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Numerical Analysis of Three-Dimensional Flow of Supercritical Fluid in Asymmetrically Heated Channels

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The knowledge of the flow behavior inside asymmetrically heated 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, the three-dimensional geometry of the passages, and the possible supercritical conditions of the fluid. In the present work, a numerical approach to study the turbulent flow of supercritical fluids is presented and validated by comparison with experimental data. Solutions of the supercritical nitrogen flowfield in an asymmetrically heated three-dimensional channel with a high-aspect ratio (channel height-to-width ratio) are presented and discussed. Emphasis is given to the analysis of the peculiar behavior and cooling performance of the supercritical fluid as compared with perfect gas. In particular, a long channel is considered, such that entrance effects are negligible, to analyze in detail wall heat-flux evolution throughout the channel.

Nomenclature

A = cross-sectional area
a = speed of sound
B = channel width
c_p = specific heat at constant pressure
c_v = specific heat at constant volume
D_h = hydraulic diameter
E = total energy per unit volume
e = internal energy
$\mathbf{F_j}$ = vector of Eulerian fluxes
f_w = skin-friction coefficient
$\mathbf{G_j}$ = vector of viscous fluxes
H = channel height
h = enthalpy
k = thermal conductivity
L = channel length
m = mass
$\dot{m}$ = mass flow rate
Nu = Nusselt number
$\mathbf{n}$ = unit vector normal to the control surface
P = cross-sectional perimeter
Pr = Prandtl number
p = pressure
Q = fluid energy
$\dot{Q}$ = heat transfer rate
q = heat flux
R = perfect gas constant
Re = Reynolds number
$\mathcal{S}$ = control surface
s = entropy
T = temperature
t = time
$\mathbf{U}$ = vector of conserved variables
u = velocity
$\mathcal{V}$ = control volume
v = specific volume
x, y, and z = length, width, and height coordinates
y^+ = nondimensional wall distance
Z = compressibility factor
α, β, and γ = modified Benedict–Webb–Rubin equation of state coefficients
ε = thermal energy absorbed by the coolant per unit length and mass
μ = viscosity
ρ = density
τ_{ij} = stress tensor

Subscripts

b = bulk
c = critical value
e = exit
i = inlet
r = reference value
w = wall
0 = stagnation value

I. Introduction

TO AVOID thermal failure in high-pressure thrust chambers of liquid rocket engines, a regenerative cooling system is generally considered. In this system, one of the propellants (typically the fuel) is forced through passages that are machined inside the thrust chamber wall, then is injected into the thrust chamber or goes to the turbine. The thermal analysis is a major issue in the design of a liquid rocket engine, because the prediction of the peak heat flux from the combustion gases to the engine wall is necessary to ensure the structural integrity of the combustion chamber. The need for thermal analysis is especially important in reusable engines (in which an effective and efficient cooling system is crucial to extend the engine life) or in expander cycle engines (in which coolant warming provides the available power for turbomachinery).

Thermal and fluid-dynamic analysis of coolant flow definitely becomes important if the goal is to search for a more efficient cooling

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