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Experimental investigation on convective heat transfer of supercritical RP-3 in vertical miniature tubes with various diameters

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ABSTRACT

This article presents convective heat transfer of hydrocarbon fuel RP-3 at supercritical pressures in vertical micro-tubes with inner diameters of 0.538 mm, 1.09 mm and 1.82 mm under heating conditions. Effects of system pressure, heat flux, mass flow rate and flow direction were experimented and analyzed with wide range of supercritical status. Also, inner diameter effect on heat transfer were compared at identical conditions. The results indicate that sharp variation of thermal properties with temperature is the key factor to influence heat transfer. Normal, deterioration and enhancement heat transfer phenomena generally occur in turn along with dimensionless position. Moreover, Nusselt number variation shows good agreement when the contrast temperature T_b/T_{pc} is lower than 0.80 and $Bo^* = 1.0 \times 10^{-8}$ could be the critical point to evaluate buoyancy influence. At last, two well-predicted empirical correlations of Nusselt number are proposed for downward and upward flow heat transfer in 1.09 mm tube.

1. Introduction

Flow and heat transfer researches on supercritical fluid have been the key point in the area of energy since 1960s. Based on the background of supercritical pressure boiler and water cooled reactor, researchers all over the world widely studied flow and heat transfer characteristics at supercritical pressures for many pure liquids, such as water, carbon dioxide, and R122. Bourke et al. [1] experimentally investigated convective heat transfer of supercritical CO_2 in a stainless steel tube with 22.8 inner diameter. The results show that local heat transfer deterioration happens at the upstream part of experimental tube due to the inhibition of turbulent kinetic energy. In addition, the degree of heat transfer deterioration reduces gradually along with the increase of mass flow rate. Yamagata et al. [2] studied heat transfer characteristics of water at pressure of 22.6–29.4 MPa flowing in vertical and horizontal tubes. The heat flux varies from 116 kW/m^2 to 930 kW/m^2. It is indicated that heat transfer coefficient near pseudo-critical point increases at the low heat flux conditions and decreases at large heat flux conditions. The relative value between heat flux and mass flow rate (q/G) has huge influence on heat transfer, which is also concluded in Krasnoshchekov research [3]. Moreover, inner wall temperature would be sharply going up at the pseudo critical point at the condition of low mass flow rate and high heat flux. Jackson and Hall [4,5] systematically analyzed mechanisms of heat transfer enhancement and deterioration in different flow directions. It is demonstrated that buoyancy could change the distribution of fluid shear force near the wall and then induce the variation of turbulent kinetic energy. Thus, the heat transfer and flow resistance would change at some location positions. In the subsequent studies [6,7], dimensionless criterions such as $Gr_b/Re_b^{2.7}$ were proposed to judge buoyancy effect. Also, the results reveal that heat transfer is enhanced in the downward flow and similar phenomena are observed in other researches [8–10]. Jiang and his group [11–14] used experimental and numerical methods to study heat transfer characteristics of supercritical CO_2 in small tubes with various diameters. The results show that buoyancy leads to the local heat transfer deterioration at large heat flux and the wall temperature shows a trend of non-linear variation, even when the inlet Reynolds number is about 9000. Yamashita et al. [15] investigated flow resistance characteristics of supercritical HCFC22 in a vertical tube with diameter 4.4 mm. Significant increase is observed near the pseudo-critical point and the increase level decreases with the increase of heat flux.

With the developing emphasis of CCA (cooled cooling air) technology [16,17] in aero-engine, flow and heat transfer characteristics are widely studied as hydrocarbon fuel is used as a typical coolant. Hydrocarbon fuel is at the status of supercritical pressure since the fuel pumping pressure is about 3.45–6.89 MPa in typical

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Nomenclature

A	surface area
$Bo*$	buoyancy number
C_p	isobaric specific heat capacity (kJ/kg K)
d	diameter (m)
D	helical diameter (m)
g	gravitational acceleration (m/s^2)
G	mass flow rate (kg/(m^2 s))
Gr	Grashof number
H	enthalpy (kJ/kg)
h	heat transfer coefficient (W/(m^2 K))
I	electrical current (A)
Kv	thermal acceleration number
k	thermal conductivity (W/(m K))
L	length (m)
m	mass flux (g/s)
Nu	Nusselt number
P	pressure (MPa)
Pr	Prandtl number
Q	heat (W)
q	heat flux (kW/m^2)
$R(T)$	electronic resistivity (Ω m)
r	radius (m)
T	temperature (K)
Re	Reynolds number
U	voltage (V)

Greek

Φ	heat power (W)
ε	uncertainty
ρ	density (kg/m^3)
η	dynamic viscosity (Pa s)
β	isothermal compression coefficient (1/Pa)
ν	kinetic viscosity (m^2/s)
λ	thermal conductivity (W/(m K))

Subscripts

b	bulk
c	critical
f	film
in	inside
out	outside
pc	pseudo-critical
w	wall
x	local position

aero-engines. Brad Hitch and Karpuk [18,19] took experimental studies on heat transfer and thermal stability characteristics of hydrocarbon fuel JP-7 and MCH at supercritical pressures. Significant mass flow rate, pressure and temperature oscillations are observed during the experiments when the relative pressure (P/P_c) is below 1.5 and inner wall temperatures are higher than pseudo-critical temperatures. Furthermore, forced and natural convections are induced mixing to generate the sharp decrease of heat transfer coefficient and increase of wall temperature while the relative pressure is >2. Hines [20] conducted experiments to investigate heat transfer of hydrocarbon fuel RP-2 at various pressures. It is indicated that system pressure has oscillation frequency in the range of 100 Hz–15 kHz with 13.1 bar amplitude at the section of pseudo-critical temperature. Heat transfer coefficient of fuel side could be enhanced by 40% due to oscillations. Over recent years, many researchers [21–28] in China have devoted investigations on flow and heat transfer of pure hydrocarbon fuel and aviation kerosene RP-3, and obtained some meaningful conclusions. Zhang et al. [29] studied heat transfer characteristics of RP-3 flowing in vertically downward miniature tube with 1.8 mm inner diameter. It is noted that heat transfer deterioration happened at the condition of buoyancy factor $Bo^* < 1.6 \times 10^{-10}$ or thermal acceleration parameter $Kv < 1.5 \times 10^{-8}$. Sun et al. [30] compared experimental and numerical results of supercritical RP-3 at 5 MPa pressure in a horizontal circular tube. It is found that the modified k-ε model with correction of decreasing $C_{\varepsilon 1}$ and increasing $C_{\varepsilon 2}$ is more suitable than the standard k-ε model. In addition, discrepancy between calculated and experimental Nusselt number is limited within 10% relative error range.

Above all the research about supercritical fluid heat transfer, most of experimental and numerical models are conducted only in one diameter circular tube. Yildiz and Groeneveld [31] gave a brief review of diameter effect on supercritical heat transfer. Some typical research data like Ackerman [32], Song et al. [33], Kim et al. [9] and others [34–36] are summarized in tubes with a diameter range from 3.18 mm to 38.1 mm. The fluids are carbon dioxide, water, R-22, R-12 and it is summarized that heat transfer coefficient appears to decrease with an increase in tube diameter in the deteriorated heat transfer model. Considering the real application of heat exchanger with light-weight and compactness in aero-engine, tube with small diameter is essential to be the unit of heat exchange equipment. Thus, this paper experimentally investigated heat transfer characteristics of Chinese aviation kerosene RP-3 flowing in vertical small tubes with various diameters.

2. Experimental

2.1. System description

The whole experiments were conducted in the system of flow and heat transfer on supercritical fluid in Beihang University as shown in Fig. 1. The hydrocarbon fuel was pumped by an infusion pump (SP6015, 15 MPa; 0.01–600 ml/min) from the fuel tank. The pump could serve fixed mass flow rate controlled by the screen panel and keep the system pressure stable. Before the fuel flowed into the pump, one filter was set to obtain liquid without impurities. Then, the fuel mass flow rate was measured using a Coriolis-force flow meter (Model: DMF-1-1, 0.15%, Sincerity). The bypass fuel path was set at the pump outlet and one back pressure valve was used to adjust the system pressure up to 15 MPa. There were two preheated sections connected before the test section in order to guarantee the experimental inlet temperature in the wide range. Each preheated section was controlled independently by DC power with capacity of 20 kW.

Two K-type armored thermocouples with wire diameter of 0.5 mm were inserted through joints to measure inlet and outlet fuel temperatures. The system static pressure was measured by a pressure gage transducer (Model 3051CA4, Rosemount) at the outlet of test section. After flowing through the test section, the hot fuel was cooled down to room temperature by fuel-water cooler and then collected to the waste fuel barrels. The measured experimental data includes static pressure, temperature, mass flow rate, heating voltage and current, and these were exported in the form of electrical signals. All signals were gathered by ADAM-4018 data acquisition, transformed by ADAM-4520 to several documents and stored in the computer.