International Journal of Heat and Mass Transfer 115 (2017) 1173–1181

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Buoyancy effects on heat transfer to supercritical pressure hydrocarbon fuel in a horizontal miniature tube

Jie Wen [a], Haoran Huang [a], Zhouxia Jia [b], Yanchen Fu [a,*], Guoqiang Xu [a]

[a] National Key Laboratory of Science and Technology on Aero-Engine Aero-thermodynamics, Collaborative Innovation Center of Advanced Aero-Engine, School of Energy and Power Engineering, Beihang University, Beijing 100191, People's Republic of China

[b] Science and Technology on Reliability and Environment Engineering Laboratory, Beijing Institute of Structure &Environment Engineering, Beijing 100076, People's Republic of China

ARTICLE INFO

Article history:
Received 22 June 2017
Received in revised form 6 August 2017
Accepted 30 August 2017
Available online 8 September 2017

Keywords:
Heat transfer
Buoyancy
Horizontal
Supercritical
Hydrocarbon fuel

ABSTRACT

Experimental investigations on heat transfer of supercritical pressure aviation hydrocarbon fuel RP-3 in a horizontal miniature round tube were conducted. The influence of buoyancy on heat transfer of RP-3 was studied. Buoyancy effect is particularly significant in horizontal flows, which leads to non-uniform temperature distributions in cross section of the test section even for the miniature round tube. The buoyancy effects of heat transfer can be well evaluated by the non-dimensional parameter Gr_q/Gr_{th} developed by Petukhov. And this criterion was first tested for the horizontal flow in miniature round tube under supercritical pressure conditions. At last, this paper proposed a correlation of Nusselt number for supercritical pressure aviation fuel in the horizontal tube.

1. Introduction

Industrial processes involving heat transfer of supercritical pressure fluids have been taken considerable attention in the past few decades. These applications include supercritical extraction systems using carbon dioxide as extractant, nuclear reactor using supercritical pressure water cooled reactor, rocket motors using hydrogen as working fluid, etc. Besides, the need for enhanced engine performance will drive future gas turbines to higher gas temperature at turbine inlet. In order to achieve this goal, improved material temperature capability and ameliorated cooling techniques have been a primary focus in this area. For these reasons above, the concept of cooled cooling air (CCA) [1,2] was proposed. The air taken off the compressor exit is cooled as it passes through an air-fuel heat exchanger, and then it is taken back into the bore of turbine to cool the rotor. In the typical aero-engine fuel system, the pressure of aviation fuel is 34–68 atm (3.45–6.89 MPa), which is beyond the critical pressure of fuel. In the fuel cooling process, the immense cooling tasks and limited fuel supply require the heat exchanger fuel temperature approaching and rising beyond the critical point.

Many studies [3–17] have been experimentally and numerically investigated on the heat transfer characteristic of supercritical fluids. For a given supercritical pressure, there is a temperature at which the specific heat capacity has a maximum, and variations in other thermo-physical properties with temperature are highest. This temperature is called pseudo-critical temperature. Due to significant variations of thermo-physical properties near the pseudo-critical temperature, heat transfer characteristics are substantially different from the heat transfer behaviors at subcritical pressures.

Petukhov [11] proposed a non-dimensional criteria to evaluate the buoyancy effects on the heat transfer for horizontal flow based on experimental and theoretical research. When $Gr_q < Gr_{th}$, the buoyancy effects on horizontal flow heat transfer is insignificant. Buoyancy effects may lead to non-uniform local wall temperature distributions in experimental pipes. The majority of the theoretical and experimental research in the past decades were for the vertical flows. Bazargan et al. [12] investigated the buoyancy effect on heat transfer of supercritical water in a horizontal round tube. They found that neglecting buoyancy could cause large discrepancies between the predictions of available empirical correlations and the experimental. Shitman [13] investigated the buoyancy effects of supercritical pressure water in horizontal tubes, and he also proposed the product of Prandtl number and Grashof number as a criterion to evaluate the buoyancy effects. Yu et al. [14] investigated the influence of buoyancy on heat transfer to the water in horizontal tube under supercritical pressure. They used two buoyancy criterions to evaluate the buoyancy effects on heat transfer. Recently, Hooman et al. systemically studied the significant buoyancy effect

* Corresponding author.
E-mail address: yanchenfu@buaa.edu.cn (Y. Fu).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.08.116
0017-9310/

Nomenclature

A	surface area
C_p	isobaric specific heat capacity (kJ/(kg·K))
D	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)
k	thermal conductivity (W/(m·K))
L	length (m)
Nu	Nusselt number
m	mass flow velocity (g/s)
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)
β	thermal diffusivity (m^2/s)
ρ	density (kg/m^3)
η	dynamic viscosity (Pa·s)
ν	kinetic viscosity (m^2/s)
λ	thermal conductivity (W/(m·K))

Subscripts

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

on turbulent convective heat transfer in different channels using numerical method, like inclined pipes [18], corrugated channels [19], concentric and eccentric annuli [20]. It is observed in their research that heat transfer enhancement and deterioration happen at different structures and Reynolds numbers. And then, the experimental research [21] about buoyancy effect of supercritical refrigerant on heat transfer in plate heat exchangers were conducted. The research indicated various heat transfer characteristics occur at different corrugation angles.

Although much work have been done to find out the mechanism of heat transfer at supercritical pressures, this issue is not quite clear and thorough. Especially, most analytical and experimental research focused on the flow and heat transfer in vertical flows. Due to the paucity of experimental data for horizontal flows, more experimental data with heat transfer in horizontal flows are needed. The effects of buoyancy due to heating and its specific convective heat transfer characteristics should be explored.

2. Experimental system

Fig. 1 shows the experimental system. It includes the preparative system, the measured system and reclaimed system. In preparative system, the fuel in tank 1 is pumped up to 15 MPa by a plunger metering pump (SP6015). The mass flow rate of the primary path fuel was measured using a Coriolis-force flow meter (DMF-1-1, 0.15%). In order to pre-heated the fluid to some level of inlet temperatures of the test section, the pre-pressurized primary path fuel was heated (up to 820 K) by two pre-heaters (20 kW, each).

In the test section, a pressure gage transducer (Model 3051CA4, Rosemount) is used to measure the static pressure at the inlet of the test section. The fuel temperature is measured at the inlet and outlet of the test tube with K-type armored thermocouples, respectively. After testing, the heated fuel was cooled lower than 310 K by water cooled shell-tube heat exchanger, and then the water was imported to the water tank after cooled down by the cooling tower. Fig. 2 shows that the test section is a stainless steel (1Cr18Ni9Ti) round tube with the outside diameter of 2.2 mm and a thickness of 0.17 mm. Ten pairs of K-type thermocouples with an accuracy of 0.3 K were welded onto the top and bottom surface of the test tube. A thermally insulated length of 125 mm preceded the heated length of 550 mm, which was followed by a thermally insulated length of 125 mm as shown in Fig. 3.

The accuracy of the mass flow meter was 0.25%. The pressure gage transducer and the differential pressure transducer were calibrated using a pressure calibrator, and the accuracy of the transducers was found to be 0.2% of the reading. All the thermocouples were calibrated in a constant temperature bath and the measurement accuracy was found to be 0.6%. The experimental system was thought to be steady when the inlet, outlet fuel and outside wall temperatures varied within the band of ±0.2 °C and the system pressure and flow rate fluctuations were within ±0.4%. All data were exported in the form of electric signals and recorded by ADAM-4520 system to the computer.

3. Data reduction

The local heat transfer coefficient (HTC) h_x is defined by

$$h_x = \frac{q_x}{T_{wx,in} - T_{b,x}} \tag{1}$$

where the heat flux q_x is the difference of impressed electrical energy and heat losses, and it was defined by

$$q_x = \frac{I^2R(T)/[\pi(d_o^2 - d_i^2)/4]}{\pi d_i} - q_{loss,x} \tag{2}$$

R(T) is the electrical resistivity of stainless steel, which was gained by correlating the measured electrical resistivity at various wall temperatures (50-600 °C). The heat loss can be gained heat loss calibration tests. Before the experiments, the tube without fuel were directly heated under various heating power and then the heat loss heat flux were fitted with temperature difference between ambient and tube wall. In this study, the proportion of heat loss is less than 4%, which indicated that the test section was well insulated. The inside wall temperature $T_{wx,in}$ was determined by solving the a 1-Dimension heat conduction equation under the cylindrical coordinate system in the following equation.

$$\frac{k}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right) + \dot{\varphi} = 0 \tag{3}$$