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Heat transfer to aviation kerosene flowing upward in smooth tubes at supercritical pressures

Wei Li [a,*], Dan Huang [b,c], Guo-qiang Xu [d], Zhi Tao [d], Zan Wu [c], Hai-tao Zhu [e]

[a] Department of Energy Engineering, Zhejiang University, Hangzhou 310027, China
[b] Department of Energy Engineering, Co-Innovation Center for Advanced Aero-Engine, Zhejiang University, Hangzhou 310027, China
[c] Department of Energy Sciences, Lund University, P.O. Box 118, Lund SE-22100, Sweden
[d] Department of Energy Engineering, Beihang University, 100191, China
[e] College of Materials Science and Technology, Qingdao University of Science and Technology, 53 ZhengZhou Road, Qingdao 266042, China

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ABSTRACT

This study experimentally investigated convective heat transfer performances of China RP-3 kerosene flowing in a vertical upward tube under supercritical pressures. Effects of mass flux, heat flux, pressure and inlet temperature on the heat transfer performance were given in detail. The influences of buoyancy and flow acceleration under different flow conditions were discussed as well. It was found that the inner wall temperature varies non-linearly at different mass fluxes. Heat transfer is improved when the fuel temperature is around the critical temperature. The heat transfer coefficient increases as heat flux or inlet temperature increases, while increase in inlet pressure reduces heat transfer coefficient. Besides, as nanofluids generally have higher thermal conductivity compared to their corresponding base fluids (i.e. kerosene), the heat transfer characteristics of Fe_3O_4-kerosene nanofluid was also investigated. It was found that the addition of nanoparticles tends to deteriorate the heat transfer performance of nanofluids flowing in a vertical tube under supercritical pressure. As the particle content increases, the heat transfer coefficient decreases due to the modification of the inner wall surface by the nanoparticles.

1. Introduction

Effective cooling technique is of great importance in fields of aerospace propulsion and industrial power-generation systems, such as the scramjet and advanced gas turbine engines. 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 coolants and travels through the cooling tubes along the chamber wall, is developed as an effective thermal management technique [1–3]. At the same time, as the fuel temperature (T_f) gradually grows by absorbing the heat generated from the chamber wall, T_f may pass the critical temperature (T_c) and finally the fuel becomes supercritical [4]. At supercritical pressures, thermo-physical properties of fuels change dramatically with small temperature variations, especially when the temperature is around the pseudo-critical temperature T_{pc} (where the c_p reaches the maximum value at $P > P_c$), which is quite different from the normal heat transfer under subcritical pressures. As the changes in thermo-physical properties of supercritical fuels might enhance the heat transfer significantly, a large quantity of researchers focus on the study of supercritical fuels.

The special heat transfer performances of supercritical fuels have been extensively investigated since 1950s. There are a lot of related investigations on heat transfer performances of supercritical H_2O and supercritical CO_2 [5–7] compared to the very limited information of supercritical hydrocarbon fuels. Deng et al. [4] presented the heat transfer performances of aviation kerosene flowing in different flow directions and found that the inner tube wall temperature (T_{wi}) and heat transfer coefficient (HTC) of aviation kerosene are different in different flow directions. They thought it may be caused by the buoyancy effects. Hua et al. [2] numerically conducted the investigation of heat transfer characteristics of *n*-heptane under supercritical pressures. Their results indicated heat transfer enhancement with increasing fluid pressure and heat transfer deterioration once when T_w or T_f reaches the pseudo-critical temperature. By comparing heat transfer coefficients (HTCs) in smooth tubes and ribbed tubes, Wang et al. [8] figured out that the heat transfer coefficients improved in ribbed tubes with the penalty of pressure drop increasing. Zhong et al. [3] suggested heat transfer was improved when T_w approached the

* Corresponding author. Tel.: +86-57187952244; fax: +86-57187952244.
E-mail address: weili96@zju.edu.cn (W. Li).

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Nomenclature

c	particle contents, wt%
c_p	specific heat, J/(kg K)
d	diameter, m
g	acceleration of gravity, m/s^2
G	mass flux, kg/(m^2 s)
Gr	Grashof number based on bulk temperature, $(\rho_f - \rho_w)\rho_f g d^3/\mu_f^2$
H	enthalpy, kJ/kg
HTC,h	heat transfer coefficient, kW/(m^2 K)
I	current, A
K_v	acceleration parameter, $4q_w/(Re^2\mu_f c_p T_f)$
L	length, m
P	pressure, Pa
Q'	internal heat, W/m^3
q	heat flux, kW/m^2
R	radius, m
Re	Reynolds number, Gd/μ_f
T	temperature, K
U	voltage, V
x	distance from the tube inlet, m

Greek symbols

β	volumetric coefficient of expansion
μ	dynamic viscosity, Pa s
λ	thermal conductivity, W/(m k)
ρ	density, kg/m^3

Subscripts

B	base fluid
c	critical
f	bulk fluid
i	inner
in	inlet
NF	nanofluid
o	outer
out	outlet
pc	pseudo-critical
w	wall
x	local value

pseudo-critical temperature and the cracking temperature of China No. 3 kerosene was in the range between 800 K and 1000 K.

Besides, as the cooling performance of coolants is of vital importance in improving cooling efficiency of thermal management systems, it is necessary to adopt a new and efficient coolant (i.e. nanofluid [9–12], PCM [13,14]). Since nanofluids are generally thought to have better thermo-physical properties (i.e. higher thermal conductivity), nanofluid fuels might be potential regenerative cooling working fluids and might further enhance heat transfer. During the last decade, nanofluids have received considerable attention in thermal science and engineering [9–11]. However, large discrepancies exist in experimental results of thermo-physical properties and heat transfer enhancement mechanisms in previous investigations. Although most studies showed that nanofuids give higher heat transfer enhancement than those of base fluids, contradictory results were also presented [12]. In this work, we also prepared Fe_3O_4-kerosene nanofluids with varying particle contents from 0.02 wt% to 0.1 wt% to explore their influences on the heat transfer performances of kerosene under supercritical pressures.

A large quantity of heat transfer correlations were proposed under supercritical pressures. The variation in properties has been taken into account and incorporated into the classical Dittus–Boelter correlation. However, there still exist significant differences in heat transfer coefficients predicted by various correlations, because these correlations were generally based on their own data.

This study experimentally investigates heat transfer characteristics of China RP-3 kerosene under supercritical pressures. The influences of important parameters such as mass flux (G), heat flux (q), pressure (P), inlet temperature (T_{fin}) and particle content (c) on the heat transfer performance are conducted to shed light on the heat transfer characteristics of China No. 3 kerosene. The influences of buoyancy force and flow acceleration under different flow conditions are discussed as well.

2. Experimental apparatus

Fig. 1 shows the experimental system schematically. As the critical temperature and pressure of China No. 3 kerosene are 373 °C and 2.4 MPa, respectively, the experimental loop in this study was constructed to bear high temperature (600 °C) and high pressure (10 MPa). The system includes a fuel tank, a piston pump, a pulse damper, a mass-control valve, a preheating section and an experimental section, a condenser, a back-pressure valve, a fuel collector and corresponding temperature, mass flow rate and pressure measuring instruments.

The fuel was pumped from the tank to the test loop and circulated in the loop by a piston pump. In order to reduce the fluctuations of P and G, a pulse damper filled with compressed nitrogen was installed at the pump outlet line. The fuel was heated to the required inlet fuel temperature in the preheating section and then sent to the test section, being heated and tested under supercritical conditions. After that, the fuel was condensed, recollected and fed into the reservoir manually. The mass flow rate was monitored by the mass flow control valve and measured by a Coriolis mass flow meter (Model DMF-1-2). The working pressure inside the experimental tube was regulated by a back-pressure valve (BYF-10) and measured by using a pressure gauge transducer (Rosemount 3051TG4) with a measuring range from 0 MPa to 12 MPa. A differential pressure transducer (Rosemount 3051CD5) with a maximum measuring value of 1 MPa was used to measure the pressure drop in the test section. All the experimental data was collected by a data acquisition system (Agilent 34970A) and recorded by a computer.

The test section is a vertical stainless steel (1Cr18Ni9Ti) tube with inside diameter of 2.3 mm and outside diameter of 3 mm. The test section is 1200 mm and was divided into 3 parts: two unheated parts of each 80 mm long (35d) and a heated part of 1040 mm long (452d) which is just located between the two unheated parts. A low-voltage direct-current power (SKD-60V/120A) is used to heat the test section and simulate constant heat flux condition. The electric power input was calculated by two parameters: the current and voltage. The local tube wall temperatures of the test section were measured using 12 equally spaced K-type thermocouples (ϕ 0.3 mm) carefully welded onto but insulated with tube outer surface. The inlet fuel temperature (T_{fin}) and outlet fuel temperatures (T_{fout}) at the experimental section were carefully obtained using armored K-type thermocouples located before and after the test section. The preheating section and the test section were electrically insulated by circular flanges and polytetrafluoroethylene (PTFE) put between the circular flanges. The

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