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CFD analysis of transcritical methane in rocket engine cooling channels

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ABSTRACT

The knowledge of the flow behavior inside cooling channels is of great importance to improve design and performance of regeneratively cooled rocket engines. The modeling of the coolant flow is a challenging task because of its particular features, such as the high wall temperature gradient, the high Reynolds number and the three-dimensional geometry of the passages. In case of methane as coolant, a further complication is the transcritical operating condition of the fluid. In this thermodynamic regime large changes of the fluid properties can greatly influence the coolant flow-field and the heat transfer. Numerical simulations of transcritical methane flow-field in asymmetrically heated rectangular channel with high aspect ratio and strong wall temperature differences are carried out by a suitable CFD solver. Results are discussed in detail and compared with supercritical methane flow-fields. Finally the aspect ratio effect on methane flow is analyzed by comparison of four different rectangular cooling channel geometries with fixed hydraulic diameter and coolant flows with the same mass flow-rate per unit area. Emphasis is given to the comparison of fluid cooling performance and pressure loss.

1. Introduction

The hot gas environment within a modern liquid rocket thrust chamber is characterized by gas temperatures up to 3600 K and heat fluxes up to 160 MW/m^2 [1]. In order to keep the temperatures of the thrust chamber walls within their application limits, an intense regenerative cooling effort, resulting in large supply pressure requirements, is necessary. Many investigators [2–4] have shown that cooling channels with high aspect ratio of the cross section (high aspect ratio cooling channels, HARCC) provide a significant increase of cooling efficiency which could be used to reduce either the wall temperature in combination with a constant pressure budget, or the overall system pressure level at constant wall temperature. This result has been found for hydrogen cooled engines which operate with coolant at supercritical pressure but far enough from the critical point. Thus, they cannot be straightforwardly extended to any other fluid and operative condition, such as fluids in near-critical condition.

The study of heat transfer to near-critical fluids, that is to supercritical pressure fluids whose temperature is close to the pseudo-critical value,[1] 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 [5,6] and as a cheaper replacement of toxic storable propellants for space propulsion [7,8]. The interest in such flows for liquid rocket engines is driven by the fact that thrust chamber is cooled by one of the available propellants, which flows in suitable narrow channels. In case of turbopump-fed engines, fluid pressure in cooling channels is typically of the order of 50–400 bar. Typical coolants are fuels, however the behavior of cryogenic fuels like hydrogen and methane is different from that of storable fuels like mono-methyl-hydrazine (MMH). In fact, MMH has a rather high critical temperature, which is never exceeded inside cooling channels. Conversely, at the other extremum, hydrogen features low values of critical temperature and pressure, such that its thermodynamic conditions are always quite far from the critical point. Different is the case of methane whose thermodynamic conditions in channels are in the near-critical range. Thus, if coolant is methane a peculiar behavior is found: it enters channels at supercritical pressure and subcritical temperature and then, under heating from hot gas, its temperature increases up to reach and exceed the pseudo-critical value. In the following, this behavior will be referred to as that of a "transcritical fluid" flow,[2] whose main feature is that many thermodynamic variables (such as specific heat at constant pressure, thermal conductivity and speed of sound) exhibit a peak value in the vicinity of the pseudo-critical temperature.

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[1] The pseudo-critical temperature is the temperature at which specific heat at constant pressure c_p has a maximum at a specified pressure.

[2] In analogy with the definition introduced in the field of combustion which identifies a "transcritical fluid" as a fluid which is injected in the combustion chamber at supercritical pressure and subcritical temperature [9].

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Nomenclature

A	cross section area
B	channel width
c_p	specific heat at constant pressure
D_h	hydraulic diameter
G	mass flow-rate per unit area
Gr	Grashof number
H	channel height
h_c	heat transfer coefficient
k	thermal conductivity
L	channel length
l_m	turbulence mixing length
P	cross section perimeter
p	pressure
Pr	Prandtl number
q	heat flux
R	gas constant
Re	Reynolds number
s	streamwise coordinate
T	temperature
u	velocity
y^+	non-dimensional wall distance
Z	compressibility factor
z	height abscissa

Subscripts

0	stagnation value
b	bulk
c	critical value
e	exit
i	inlet
t	turbulent
w	wall

Greek letters

α	thermal diffusivity
λ	channel aspect ratio
ρ	density

Although many studies have been carried out for supercritical-hydrogen flows in LOX/LH$_2$ engines and for supercritical-nitrogen flows in many cryogenic-research laboratories, only a small amount of investigations on the behavior of transcritical methane flows inside cooling channels can be found in the literature [10–14]. Moreover, these studies do not refer to rectangular cross section cooling channels, which are of great interest in rocket engine applications. Goal of the present work is to partially fill this lack by investigating transcritical methane flow inside asymmetrically heated channels characterized by rectangular cross section, with particular attention to high-aspect-ratio-cooling-channels. The investigations are performed by numerical simulations carried out by a proper in-house CFD solver [15–20]. The results obtained for a straight three-dimensional channel with strong wall temperature gradients and transcritical methane flow are compared with those of supercritical methane flow for the same channel geometry to underline the peculiar behavior of transcritical fluid flow in cooling channel. Moreover, numerical simulations are carried out to analyze the aspect ratio effect on cooling performance. This parametric study is performed considering channels with imposed hydraulic diameter and wall temperature distribution and coolant flows with constant mass flow rate per unit area. By imposing the above parameters, the influence of the channel aspect ratio on Reynolds number and wall temperature distribution is removed and thus the attention is focused on the coolant fluid-dynamics only. Discussion is performed analyzing the behavior of the heat transfer coefficient and pressure loss along the channel for both cases of supercritical and transcritical methane.

2. Fluid model

The thermodynamic properties of methane have been evaluated by the modified Benedict–Webb–Rubin equation of state presented in [21], whose implementation has been validated by comparison with NIST database [22]. This equation of state has been selected because it shows high accuracy to determine the correct pressure–volume–temperature behavior of a fluid and to compute specific heat at constant pressure, speed of sound, and internal energy also in the near-critical region. The remaining necessary relations used in conjunction with the equation of state are those for viscosity and thermal conductivity, which are also taken from [21].

The resulting thermodynamic behavior of methane density is presented in Fig. 1(a) on pressure–temperature state diagrams. In this diagram the position of the critical point (identified by pressure $p_c = 45.98$ bar and temperature $T_c = 190.53$ K) is emphasized by a black circle. Above critical pressure the phase-change no longer occurs and density variation with temperature, although strong, is continuous. In general, in the case of supercritical pressure all thermophysical properties present significant variation near the pseudo-critical line. Near the critical point the variation is dramatic. In particular, properties such as density, speed of sound, viscosity and thermal conductivity undergo a significant drop within a very narrow temperature range, while properties such as enthalpy and entropy undergo a sharp increase. Moreover, thermal expansion, specific heats, and Prandtl number have a peak near the pseudo-critical points. The magnitude of these peaks decreases as pressure increases [23]. For example, methane specific heat at constant pressure is presented as a function of temperature and for various pressures in Fig. 1(b). In case of subcritical pressure, the specific heat presents a discontinuity at the saturated temperature, which is due to the different thermal behavior of the liquid and the vapor. At the critical pressure and temperature the specific heat reaches a maximum value which tends to infinity. As pressure increases to supercritical values the discontinuity disappears because phase change no longer occurs, and the specific heat peak value reduces, up to vanish at very high values, while temperature of maximum specific heat (the "pseudo-critical temperature") increases. Hence, strong specific heat variations are expected near the pseudo-critical temperature, the variations being larger as the pressure gets closer to the critical value. On the contrary, mild specific heat variations are expected both in case of temperature larger than the pseudo-critical value and in case of pressure far larger than its critical value.

3. Supercritical/transcritical coolant flow

The different evolution of reduced pressure and temperature of methane and hydrogen flow in cooling channels is qualitatively represented in Fig. 2. The typical thermodynamic state of the coolants is roughly drawn on a reduced pressure–temperature state diagram of a generic fluid by a segment whose starting point represents the coolant state at the inlet manifold. Then, along the channel length, pressure decreases and temperature increases because of friction and heat addition. Differences between the two coolant flows can be understood looking to the behavior of constant pressure specific heat contour lines which are presented in Fig. 2. Note that the specific heat has been non-dimensionalized with its value of the perfect gas. In fact, constant pressure is usually decomposed by the perfect gas contribution, which is a function of temperature