Transient Fluid-Structure Interaction Analysis of a Cooled Rocket Thrust Chamber Based on Three Coupling Domains

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Abstract

The combustion processes in liquid rocket engines are optimized to fullfill the todays needs for the best thrust performance in conjunction with minimal fuel and oxidizer loads. The aim is a cost optimized compatible transporter to space with maximal payload available. In order to achieve this goal a trend to increasing combustion chamber pressures is oberserved.

Higher pressures result in increasing thermal loads acting on the thin cooling channel structure. Care must be taken during the design process of the cooling channel structure in order to fulfill the life time requirements of a liquid rocket engine. Therefore, a detailed knowledge about the coupled phenomena causing the failure of the structure is essential. Riccius et al. discussed in [1] the importance of capturing the transient heating and cooling phase in order to address the structural failure mode called “dog-house”-effect.

The aim of our work focuses on the development of a 3D coupled simulation approach, which allows us to study transient engine cycles of cooled liquid rocket engines using a partitioned fluid structure interaction (FSI) approach. We focus on a different approach compared to the conjugate heat transfer approach followed by Nigishi et al. [2] or Pizzarelli et al. [3], where a detailed heat transfer model of the static hot gas state is desired. Their approaches focus on the integration of all coupling domains in one finite volume simulation code. We focus on the modularity of the coupling environment in order to have the possibility to substitute different modelling depth for the different coupling domains, e.g. real gas RANS or Nusselt correlations on the cooling side, ideal gas or real gas flamelet RANS on the hot gas side. Furthermore, the aim is to be able to take different coupling phenomena into account and substitute these as desired, e.g. pure heat transfer, sequentially or fully coupled thermomechanical interactions. The structural domain is modelled via the finite element method, which allows us to easily integrate temperature dependent material parameters and different material modells in the coupling approach to be able to also analyse material failure.

In the present paper we focus on the analysis of the transient heating phase of a typical liquid rocket engine cylce. The analysed test case is a 40kN LOX/H_2 subscale rocket thrust chamber operating at 100 bar combustion pressure. The cooling channel setup consists of 80 cooling channels in the combustion chamber and 160 cooling channels in the nozzle extension. The hydrogen enters the cooling channels at the manifold with a pressure of 250 bar and a temperature of 40 K. The system is not regeneratively cooled, meaning the exiting cooling fluid is not used as boundary condition for the combustion process. The 3D modelling strategy uses symmetry conditions. Half of a cooling channel in the combustion chamber and a full cooling channel in the nozzle extension is modelled for the structural domain. For the sructural model a transient heat transfer problem using the finite element method with temperature dependant material parameters is analysed. On the hot gas side an ideal gas RANS model is conducted, which utilizes adapted gas constants using the assumption of finalized combustion at the inlet. The hydrogen flow in the combustion chamber cooling channel is analysed via a real gas RANS model, whereas the cooling channel of the nozzle extension is simplified by the application of a constant heat transfer coefficient and bulk temperature.

The developed simulation environment ifls uses the DLR-TAU Code, a RANS based finite volume code for the simulation of the two fluid domains and ABAQUS, a multiphysics based finite element code for the simulation of the structural response [4,5,6]. Ifls provides coupling techniques for non conforming grids and numerical algorithms for the analysis of nonlinear and transient FSI problems. In this study a strong coupling scheme based on the Dirichlet Neumann scheme is analysed. In one iteration loop the two fluid domains are solved individually by applying the Dirichlet conditions, i.e.

temperatures on the coupling interfaces and subsequently the structural response is solved by applying Neumann conditions, i.e. heat flux on the coupling interfaces. Different stabilization methods of the fix point iteration concerning the heat transfer problem are discussed. The analysis of a supercritical cooling fluid in such FSI problems has an impact on the stability behaviour of the equilibrium iteration. The Aitken Extrapolation is used to accelerate the fixed point iteration scheme. Summing up, a transient 3D coupling strategy combining the fluid structure interaction of the three domains hot gas, structure and cooling fluid is presented and studied in the present paper. Numerical results of the transient heating phase will be discussed in detail. Furthermore, a sensitivity study shows the influence on the local heat flux distribution of bulging cooling channel structures.

References

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