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Heat transfer deterioration of aviation kerosene flowing in mini tubes at supercritical pressures

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ABSTRACT

Heat transfer performances of aviation kerosene flowing in mini tubes at supercritical pressures were investigated experimentally and numerically. A ten-species surrogate model with the extended corresponding state was used to calculate the thermophysical and transport properties of kerosene and the Re-Normalization Group (RNG) k-ε turbulent model with the enhanced wall treatment was adopted to consider the turbulent effect. The numerical results agree well with the experimental data. Two types of heat transfer deterioration were observed in this paper. The first type of deterioration occurs at the place where the wall temperature exceeds the pseudo-critical temperature, while the second type occurs when the bulk fluid temperature exceeds the pseudo-critical temperature. The effects of several key parameters, such as mass flow rate, heat flux, pressure and inlet temperature on heat transfer deterioration were studied in detail. The results reveal that the heat transfer coefficient increases with increasing mass flow rate and inlet temperature. The effect of heat flux on heat transfer is complicated, while the effect of pressure on heat transfer is insignificant. Heat transfer deterioration can be effectively eliminated by increasing mass flow rate and pressure and decreasing heat flux and inlet temperature. The dramatic variation of thermo-physical properties is the main reason for the heat transfer deterioration.

1. Introduction

As the speed of flight systems increases to the supersonic and hypersonic regimes ($Ma > 5$), the compressor delivery temperature of fluid increases, and therefore, the cooling efficiency decreases and the turbine components suffer more and more thermal stress and heat load. Maintenance of safe working temperature by dissipating heat is essential for turbine performance and lifetime. To improve the cooling efficiency of heat transfer systems, the regenerative cooling system, where engine fuel works as a coolant and travels through the cooling tubes along the chamber wall, is developed as an effective thermal management technique [1–3].

Aviation kerosene is a universal jet fuel for scramjet engines. Technically, the working pressure of the aviation kerosene in the cooling process is higher than its critical pressure and thus leading to supercritical-pressure fluid flow and heat transfer phenomena [4]. The major concern using supercritical aviation kerosene as working fluid is the heat transfer characteristics due to dramatic variations of thermo-physical properties near pseudo-critical temperature (T_{pc}, where the c_p reaches the maximum value at $P > P_c$). The special heat transfer performances of supercritical fluids have been extensively investigated since 1950s [5–8]. However, the investigations on heat transfer characteristics of supercritical hydrocarbon fuels are limited compared to those of simple fluids, such as water and carbon dioxide [9–11]. Li et al. [12] experimentally investigated the heat transfer performance of China RP-3 aviation kerosene in a vertical smooth tube at supercritical pressures. Their results showed that heat transfer coefficient increased with increasing heat fluxes or inlet temperatures, but decreased with increasing inlet pressures. Zhu et al. [13] numerically studied the heat transfer characteristics and flow resistance of kerosene at supercritical pressures. They found that the local Nusselt number first increased and then suddenly dropped at a certain point. The pressure drop under different pressures were almost the same when the fuel temperature was lower than the critical temperature, while the diversity of pressure drop under various pressures became manifest when the fuel temperature was higher than the critical temperature.

At supercritical pressures, either heat transfer enhancement (HTE) or heat transfer deterioration (HTD) may occur. Some of the experiments observed no heat transfer deterioration, but Zhu et al. [13], Dang et al. [14], Zhao et al. [15] and Li et al. [16] did. They found the deterioration of the heat transfer occurred when

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Nomenclature

a_k	inverse effective Prandtl number for k
a_ε	inverse effective Prandtl number for ε
$C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$	constants
c_p	specific heat, J/(kg·K)
d	diameter of tube, m
G_b	generation of kinetic energy due to buoyancy
G_k	generation of kinetic energy due to the mean velocity gradients
g	acceleration of gravity, m/s^2
HTC	heat transfer coefficient, kW/(m^2·K)
HTD	heat transfer deterioration
HTE	heat transfer enhancement
H	enthalpy, kJ/kg
h	fin height, m
k	turbulent kinetic energy, J/kg (m^2/s^2)
Ma	Mach number
Nu	Nusselt number, hd/λ
Q'	internal heat, W/m^3
P	pressure, Pa
Q_m	mass flow rate, kg/s
q	heat flux, kW/m^2
R_ε	R term in the RNG ε equation
Re	Reynolds number, $4Q_m/(\pi d\mu)$
R	radius, m
T	temperature, K
u	velocity, m/s
x	distance from the tube inlet, m

Greek symbols

λ	thermal conductivity, W/(m·K)
μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3
ε	dissipation rate, m^2/s^3

Subscripts

c	critical
cal	calculated
exp	experimental
f	bulk fluid
i	inner
in	inlet
o	outer
pc	pseudo-critical
theo	theoretical
w	wall
x	local value

the inner wall temperature or the fluid temperature was close to the pseudo-critical point. In the literatures, there are several explanations for the mechanism of heat transfer deterioration. HTD can be caused by intensive variations of thermo-physical properties, buoyancy effect, flow acceleration or combination of these factors. Researchers also made a lot of efforts to determine the onset of heat transfer deterioration. Yin et al. [17] conducted experimental study on heat transfer of supercritical water. The critical value of ratio of wall heat flux to mass flux for the onset of heat transfer deterioration was also discussed. Kim et al. [18] proposed a HTD correlation, $q = 0.0002G^2$ (q: kW/m^2, G: kg/(m^{2}s)), based on the experimental data of CO_2 at different geometries including circular, equilateral triangular and square cross-section channels and it predicted the experimental data well. Mokry [19] collected a large set of experimental data of supercritical water and studied the flow and wall heat flux conditions for the occurrence of heat transfer deterioration. They also developed a correlation, $q = -58.97 + 0.745G$ (q: kW/m^2, G: kg/(m^{2}s)), to predict the critical heat flux.

The comparison of some existing HTD criteria have been presented by Huang [20] and differences have been indicated. For example, the correlation proposed by Kim et al. [18] predicts the experimental data of CO_2 well, however, it significantly underestimates the deteriorated heat flux of water. This indicates that the correlation developed based on one fluid cannot be applied directly to another fluid. As far as the authors know, there are few heat transfer deterioration correlations based on the experimental data of hydrocarbon fuels. Since the property variations of hydrocarbon fuels differ from those of carbon dioxide and water, it is also not appropriate to apply the criteria from carbon dioxide and water to hydrocarbon fuels. Thus, further investigations on heat transfer of hydrocarbon fuels are needed.

Besides, since hydrocarbon fuel is composed of several hundred species, modeling their thermo-physical properties and numerical simulation of their heat transfer performances are difficult, as a result, there are only a few relevant numerical studies available in the open literature. As the simulation work can help to obtain detailed information on the flow and heat transfer performances of hydrocarbon fuels at supercritical pressures, it is useful to conduct numerical studies.

In this paper, the heat transfer characteristics of aviation kerosene at supercritical pressures were investigated experimentally and numerically. The heat transfer deterioration was observed clearly by numerical simulation and the results were compared with the experimental data to identify the physical phenomenon of heat transfer deterioration. The key parameters, such as mass flow rate, heat flux, inlet temperature and pressure on heat transfer deterioration were also presented. Two types of heat transfer deterioration were discussed in detail.

2. Experimental apparatus

2.1. Experimental loop

The measured critical pressure and temperature of aviation kerosene are 2.4 MPa and 373 °C [16], respectively. The experimental loop, as shown in Fig. 1, was constructed to operate at high temperature (600 °C) and high pressure (10 MPa). The fuel stored in the tank was circulated and compressed by a piston pump and then heated to the required inlet temperature in the preheating section under proper heat flux by the direct current power supplied on the stainless tube. After that, the fuel was sent to the test section, being heated and tested at supercritical condition and then was condensed, recollected and fed into the reservoir manually. The test tube is a vertical stainless steel tube with inner diameter of 1.8 mm and outer diameter of 3.0 mm. The heated section of the test tube is 1000 mm long, and the two unheated sections (each with a length of 100 mm, i.e., 50d) are located before and after the heated section. A low-voltage direct-current power was used to heat the test section and simulate constant heat flux condition. The inlet and outlet temperatures of the test section were carefully obtained using armored K-type thermocouples (Accuracy: 0.4%).