineering and Physics from the University of Adelaide in South Australia, and then moved to Germany to work on the topic of high frequency combustion instabilities in cryogenic engines at the German Aerospace Center (DLR), at Lampoldshausen. He completed his PhD in 2012, then in 2013 went to Purdue University in the US for a Post-Doctoral placement at Zucrow Labs. He then returned to DLR, becoming group leader for combustion dynamics.

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