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Heat transfer modeling for supercritical methane flowing in rocket engine cooling channels

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HIGHLIGHTS

- Numerical simulation of methane in supercritical pressure and subcritical to supercritical temperature.
- Fluid and structure thermal coupling.
- Asymmetrically heated channels of rectangular cross section.
- Supercritical-pressure methane may exhibit heat transfer deterioration.
- Heat transfer deterioration is mitigated increasing coolant pressure and/or surface roughness.

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ABSTRACT

To investigate the methane behavior inside rocket engine cooling channels, a test article has been specifically designed by the Italian Aerospace Research Center. In this study, the expected wall and coolant behavior of this test article is analyzed by a three-dimensional conjugate heat transfer model. Different coolant pressure and surface roughness levels are considered in order to understand their influence on the heat transfer capability of the cooling system. Results show that heat transfer deterioration may occur in principle when methane is operated in near-critical condition. However, the resultant wall temperature peak reduces for increasing coolant pressure and for increasing surface roughness.

1. Introduction

The hot gas environment within a modern liquid rocket combustion chamber can be characterized by gas temperatures as large as 3600 K and heat fluxes as large as 160 MW/m^2, depending on propellants, mixture ratio and chamber pressure [1]. 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. In this case, high supply pressure is required because of the inevitable losses which occur in the cooling circuit [2]. Regenerative cooling performance is especially important in case of reusable or long-duration-expendable engines, where an effective and efficient cooling system is crucial to extend the engine life, or in expander cycle engines, where coolant heating provides the available power for turbo-machinery. In the latter case, thermal analysis of regeneratively cooled engines is essential to predict not only wall temperature but also coolant temperature and pressure at the channel exit.

The study of heat transfer to near-critical fluids, that is to supercritical pressure fluids whose temperature is close to the pseudo-critical value (i.e., the temperature at which specific heat at constant pressure has a maximum at a specified pressure), has recently captured the interest of liquid rocket engine designers because of the possible use of methane as a denser and cheaper replacement of hydrogen in launch vehicles and as a cheaper replacement of toxic storable propellants for space propulsion [3,4]. In case of liquid-oxygen/liquid-methane engines with chamber

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Nomenclature

$\dot{m}$	mass flow rate
b	channel width
c_p	specific heat at constant pressure
h	channel height
h_c	heat transfer coefficient
k	thermal conductivity
L	channel length
p	pressure
q	heat flux
s_w	internal wall thickness
T	temperature
t_w	rib thickness
x	axial coordinate

Subscripts

0	total
c	critical
e	exit
i	inlet
inn	inner-interface
pc	pseudo-critical
w	wall

Greek

ε	surface roughness

pressures larger than about 50 bar, a peculiar behavior of methane as a coolant is found: it enters channels at supercritical pressure and subcritical temperature and then, under heating from hot gas, its temperature may increase up to reach and exceed the pseudo-critical value. As a consequence, because the typical pressure and temperature of methane in cooling channels are relatively close to the critical point, the coolant flow behavior is strongly affected by the large property variations that occur in the near-critical region. This behavior is often referred to as that of a “transcritical fluid” flow. In particular, variables such as specific heat at constant pressure, thermal conductivity and speed of sound exhibit a relevant peak value in the vicinity of the pseudo-critical temperature. The peak values decrease with increasing pressure; consequently, for sufficiently large pressure levels the influence of the near-critical region on the flow behavior vanishes.

To better understand the fluid-dynamic phenomena that occur in case of transcritical fluids, it is interesting to compare the thermodynamic behavior of a transcritical fluid with that of fluid boiling at subcritical pressure. In the latter case, under wall heating, the fluid phase changes from liquid to vapor, with an abrupt variation of its thermodynamic properties. More specifically, in case of low heat flux nucleate boiling occurs and wall heat transfer increases, whereas in case of high heat flux a gaseous film insulates the hot wall (film boiling), leading to a progressively increasing wall temperature. In case of supercritical pressure the phase-change does not occur. However, if pressure is rather close to the critical point, in case of wall heating the fluid passes from a liquid-like state to a gas-like state: a pseudo phase-change takes place. As a result, heat transfer deterioration may occur in case of low mass flow rate, high heat flux, and fluid and wall temperature respectively lower and higher than the pseudo-critical value [5,6].

Although a number of studies have been conducted on supercritical hydrogen flow in cooling channels to investigate the thermal behavior of LOX/LH_2 rocket engines, only few experimental investigations on supercritical-methane flow inside cooling channels can be found in the literature [7–9]. Moreover, apart the very few data presented in Ref. [8], these studies do not refer to rectangular-cross-section cooling channels, which are of great interest in rocket engine applications. As for numerical computations, supercritical-methane flow in both heated circular-cross-section tubes and rectangular-cross-section cooling channels have been studied by means of two-dimensional (e.g., [10,11]) and three-dimensional (e.g., [12–14]) CFD models.

The Italian interest on methane as coolant for liquid rocket engine cooling channels has led to the HYPROB program, which is carried out by CIRA under contract by the Italian Ministry of Research [15]. The main objective of the program is to improve the National system and technology capabilities on liquid rocket engines for future space applications, with specific regard to LOX/LCH_4 technology. In this framework, the design and development of rocket engine demonstrators has been established, including intermediate test articles. A specific test article (referred to as Methane Thermal Properties, MTP, test article) has been designed to investigate the thermo-fluid dynamic behavior of methane inside a straight cooling channel with rectangular cross section, which can be representative of a regenerative system. In fact, the channel cross section has a dimension of 1 mm $\times$ 3 mm and the envisioned operative conditions are: maximum heat flux of the order of 10 MW/m^2; inlet pressure ranging from 60 to 150 bar; inlet temperature of about 120 K; mass flow rate ranging from 10 to 30 g/s. A drawing of the experimental apparatus is shown in Fig. 1.

Goal of the present work is to investigate the transcritical methane flow inside the MTP test article of the HYPROB program. The flow inside the asymmetrically heated channel, characterized by rectangular cross section, is studied by a three-dimensional Conjugate Heat Transfer (CHT) model based on the numerical integration of the Navier–Stokes and Fourier's equations. Such a model is able to describe the whole cooling device composed by the coolant and the solid domain, whose heat input is represented by a condition of assigned entering heat flux. Computations with variable coolant pressure are performed in order to investigate the behavior of the MTP test article at different operative conditions. Moreover, also the effect of the wall surface roughness is investigated.

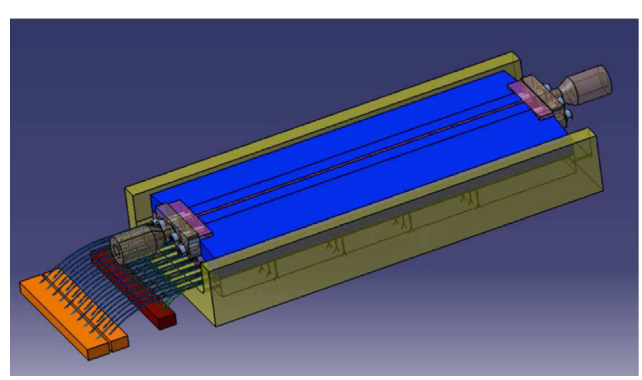

Fig. 1. Drawing of the MTP test article with electrical, mechanical and thermal insulation interfaces.