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REST HF-7 and HF-9 Test Case: Lessons learned for comparing simulation results with test data of a representative LOX/H2 thrust chamber with high-frequency combustion instabilities

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Abstract

As a result of high-frequency combustion instability issues in European rocket engines, the Franco-German cooperation REST (Rocket Engine Stability iniTiative) was founded in 1999. Since then, several experimental test cases have been modelled numerically by different partners. The DLR research thrust chamber BKD shows self-excited high-frequency combustion instabilities at conditions representative for European LOX/H_2 rocket engines. Therefore, the experimental BKD data was formulated into the test case descriptions HF-7 and HF-9. In this paper, these two test cases will be described in detail. Furthermore, the simulation results of several international partners are summarized and compared to the experiment. Finally, lessons learned are described and additional experimental data is presented which could be used for the further validation of instability modelling.

1. Introduction

High-frequency combustion instabilities in liquid propellant rocket engines (LRPEs) present a large risk for rocket development programs. A well-known example is the development of the F1 engine for the Apollo missions [1]. The European Ariane program also experienced combustion instability problems [2]. All of the given examples required extensive, full-scale ground testing before returning to flight. The costs of full-scale tests are extreme and prohibitive in today's more competitive launcher environment [2].

Despite the fact that high-frequency combustion instabilities have been a well-known problem in the liquid propellant rocket engine community for decades, stable operation of a new engine cannot yet be guaranteed at the design stage [2], [3]. This can also be observed in recent examples of liquid propellant rocket engine developments, which, despite the current modelling capabilities, still showed unexpected unstable behaviour [4], [5]. Therefore, it is the goal of industry to have modelling tools which can predict combustion instabilities during the design stage of an engine in order to reduce expensive full-scale testing. In recent years, new generations of system stability models based on modern numerical methods have been developed. But before these stability prediction models become useful to industry they require rigorous validation, which can be performed more economically using sub-scale experiments with representative conditions. However, LPRE-like experiments capable of producing test cases suitable for validating such tools are rare [2].

This paper focuses on a well-known DLR hot-fire experiment, designated BKD, which has been used for benchmarking modelling approaches in the French-German combustion instabilities community. During tests with the propellant combination liquid oxygen/hydrogen (LOX/H_2), self-excited combustion instabilities appeared [6], [7]. The geometry and operating conditions of this particular research thrust chamber are highly representative of European cryogenic rocket engines, such as Vulcain 2, HM7-B or VINCI. For that reason, the experimental data set presents a valuable test case for the modelling and investigation of the underlying coupling mechanism.

From the experimental data of BKD test campaigns at the DLR research and technology test bench P8, a test case was formulated. The test case was addressed in the context of a Rocket Engine Stability iniTiative (REST) modeling workshop. REST is a French-German cooperation between the institutional partners ArianeGroup, The French Space Agency (CNES), the National Center for Scientific Research (CNRS), the COmplexe de Recherche Interprofessionnel en Aérothermochimie (CORIA), the German Aerospace Center (DLR), the Laboratoire Energétique Moléculaire et Macroscopique, Combustion (EM2C) of CentralSupelec Paris, the Institut de Mécanique des Fluides de Toulouse (IMFT), The French Aerospace Lab (ONERA), and the Chair of Thermodynamics at the Technical University of Munich (TUM). The cooperation was initiated in 1999 in response to HF instabilities observed during testing of the Aestus engine. Since then, REST has worked towards understanding combustion instability phenomena in support of the European launcher industry. As part of this program, modelling workshops are undertaken to provide focus for

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combustion instability modelling efforts. The hot-fire experimental data from previous BKD test campaigns were presented as a test case. The test case is now known as the REST test case HF-7, which was provided at the third modelling workshop in 2014. Based on the experience gained and the feedback from the numerical partners, the HF-7 test case was then modified and extended into the HF-9 test case, which was presented at the fourth REST modelling workshop at the DLR Institute of Space Propulsion in Lampoldshausen in 2019. The recent publications from test case participants [8], [9], [10], [11], [12], [13], [14] provides an opportunity to reflect on the test cases.
Additional experimental results including the 2D flame visualization of the combustion dynamics in BKD were obtained and published since the last REST modelling workshop. It is believed that these flame visualization data can also play an important role in the validation of the stability prediction tools. Thus, exemplary flame visualization results are also presented in this paper.

2. Experimental setup and stability characteristics

In this chapter the most important aspects of the experimental setup and the previous stability characteristics are summarized. More details about the experiment, the chamber acoustics and insights into the stability driving mechanism can be found in literature [6], [7], [15], [16], [17], [18].

2.1 Experimental setup: DLR thrust chamber BKD

The hot-fire tests were conducted with the DLR research thrust chamber “D” (BKD) at the European Research and Technology Test Bench P8 for cryogenic high-pressure combustion [19]. BKD is a sub-scale, multi-injector thrust chamber, that was designed to study the regenerative cooling of the chamber walls under realistic conditions [19]. During operation the combustor showed self-excited combustion instabilities for certain operating conditions, or ‘load points’ (LPs). For the stability investigation test campaigns, the combustor was operated with the cryogenic propellant combination liquid oxygen/hydrogen (LOX/H_2) [6]. For other research purposes BKD has also already been operated with the propellant combination LOX/CH_4, for which it also showed combustion instabilities for specific operating conditions [20]. The specimen, shown in Fig. 1, consists of the injector head, a specially designed HF measurement ring, a cylindrical chamber segment of 200 mm length and the nozzle. The inner diameter of the chamber is 80 mm. The nozzle diameter is 50 mm, yielding a contraction ratio of 2.56 and a characteristic chamber length of L*=0.64 m. Chamber and nozzle are made of a copper alloy with high thermal conductivity and include milled cooling channels. For the investigation of instabilities, the combustor is water cooled.

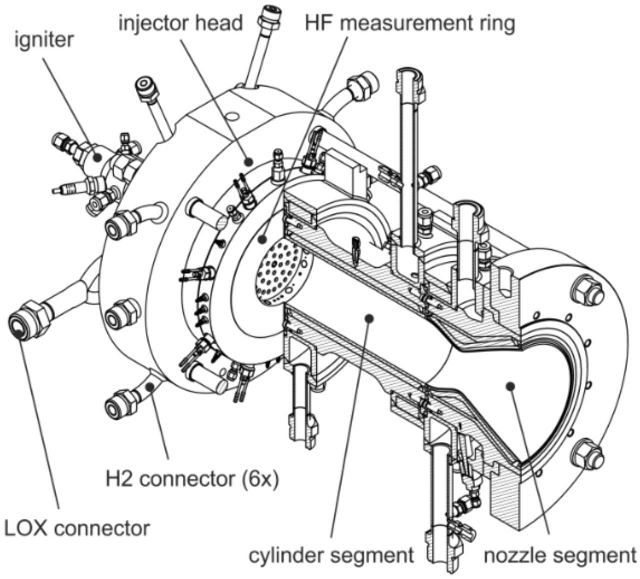

Figure 1: DLR research thrust chamber BKD [6]

The liquid oxygen is fed to the oxygen manifold asymmetrically from one side, as shown in Fig. 1. On the hydrogen side, six inlet connectors lead the hydrogen to the corresponding manifold in a symmetrical way. These six inlets are joined to one feed line using a corresponding feed-line setup [6]. The propellants are injected through 42 shear coaxial elements with a recessed and tapered LOX post. The injectors have a recess of 2 mm and a taper angle of 5° (full opening angle of 10°). The LOX post internal diameter is 3.6 mm. The outer diameter of the hydrogen annulus is 4.5

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mm, the inner diameter is 4 mm, creating a narrow hydrogen injection annulus with a height of only 0.25 mm. The length of the LOX posts is 68 mm. A sketch of one shear coaxial element of BKD is presented in Fig. 2.

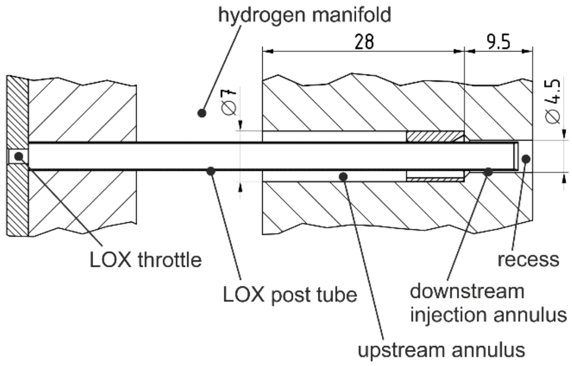

Figure 2: Shear coaxial injector element of BKD

The injector pattern of the 42 shear coaxial injectors is shown in Fig. 3. As can be seen, the injectors are distributed on three rings. The central tube corresponds to the igniter tube.

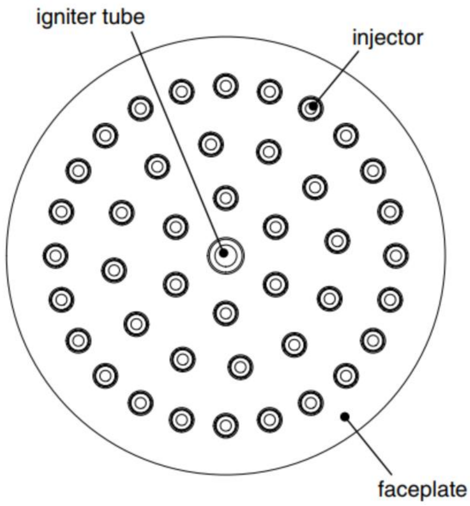

Figure 3: Injector pattern of the L42 injector head used in the BKD stability investigations

2.2 Measurement technique

The temperatures and pressures of the propellants are measured in each manifolds of the injector head using type K thermocouples and static pressure sensors. The cylindrical segment and the nozzle segment have independent water-cooling systems that allow the measurement of the integrated heat flux for each cooled segment [6]. The propellant mass flow rates are measured through turbine flowmeters at the test bench.

Due to the representative combustion chamber conditions in BKD, including high pressures and temperatures of up to 3600 K, the mounting positions of diagnostics into the combustion chamber are limited to the region close to the injection plane. For that reason, a so-called ‘measurement ring’ is installed between the injector head and the cylindrical combustion chamber segment (see Fig. 4). This measurement ring contains the majority of sensors for measurements of the combustion chamber, such as temperatures and static pressure sensors. For the study of combustion instability, the ring is also equipped with eight equally distributed, high-frequency, acoustic pressure sensors (Kistler type 6043A) and fibre-optical probes, which measure local OH* emission of the flame to allow the combustion dynamics to be investigated. Both the high-frequency pressure sensors and the fibre-optical probes are mounted in a common measurement plane, which is located 5.5 mm downstream of the injection plane. The eight circumferentially distributed acoustic pressure sensors are optimized for the measurement of the acoustic field of the first tangential (1T) mode, which is usually the driven resonance mode in BKD. The signals of the optical probes and the acoustic pressure sensors are both recorded with a 100 kHz sampling rate and a 30 kHz anti-aliasing filter is applied.

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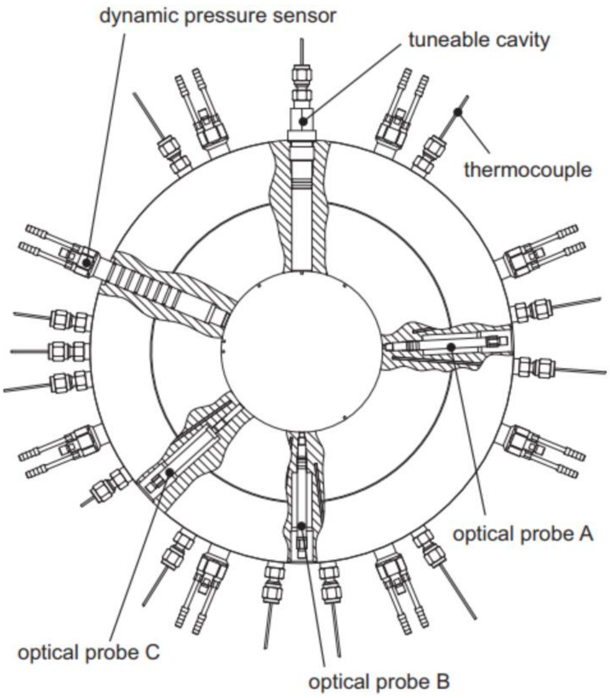

Figure 4: High-frequency measurement ring used in previous BKD stability campaigns [21]

2.3 Operating conditions

The P8 test bench uses closed-loop mass flow regulation systems for the liquid oxygen and hydrogen interfaces. This gives the possibility to incorporate a large number of load points into one test run. At the bottom of Fig. 5, a test sequence of a typical BKD test run can be observed. During the test runs, which were used in the test case description, the mean chamber pressure p_{cc} was varied between 50 and 80 bar and the mixture ratio (ratio oxidizer to fuel, ROF = $\dot{m}_{O2}/\dot{m}_{H2}$) range was between 3 and 6. For the operating condition of p_{cc} = 80 bar with ROF = 6.0, the total propellant mass flow rate is 6.7 kg⁄s and a thrust of approximately 25 kN is achieved with a thermal power of almost 90 MW [2]. In past test campaigns, BKD was operated with different hydrogen temperatures (T_{H2}) in order to study the impact of T_{H2} on the self-excited instabilities. For that purpose, the P8 test bench is equipped with two different hydrogen feed systems, called the GH (gaseous H_2), or LH (liquid H_2) interface, respectively. The hydrogen at the GH interface is stored in high pressure tanks under ambient temperature. Using a liquid nitrogen heat exchanger, the hydrogen temperature can be brought down to around 95 K at injection. The LH interface feeds the test bench with hydrogen which is stored as a cryogenic fluid. Using the LH interface yields a T_{H2} of around 45 K. Using both hydrogen interfaces simultaneously and mixing both mass flows has also been used to perform a hydrogen temperature ramping (HTR) experiment with BKD [7]. Overall the operating conditions as well as the non-dimensional chamber geometries of BKD are highly representative for European industrial LOX/H_2 engines. Furthermore, the thrust and thermal power values bring BKD at the lower end of upper stage engines. For example, if fitted with a vacuum nozzle, BKD approximately achieve the thrust of the Ariane 5 ES upper stage engine Aestus.

2.4 Stability characteristics of BKD

In tests with hydrogen injection temperatures around 95 K, self-excited instabilities of the 1T mode occurred. This type of instability is presented in Fig. 5, in which spectrograms of chamber pressure oscillations (left) and OH* fluctuations (right) are compared for a typical test sequence of previous BKD test campaigns. In the pressure oscillation spectrogram, the dependency of the acoustic resonance frequencies of the combustion on the operating conditions can be observed. For each ROF change, there is also a corresponding change in resonance frequencies. For the operating condition of p_{cc}= 80 bar and an ROF of 6 (here between 16 and 25 s of the testing time) there is an increase of oscillation amplitude at a frequency at 10.3 kHz and its corresponding overtone at about 21 kHz. The peak of the main instability frequency at 10 kHz corresponds to the chamber 1T mode.

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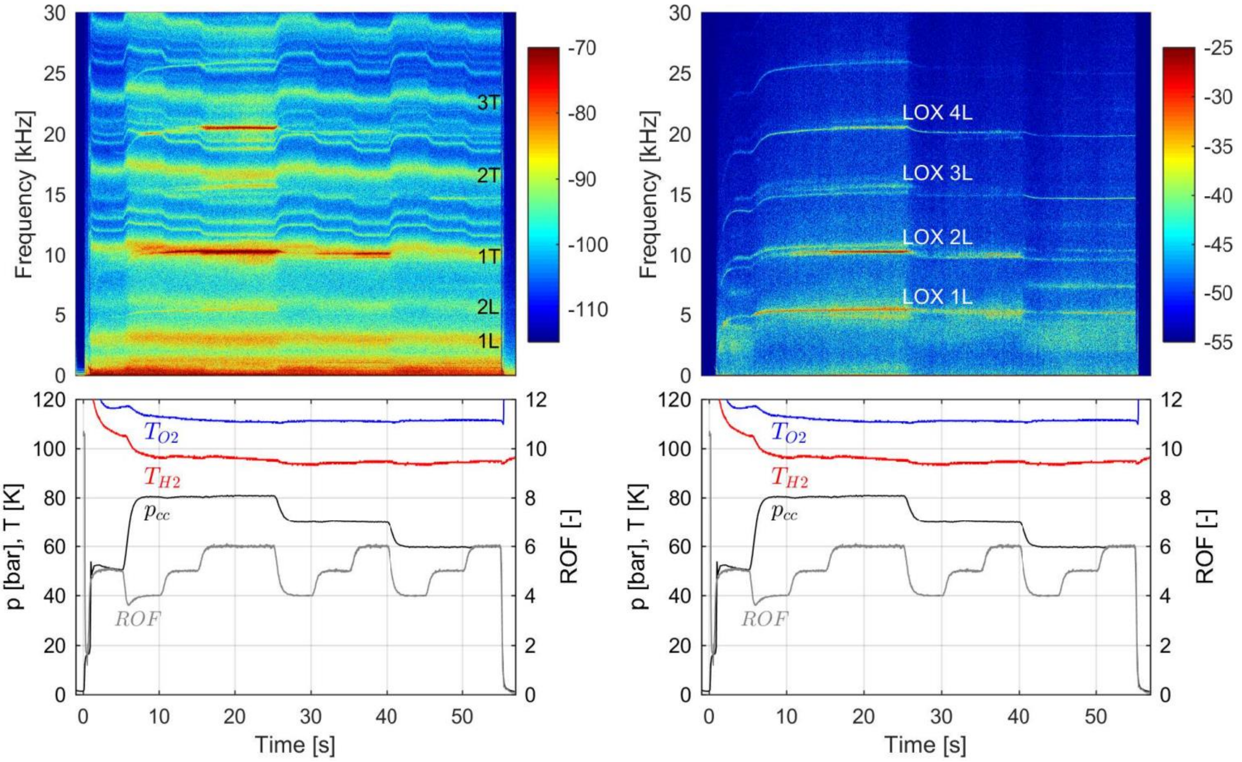

a) Chamber pressure oscillation spectrogram b) Combustion dynamics (OH*) spectrogram

Figure 5: Stability characteristics of the BKD thrust chamber of a typical test run *[6]*, *[16]*

The signals of the optical probes, capturing radiation filtered to OH* wavelengths, revealed that dominant frequencies at multiples of 5 kHz are present. As can be seen in the OH spectrogram in Fig. 5 b, the dominant lines are present for both stable and unstable conditions and do not follow the evolution of chamber mode frequencies. Gröning et al. [6] were able to prove that these frequencies of the combustion dynamics are showing the acoustic resonance modes of the LOX injector tubes, or LOX posts. It was shown that the combustion process is modulated with frequencies matching the longitudinal resonant modes of the LOX posts. The observations in BKD were therefore explained with an injector-driven mechanism [6]. As soon as the 1T frequency matches the frequency of the LOX post 2L mode at a frequency of about 10 kHz, the Rayleigh criterion can be fulfilled and the acoustic oscillations in the chamber can be amplified. This relation is shown in Figure 6. Here the averaged 1T-amplitude is plotted for a large set of different operating conditions over the frequency difference between the chamber 1T mode and the LOX post 2L mode. Only if a close frequency spacing is achieved can the chamber 1T mode become excited. For the stability prediction modelling, this observation also indicates that an accurate frequency prediction of both the chamber 1T mode and the LOX injectors is required to accurately predict this instability driving mechanism in BKD.

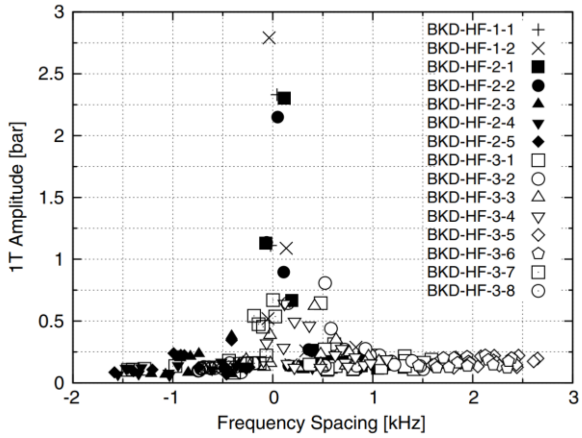

Figure 6: Averaged 1T-mode oscillation amplitude plotted over the frequency spacing between the 1T-mode and the 2L mode of the LOX injectors *[6]*

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To analyse the effect of hydrogen injection temperature on stability, test runs with cold H_2 were also conducted. However, in contrast to what is generally expected [22], [23], [24] the 10 kHz instability no longer occurred. This was explained by the influence of the fuel temperature on the 1T mode frequency. For lower hydrogen temperatures, the 1T-mode frequency is reduced and thus doesn't match to the LOX post 2L frequency any more [7].
The described instability excitation phenomenon is known to the rocket engine community as injection-coupling. Cases of coupling between the LOX tube and the combustion chamber have been reported for the J-2S engine [22], [25] by Klein et al. [26], Martin et al. [20] and others [5], [23], [24]. This shows that LOX injection coupling is a common excitation source of high frequency combustion instabilities in cryogenic rocket engines and thus there is a strong motivation of this test case to evaluate the capabilities of the different numerical stability prediction methodologies as well as to gain more insights into the detailed processes during the injection-coupling with the CFD simulation results.

3. REST test case descriptions

As was described before, the experiment and the results from the hot-fire tests with BKD have been formulated into two test cases descriptions within the framework of REST. The first test case HF-7 was presented at the REST modelling workshop 3 in 2014. Based on the feedback from the modellers, this test case was then modified to the test case HF-9 with an extended data-set, which was presented at the REST modelling workshop 4 in 2019.

3.1 REST HF-7 test case

As was described before, the BKD experiment for the investigation of high-frequency combustion instabilities consists of four main parts, the L42 injector head including 42 shear coaxial injection elements, the cylindrical combustion chamber segment with a diameter of 80 mm and a length of 200 mm, the convergent-divergent nozzle segment with a contraction ratio of 2.56 and a measurement ring, which includes the majority of the high-frequency diagnostics and covers the first 15.5 mm of the cylindrical combustion chamber. Thus, the overall chamber length from faceplate to the nozzle throat is about 264 mm. The inner volume of the test case can be seen in Figure 7. As can be observed the manifold volumes of LOX and hydrogen in the injector head is also included.

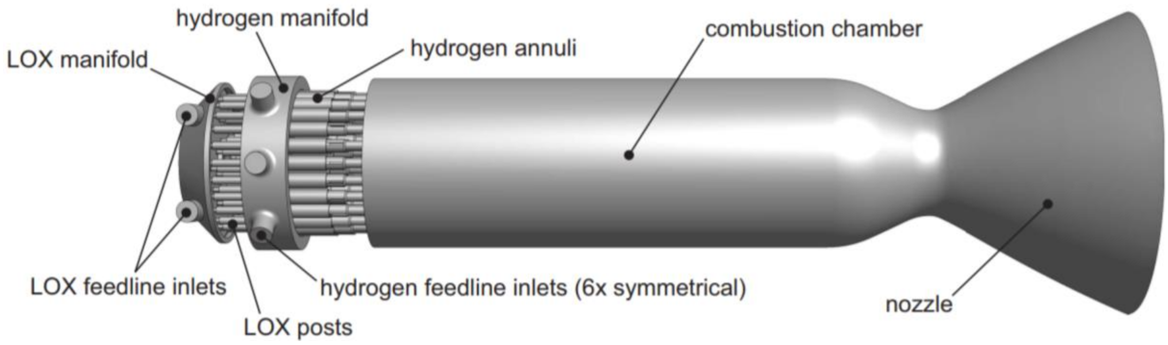

Figure 7: Inner volume of the BKD combustion chamber with the L42 injector head of the HF-7 test case

Based on the feedback of the numerical partners, also an updated version of the inner volume of BKD was created, which includes the last parts of the feedline inlets into the injector head. By doing so, the influence of the mass flow inlet into the manifolds can also be considered.
Originally, at the 3rd REST modelling workshop, HF-7 was a presented as a "blind" test case, which means that only the minimum required input parameters for the simulation were distributed together with the geometry. For that reason, the data set included only the total propellant mass flow rates, the propellant temperatures measured in the injector head manifolds and the manifold pressures. In total, four operating conditions, also called load points (LPs) were defined in the HF-7 test case description. The experimental data set of the HF-7 test case is summarized in Table 1. Requested results for the validation of the numerical results were the following:

- Average combustion chamber pressure
- Acoustic resonance frequencies of the combustion chamber up to 25 kHz
- Chamber 1T mode amplitude
- Full-width at half maximum (FWHM) of a Lorentzian profile fitted to the 1T mode peak

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Table1: Provided data set of the four load points in the HF-7 test case

Load points	**LP1**	**LP2**	**LP3**	**LP4**	
$\dot{m}_{H2}$	kg/s	1.11	0.84	0.96	0.96
$\dot{m}_{O2}$	kg/s	4.44	5.04	5.77	5.75
T_{H2}	K	93.7	94.9	47.6	95.7
T_{O2}	K	111.8	111.5	107.7	111.4
p_{H2}	bar	100	89.7	90.1	102.9
p_{O2}	bar	78.4	81.1	91.9	94.1

3.2 REST HF-9 test case

Continued interest in the case has motivated the extension of HF-7 into the current HF-9 case for the 4th REST modelling workshop at the DLR Lampoldshausen. This new test case is heavily based on the previous HF-7 case, extended with additional load points covering a wider range of operating conditions and data from optical diagnostics. Also, more information, such as the measurement uncertainty was given. Furthermore, the data of the fibre-optical probes measuring local OH* emission as an indicator of the combustion dynamics, were also added to three of the previous load points. A summary of the provided data of the HF-9 test case description is presented in Table 2. The simulation domain of BKD stayed identical to the HF-7 test case. Requested results from the modelling of the HF-9 test case can be summarized as follows:

- Part I: acoustic characteristics of the combustion chamber
  - Mean combustion chamber pressure
  - Acoustic resonance frequencies of the combustion chamber up to 25 kHz
  - RMS amplitude of the 1T mode oscillations
  - FWHM of the 1T mode peak
- Part II: Flame response
  - Dominant frequencies of the flame dynamics up to 30 kHz at the location of the fibre-optical probes
  - Average phase relationship (or time lag) between the flame response and the pressure oscillations
  - Relative oscillation amplitudes of the flame response by means of OH* emission oscillations

Table 2: Provided data set of the four load points in the HF-9 test case

Load points		**LP1 opt**	**LP2 opt**	**LP3**	**LP4 opt**	**LP5**	**LP6**
$\dot{m}_{H2}$	kg/s	1.11	0.84	0.96	0.96	1.18	0.6
$\dot{m}_{O2}$	kg/s	4.44	5.04	5.77	5.74	3.55	3.62
T_{H2}	K	93.5	94.9	47.6	95.3	93	99.7
T_{O2}	K	111	110.8	107.7	110.6	112.9	112.8
p_{H2}	bar	99.6	89.3	90.1	102.6	97.4	64.3
p_{O2}	bar	77.8	80.7	91.9	93.6	65.2	56

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4. Modelling approaches and simulation results for the test cases

Since the third modelling workshop in 2014 several research groups applied their models to the BKD test case. For that reason, it is outside the scope of this paper to summarize all details of the different modelling approaches and all the results of the different research groups. Instead for each institution a short summary of the basic principle of the stability prediction model is given and only the most important findings are described. For more detailed information about the different modelling approaches and simulation results, the readers are referred to the referenced publications.

4.1 TUM

At the TU Munich a so-called hybrid CFD/CAA approach was applied to the HF-7 test case. Hereby the mean flow field of the chamber and the flame response are modelled by CFD simulations of a single flame. These results are then used as input for an acoustic simulation of the chamber acoustics with a Linearized Euler Equations (LEE) solver in the commercial software environment COMSOL Multiphysics. This is a rather efficient stability modelling approach, because the larger scales of the acoustic modelling are decoupled from the smaller scales of the CFD. For that reason, all four load points of the REST HF-7 test case were addressed by TUM. Using this hybrid CFD/CAA approach, it was possible at the Technical University of Munich to model the frequencies of the acoustical chamber modes with deviations of less than ±2 % [11], [27]. The simulation results also showed how changes in operating conditions influence the mean flow and thus the acoustic field in the chamber and how that impacts the chamber eigenfrequencies. The BKD stability behaviour could be reproduced for the four load points of the HF-7 test case [11], [27]. The results indicated that the acoustics of the oxygen injectors played an important role in the flame response. The mode shapes corresponded approximately the longitudinal modes of a tube open on both sides [27]. Furthermore, it was investigated if the coupling between the heat release rate and the chamber acoustics is dominated by the pressure or acoustic velocity response of the flames. The results indicate that in BKD pressure coupling seems to be the dominant mechanism.

4.2 DLR

The phenomenon on injection-coupling was also investigated in an ESA project by the partners DLR Lampoldshausen und ArianeGroup Ottobrunn. Different load points from the BKD test case have been modelled by both partners. The modelling approaches of both partners have in common that the chamber and the injector acoustics were modelled independently. The goal of the modelling was to compare if an injection-coupled instability could be predicted for specific load points by means of a close frequency difference between the chamber 1T mode and the LOX post 2L modes.

At DLR a similar approach to that developed together by ArianeGroup and TU Munich was applied for the chamber acoustics. First, a RANS simulation of a single flame is conducted. The resulting acoustic field, mainly the speed of sound and the density are then radially averaged to produce 1D axial profile of the gas properties. This 1D distribution is then used as an input into the acoustic modelling of the combustion chamber. At DLR Lampoldshausen the single flame CFD simulation was conducted with the DLR TAU code and the acoustic simulations with a conventional Helmholtz solver within the commercial software COMSOL Multiphysics. The injector acoustics were also modelled with the same acoustic solver in COMSOL.

From the experience gained in the REST community, it became evident that comparing optical data from within the combustion chamber is a very powerful method for the validation of the simulations. However, in the recent years it was also revealed that at the conditions in rocket engine combustion chambers, the flame emission is not directly correlated with thermodynamic properties of the combustion, such as the heat release rate [28]. The comparison between simulation results and experiments based on optical data is not straight forward [2]. At the DLR Institute of Space Propulsion, a post-processing algorithm was therefore developed which includes an emission and absorption model and ray-tracing in order to allow better comparison of flame emission intensity distributions between CFD and experiments [29]. This algorithm was then applied to the BKD HF-9 test case [14]. The latest results will be presented at this conference [30].

4.3 ArianeGroup

The team at ArianeGroup used a similar hybrid modelling approach as TUM. The model is based on the PIANO-SAT solver, which was jointly developed with TUM. The calculation of the acoustics is separated from the simulation of the combustion process which is performed in a preparatory step using RANS/URANS CFD approaches of a single flame. From the CFD results again a mean flow field for the acoustic simulation was obtained. The applied acoustic solver is derived from DLR's PIANO solver and solves the LEE equations. Potentially also FTF can be calculated

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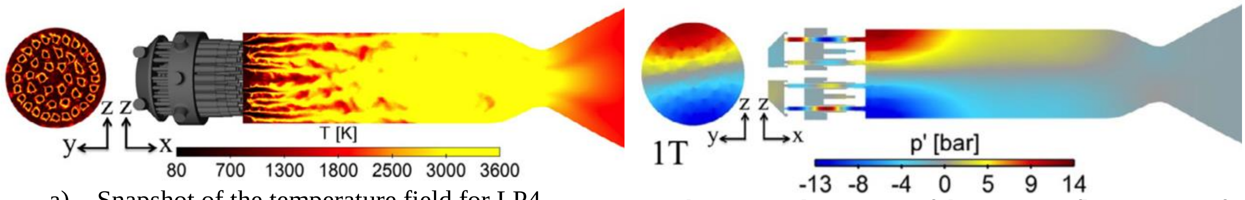
from single flame unsteady CFD simulation (URANS) and also added to the acoustic simulation. However, for this REST test case FTFs were not calculated. Instead, in an ESA project together with DLR the modelling concentrated on the detection of injection-coupling by means of close frequency spacing between chamber and injector eigenmodes. The injector acoustics were modelled with an acoustic network model [12].

4.4 IMFT

IMFT sought to demonstrate that LES is applicable to rocket engines with the injection of cryogenic liquids and supercritical combustion in order to accurately predict high-frequency combustion instabilities. The simulation was performed with the real gas extension of the AVBP solver. The mesh consisted of 75 Million elements and thus the calculations needed to be performed on a supercomputer [8], [9], [10]. Figure 8 shows two exemplary results of the LES simulation of BKD from IMFT. Fig. 8a shows a snapshot of the temperature field in the centre plane of BKD. Fig. 8b shows the spatial mode shape of pressure oscillations inside the combustion chamber at the main instability peak from the LES.



a) Snapshot of the temperature field for LP4

b) Spatial structure of the pressure fluctuations of the most unstable mode in the LES

Figure 8: Exemplary simulation results of the LES of BKD from Urbano et al. [10]

Due to the impressive results and being the first of such kind of LES of cryogenic rocket engines at these representative conditions, the publications by Urbano et al. still serve as a benchmark for the modelling approach. However, even by the use of supercomputers, performing an LES of a full-scale, main-stage rocket engine is still not feasible for industry. For that reason, Urbano et al. also studied the flame dynamics of one of the 42 flames out of BKD with LES on a finer mesh to gain an even more detailed understanding of the combustion dynamics of this combustor [31].

4.5 EM2C

At the EM2C lab of CentraleSupélec, the researches followed a similar approach as by IMFT. The BKD was modelled with a high-fidelity LES with the AVBP-RG solver. Based on the experience gained by IMFT it was still the goal to realize a self-excited combustion instability with the LES. For that reason, a finer mesh with 300 Million elements was chosen [13]. Additionally, the boundary condition at the chamber wall was chosen to be isothermal with a realistic temperature value of 500 K. Compared to adiabatic walls the heat transfer from the chamber into the cooled chamber walls is more accurately modelled. The chosen operating conditions were slightly different than the ones defined in the HF-7 test case and based on the hydrogen temperature ramping experiment with BKD [7]. The results of these two load points with different hydrogen temperatures were already published [13]. For the fourth modelling workshop with the HF-9 test case, the researchers at EM2C modelled again the unstable operating condition LP4. The latest results will be presented at this conference [32].

5. Summary of simulation results and lessons learned

Giving a detailed summary of all the simulation results of the different participants is out of the scope of this paper. Only the most important parameters, which were requested in the test case descriptions will be summarized and compared to the experiment. The interested reader is referred to the references of the different numerical contributions to gain more information about the modelling approach and the simulations results.

5.1 Mean chamber pressure

The requested result of mean or time-averaged combustion chamber pressure was closely matched by all simulations. It should be mentioned though, that in some simulations the chamber pressure was set as a boundary condition at the

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end of the domain [11], [14]. Table 3 summarizes the comparison of the modelled mean chamber pressure p_{cc} and the experimentally measured pressure for the load points LP4, which was addressed by most participants.

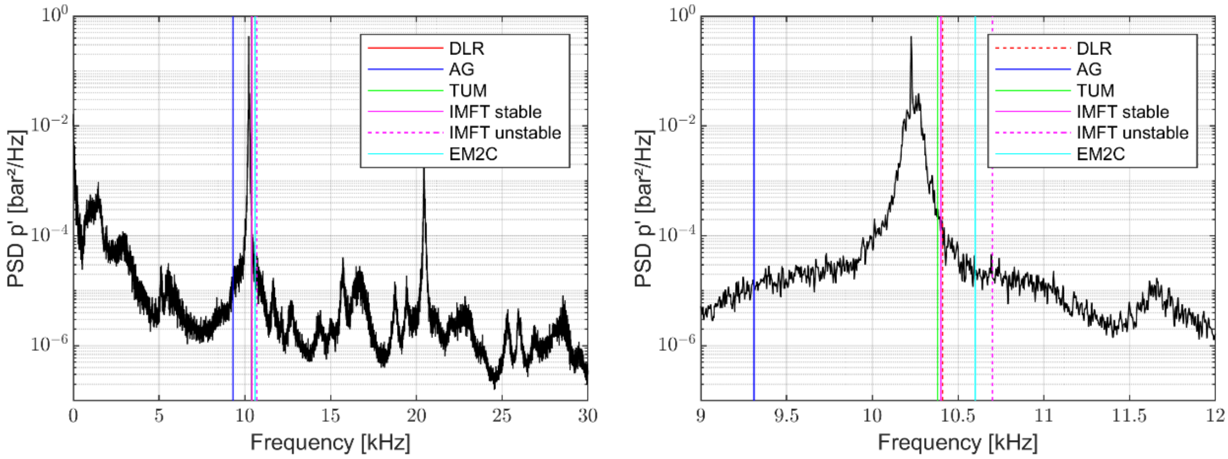
Table 3: Comparison of the mean chamber pressure for the load point LP4

Load points		**Experiment**	**DLR**	**ArianeGroup**	**TUM**	**IMFT**	**EM2C**
p_{cc}	[bar]	81	80	79	80	74.5	79.6
Error	[%]	-	1.2%	2.5%	1.2%	8.5%	1.5%

The measurement uncertainty of the chamber pressure in the experiment is about ±1%. Thus, most of simulated chamber pressures are close to the measurement and its uncertainty. The good agreement between the experiment and the simulations indicate that the simulations have a similar combustion efficiency to the experiment. In the IMFT simulation, the chamber pressure was lower than the experiment. This was attributed to a certain amount of unburnt propellant which leave the combustion chamber through the nozzle.

5.2 Acoustics of chamber and injectors

For the chamber acoustics, the focus is set on the chamber 1T mode, because this is known to be the most dangerous combustion instability mode in liquid propellant rocket engines in general and is also the unstable chamber mode in BKD. Figure 9 compares the experimentally obtained chamber acoustics for the load point LP4 in terms of a power spectral density of the pressure oscillations inside the chamber, averaged over all eight pressure sensors in the measurement ring. The 1T frequency can be observed with a sharp peak slightly above 10 kHz. In addition, the 1T frequencies predicted by the different models are also indicated by vertical lines. As can be seen in the Figure, all of the modelling results of the chamber acoustics predicted a 1T mode in the range of 10 kHz. The errors compared to the experimental 1T frequency for the load points LP4 is less than 5% for most models. This is significantly less than just using hot gas properties from CEA to calculate the chamber frequencies. By this common approach, the discrepancy between predicted frequencies and experimental frequencies can easily exceed 20%. So, all of the applied models show a significant improvement compared to estimations of the chamber frequencies by chemical equilibrium. This effect can be mostly attributed to the axial distribution of the speed of sound in the chamber [12], [27]. In all of the simulations the 1T mode oscillated with the highest amplitudes at the head end of the chamber [8], [11], [12], [13]. This is a well-known and expected behaviour of tangential modes in liquid propellant rocket engines. Unfortunately, the experimental setup of BKD only allows the measurement of the acoustic oscillations in the measurement plane close to the faceplate. So, there is no validation data from the experiment about the axial distribution of acoustic eigenmodes in the combustion chamber. Also, all studies showed an interaction of the combustion chamber with the LOX post-acoustics [8], [13], [27] or indicated it due to a small frequency spacing to the chamber 1T mode [12].



a) Frequency range from 0 to 30 kHz b) Zoomed in around the chamber 1T mode

Figure 9: PSD of chamber pressure oscillations in comparison with the simulation results for the load point LP4

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5.3 Stability modelling

As was described before, the approaches used by DLR and ArianeGroup in the ESA project were not able to accurately predict unstable combustion. The focus of this study was set on the influence of different operating conditions on the chamber and injectors acoustics and thus injection-coupled combustion instabilities. The obtained frequencies from both ArianeGroup and DLR showed a close frequency spacing between the chamber 1T mode and the LOX post 2L modes, similar to the experiment [12]. However, the accuracy of the predicted frequencies, mostly the chamber 1T frequency, by both partners was not sufficient to identify unstable LPs.

The hybrid CFD/CAA approach of TUM is restricted to linear acoustics and therefore not able to calculate a limit cycle amplitude. The results can still be compared quantitively between experiment and simulation results based on the measured and modelled linear growth or damping rates. The results of the linear growth rate estimation compared well to the experimental values [11], [27]. Thus, the applied modelling approach is, at least for the test case BKD, able to predict stable and unstable LPs for four different operating conditions.

The LES from IMFT for two different load points (stable and unstable) initially showed stable combustion for both LPs. So, the LES was not able to predict self-excited combustion instability in BKD. However, after applying a non-linear trigger in the form of a 1T-mode pressure field to the simulation, the experimental stability behaviour was reproduced. For the stable load point, the pressure oscillations were damped out within a few cycles, whereas for the unstable load point, the pressure oscillations in the LES developed into a limit cycle with similar amplitudes as in the experiment. A modal analysis of the limit cycle identified the dominant modes as the 1T and 1R, both coupled with longitudinal modes of the LOX posts. This result is in excellent agreement with experimental observations.

The modelling of EM2C was indeed able to generate a self-excited instability by the LES. Pressure amplitudes starting growing spontaneously to a limit-cycle and the amplitude was comparable to in the experiment. The self-excited pressure oscillation had the form of the 1T mode and was at approximately 10 kHz. However, the instability was observed for a different LP than in the experiment with lower H_2 injection temperature.

All the contributions, which included unsteady simulations, also showed a significant reduction in flame length due to the tangential oscillations [8], [13], [27]. Furthermore, the analyses of the thermoacoustic energy-transfer by Schulze [11], [27] and Urbano et al. [8], [9], [10] came to the conclusion that driving occurs mainly via pressure coupling.

5.4 Lessons learned from the two modelling workshops

Overall, the experience gained in the two REST modelling workshops highlighted the advantages of combining the analysis from CFD and experiments. Through validated simulations one can get insights into parameters and processes which cannot be measured experimentally. For example, the heat release rate, which is of great importance for the flame response, cannot be measured. Some of the BKD simulations also showed significant acoustic oscillations in the LOX injectors. While it was known from the experiment that the combustion is modulated by the acoustic eigenmodes of the LOX posts, the exact acoustic oscillations inside the injectors can also not be measured. Therefore, the simulations can help to gain a better understanding of the coupling mechanism that leads to the instability in BKD.

Even though all the applied models were cutting edge, no contribution could successfully reproduce the self-excited combustion instability of the correct chamber resonance mode for the experimentally unstable load point. The modelling approach of TUM was able to calculate the resonance frequencies and predict the linear growth rates for all four load points of the HF-7 test case quite accurately. However, due to the linear analysis the approach is not capable of predicting amplitudes of the limit cycle.

The LES simulations of IMFT and EM2C proved that LES can be a powerful tool to predict combustion instabilities in liquid propellant rocket engines. However, it still is unclear when it will be feasible to model full-scale rocket engines with LES. The most suitable candidate for industrial needs is currently the so-called hybrid approach, similar to that used by TUM. Here, LES of single flames could be applied to improve the flame response functions for the acoustic simulations.

If more simple stability prediction methods are used in order to detect the risk of injection-coupled combustion instabilities, it is necessary to work on the accuracy of the frequency prediction, mostly on the chamber side. The experimental data from Gröning et al. [6] indicate that the frequencies of the LOX post and the 1T mode need to have a smaller frequency spacing than 2% in order to excite the chamber 1T mode. Thus, this is approximately also the required accuracy of the frequency estimation of the simulations, if the injection-coupling should be accurately captured. Such an accuracy was not achieved by both partners for all load points. Before being applicable for industrial engines with a high reliability and accuracy, all of the modelling approaches need further validation in future work also on different experimental configurations.

There remains not only room for improvement for the numerical methodologies, but also for the design of experiments and the processing of measured data. For example, one lesson learned in the HF-7 test case based on the feedback from the numerical partners was that the inflow conditions of the propellants into the injector head should be well defined

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in the test case description. Information about the measurement accuracy and where the properties are measured have been updated in the HF-9 test case. Furthermore, the HF-7 test case only included 4 load points with a limited range of operating conditions. If the stability limit lies in between two of those operating conditions and a load point is only marginally stable, predicting the current stability behaviour is very challenging. For that reason, also the range of operating conditions has been increased for the HF-9 test case.

Another important lesson learned from the workshops is that for future work the criteria for comparing simulation results with experiments need to be clarified. As was shown before, the most common validation parameters were the averaged chamber pressure measured in the common measurement plane 5.5 mm downstream the injection plane, and the 1T frequency of the chamber. However, the meaningfulness of the comparison of both validation parameters also have strong limitations. The mean chamber pressure was met by almost all participants within the measurement accuracy of the experiment. However, if the chamber is long enough to achieve near-complete combustion, as is the case in BKD with LOX/H_2, the mean chamber pressure measured close to the injection plane gives no insight into the extent of the combustion zone.

Information on the flame length is to a certain extent included in the validation of the chamber mode frequencies, because the axial distribution of the acoustic field (speed of sound and density) has a direct influence on the acoustic eigenfrequencies of the chamber. Therefore, one could argue that if the mean chamber pressure and the chamber resonance frequencies are validated by the simulations, the length of the combustion zone should also be well met.

However, the unsteady modelling with significant pressure amplitudes [8], [13], [27] also showed that the flame lengths and thus the chamber resonance frequencies are strongly dependent on the pressure oscillations as well. This has also been observed in hot-fire experiments [33] which served as another test case for the 3rd REST modelling workshop. Thus, an important conclusion from the REST modelling workshops is, therefore, that accurate prediction of the chamber resonance frequencies for unstable operating conditions can only be achieved if accurate pressure oscillation amplitudes are also present in the unsteady CFD.

The experience from several workshops also proved that optical diagnostics of the flame dynamics are highly valuable for validation purposes. However, interfacing numerical results with optical imaging also requires further work, from both the modelling and experimental sides. One promising way forward seems to be to approach the imaging data from the modelling side by including flame radiation models in high fidelity CFD simulations. A first attempt to combine an advanced radiation model with a ray-tracing algorithm was recently applied to simulations of the BKD test case. Future improvement on the experimental side should foresee the optical measurements be calibrated with physical quantities. These methods should allow two-dimensional images to be rendered from CFD results which are quantitatively comparable with optical measurements. These validated simulations can then finally be used to derive reliable flame response models.

6. Additional experimental results to improve the validation data

A large drawback in the BKD test cases was the limited optical access by the fibre-optical probes, which only measured locally the combustion dynamics with a 1D line-of-sight integrated signal. While these measurements were extremely important in identifying the instability driving mechanism with the modulation of the combustion by the resonance frequencies of the LOX posts [6], it was impossible from the fibre-optical probe data alone to understand how the flames react to the acoustics of both the injectors and the chamber. However, the LES simulations from IMFT and EM2C as well as the unsteady simulation of DLR all indicated how the flames may react to the acoustic disturbances. The shape of the small-scale waves can thereby be symmetric or varicose-like, or have an asymmetric sinuous-like motion [13], depending on the kind of acoustic disturbance. So, a 2D flame-visualization could contribute significantly to the validation of the simulations and also to gain further insights into the coupling processes that lead to the combustion instability.

For that reason, a small-scale optical access was realized in BKD [16], [17]. With the small window the combustion dynamics within the first 5 injector diameters of one of the 42 flames in BKD can be investigated. The high-speed flame emission data was then analysed with Dynamic Mode Decomposition in order to extract the flame dynamics at specific frequencies. A detailed description about the optical diagnostics setup and the data processing method can be found in [16], [17]. Figure 10 shows two exemplary results of the 2D flame visualization in BKD at an operating condition, which is similar to the HF-7 LP4 test case. Left is the mean or time-averaged image in OH* and the visible range of the oxygen-hydrogen flame emission spectra. From these time-averaged images the flame topology inside BKD can be observed and these images could serve as a qualitative validation of steady simulations, which are required for the hybrid methods as an input into the acoustic simulations. On the right side of Fig. 10, the reconstructed DMD mode of the flame response to the first longitudinal resonance mode of the LOX injectors in the blue wavelength range of the flame emission spectra can be seen. Due to the background light of the other flames in BKD, the dense LOX core is visible in the blue radiation images. By using DMD it can now be observed that the flames react with an almost symmetrical or varicose shape to the periodic LOX injection. The provided data can be used to further validate the simulations of the BKD combustion instability in future studies.

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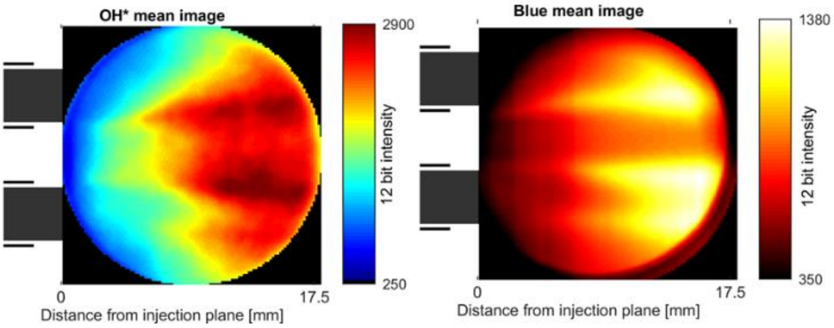
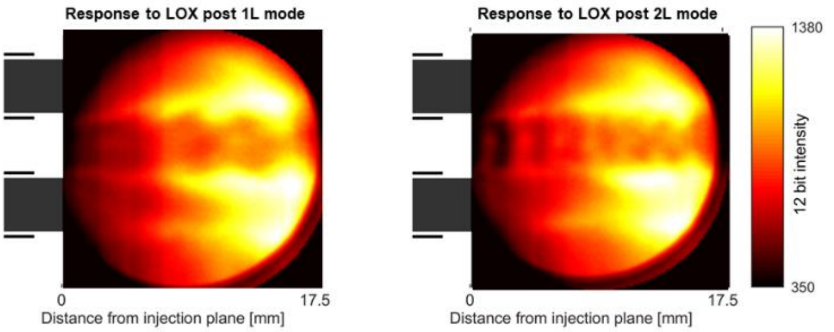


a) Time averaged images showing the general flame topology inside BKD

b)



c) Reconstructed response of the LOX injection and the flame to the 1L and 2L mode of the LOX posts calculated via DMD for the blue radiation of hydrogen-oxygen flames

Figure 10: Exemplary images from the recently realized 2D flame visualization into the BKD thrust chamber for the operating condition 78 bar and ROF 5.3 [34].

7. Summary and conclusions

The BKD research thrust chamber is a well-known rocket combustion instability experiment that shows self-excited, high-frequency combustion instabilities at highly representative operating conditions. For that reason, it is a valuable platform to test the modelling capabilities of international partners, especially with respect to stability prediction tools. Within the French-German research cooperation REST, the experimental data from previous BKD test campaigns have therefore been transformed into two different test case descriptions. The REST test case HF-7 has been modelled by various partners of the REST community and was a great success in benchmarking the capabilities of different stability prediction modelling approaches. Based on the feedback of the numerical partners, the HF-7 test case has been extended for the HF-9 test case. The most important update from the HF-7 test case to the HF-9 was the addition of information about the flame dynamics in terms of locally measured OH* emission oscillations.

The goal of the test cases was to test the ability of different stability prediction models to predict stable and unstable operation of a representative thrust chamber with self-excited combustion instabilities. Even though all the applied models were cutting edge, no contribution could successfully reproduce the self-excited combustion instability of the correct chamber resonance mode for the experimentally unstable load point. However, significant progress of the models was demonstrated by the simulations of the test cases.

Until reliable and accurate stability prediction models are available to the launcher industry, further validation of the developed models will be required in future work. The experience of the modelling workshop and the BKD test case shows the importance of extensively equipped experiments with representative conditions to test the capabilities of the models.

An important lesson learned in the workshop is that the simulations are not only important to reproduce observations from the experiment, but can also contribute significantly to gain a better understanding of the processes inside the experiment. Some examples are:

- Identification of acoustic modes in the combustion chamber, which could not be fully confirmed from the experiment due to lack of sensors, especially with an axial distribution along the chamber axis
- More detailed information about the mode shapes inside the chamber, which have already been identified, such as the chamber 1T mode, but which also lacked measurements in the axial chamber direction
- Insights into the acoustic oscillations within the injection elements

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- Extraction of the heat release rate dynamics, which cannot be experimentally measured. Thus, the capability of calculating flame transfer functions.
- Analysis of the instability driving processes. For example, the proportion of pressure and velocity coupling between the chamber acoustics and the flame response can be evaluated

A further focus for future work should be clarifying the criteria for comparing simulation results with experiments. Even the presumably simple task of comparing dynamic pressure signals with numerical results is not straight forward. The experience from several workshops also proved that optical diagnostics of the flame dynamics is a powerful measurement for validation purposes of the simulations. However, interfacing numerical results with optical imaging also requires further work, from both the modelling and experimental sides. The goal is to allow two-dimensional images to be rendered from CFD results which are directly comparable with optical measurements. The validated simulations can then finally be used to derive reliable flame response models for the stability prediction.

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