RANS simulations of reacting cooling films

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The main goal of the work is to evaluate heat fluxes on the hot-gas side of a rocket combustion chamber. In a liquid rocket engine the cooling system is usually a combination of film cooling, regenerative cooling, radiation cooling or ablative cooling. In high performance rocket engines only a regenerative cooling system is not sufficient to keep the combustion chamber wall temperature in a safety range and guarantee structural integrity. In modern first-stage rocket engines, as SSME or Vulcain2, regenerative cooling is augmented with film cooling, using LOX/LH_2 currently as propellant. For future launch vehicles alternative hydrocarbon propellant systems are developed. Especially LOX/methane propellant is preferred due to its good overall performance [9]. Methane has also a density six times higher than liquid hydrogen and therefore the fuel tank size can be drastically reduced.

The cooling film is a buffer layer of liquid or gaseous fuel applied to the cylindrical part of the thrust chamber [11]. The fuel, used as coolant, can react with left-over oxidizer of the main chamber flow when it mixes with hot exhaust gases. Due to high temperatures in the main reaction zone dissociated species are produced, for example CO, HC, OH and O. In the cold film cooling layer, these radicals can recombine. These reactions are exothermic which leads to an increased temperature near the chamber wall. Both effects, reactions and recombinations, increase heat loads to the wall and have to be taken into account to evaluate film cooling efficiency.

Numerical investigations of the increased heat fluxes due to near wall reactions are performed in this work over a range of different operating conditions. Incompressible laminar reacting cooling films are simulated with a RANS-approach. The convective heat transfer is considered for a gaseous cooling film over a flat-plate. Parametric analyses are performed varying the blowing ratio, the hot flow composition and the chamber pressure. Cooling films of hydrogen, methane and nitrogen, as a non-reacting reference simulation, are regarded. Pre-processed flamelet tables, obtained with different kinetic mechanisms, are used as chemistry model. Simple one-step chemistry, as well as O'Conaire mechanism [12] is used for hydrogen/oxygen chemistry. The detailed GRI 3.0 mechanism for methane/oxygen is compared with the reduced 15-step mechanism, obtained by Chen [10].

Counterflow diffusion flame calculations are performed to obtain flamelet tables for ideal gas. Two opposing axisymmetric jets of fuel and oxidizer create a stagnation plane with a laminar diffusion flame stabilized at the location of stoichiometric mixture fraction. Along the symmetry axis, the one-dimensional balance equations for mass, radial momentum, species mass fractions and energy are solved. As chemistry solvers Cantera and Cosilab are used. The influence of differential diffusion is evaluated, comparing with unity Lewis number assumption.

A 2-D test geometry, based on the sub-scale DLR BK-E rocket combustion chamber, is selected. The cooling film is injected tangentially to the wall. The dimension of the cooling inlet resembles the experimental setup. The results obtained with commercial and non-commercial codes are compared.

Different experimental data are available to validate our results. Experimental investigations of film cooling effectiveness in a LOX/H2 and LOX/CH4 sub-scale rocket combustion chamber with regenerative cooling are performed by the DLR research group under the direction of Prof. Haidn [1, 2, 3].

The effects of near-wall reactions are mainly investigated for gas turbines. Experiments of a typical gas turbine hot flow over a film-cooled flat wall are performed for example by Polanka et.al.[6], Blunck et al.[4, 5] and Kirk et al.[7, 8].

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