Experimental Thermal and Fluid Science 85 (2017) 257–265

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

# Surface coking deposition influences on flow and heat transfer of supercritical hydrocarbon fuel in helical tubes

Yanchen Fu, Jie Wen *, Zhi Tao, Guoqiang Xu, Haoran Huang

*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, China*

ARTICLE INFO

*Article history:*
Received 12 November 2016
Received in revised form 19 February 2017
Accepted 11 March 2017
Available online 14 March 2017

*Keywords:*
Supercritical RP-3
Surface coking deposition
Helical tubes
Heat transfer
Pressure drop

ABSTRACT

Surface coking deposition influences on flow and heat transfer of aviation kerosene RP-3 in helical tubes were experimentally investigated at supercritical pressure. Four types of helical tubes with fixed pitch and various helical diameters have 1.86 mm inner diameter and 2.2 mm outer diameter. The system pressure, inlet temperature, mass flow rate were fixed at 5 MPa, 400 K and 1178 kg/m$^2$ s, respectively. The results indicate that the helical centrifugal force could inhibit the thermal oxidation coking and slow down the growth rate of press drop within maximum value of 47.6%. For the same cross section, the outer heat transfer coefficient (HTC) decreases gradually and eventually is less than the inner side due to coking deposition. Finally, a correlation of Nusselt number considering coking deposition was simulated to predict the heat transfer characteristics.



## 1. Introduction

With the increase of pressure ratio and turbine inlet temperature in modern aero engines, the cooling system for turbo components faces much more challenges. As the developments of new material and internal cooling technology could not satisfy the demand, one technology named CCA [1] (Cooled Cooling Air) is proposed to improve the cooling air quality and energy utilization rate. Hydrocarbon fuel would be used in the technology, heated and compressed in the supercritical status because the fuel feed system varies from 3.45 to 6.89 MPa in typical aero engines [2]. Thus, flow and heat transfer characteristics of hydrocarbon fuels at supercritical pressures are vital important in the CCA technology for advanced aero engines.

Previous researches on flow and heat transfer of supercritical fluid are mainly into pure liquid such as water and carbon dioxide. Jackson and Hall [3] investigated the heat transfer enhancement and deterioration mechanisms for supercritical fluid in different flow directions. Under the condition of heating, the buoyancy effect is reduced by the radial thermal property gradient due to the temperature difference between the inner wall and bulk. The buoyancy could influence the fluid shear force near the wall and then change the turbulence kinetic energy. This variation leads to the heat transfer enhancement or deterioration and flow resistance difference. Some criteria to evaluate the buoyancy in vertical tubes were proposed, such as $Gr_b/Re^{2.7} > 10$ [4] and $Bo^* = Gr^*/(Re^{3.425}Pr^{0.8})$ [5]. Many similar results were concluded that buoyancy could enhance the heat transfer in downward flow [6,7]. Furthermore, thermal acceleration was observed and heat transfer deterioration occurred due to the flow laminarization. Based on the air heat transfer in tubes, McEligot et al. [8] presented the dimensionless acceleration factor $K_v$ to judge the thermal acceleration level. The results show that when $K_v \geqslant 4 \times 10^{-6}$, thermal acceleration could significantly influence the HTC and the level decreases to the same with laminar flow. What's more, Liao and Zhao [9,10] experimentally investigated convective heat transfer for supercritical carbon dioxide in miniature tubes and results show that heat transfer deterioration happens due to the buoyance effect in downward flow when the Reynolds number is higher than $10^5$. In Jiang [11–14] recent researches, similar phenomena were observed and buoyancy significantly influences the heat transfer of supercritical carbon dioxide.

Compared with pure liquid, hydrocarbon fuel consists of thousands of components and some chemical reactions lead to complicated heat transfer characteristics during the heating process. Also, thermal oxidation coking would deposit on the inner surface to decrease the HTC between the flow and the wall. Krieger and Chen [15] adapted SF6 replacing aviation kerosene to research inlet Reynolds number, system pressure and flow direction influences on heat transfer characteristics at supercritical pressures. The results indicate that system pressure and flow direction almost have no

* Corresponding author.
*E-mail address:* wenjie@buaa.edu.cn (J. Wen).

http://dx.doi.org/10.1016/j.expthermflusci.2017.03.016
0894-1777/

**Nomenclature**

| | |
|---|---|
| $A$ | surface area |
| $C_p$ | isobaric specific heat capacity ((kJ/kg) K) |
| $d$ | diameter (m) |
| $D$ | helical diameter (m) |
| $G$ | mass flow rate (kg/(m$^2$·s)) |
| $H$ | enthalpy (kJ/kg) |
| $h$ | heat transfer coefficient (kW/(m$^2$·K)) |
| $I$ | electrical current (A) |
| $L$ | length (m) |
| $m$ | mass flux (g/s) |
| $Nu$ | Nusselt number |
| $n$ | coil numbers |
| $P$ | pressure (MPa) |
| $Q$ | heat (W) |
| $q$ | heat flux (kW/m$^2$) |
| $R(T)$ | electronic resistivity (Ω·m) |
| $r$ | radius (m) |
| $T$ | temperature (K) |
| $t$ | time (min) |
| $Re$ | Reynolds number |
| $U$ | voltage (V) |

*Greek*

| | |
|---|---|
| $\Phi$ | heat power (W) |
| $\rho$ | density (kg/m$^3$) |
| $\mu$ | dynamic viscosity (Pa·s) |
| $\nu$ | kinetic viscosity (m$^2$/s) |
| $\lambda$ | thermal conductivity (W/(m·K)) |
| $\varepsilon$ | uncertainty |

*Subscripts*

| | |
|---|---|
| $b$ | bulk |
| $c$ | coking |
| $i$ | inner |
| $in$ | inlet |
| $o$ | outer |
| $out$ | outlet |
| $pc$ | pseudo-critical |
| $w$ | wall |
| $x$ | local position |

effects on heat transfer when Reynolds number is lower than $10^5$. Four various heat transfer period were concluded in Li and Zhu [16] research for supercritical hydrocarbon fuel: normal heat transfer, heat transfer enhancement, heat transfer deterioration, second heat transfer enhancement. At present, almost all correlations related to supercritical fluid heat transfer are simulated based on water or carbon dioxide experimental data and bulk temperature, wall temperature or film temperature are defined as qualitative temperature. Dickinson and Welch [17] adopted Dittus-Boelter equation to compare with experimental data and found that there exists large errors when the bulk temperature comes to pseudo critical temperature. Krasnoshchekov and Protopopov [18] considered that the equation with property changes correction factor $\rho_w/\rho_b$ and $\bar{C}_p/C_{pb}$ could simulate experimental data better. Above all, many kinds of correlations [19–22] are simulated and these does not show large difference due to the experimental factors, thermal load and buoyancy effects.

As fundamental research in CCA technology applied in aero engines, flow and heat transfer of aviation kerosene RP-3 in straight tubes at supercritical pressures have been deeply studied in our previous research [23–27]. Helical tube as one typical curved tube would be widely used in the future heat exchange component in CCA technology. Berger et al. [28], Shah and Joshi [29], Naphon and Wongwises [30] all summarized flow and heat transfer characteristics of common fluid flowing in curved tubes. Otherwise, mechanism of heat transfer for supercritical hydrocarbon fuel in helical tube is still unclear, especially when the inner wall surface starts to emerge thermal coking. To consider the real application for air-fuel heat exchanger in aero engines, flow and heat transfer with thermal oxidation coking influence of aviation kerosene RP-3 at supercritical pressure in helical tubes were experimentally researched in this paper.

## 2. Test facility

### 2.1. Experimental system

Supercritical fluid flow and heat transfer system in Beihang University is shown in Fig. 1. The whole system consists of four main sub-systems: fuel feeding system, heating system, sampling system and cooling separation system. The aviation kerosene was exported from the fuel tank and then would be removed impurities through filter. The main flowing path could be pumped to maximum 15 MPa by the infusion pump (SP6015,15 MPa, 0.01–600 mL/min). When the fuel pressure is larger than 10 MPa, the pump pressure could relief automatically to guarantee the system security and stability. Then the system absolute pressure was measured by a capacitance-type pressure transmitter (Model: Rosemount 3051CA4, ±0.15%) and controlled by the back pressure valve equipped at the path outlet. Furthermore, the pressure drop of test section was measured by capacitance-type pressure transmitter (Model: Rosemount 3051CD4, ±0.065%) set between the inlet and outlet of experimental tube. The mass flow rate was measured by a Coriolis-force flow-meter (Model: DMF-1-1, 0.15%, Sincerity) before the fuel flew into the pre-heating section. To achieve the required inlet temperature, two current powers (TN-KGZ01, 100 V, 200 A) were set on the stainless steel tube. The fuel was cooled down to 310 K by the water-fuel heat exchanger after flowing through the test section and then accumulated to the waste fuel barrels.

Experimental set-up has absolute pressure, differential pressure, temperature, mass flow rate, heating voltage and current measuring instruments and equipment. All the measured experimental data are output in the form of electrical signals. Signals are gathered by ADAM-4018 data acquisition, transformed by ADAM-4520 to several documents and stored in computer.

### 2.2. Test section

The experimental test section is stainless steel (1Cr18Ni9Ti) tube and all helical tubes have total length of 1800 mm. The test tube has 1.82 mm inner diameter and 2.2 mm outer diameter. Two 150 mm-length thermal insulation sections were set both in the inlet and outlet, and the middle 1500 mm length was bent to helical type as experimentally heated section. Four kinds of helical tubes with same pitch were manufactured in order to evaluate helical diameter effects on heat transfer and coking characteristics. Table 1 shows the detailed parameters of experimental helical tubes. The experimental section was connected to the system by silver weld special joint to reduce the local flow resistance. 30