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Thermal investigation of an internally cooled strut injector for scramjet application at moderate and hot gas conditions

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ABSTRACT

In this paper, we present a combined experimental and numerical approach to assess the thermal loads and the cooling mechanism of an internally cooled strut injector for a supersonic combustion ramjet. Infrared measurements of the injector surface are conducted at a moderate external flow temperature. In addition, the main flow field is investigated with the LITA technique. Main features of the cooling mechanism are identified based on experimental data. However, a full evaluation can only be obtained using a complex, conjugate CFD simulation, which couples the external and internal flow fields to the heat conduction inside the injector body. Furthermore, numerical simulations are also presented for hot gas conditions corresponding to combustion experiments. Both hydrogen, which would be used as fuel for flight tests, and air are considered as coolants. While the main features of the cooling mechanism will be shown to remain unchanged, the combustor wall temperature is found to have a significant influence on the cooling. This emphasizes the importance and the usefulness of such complex conjugate numerical simulations.

1. Introduction

When pursuing a stable, supersonic combustion in a scramjet engine, one of the major challenges is the fast and efficient injection and mixing of the fuel. Therefore, a wide range of investigations regarding fuel injection concepts is available in literature. Many studies focus on wall-bound injection schemes using simple port holes or ramped geometries [1–3]. This is often combined with geometrical features, e.g. cavities, to create favorable ignition conditions and to promote flame stabilization [4–8]. Wall injection schemes are not only advantageous due to their simple implementation, but also avoid the insertion of drag-inducing objects into the main flow path of the combustion chamber.

However, the penetration depth of wall injectors is limited, and especially for large combustion chambers it is beneficial to inject the fuel directly into the center of the flow. This can be achieved using strut injectors, which either cover the whole width of the combustor [9–12] or are designed as semi- or partial struts [13]. A second advantage of this type of injector is the addition of momentum to the thrust output of the engine, as the injection of the fuel is in direction of the main flow. The simplest possible geometry is a wedge-shaped strut with fuel injection at the trailing edge. A sharp leading edge is often used to minimize the intensity of the bow shock. The geometry of the trailing edge can be modified to enhance the fuel mixing process. This ranges from the introduction of two-dimensional features such as steps [14] or corners [15] to fully three-dimensional concepts as investigated by Gaston et al. [16], by JAXA [17,18] or within the framework of the German Research Training Group GRK 1095 [19,20].

In contrast to wall-bound injection schemes, a strut injector is fully exposed to the supersonic combustor flow. This leads to considerable heat loads especially at the leading edge. Even high-temperature materials, as for example tested by Bouchez et al. [21], may not withstand the resulting temperatures without active cooling. Rounding the leading edge reduces the thermal loads due to dissipation of energy downstream of the bow shock, but induces unwanted drag and increases pressure losses. Instead, active internal cooling of the injector is a promising concept. While water can be used during ground tests [10,22], using the fuel as coolant is a logical choice for flight experiments. With this approach, cooling of the structure and preheating of the fuel can be combined and no additional coolant has to be transported on board. This has already been studied within the French PREPHA program [23], where hydrogen was fed through a bore along the leading edge prior to injection. Alternatively, the use of porous injector materials has been investigated [24,25]. However, in case the leading edge is cooled with this method, high internal pressures are required to account for the stagnation pressure of the combustor flow.

As the thermal loads onto such a strut injector can hardly be measured experimentally, a numerical approach is inevitable to

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Nomenclature

a	speed of sound, m/s
C	Courant number, –
c	specific heat capacity, J/(kg K)
D	mass diffusivity, m^2/s
e	specific internal energy, J/kg
k	heat conductivity, W/(m K)
M	Mach number, $M=u/a$, –
$\dot{m}$	mass flow rate, kg/s
p	pressure, Pa
Pr	Prandtl number, –
$\dot{Q}$	heat flux, W
$\dot{q}$	heat flux density, W/m^2
Sc	Schmidt number, –
St	Stanton number, –
T	temperature, K
t	time, s
u	velocity, m/s
Y	species mass fraction, –
δ_{ij}	Kronecker delta, –
ϵ	emissivity, –
μ_t	turbulent viscosity, kg/(m s)
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
σ	standard error of the mean, –
τ	shear stress, N/m^2
τ_{ij}	Reynolds stress tensor, N/m^2
Θ	dimensionless temperature, –

quantify the heat loads and to optimize the internal cooling. For an accurate analysis, coupled numerical simulations have to be conducted, which take the heat conduction inside the solid injector structure into account. Zhong et al. [26] performed loosely coupled simulations for a semi-strut with simple fuel bores, where they identified highly stressed regions along the strut leading edge. A better cooling can be achieved by a more complex internal geometry, as realized for the strut used within the GRK 1095. First conjugate simulations for this strut with a modified and simpler internal geometry have been conducted by Rust et al. [27]. Gerlinger and Simsont [28,29] then continued this work for a version with a more realistic enhanced internal flow path and a blunted leading edge. However, due to the use of structured grids, the internal geometry still had to be simplified. Yet, a characterization of features for both the internal flow and the injector surface was achieved. Both studies were conducted using two separate numerical solvers for the fluid and solid regions, which exchanged data at regular intervals. For the present study, an OpenFOAM solver for the investigation of conjugate heat transfer in supersonic flows has been developed, which combines both the fluid and the solid regions within one solver architecture. In contrast to previous investigations, it can handle hybrid computational grids and thus allows to model the actual geometry of the strut and its internal flow path. This solver has been validated before using various test cases [30–32], where the correct prediction of the relevant flow phenomena could be proven.

In this study, we present a combined experimental and numerical approach to assess the thermal loads onto the GRK 1095 injector. Experiments are conducted in a direct-connect facility at moderate flow temperatures to identify well and poorly cooled regions of the strut, and also to provide additional data for the comparison with the new numerical solver. This includes the application of infrared thermography to evaluate the strut surface, as well as laser-induced thermal acoustics (LITA) to provide quantitative data for the external flow field. Besides the comparison to the experimental data, also simulations for hot gas conditions are conducted, where both air and hydrogen are evaluated as coolants. Furthermore, two different side wall temperatures related to ground testing and water-cooled combustion chamber walls are investigated numerically to assess the influence of lateral heat conduction inside the strut injector.

2. Methods

2.1. Experimental methods

Experimental investigations are conducted at the supersonic test facility of the Institute of Aerospace Thermodynamics (ITLR) at the University of Stuttgart. This facility classifies as direct-connect test bench and is shown schematically in Fig. 1. A combination of a screw compressor and an air dryer supplies up to $\dot{m} = 1.45$ kg/s of dry air at a maximum total pressure of 10 bar. The air can be heated electrically by a three-staged heater system, which allows for a total temperature of up to 1300 K at the inlet of the test section. At the exit of the test section, the exhaust gas is blown out into the ambient. An auxiliary air supply is available as emergency backup for the screw compressor. Coolant gases are supplied via an additional line, which leads directly to the test section.

2.1.1. Test channels

Different experimental channels can be mounted in the test section of the facility, two of which are investigated in the present work. For hot gas and combustion experiments a model combustion chamber is available, which has been used to evaluate the performance of different fuel injection techniques for supersonic combustion experiments in the past [33–35]. These studies proved that the lobed central strut injector, as presented in more detail in Section 2.1.2, is well suited as first stage in a multi-stage injection scheme.

The combustor is made of copper and is water-cooled during experiments, which results in a constant wall-temperature of approximately 400 K. It is divided into four segments: A segment with a constant cross section and a height of 35.4 mm is followed by a divergent section with a fixed opening angle of 1°. The last two segments exhibit variable opening angles, which are set to 2° for the present study. The combustor width is constant at 40 mm over the whole length. A main flow Mach number of 2.5 is evaluated. Fig. 2 shows a schematic of the model combustion chamber. The strut injector is installed in the first divergent part of the combustor with a trailing edge location of $x_1 = 513$ mm. The combustion chamber is only used for experiments at hot gas conditions with $T_t = 1300$ K within the present study, as it does not allow direct optical access to the strut. Accordingly, the numerical simulations at these conditions feature the model combustor geometry to maintain comparability to the experimental flow conditions.

Secondly, a modular channel is considered, which is presented in Fig. 3. The modules 2 – 5 are interchangeable to allow an adaption to experimental requirements. The channel is manufactured from stainless steel. As it is not actively cooled during experiments, the total main flow temperature is limited to approximately 550 K due to measure-

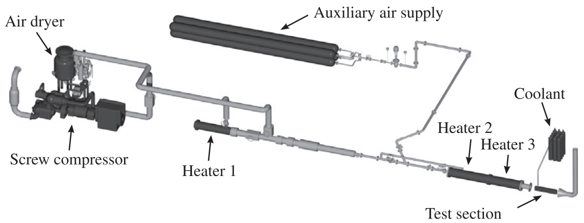

Fig. 1. ITLR supersonic test facility.