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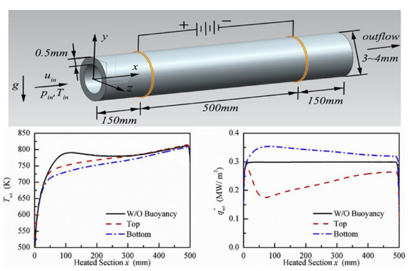
Buoyancy effects on supercritical-pressure conjugate heat transfer of aviation kerosene in horizontal tubes

Xing Sun, Keke Xu, Hua Meng*, Yao Zheng

School of Aeronautics and Astronautics, Zhejiang University, Hangzhou, Zhejiang 310027, China

GRAPHICAL ABSTRACT



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ABSTRACT

Buoyancy effects on supercritical-pressure conjugate heat transfer of the aviation kerosene RP-3 are numerically studied in horizontal tubes under operating conditions of different inlet flow velocities, electric heating currents, and tube diameters. Results indicate that buoyancy makes significant impacts on supercritical-pressure heat transfer of RP-3 at a low inlet flow velocity, under a high electric heating current (surface heat flux), and with a large tube diameter. Buoyancy effects help eliminate heat transfer deterioration in the tube inlet region and serve to redistribute surface heat flux circumferentially in the solid tube wall. An empirical criterion is found to work reasonably well in determining the relative importance of buoyancy effects on supercritical-pressure heat transfer of RP-3 in horizontal tubes.

1. Introduction

In supersonic and hypersonic air-breathing flight vehicles, temperature of the inhaling air significantly increases and thus its cooling capacity drastically decreases during the deceleration/compression process. Regenerative cooling, in which fuel is used as the coolant prior to combustion, becomes an effective approach for thermal protection of the propulsion systems [1,2]. Supercritical-pressure heat transfer generally occurs in the regenerative cooling process.

Heat transfer at a supercritical pressure shows different characteristics from its subcritical-pressure counterpart, such as disappearance of the phase-change phenomenon and two-phase flows, and occurrence of heat transfer deterioration/enhancement caused by strong thermophysical property variations in the pseudocritical region etc. Many experimental and numerical studies have been carried out to analyze the supercritical-pressure heat transfer characteristics of various hydrocarbon fuels, including methane [3–6], aviation kerosene and n-decane (a main component and also a simple surrogate of kerosene) [7–13]. Since heavy hydrocarbon fuels, such as aviation kerosene, are generally used in air-breathing propulsion systems, the following sections of introduction focus solely on studies of these hydrocarbon fuels.

Experimental investigations have been carried out to obtain fundamental understanding and accumulate reliable databases for supercritical-pressure heat transfer of the aviation kerosene and n-decane.

* Corresponding author.
E-mail address: menghua@zju.edu.cn (H. Meng).

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Nomenclature

A	cross section area in fluid region, m^2
C_p	constant-pressure heat capacity, J/kgK
C_1, C_2, C_3	constants in k-ε turbulence models
D	diameter, m
e_t	total energy, J/kg
g	gravitational acceleration, 9.8 m/s^2
G_k	generation of k due to mean velocity gradients
G_b	generation of k due to buoyancy
Gr	Grashof number
i	coordinate index
I	electric current, A
k	turbulent kinetic energy, m^2/s^2
p	pressure, Pa
Pr	Prandtl number
$\dot{q}''$	surface heat flux, W/m^2
$\dot{q}'''$	electric heating source, W/m^3
R	electrical resistivity, Ωm
Re	Reynolds number
S	modulus of the mean rate-of-strain tensor, s^{-1} or cross section area in solid region, m^2
T	temperature, K
$\vec{u}$	velocity vector, m/s

Greek letters

β	thermal expansion coefficient, K^{-1}
ε	turbulent dissipation rate, m^2/s^3
λ	thermal conductivity, W/mK
μ	viscosity, kg/ms
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
σ	turbulent Prandtl number
τ	viscous stress tensor, N/m^2

Subscripts

ave	averaged parameter
b	bulk parameter
k	turbulent kinetic energy
in	inlet parameter
inner	inner parameter
t	turbulent parameter
we	exterior wall parameter
wi	interior wall parameter
ε	turbulent dissipation rate

Zhang et al. [8] conducted experimental study on heat transfer of the aviation kerosene, RP-3, at supercritical pressures. Results revealed that wall temperature sharply increases in the inlet section under a high surface heat flux and a relatively low inlet Reynolds number, and it then gradually decreases. Yang et al. [10] studied flow instabilities in supercritical-pressure heat transfer of RP-3 and indicated that the instability process could improve heat transfer performance. Liu et al. [11] carried out a serious of experiments on fluid flows and heat transfer of n-decane at supercritical pressures in vertical cooling tubes and revealed that in a cooling tube with an inner diameter of 2 mm, heat transfer deterioration could easily occur in upward flows under buoyancy effect. Wang et al. [13] conducted experimental studies and focused on parametric effects of the inlet temperature, pressure, and mass flow rate on flow and heat transfer instabilities of hydrocarbon fuels at supercritical pressures.

During a regenerative cooling process, fuel pyrolysis occurs once temperature of the hydrocarbon fuel reaches around 800 K (this phenomenon is strongly temperature dependent, and significant fuel pyrolysis generally occurs at around 1000 K). This is an endothermic process and can increase the fuel's heat-absorbing capacity. Therefore, experimental studies have been carried out to investigate the physicochemical phenomena. Ward et al. [14] conducted experimental studies on mild thermal cracking of n-decane (with fuel conversion rate less than 25%) at supercritical pressures ranging from 3.45 to 11.38 MPa. A simple one-step proportional product distribution (PPD) chemical mechanism was proposed. Zhou et al. [15] further analyzed pressure effects on the heat sink of n-decane in fuel pyrolysis. Jiang et al. [16] carried out a series of experiments on the endothermic fuel pyrolysis of RP-3 at a supercritical pressure of 5 MPa. A detailed pyrolytic reaction mechanism, which consists of 18 species and 24 chemical reactions, was developed.

Many numerical investigations were also made to provide a fundamental understanding of the underlying physical and chemical mechanisms in supercritical-pressure heat transfer of heavy hydrocarbon fuels. Hua et al. [17] studied the turbulent heat transfer of n-heptane at supercritical pressures. Parametric effects of the inlet pressure, inlet flow velocity, surface heat flux, and inlet fluid temperature on heat transfer were examined in detail. Dang et al. [18] and Zhu et al. [19] both studied the turbulent heat transfer of aviation kerosene at supercritical pressures. Heat transfer deterioration and flow resistance were analyzed [18,19]. Li et al. [20] and Liang et al. [21] conducted numerical studies on turbulent heat transfer of hydrocarbon fuels in curved cooling channels. Results indicated that secondary flows in curved regions could improve heat transfer.

The effect of fuel pyrolysis on supercritical-pressure heat transfer of hydrocarbon fuels were numerically investigated, as well. Ward et al. [22] simulated the fluid flows and heat transfer of n-decane with mild thermal cracking, based on the PPD chemical mechanism proposed by their own group [14]. Ruan et al. [23] made a simplification of the PPD model [14] to improve computational efficiency. The simplified mechanism was applied to study the effect of mild fuel pyrolysis on supercritical-pressure heat transfer of n-decane [23]. Zhu et al. [24] derived a global pyrolytic reaction mechanism and conducted numerical studies on heat transfer and fuel pyrolysis of n-decane at supercritical pressures. Feng et al. [12,25] also studied the supercritical-pressure heat and mass transfer of n-decane, focusing on the strong interactions between fuel pyrolysis and heat transfer. These work [22–25] clearly indicated that wall temperature could be significantly reduced at the high fluid temperature region, due to extra heat absorption from the pyrolytic reactions. Xu and Meng [9] recently developed a numerical model for simulating supercritical-pressure turbulent heat transfer of the aviation kerosene, RP-3, with a detailed pyrolytic chemical reaction mechanism from Ref. [16]. The model is capable of studying fuel pyrolysis of RP-3 with up to 90% fuel conversion rate. Numerical studies were further conducted on fluid flows and heat transfer of heavy hydrocarbon fuels at supercritical pressures, with consideration of fuel pyrolysis and surface coking [26,27].

In heat transfer at supercritical pressures, buoyancy effects could play a very important role under certain operation conditions, because of the strong variation of fluid density. In the open literature, many experimental and numerical studies have been conducted on supercritical-pressure heat transfer of carbon dioxide and water in horizontal tubes, with consideration of the buoyancy effects. Pidaparti et al. [28] experimentally studied buoyancy effects on fluid flows and heat transfer of carbon dioxide at supercritical pressures in horizontal tubes. It was revealed that the circulating flows in a cross section that are caused by density variation in heat transfer could lead to higher wall temperature at the top tube surface and lower temperature at the