



Conjugate heat transfer, endothermic fuel pyrolysis and surface coking of aviation kerosene in ribbed tube at supercritical pressure

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ABSTRACT

Supercritical-pressure heat transfer of hydrocarbon fuel plays an important role in regenerative engine cooling in propulsion systems. Conjugate heat transfer, fuel pyrolysis, and surface coking of the aviation kerosene RP-3 in ribbed tubes are numerically studied at a supercritical pressure of 5 MPa, with consideration of detailed pyrolytic chemical reactions. The rib effects on heat transfer, pressure loss, endothermic fuel pyrolysis, and surface coking are comprehensively examined. Results indicate that a ribbed tube is very effective in enhancing heat transfer of a hydrocarbon fuel at supercritical pressure, particularly in the inlet region, in which the tube wall temperature can be reduced by around 300 K. A ribbed tube surface makes significant impacts on fluid temperature distribution and thus fuel pyrolysis. The enhanced heat transfer leads to higher fluid temperature inside a ribbed tube in the downstream section, in which strong fuel pyrolysis occurs not only in the near-wall region, as in a smooth tube, but also inside the tube. Therefore, the pyrolytic chemical reaction rate of RP-3 increases in the downstream section in a ribbed tube. Owing to the decreased tube wall temperature and decreased species molar concentrations of coking precursors in the near-wall region, pyrolytic surface coking is weakened in a ribbed tube. The thermal performance factor is used to quantify the combined effects of different rib heights on both heat transfer and pressure loss for supercritical-pressure heat transfer of RP-3 in ribbed tubes.

1. Introduction

Hydrocarbon fuel is used as the coolant in a regenerative cooling process for effective thermal protection of the propulsion systems, including the rocket, supersonic combustion ramjet (scramjet), and advanced gas turbine engines [1,2]. The cooling process is accomplished by circulating the hydrocarbon fuel in micro channels surrounding the combustion chamber, prior to fuel injection. The operating pressure is generally higher than the fuel's critical pressure, thus leading to fluid flows and heat transfer at a supercritical pressure.

The thermophysical properties of the hydrocarbon fuel undergo drastic variations and exert strong influences on supercritical-pressure heat transfer. Many experimental and numerical studies have been carried out to analyze flow dynamics and heat transfer characteristics of various hydrocarbon fuels at supercritical pressures. The supercritical-pressure heat transfer phenomena of cryogenic methane have been comprehensively investigated in the open literature [3–8], intended for applications in regenerative cooling of the reusable rocket engines operated on liquid oxygen (LOx) and methane as propellants. The supercritical-pressure heat transfer phenomena of heavy hydrocarbon fuels, including *n*-decane (a simple surrogate of kerosene) and the aviation

kerosene RP-3, have also been studied [9–16], mainly intended for applications in active cooling of the scramjet engines.

As the fuel temperature exceeds a threshold value, around 800 K for most hydrocarbon fuels, endothermic pyrolytic chemical reactions occur, which thermally decompose the hydrocarbon fuel into many small-molecule chemical components and absorb a large amount of heat, consequently improving the fuel's heat sink [17]. The chemical phenomenon of endothermic pyrolysis of a hydrocarbon fuel plays an important role in an engine cooling process, particularly for the scramjet engine applications due to its high heat load and limited fuel supply rate (These issues have been discussed in detail in the open literature [9,18]). Significant research efforts have been expended to study fuel pyrolytic mechanisms at supercritical pressures. Ward et al. [19] experimentally examined thermal decomposition of *n*-decane at supercritical pressures from 3.45 to 11.38 MPa and proposed a one-step proportional product distribution (PPD) chemical reaction mechanism to consider mild thermal cracking of *n*-decane (with fuel conversion rate generally less than approximately 25%). Zhu et al. [20] conducted experimental studies on heat transfer and fuel pyrolysis of *n*-decane and derived a global pyrolytic chemical reaction mechanism at supercritical pressures. Jiang et al. [21] recently carried out a series of experiments

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Nomenclature

A	cross section area, m^2
c_p	constant-pressure heat capacity, $\text{J}/(\text{kgK})$
C_1, C_2	constants in k - ε turbulence models
C_{p1}, C_{p2}	species molar concentrations, mol/m^3
D	interior tube diameter, m
E_a	activation energy, J/mol
e_t	total energy, J/kg
f	friction factor
G_k	turbulence generation term
h	heat transfer coefficient, $\text{W}/(\text{m}^2\text{K})$
k	turbulent kinetic energy, m^2/s^2
k_{c0}, k_{l0}	preexponential constants
L	tube length, m
M_w	molecular weight, kg/mol
Nu	Nusselt number
p	pressure, Pa
\dot{q}''	surface heat flux, W/m^2
R	universal gas constant, $8.314 \text{ kJ}/(\text{kmolK})$
Re	Reynolds number
SC	surface coking
S_i	chemical source term of species i , $\text{kg}/(\text{m}^3\text{s})$
t	time, s
T	temperature, K
u	flow velocity, m/s
x	axial coordinate along the flow direction, mm

Y_i mass fraction of species i

Greek letters

ε	turbulent dissipation rate, m^2/s^3
η	thermal performance factor
γ	coking reaction constant
λ	thermal conductivity, $\text{W}/(\text{mK})$
μ	viscosity, $\text{kg}/(\text{ms})$
ρ	density, kg/m^3
τ	viscous stress tensor, N/m^2
σ	turbulent Prandtl number
$\dot{\omega}$	chemical reaction rate, $\text{mol}/(\text{m}^3\text{s})$

Subscripts

b	bulk parameter
d	diffusion
eff	effective value in turbulent flows
i	species i
w	wall
w_{ex}	exterior surface of the solid wall
w_{in}	interior surface of the solid wall
k	parameter related to turbulent kinetic energy
s	solid
t	turbulent parameter
ε	parameter related to turbulent dissipation rate

to analyze endothermic pyrolysis of the aviation kerosene RP-3 at a supercritical pressure of 5 MPa and developed a detailed pyrolytic chemical reaction mechanism, which is applicable with the fuel conversion rate up to 90%.

Based on the pyrolytic reaction mechanisms obtained in the early experimental work, detailed numerical simulations have been conducted to obtain fundamental understanding of the physicochemical processes in supercritical-pressure heat transfer of various hydrocarbon fuels with endothermic fuel pyrolysis. Ruan et al. [22] studied the effect of fuel pyrolysis on supercritical-pressure heat transfer of n -decane

using a simplified PPD chemical reaction mechanism. A simplification to the original PPD model [19] was made to improve computational efficiency. Bao et al. [23] studied turbulent heat transfer and fuel pyrolysis of n -decane in rectangular channels with asymmetrical heating at a supercritical pressure. The effect of channel aspect ratio on fuel pyrolysis [24] and the complex interactions between heat transfer and fuel pyrolysis [25,26] were analyzed. Xu and Meng [27] developed a numerical model, incorporating the detailed pyrolytic chemical reaction mechanism [21], for studying supercritical-pressure fluid flows and heat transfer of the aviation kerosene RP-3. Results revealed that

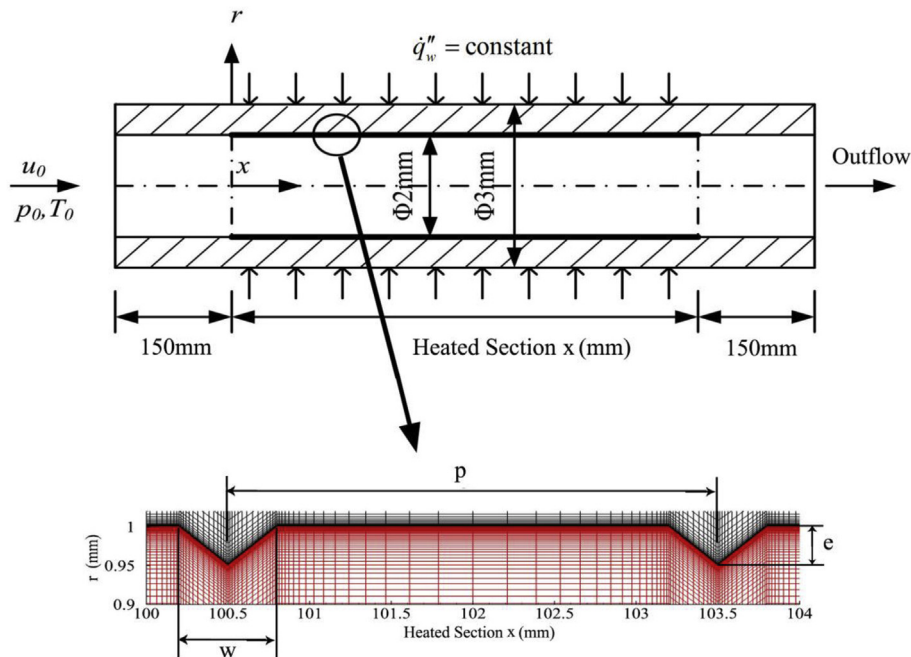


Fig. 1. Schematic configuration of a ribbed tube and illustration of computational meshes.

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