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REST HF-10 test case: URANS Simulations of Excited Methane Flames under Real Gas Conditions

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Abstract

The European REST combustion instability research group has proposed a test case for the calculation of a excited Lox Methane flame, “HF-10”. This test cases consists of a single flame of a coaxial injector. Ariane Group has calculated the test case, steady state as well as dynamic cases with Lox and Methane mass flow excitation. Dynamical effects can be observed as well as changes in the meand values. The results are presented in this paper.

1. Introduction

Combustion instabilities are a feared event in the development and operation of liquid propellant rocket engines. Such instabilities arise from the constructive interaction of combustion process and the combustion chamber acoustics. In case of an instability, an acoustic eigenmode develops and gains amplitude until it reaches a limit cycle that can be close to 100% of the mean chamber pressure. As consequence, the thermal boundary layer of the combustion chamber hot gas flow collapses, the walls get overheated and melting of the combustion chamber’s liner can start until complete mechanical failure of the structure. At the same time, the combustion process is altered, couples into the oscillation and feeds the instability [1].

Such instabilities have occurred to many rocket engine development programs and can cause massive cost excesses and schedule delays. Therefore, research in combustion instabilities can help to avoid such phenomena and keep programs on an uncritical track.

REST (Rocket Engine Combustion Stability Initiative) is a European Network of Industry, Institutes and Academia that collaborate in and share their experience in Liquid Rocket engine Combustion Stability. The REST members share their knowledge and interesting developments in scientific workshops. Additionally modelling workshops are held every 3-5 years where dedicated test cases are proposed to the members. These are open to participation by all members and permit to benchmark developments and compare methods.

The focus of Europe’s space activities on Methane as fuel has given the research in combustion instabilities new impulses as the stability properties of this fuels needs to be carefully assessed.

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As described above, the combustion process is a crucial element for the instability process. The simulation of combustion is the key for the understanding and in the end for the prediction of combustion instabilities. Therefore, the REST community proposed a joint test case consisting in the simulation of methane combustion under periodic excitation, the HF-10 test case. The corresponding overview publication is being presented at the present conference [3]

2. HF-10 Test Case Description

HF-10 is a numerical test case and consists in the simulation of a single, representative LOX-Methane flame under steady state conditions and dynamic excitation. Domain, geometry as well as post-processing were quite strictly described in order to facilitate the evaluation of the results over all contributors [2],[3].

The choice of the element and operating conditions is crucial for the properties of the fame and a representative geometry is relevant to have a relevant test case. Both was kept in mind when choosing an element from DFG SFB TRR 40[1] project as reference [4]. The DFG case was designed to be representative and at the same time does not bring complications with confidentiality and helps to avoid adding a new geometry to the general portfolio test geometries.

2.1 Geometry and operating conditions

The geometry of the test case is visible in Figure 1and Figure 2

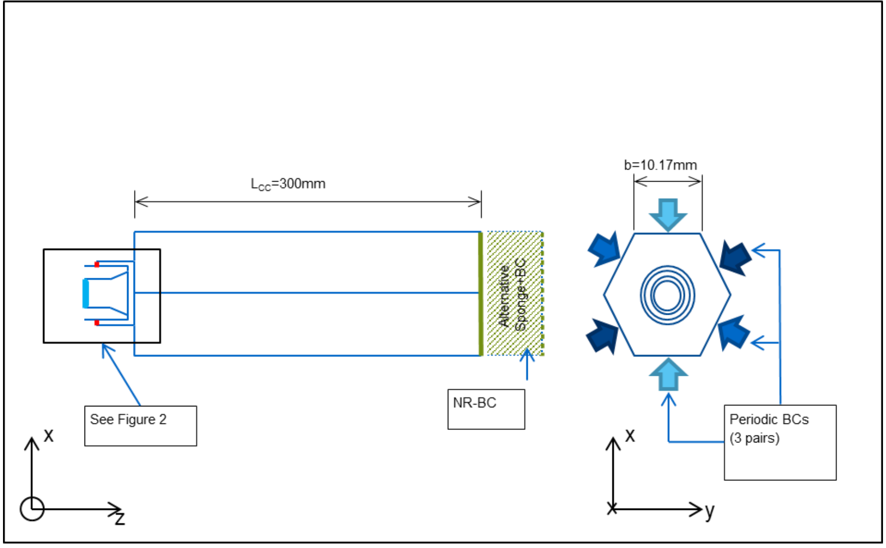

Figure 1: Schematic of the overall simulation domain

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[1] Deutsche Forschungsgemeinschaft, Sonderforschungsbereich Transregio 40, Teilbereich K04

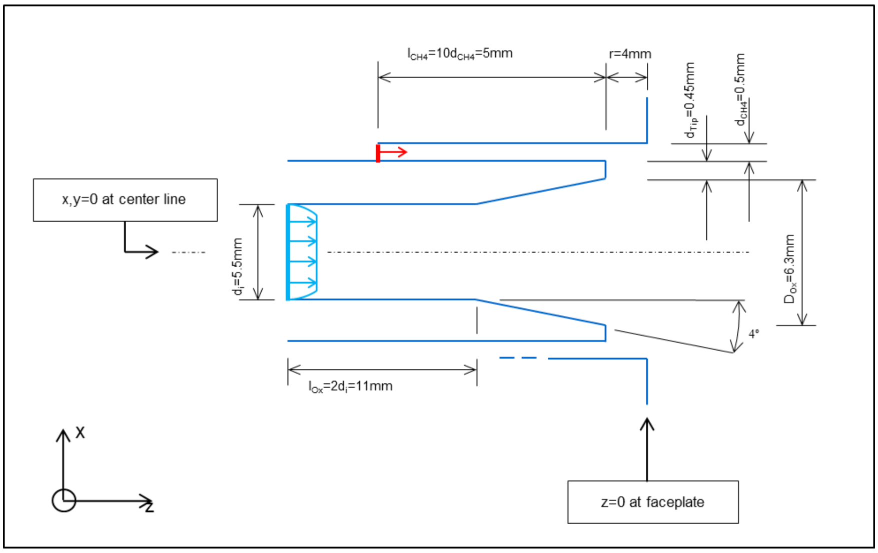

Figure 2: Detailed schematic of the injection element

The following operating conditions were given:

- CH_4/O_2 (with O_2 in the center)
- Mass flow per element:
  - CH_4: 0.136kg/s @ 231K
  - LOX: 0.46kg/s @ 100K
- 100bar chamber pressure
- Outlet non reflecting

2.2 Requested simulations

The test case proposed the following simulations to be performed:

1. Steady state
2. CH_4 mass flow modulation of ±10% @ 5kHz
3. O_2 mass flow modulation of ±10% @ 5kHz
4. O_2 mass flow modulation of ±10% @ 1kHz

3. Simulation Approach

The mesh was generated using ANSYS ICEM meshing software. It is in principal block structured but written into an unstructured format. I has 5.8 million elements and the lip of the Ox-post is resolved with 11 cells (Figure 3). The boundary conditions of the hexagonal combustion chamber domain are pairwise periodic (always the opposing faces), the rest of the walls is non slip adiabatic. The pressure outlet is low reflecting (7.5%) to prevent unwanted eigenmodes to appear and to control pressure at the same time.

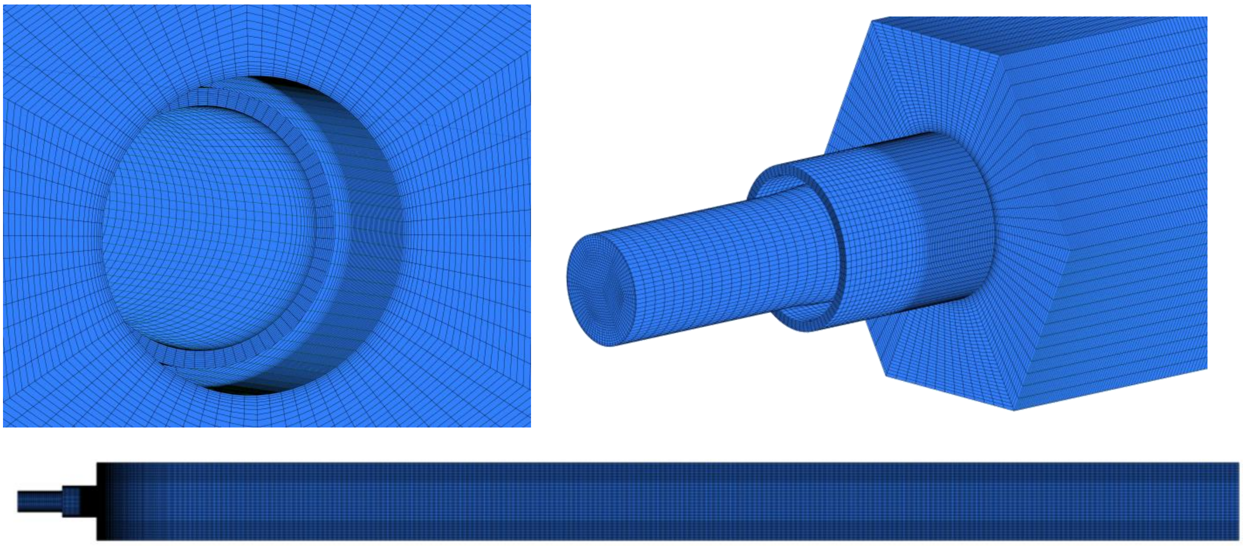

Figure 3: Computational mesh: view from chamber into injection element, outer view of injection element, longitudinal cross section (top left, top right, bottom)

The commercial CFD solver ANSYS CFX was used for the calculations. The simulations were implicit URANS SST type which permitted to keep the numerical effort at a moderate scale. Time steeping was implicit with 2.e-6s time step using 13 sub-iterations.

Numerical stability was tedious to achieve and the numerics were kept at 1st order except for momentum which was 2nd order. For Oxygen, tabulated real gas values were used, the rest of the species (CH4, CO2 and H2O) were ideal gas with NASA polynomial for transport properties. Combustion modelling was kept very simple again to keep the numerical effort low.

A single step chemistry was used which, as a disadvantage, leads to exaggerated temperatures in the flow field, even though the reaction rate was limited which reaching stoichiometric combustion temperature (3700K). The rate was controlled by a combined eddy dissipation – Arrhenius approach. A Modification had to be dome on the pre-exponential factor to prevent blow off in certain conditions; the factor was doubled.

The simulation time for a transient case for evaluation with 5000 time steps was around 2-3 days on 140 cores. These correspond to 50cycles for the 5kHz excitation and 10 cycles for the 1kHz excitation. These simulations for evaluation were started from already oscillating solution to have no run-in effect.

4. Results

Simulations were conducted on Ariane Groups cluster. Post processing was performed with Ansys CFX post software.

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4.1 Steady State Results

First, a steady state simulation (i.e. non-modulated, transient) was performed in order to obtain a basis for comparing the modulated cases. The results for temperature and reaction rate are shown in Figure 4. The flame has the typical pattern for a coaxial element with a slim root, opening up to a shoulder like structure and then ending in long a cylindrical - conical pattern. The temperature, as expected is fairly hot as no dissipating reaction is implemented

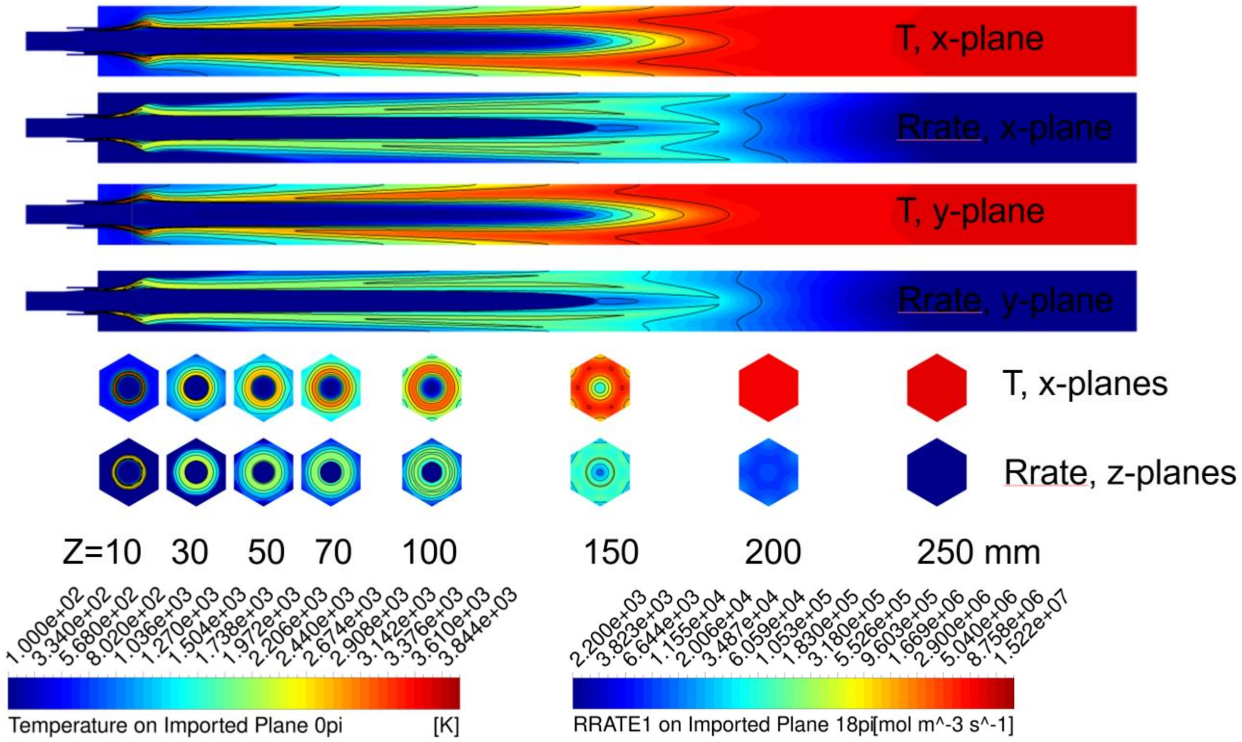

Figure 4: Steady state simulation results of HF-10

4.2 Dynamic Results

Dynamic simulations were conducted for all requested cases and a brief evaluation of the results is presented, here. A comparison to other participants' contributions is given in a different publication of the same session in this conference [3]

4.2.1 Averaged values

Figure 5 shows the average axial temperature fields of non-excited and the different excited configurations. Especially for the 5kHz O_2 modulation, a significant shortening of the flame can be observed. The other two cases only show a minor effect.

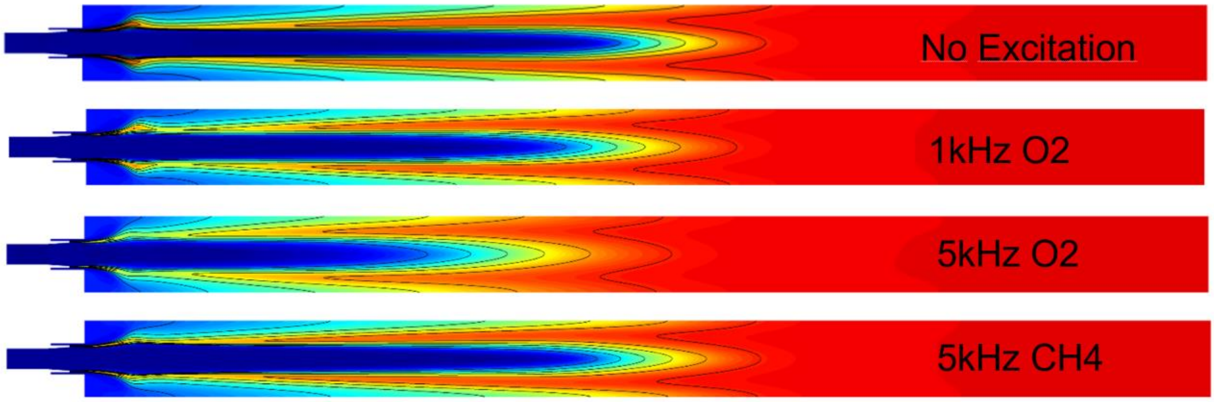

Figure 5: Averaged temperature field on a central axial slice for the 4 simulated configurations

4.2.2 Phase averaged results

For the modulated cases, the results proved to be quite different depending on modulation type and are shown in the following, mainly using the temperature profiles. In order to show the ongoing phenomena clearer, the solutions have been averaged at different phase positions of the excitation signal. These phase averaged values are presented as series of contour plots sorted as shown in Figure 6.

Figure 6: Order of the phase averaged images for the modulated cases

4.2.3 CH4 mass flow modulation of ±10% @ 5kHz

The CH_4 modulation can be seen to affect the outer zone of the flame (Figure 7). The effect, however stretches out quickly and the impact on the overall flame remains quite limited. The blue lines show the propagation of the modulations. The overall effect on the mean values of the flame is limited compared to the unexcited case (Figure 5). The “shoulder” structure of the flame is not as pronounced as it is affected by the modulations. The flame length is nearly identical to the unexcited case.

4.2.4 O2 mass flow modulation of ±10% @ 5kHz

For the 5kHz modulation of the oxygen, the visible phase average effects are fairly low (Figure 8). However, when looking at the transient time series, the flow field is very dynamic with visible oscillations of the Ox core. Furthermore, this was the case why the pre-exponential had to be increased as mentioned before. The flame becomes highly dynamic and for the non-modified pre-exponential factor case loses anchoring and gets blown off. The effects on the mean flame characteristics are maximum for this case as already shown in Figure 5 as the flame shortens significantly. This is a known observation for highly perturbed flames and this calaultions show, that this effect can be already reproduced using this fairly basic CFD approach.

4.2.5 O2 mass flow modulation of ±10% @ 1kHz

For the 1kHz modulation of the oxygen, the phase averaged plots show pronounced periodic structures of “bubbles” that are being convected downstream. The overall effect, however appears to be limited (Figure 5) as the mean flame length is hardly affected. This oscillation case shows the most visible periodic reaction but with limited effect on the averaged values

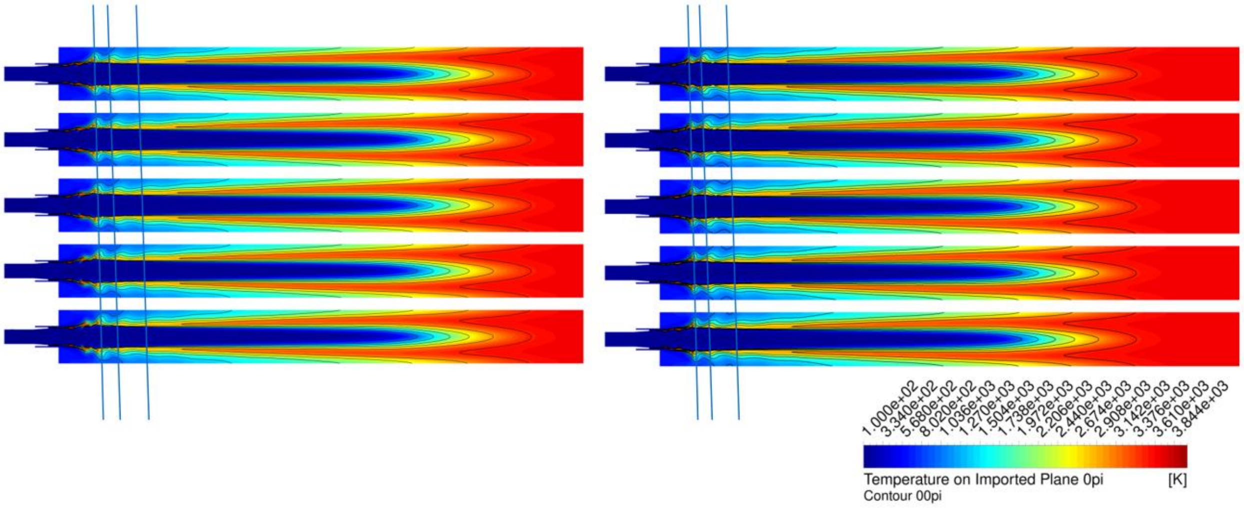

Figure 7: Phase averaged temperature plots on a central axial slice for 5kHz CH_4 modulation (order, see Figure 6). Lines show convective perturbation propagation

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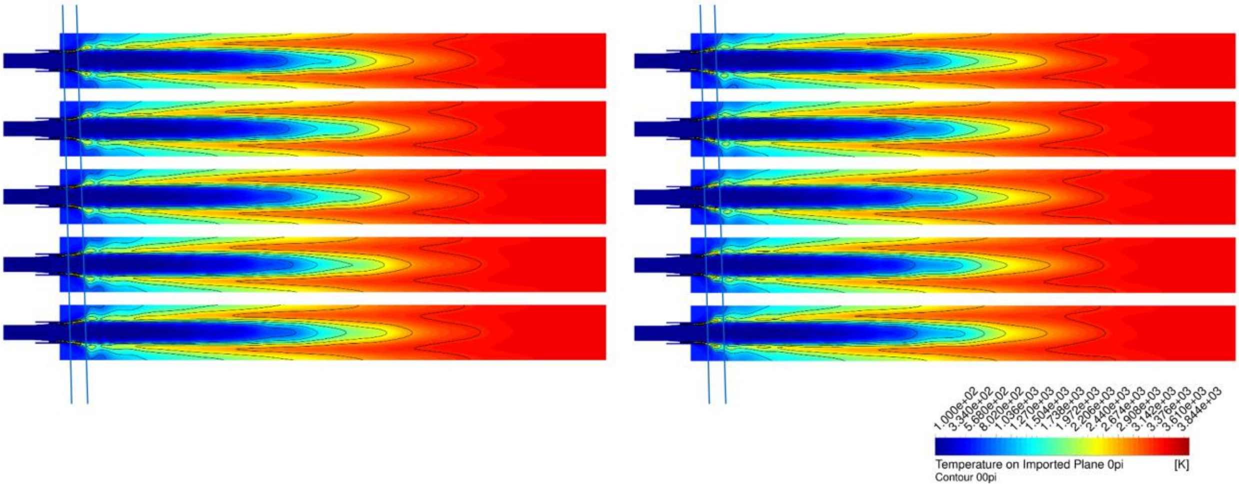

Figure 8: Phase averaged temperature plots on a central axial slice for for 5kHz O_2 modulation (order, see Figure 6). Lines show convective perturbation propagation

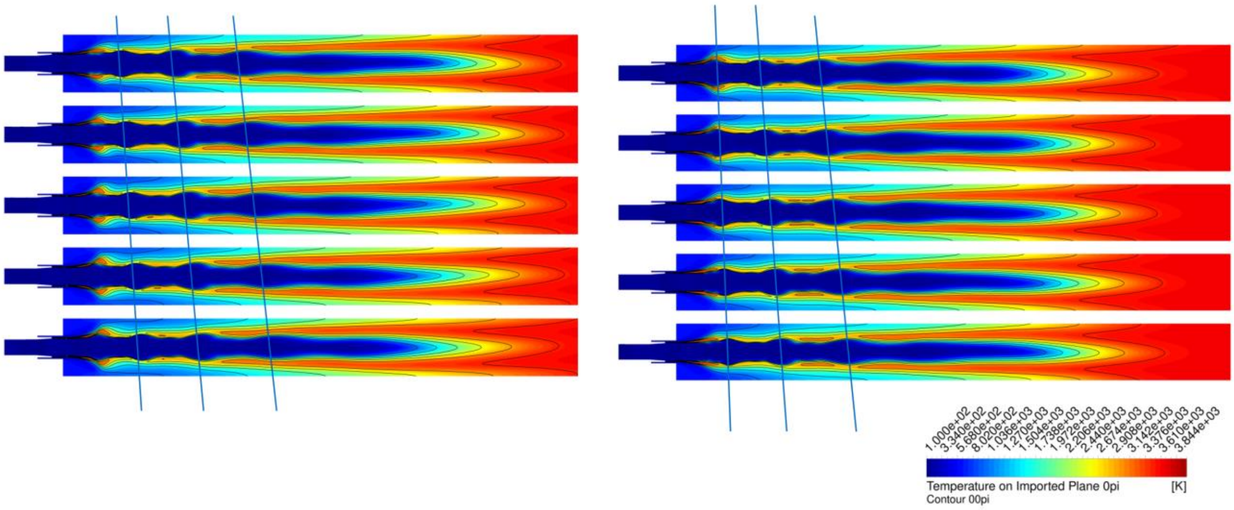

Figure 9: Phase averaged temperature plots on a central axial slice for for 1kHz O_2 modulation (order, see Figure 6). Lines show convective perturbation propagation

5. Summary and Conclusion

One non-modulated and three modulated cases of the REST HF-10 test case have been calculated. The chosen numerical approach was quite basic in terms of modelling and optimized for moderate computational demands.

The different kinds and frequencies of the modulation have significantly different impact on the flame. Despite the fairly simple modelling approach, the effects can be well seen and e.g. the typical shortening of the flame in case of modulations can be observed. The most dynamic case (5kHz O_2 modulation) showed quite turbulent flames (which cannot be seen in the phase averaged solution) and led to blow off for the default combustion modelling.
This is an interestingly strong dynamic effect considering und used URANS approach.

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The strong averaged effects on the flame shape show that purely linear low order modelling will not be able to characterize the onset and growth of such instabilities as there are significant changes in the overall set-up of heat release during instability growth.

The comparison to other contributions of the test case will be performed and is expected to give further insights into the mechanisms present and the potential of different computational approaches [3]

[1] AIAA. Liquid Rocket Engine Combustion Instability. Yang, V. and Anderson, W. and Zarchan, P., 1995.
[2] JOLE42-TN-124/2018: REST Test case HF-10 – Test Case Description [not publicly available]
[3] EUCASS-7114663: REST HF-10 test case: Synthesis of the Contributions for the Simulation of Excited Methane Flames under Real Gas Conditions*, Eucass 2022, Lille, France (* title is preliminary)
[4] Eiringhaus, Daniel & Riedmann, Hendrik & Knab, Oliver & Haidn, Oskar. (2018). Full-Scale Virtual Thrust Chamber Demonstrators as Numerical Testbeds within SFB-TRR 40. 10.2514/6.2018-4469.