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Experimental study on heat transfer of nanofluids in a vertical tube at supercritical pressures ☆

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ABSTRACT

Regenerative cooling system at supercritical conditions can accommodate high heat fluxes effectively in aerospace applications. The potential of nanofluids as regenerative coolants at supercritical pressures was evaluated in this work. Experiments were carried out to study the heat transfer characteristics of Al_2O_3-kerosene nanofluids flowing upward in a vertical minitube at supercritical pressures. Parametric effects of mass flow rate, heat flux, pressure and particle content on the heat transfer performance are presented. Results show that increasing the mass flow rate or pressure enhances heat transfer, while higher heat fluxes lead to poorer heat transfer performance. Nanofluids tend to deteriorate heat transfer at supercritical pressures because deposition of the nanoparticles smoothens the wall roughness and presents an additional thermal resistance. As the particle content increases, the heat transfer performance becomes worse. Based on the experimental data, a heat transfer correlation was established for Al_2O_3-kerosene nanofluids at supercritical pressures and the correlation shows good predictive ability.

1. Introduction

Effective cooling techniques are of great importance in high heat flux applications, such as large parallel computer systems and aircraft combustion chambers. As the temperature and heat load in scramjet applications are very high, effective heat transfer systems and efficient coolants are necessary for scramjet engines to survive the extreme heat generated in hypersonic flight. Regenerative cooling system, where coolant (e.g., engine fuel) travels through the cooling tubes along the chamber wall to dissipate heat by forced convection and thermal cracking, is developed as an effective thermal management technique [1,2]. Technically, the pressures in scramjet applications are above supercritical pressures, and the fuel temperature may also exceed the critical temperature by absorbing heat from the chamber wall. At supercritical pressures, the thermo-physical properties of fuels exhibit extremely rapid variation with temperature, especially near the pseudo-critical point, which is quite different from that at subcritical pressures. The unusual variations of the thermo-physical properties of supercritical fuels may enhance the heat transfer significantly and thus have attracted researchers' attention.

More investigations are required for convective heat transfer of hydrocarbon fuels at supercritical pressures. Experimental and numerical investigations have been extensively conducted on heat transfer performance of fuels at supercritical pressures, but the previous studies in the open literature are mainly focused on supercritical heat transfer of CO_2 and H_2O [3–5]. Compared to CO_2 and H_2O, there are very limited information on the convective heat transfer of hydrocarbon fuels under supercritical pressures [6,7].

By dispersing Al_2O_3 nanoparticles into hydrocarbon fuel kerosene, the formed Al_2O_3-kerosene nanofluid might be a promising coolant as the nanoparticles can enhance the thermal conductivity of kerosene, especially at high temperatures near the critical point. High temperature induces fierce Brownian motion and enhances the thermal conductivity. In addition, the thermal conductivity of kerosene between the critical temperature and pseudo-critical temperature is very low. Therefore, the Al_2O_3-kerosene nanofluid probably has a higher thermal conductivity than kerosene (the base fluid). As far as we know, this is the first attempt to evaluate the thermal performance of nanofluids at extreme conditions such as at supercritical pressures. The performance of nanofluids at supercritical pressures might be very different from that at normal conditions (e.g., subcritical temperature and subcritical pressure) as the thermo-physical properties of the base fluid change greatly with temperature at the supercritical pressure.

Nanofluids have received considerable attention in thermal science and engineering during the last decade [8–10]. However, large

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Nomenclature

c	particle content, wt%
c_p	specific heat, J/(kg · K)
d	diameter, m
H	enthalpy, kJ/kg
HTC,h	heat transfer coefficient, W/(m^2 · K)
I	current, A
L	length, m
P	pressure, Pa
Pr	Prandtl, $c_p\mu/\lambda$
Q_m	mass flow rate, kg/s
Q'	internal heat, W/m^3
q	heat flux, W/m^2
R	radius, m
Re	Reynolds number, $4Q_m/(\pi d\mu)$
T	temperature, K
U	voltage, V
x	distance from the tube inlet, mm

Greek symbols

λ	thermal conductivity, W/(m · K)
μ	dynamic viscosity, Pa · s
ρ	density, kg/m^3
ϕ	volume content, vol.%

Subscripts

c	critical
cal	calculated
exp	experimental
f	fluid
i	inner
in	inlet
loss	heat loss
nf	nanofluid
o	outer
p	particle
pc	pseudo-critical
w	wall
x	local value

discrepancies still exist in convective heat transfer performance of nanofluids [8]. Most studies showed heat transfer enhancement of nanofluids over their base fluids by comparing the Nusselt numbers or heat transfer coefficient values at constant Reynolds number. Recently, different comparison bases were proposed in Refs. [9,10], such as the constant flow velocity basis and the constant pumping power basis. Little heat transfer enhancement was observed based on the constant flow velocity. The heat transfer coefficient of nanofluids is even lower than that of the base fluids based on constant pumping power. The above discussion shows that comparison results from different groups vary widely even for nanofluids at normal conditions. Therefore, further research on convective heat transfer of nanofluids at supercritical conditions is important and inspiring.

Based on the experimental and analytical studies, researchers proposed a large quantity of correlations for heat transfer of nanofluids at subcritical pressures [11]. There are also some correlations for kerosene at supercritical pressures [12]. However, there still exist significant differences in heat transfer coefficients predicted by various correlations. Besides, there is no correlation for nanofluids at supercritical pressures. Hence, further investigation is needed to develop a general heat transfer correlation for nanofluids at supercritical pressures.

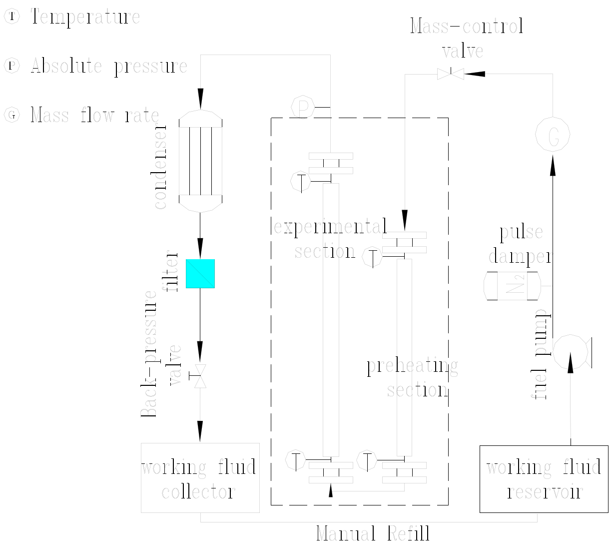

Fig. 1. Schematic of the experimental setup.

The aim of this work was to experimentally investigate heat transfer characteristics of Al_2O_3-kerosene nanofluids flowing in a vertical upward minitube at supercritical pressures. Parametric effects of mass flow rate, pressure, heat flux and particle content on heat transfer characteristics are performed specifically. Based on the experimental data, a new correlation is proposed to predict the heat transfer performance of Al_2O_3-kerosene nanofluids at supercritical pressures.

2. Experimental apparatus

The measured critical pressure and temperature of China No. 3 kerosene are 2.4 MPa and 373 °C [13], respectively. The experimental loop, as shown in Fig. 1, was constructed to operate at high temperature (600 °C) and high pressure (10 MPa). The nanofluid was circulated and compressed by a piston pump. A pulse damper filled with compressed nitrogen was installed after the pump to reduce the fluctuation of the flow rate. The nanofluid was heated to the required inlet fuel temperature in the preheating section (i.e., 150 °C) and then sent to the test section, being heated and tested at supercritical conditions. After that, the fuel was condensed, recollected and fed into the reservoir manually. The test tube is a vertical stainless steel (1Cr18Ni9Ti) tube with inner diameter (d) of 2.0 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 (SKD-60 V/120A) was used to heat the test section (i.e., the heated section) and simulate constant heat flux condition. The inlet and outlet temperatures of the test section were carefully obtained using armored K-type thermocouples. The local wall temperatures of the test section were measured by twelve K-type thermocouples (ϕ 0.3 mm), which were carefully welded onto but insulated with the tube outer surface. Details of the control parameters and operation of the experimental loop were given in Ref. [14].

A two-step method was applied to prepare Al_2O_3-kerosne nanofluids. China No. 3 kerosene was used as the base fluid, and the

Table 1
Error analysis.

Item	Error (%)
Temperature	0.78
Pressure	0.36
Mass flow rate	1.67
Heat flux	2.36
Heat transfer coefficient	2.6