COUPLED ANALYSIS OF HOT-GAS AND COOLANT FLOWS IN LOX/METHANE THRUST CHAMBERS

M. Pizzarelli, B. Betti, F. Nasuti

Università di Roma "La Sapienza"
Dipartimento di Ingegneria Meccanica e Aerospaziale

via Eudossiana 18, I-00184 Rome, Italy

ABSTRACT

The analysis of the flow-behavior and the heat transfer characteristic in a regeneratively cooled thrust chamber is of paramount importance for the development of a high-performance liquid rocket engine and to guarantee its structural thermal design. The accurate analysis of such a problem can only be obtained by costly experiments or by complex numerical simulations, because of the three-dimensional shape of the cooling channels and of the coupling among flow evolution in hot-gas and coolant sides and wall heat transfer. However, the parametric investigations of rocket thrust chambers thermal environment can be efficiently made by accurate engineering tool. In the present study, a computational procedure able to describe the coupled hot-gas/wall/coolant environment that occurs in most liquid rocket engines and to provide a quick and reliable prediction of thrust-chamber wall temperature and heat flux is developed. The coupled analysis is performed by means of an accurate CFD solver of the Reynolds-Averaged Navier-Stokes (RANS) equations for the hot-gas flow and a simplified "quasi-2D" approach, which widely relies on semi-empirical relations, to study the problem of coolant flow and wall structure heat transfer in the cooling channels. Numerical results, relevant to a sample expander-cycle engines fed with oxygen and methane, are presented. In particular, the attention is focused on the wall heat transfer characteristic and its dependence on the cooling channel geometry, coolant mass flow rate and inlet conditions.

INTRODUCTION

The oxygen/methane propellant combination is currently considered for the development of future European liquid propellant thrust chamber [1; 2]. Compared to kerosene, methane can provide a higher specific impulse, together with lower pressure loss in the cooling channel, better cooling abilities and less soot deposition. With respect to oxygen/hydrogen propellant combination, oxygen/methane can be considered "space storable" and it is favored by a higher density [3], although it gives lower specific impulse.

The hot gas environment within a modern high performance rocket combustion chamber is characterized by gas temperatures up to 3600 K and heat fluxes up to 160 MW/m^2. In order to keep the temperatures of the thrust chamber walls within their allowed limits, an intense cooling effort is necessary, which, in case of regenerative cooling, is achieved by flowing one of the two propellants into suitable channels surrounding the thrust chamber. The adequate understanding and accurate prediction of regenerative cooling heat transfer characteristics, heat pick-up and wall temperature distribution in the thrust chamber are considered key features for the development of oxygen/methane engines, especially in the case of expander cycle feed system. In fact, in this case, the driving power for the turbo-pumps comes from the methane used as a coolant in the regenerative cooling circuit.

Expander cycle engines are an attractive solution for upper stage and in-space propulsion because of their longevity and capability for multiple restarts and throttling. They have the simplest configuration among the pump-fed cycles because they do not require components such as gas generators or preburners. Development and testing of expander cycle engines continues to be of interest for the international industries and space agencies, as demonstrated by the studies on RL-10 in all its configurations in US since '60 [4; 5], on RD0146 in Russia [6], on LE-5B in Japan [7], and on Vinci in Europe [8]. All of these expander cycle engines are operated with oxygen/hydrogen propellant combination. Although no known oxygen/methane engines have been flown for aerospace applications, space agencies in the US, Russia, Europe and Japan have been considering methane fueled propulsion system for various applications. Recently, studies on existing oxygen/hydrogen expander cycle engines modified by replacement of hydrogen with methane have been performed by industries [9; 10] and universities [11], in order to better understand feasibility and limits of envisaged oxygen/methane expander cycle engines.

The objective of this study is to develop a computational procedure able to describe the coupled hot-gas/wall/coolant environment that occurs in most liquid rocket engines and to provide a quick and reliable prediction of thrust-chamber wall temperature and heat flux as well as the coolant-flow characteristics, that are, pressure drop and temperature gain in the regenerative cooling circuit. These parameters, which are of great importance in the development of an expander-cycle engine, will be analyzed for the case of LOX/methane propellant combination. The coupled analysis is performed by means of an accurate CFD solver of the Reynolds-Averaged Navier-Stokes (RANS) equations for the hot-gas flow and a simplified "quasi-2D" approach, which widely relies on semi-empirical relations, to study the problem of coolant flow and wall structure heat transfer in the cooling channels.

HEAT TRANSFER

A comprehensive thermal model for a regeneratively cooled thrust chamber must account for convection from hot-gas, conduction within the wall, and convection to the cooling channels. In fact, heat transfer can be described as the heat flux between two moving fluids, separated by a solid wall. In its simplest form regenerative cooling can be modeled as a steady heat flux from a hot gas through a solid wall to a cold fluid. This problem can be divided into three sub-problems, which are defined as follows:

- The turbulent flow of a mixture of gases in a rocket engine, including combustion chamber and converging-diverging nozzle.
- The heat conduction through the wall of the rocket engine between the hot gases and the coolant.
- The turbulent flow of the coolant in the channels surrounding the rocket engine.

These subproblems are coupled by the two steady-state balances of three heat fluxes: from hot-gases to the wall; through the wall; and from the wall to the coolant.

HOT-GAS FLOW

The demand of a more comprehensive engineering tool for parametric investigations of rocket thrust chambers thermal environment is pushing the improvement of hot-gas side heat transfer prediction tools. In fact, computational fluid dynamics (CFD) has the potential to improve the traditional thrust chamber design and development process by replacing the 1D analytical approaches [12; 13] which are based on Nusselt-type correlations.

In this work, a Reynolds-Averaged Navier-Stokes (RANS) approach is used to simulate the hot-gas flow-field and heat transfer in the thrust chamber. In particular, combustion is not simulated, but a flow of combustion products in chemical equilibrium at the chamber temperature and pressure is injected using a "full-inlet" approach. The numerical solutions are carried out by means of an in-house 2D-axisymmetric multi-block finite volume RANS equations solver [14; 15], modified to simulate multi-component mixtures of thermally perfect gases. Turbulence is described by means of the Spalart-Allmaras one equation model [16], modified to take into account compressibility effects [17]. A constant turbulent Schmidt number is adopted to model turbulent diffusivity.

COOLANT FLOW

A simplified "quasi-2D" approach [18; 19] is used to study the coupled problem of coolant flow and wall structure heat transfer in the cooling channels of liquid rocket engine thrust chambers. This approach is based on 1D hydraulic model of the coolant mass and momentum governing equations and on 2D stratified model of the coolant energy equation which is coupled to the wall heat transfer balance in the radial direction. The turbulent thermal conductivity, fluid skin friction and coolant-wall heat transfer coefficients are evaluated by semiempirical relations provided in the literature. This model permits to have a fast prediction of both the coolant flow evolution and the temperature distribution along the whole cooling channel structure. The model, aiming to the study of any fluid evolving through cooling channels, considers a generic equation of state, and thus the coolant fluid can be either a compressible gas, or a supercritical fluid or a liquid. To consider fluids other than perfect gas or incompressible liquid is mandatory in the case of methane as coolant in rocket engines, since its thermodynamic conditions in the cooling circuit of an expander cycle engine are quite close to the critical point. In this regime, the fluid cannot be modeled either as a perfect gas or as a liquid. The thermodynamic properties of methane are evaluated by the modified Benedict-Webb-Rubin (MBWR) equation of state and by proper relations for viscosity and thermal conductivity, taken from Ref. [20]. This equation of state is selected because it shows high accuracy to determine the correct pressure-volume-temperature behavior of a fluid also in the near-critical region.

HOT-GAS/COOLANT COUPLING

The coupled heat transfer analysis between the hot-gas flow and the cooling circuit is performed by means of:

- CFD evaluation of the hot-gas flow, imposing the wall temperature T_w as boundary condition.
- "Quasi-2D" solution of the cooling circuit, imposing the heat transfer coefficient h_c and the adiabatic wall temperature T_{aw} at the hot-gas side.

The adiabatic wall temperature T_{aw} at the hot-gas is obtained by means of the CFD tool imposing the adiabatic wall boundary condition. Once the evolution of the adiabatic wall temperature is known, the coupled computation between the hot-gas flow and the cooling circuit is obtained by means of an iterative loop between the above mentioned tools. In particular, the iterative loop is composed by the following steps:

1. Evaluation of the heat transfer coefficient h_c by means of the CFD tool, imposing the isothermal wall boundary condition at $T_w = 700$ K.

2. Evaluation of the wall temperature profile at the hot-gas side, by means of the "quasi-2D" tool, imposing the heat transfer coefficient h_c (provided by the previous step) and the adiabatic wall temperature T_{aw}.

3. Evaluation of the heat transfer coefficient h_c by means of the CFD tool, imposing the wall temperature profile provided by the previous step.

4. Step 2 & 3 are repeated until a convergence criterion is satisfied.

RESULTS

Preliminary results are presented for a reference LOX/methane engine. The hot-gas flow solutions are performed with the assumption of full-inlet 2D axisymmetric configuration; in particular, the following approximations are considered:

- the injector plate is not simulated;
- equilibrium combustion products are injected through the whole chamber section;
- the cylindrical section of the combustion chamber is treated as a smooth wall.

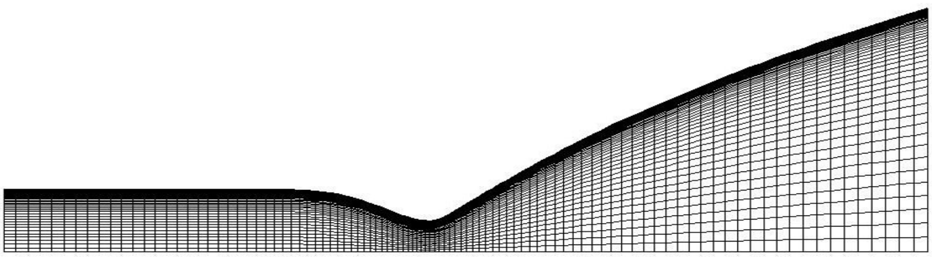


Figure 1: Full inlet computational grid features

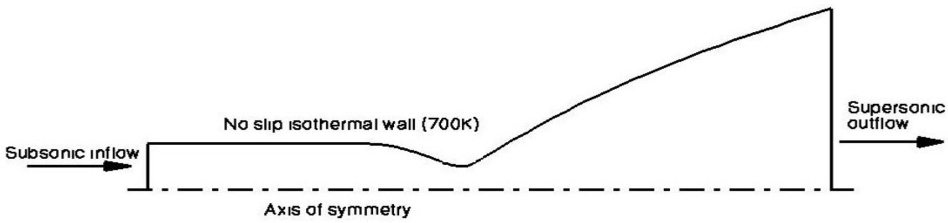


Figure 2: Full inlet computational grid features: boundary conditions enforced

Subsonic inflow boundary condition prescribes total pressure, total temperature and composition of the injected mixture. Chamber pressure is assigned as total pressure. Adiabatic flame temperature of oxygen/methane equilibrium combustion products is assigned as total temperature. Injected mixture is composed by equilibrium combustion products [21]. Isothermal wall temperature is 700 K for the upper no slip wall. Temperature and axial velocity flow-fields are shown in Figure 3.

Once achieved the hot-gas flow solution with $T_w = 700$ K the coupled solution with wall conduction and coolant flow is achieved in few steps. In Figures 4(a) and 4(b) the iteration history is displayed for the

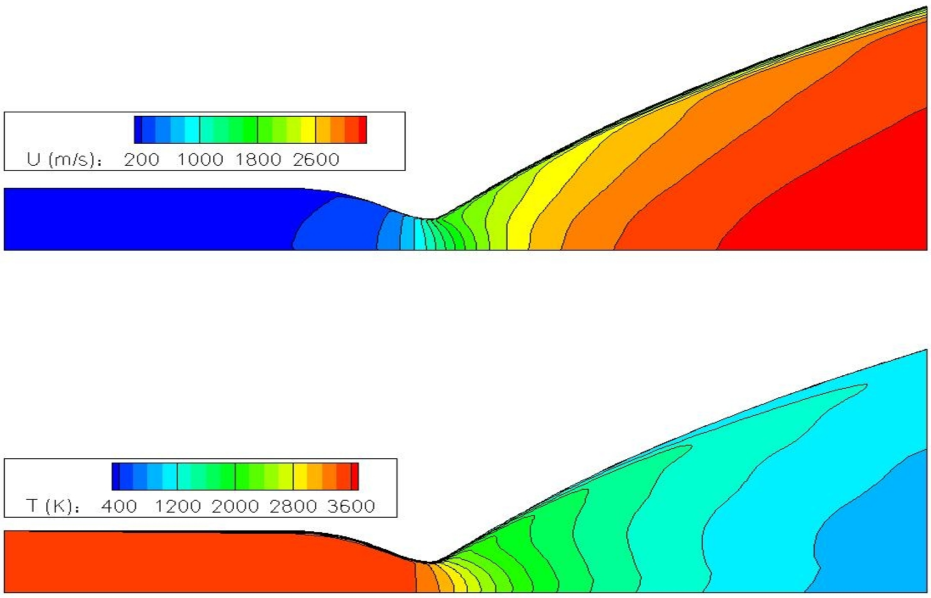
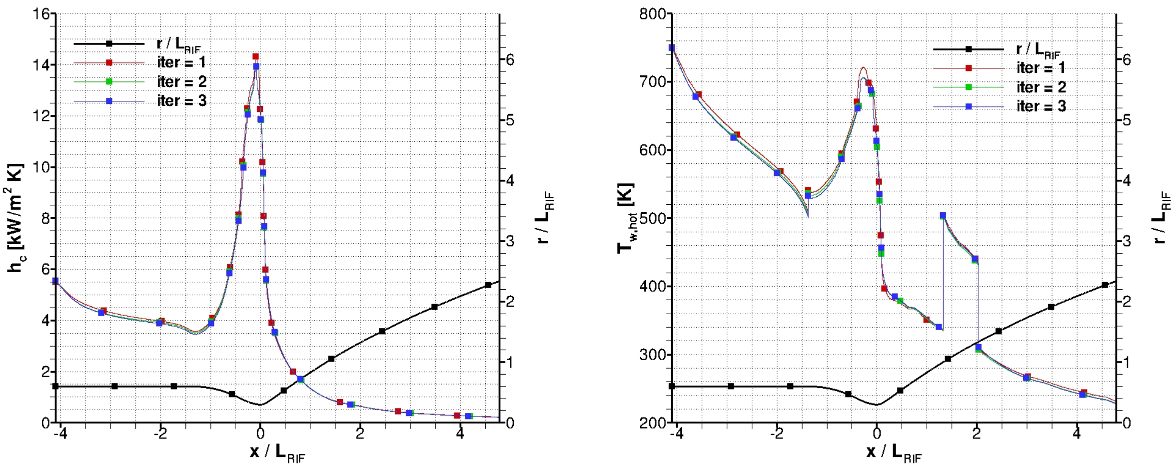


Figure 3: Temperature and axial velocity flow-field



(a) Heat transfer coefficient of the hot-gas.

(b) Wall temperature at the hot-gas side.

Figure 4: Convergence history of the numerical coupled procedure.

heat transfer coefficient and the wall temperature at the hot-gas side, respectively. It can be noticed that convergence is clearly reached in three iterative coupling between the CFD and the "quasi-2D" tools.

In the final paper a parametric analysis will be presented to discuss the role of cooling channel geometry, mass flow rate and inlet conditions in determining the resulting wall temperature.

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