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Research paper

Experimental study of flow distribution for aviation kerosene in parallel helical tubes under supercritical pressure

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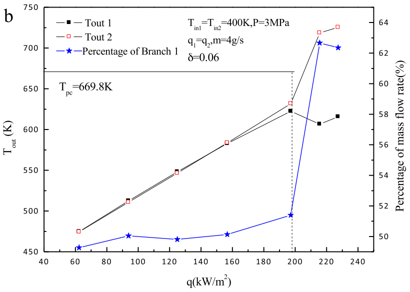
HIGHLIGHTS

- A new method based on the conservation of energy was adopted to measure mass flow rate.
- Fuel density variation is the key factor to influence the flow distribution under supercritical pressure.
- Flow distribution deviation between parallel helical tubes is less than 0.5% when the system pressure is 2.09 times of critical pressure.
- There exists a curvature value between 0.045 and 0.09 to generate significant flow mal-distribution.

GRAPHICAL ABSTRACT



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ABSTRACT

Experiments on flow distribution for supercritical jet fuel RP-3 in parallel helical tubes were conducted. A heating and energy balance method is proposed to test the flow mass rate in two branches. The flowing RP-3 is stressed from 3 MPa to 5 MPa and the total mass flow rate fixed to 4 g/s. Two identical parallel helical tubes were set by connecting headers and the flow direction was arranged in Z-type. The helical tubes have curvatures of 0.045, 0.06 and 0.09 with same pitch. Effects of heat flux, system pressure, heat flux inhomogeneity and helical curvature for flow distribution are analyzed through the various experiments. Also, the flow distribution calculation variation is obtained to compare to the experimental results. The results indicate that the flow mal-distribution is easy to happen at the pseudo-critical point as the thermal properties have serve changes. The flow distribution deviation between the two helical tubes is less than 0.5% when the system pressure reaches 2.09 times of critical pressure and the helical curvature can influence the flow distribution significantly. Furthermore, the calculated results can distinctly match the experimental due to the fuel density variation model.

1. Introduction

To meet the continuous improvement demand of the aero-engine turbine temperature and pressure, it is very necessary to explore new ways to improve the quality of the cooling air, continuing to study new cooling structure at the same time. Using high heat capacity aviation kerosene to cool the cooling air from the exit of the compressor by installing the air–fuel heat exchanger has two benefits [1,2]: figuring out the cooling problem and promoting atomizing and combustion [3,4]. Multi-helical tubes heat exchanger can be used as the air–fuel heat exchanger to cool the compressor exit air, owing to their compactness of saving space,

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Nomenclature

A	tube section area (m^2)
d	tube diameter (m)
D	helical diameter (m)
f	friction coefficient
H	enthalpy (kJ/kg)
L	tube length (m)
m	mass flow rate (g/s)
n	number of coil
P	pressure (MPa)
Q	heat power (kJ)
q	heat flux ($\mathrm{kW/m}^2$)
T	temperature (K)
u	flow velocity (m/s)
Greek	
μ	dynamic viscosity (Pa s)
ρ	density ($\mathrm{kg/m}^3$)
δ	curvature ratio
ζ	local friction coefficient
λ	thermal conductivity (W/(m K))
Subscripts	
b	bulk
in	inlet
out	outlet
Pc	pseudo critical

weight and profiled-followed. As the pressure of the typical aero-engine fuel pumping system is about 3.45–6.89 MPa [5] and the critical pressure of RP-3 jet fuel is 2.33 MPa [6], the RP-3 jet fuel will undergo from the sub-critical to supercritical condition while flowing through the heat exchanger tubes. At the nearby section of pseudo-critical point, the fluid thermal properties vary significantly. These lead to the interactive influences between heat transfer and flow resistance characteristics, and then cause the flow rate variation in parallel branch of the heat exchanger. If the flow distribution deviation becomes large, local over-temperature may occur and trigger the security accidents. Thus, the flow distribution of the parallel branch plays a vital important role in the air–fuel heat exchanger design.

Many researchers have done lots of work about the flow instability and distribution in heat exchanger parallel channels. Some beneficial results have been obtained mainly on the working medium of water and air. For the early research, J. Keller [7] systematically described the research problems of flow distribution in parallel tubes and presented that inertia and frication are two main factors to influence the flow distribution. Also, various measures were supplied to control the flow distribution. Two simplified-continuous models to describe the flow characteristics in manifolds were proposed in R.A. Bajur and E. H. Jones [8,9] research. The first-order differential pressure-flow equation and a second order nonlinear differential equation of flow distribution were obtained to predict the flow distribution in manifolds. As the development of the computer science, the discrete model corresponding with the practical situation and the numerical method were widely used to predict the flow distribution [10–15]. However, this model still exists some limitations that only axial velocity component was considered [14] and the manifold was confined to the two branches of square-section [16]. Wang [17–19] developed a theoretical model that is suitable not only to discrete various shape geometry using wetted perimeter and hydraulic diameter but also to continuum manifolds design. Also, the model demonstrates that the pressure drop and flow distribution in manifolds are determined by three general characteristic parameters: ratio of manifold length to diameter (E), ratio of sum of all the port areas to area of manifold (M) and average total head loss coefficient for port flow (ς).

Plate heat exchanger is used as one typical equipment in industries around the world and pressure drop as well as heat transfer characteristics depends critically on the fluid distribution [16,20–24]. Investigators mainly study the flow distribution in plate heat exchangers using experimental [25–28] and computational [18,29–34] methods, as this type of heat exchanger is broadly applied in the electronic packaging, solar collector, evaporator and fuel cells. M. Bassiouny [35,36] adopted the analytical method to calculate the axial velocity, the pressure distribution and flow distribution in the channels for U-type and Z-type arrangements in plate heat exchangers. The results show that the general characteristic parameter (m) is the main factor to determine the flow distribution in both two arrangements and the nearly uniform flow distribution appears when the value is equal to zero. Also, the results can be applied to various dimensions, fluid velocity and channel geometries of heat exchangers. A.C. Mueller and J.P. Chiou [37] presented a paper about the reasons and effects of various types of flow mal-distribution on the heat exchanger performance. The results shows that large temperature difference and thermal stress failure can be generated and flow mal-distribution can lead large heat transfer performance loss at nominal NTU > 10. Compared with single phase flow, flow distribution of two-phase fluids [38–40] in parallel channels is much more complicated. A good review work about two-phase flow distribution in multi-channels has been carried out by E.R. Dario et al. [41]. Flow distribution in micro and macro channels is summarized, including experimental, numerical and theoretical methods. The author concludes that the header and the feeding tube positions are the main two factors to affect the mass flow rate and inserting specific devices into the header or the feeding tube is the feasible method to uniform the two-phase flow distribution.

As supercritical hydrocarbon fuel is kind of specific status applied in the aero-engine heat exchanger, flow distribution plays a vital important role in the safety and heat transfer performance. The few studies are available on flow distribution and mal-distribution, even in the theoretical analysis. Based on the principle of helical parallel tube unit of spiral tube exchanger set in the aero-engine, experiments of influences factors on supercritical fuel distribution are made in this paper.

2. Experimental procedure and calculated method

2.1. Experimental system and test section

This work was conducted in the experimental platform of supercritical fluid flow and heat transfer in Beihang University. Fig. 1 shows the schematic of the experimental system. The aviation kerosene in Tank 1 was pumped up to 12 MPa using the piston pump (Model: 2J-Z 104/16, Ailipu) and then pushed into the air bag pulsation damper (Model: NXQ-L04/16-H, Ailipu) to reduce the pressure pulsation to lower than 0.5% of the test inlet pressure. The preparative fuel was divided into two paths: the main path was extended to the fuel collector through the test section; the bypass connected with a relief valve and returned to the fuel tank. The mass flow rate of the major path fuel was measured by