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Heat transfer to supercritical pressure hydrocarbons flowing in a horizontal short tube

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ABSTRACT

The heat transfer characteristics of hydrocarbon fuel were investigated in a short horizontal tube with a 1.0 mm inside diameter. The experiments were conducted in test tubes that were 46 mm and 116 mm in length at a supercritical pressure of 3.0 MPa. The experimental parameters included a liquid velocity of 0.21–1.20 m/s, an inlet fluid temperature of 298–673 K, and various heat fluxes. Different heat transfer regions were designated based on the heat transfer behavior. The mechanisms of heat transfer enhancement and deterioration are discussed. Heat transfer was improved by thermophysical property variation, thermoacoustic oscillation, and endothermic reactions of the hydrocarbons in the respective processes. Heat transfer deterioration was characterized by gas resistance and coke deposition in the boundary fluid. Heat flux, fluid velocity, and inlet temperature were studied in depth as effective parameters. The allowed maximum ratios between heat flux and mass flow rate at various velocities and inlet fluid temperatures are given and could be used as criteria for future applications.

1. Introduction

The supercritical heat transfer of hydrocarbon fuel plays a key role in heat management technology for liquid rocket and scramjet engines [1–3], which endure high heat loads from aerodynamic heating, high temperature engine components, and other heat producers [3]. Regenerative fuel cooling has been considered the most effective cooling method for both the liquid rocket engine [4,5] and the scramjet [6,7]. In a regenerative cooling system, hydrocarbon fuel absorbs the heat by physical sensible heat and endothermic chemical reactions in the flow channel, resulting in a reduction in the engine wall temperatures. Meanwhile, the fuel's enthalpy increases and the ignition is improved in the combustor. In this process, the hydrocarbon fuel needs a remarkable endothermic cooling ability, with high stability and low coking [1,8]. Deposit formation on the wall surface causes an increase in thermal resistance, leading to a progressive increase in the wall temperature and, ultimately, failure [9].

Thus, extreme operating conditions, such as high heat flux, a large temperature difference between the engine wall and the fluid, severe composition variation, and limited flow rate, exist in a regenerative cooling system [3,10–12]. A fundamental understanding of the heat transfer characteristics of the hydrocarbon fuel under different conditions is required, and would be beneficial for the design and management of the regenerative cooling system.

A series of studies have been carried out on heat transfer of supercritical fluid. Most have focused on the supercritical water [13–15] and the refrigerants [16–18], due to their practical applications in the power industry and refrigeration fields. A number of theories and computational formulas have been developed to interpret the various phenomena.

Due to the particular application of hydrocarbon fuel, the heat transfer characteristics of supercritical hydrocarbon fuel have attracted the attention of researchers in the aerospace and power engineering industries. Yanovskii and Kamenetskii [19] conducted experiments on the heat exchange of RT and T-6 fuel oil in forced flow, at supercritical pressure. They summarized the limit condition of impaired heat transfer as a dimensionless relationship. Hitch and Karpuk [20] studied the heat transfer of JP-7 hydrocarbon fuel in a supercritical flow. They found that tube wall temperature above pseudocritical temperature could cause significant pressure and temperature oscillations when reduced pressure values (the ratio of operating pressure to critical pressure) were below 1.5. However, no significant heat transfer enhancement was observed under the oscillating conditions. Kelbaliev [21] investigated a mode transition from improved heat transfer to deteriorated heat transfer for toluene at supercritical pressures in small tubes. Chen and Dang [22] conducted experiments on the supercritical heat transfer of JP-7 and ascertained the characteristics of the heat transfer and the coking properties of the fuel.

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Nomenclature

Abbreviations

d	diameter of the tube (mm)
g	gravitational constant (m/s^2)
l	length of test section (mm)
u	fuel velocity (m/s)
p	pressure (MPa)
q	heat flux (kW/m^2)
T	temperature (K)
Q	absorbed heat (W)
x	location from inlet of the tube (mm)
h	heat transfer coefficient (W/(m^2 K))
G	mass velocity (kg/(m^2 s))

Greek

ρ	density (kg/m^3)
μ	dynamic viscosity (Pa s)
λ	thermal conductivity (W/(m K))

Subscripts

b	bulk
f	film
inl	inlet of tube
in	inside of tube
out	outside of tube
pc	pseudocritical
w	tube wall

Edwards [8] reviewed progress in the thermal instability of supercritical hydrocarbon aviation fuels in the cracking process. Hua et al. [23] simulated the forced convective heat transfer of n-heptane inside a horizontal mini-tube. Heat transfer deterioration occurred when tube wall or fluid temperature reached the pseudocritical temperature, while high pressure enhanced the heat transfer. Jiang et al. [24] tested a series of model compounds (n-octane, n-decane, n-dodecane, cyclohexane, methylcyclohexane) and RP-3 in a heated tube at supercritical pressure and obtained their critical points of thermal cracking and deposition.

Although numerous studies have been done on supercritical hydrocarbons, there have been few investigations into the heat transfer characteristics at practical conditions, an area that needs to be addressed. In this paper, the heat transfer behavior of a kerosene-based hydrocarbon fuel was studied in a short horizontal tube at supercritical pressure. The improved and deteriorated heat transfer characteristics of the respective mechanisms are expounded. The effects of fluid velocity, inlet temperature, and heat flux are discussed.

2. Experimental apparatus and procedure

2.1. Experimental apparatus

The experiments were conducted in our laboratory using a home-designed hydrocarbon fuel test loop. The schematic diagram of the experimental system is shown in Fig. 1. Each kerosene fuel was driven by high pressure nitrogen. The fuel passed the flow regulating valve and mass flow meter and flowed into a horizontal tube (inner diameter, 1.0 mm; wall thickness, 0.5 mm) made of GH3128 high temperature nickel alloy. The tube was in series connected in power circuit to heat the fuel by its joule heat. Two low-voltage AC power supplies (40 V, 250 A) were available in the preheated section and the test section, respectively. Following the test tube, a circular quartz silica tube with the same diameter was installed, to visualize the flow [25]. Finally, the fluid was cooled by a condenser and separated by a gas–liquid separator. A back pressure valve was used to control the work pressure.

In the test section, two Φ 1.5 mm K-type armored thermocouples were installed at the inlet and outlet to measure the bulk temperature. Eight pairs of Φ 0.2 mm K-type thermocouples were uniformly welded on the outside surface of the test tube to measure wall temperatures. The distribution of these thermocouples is shown in Fig. 2. Work pressure was measured by a Rosemount 3051 capacitance-type pressure transmitter at the outlet and the pressure drop was obtained by a Rosemount 3051 differential pressure transducer. In the visualization section, flow images were recorded by a high-speed camera (1000 flames per second). The terminology used by Wojtan et al. [26] was applied to characterize the flow patterns in the images. All information was recorded using a computerized data acquisition system (IMP3595). Specific experimental parameters are listed in Table 1 and the estimated uncertainties of the measured and calculated parameters are presented in Table 2.

2.2. Experimental material

Hydrocarbon fuel is made up of a blend of hydrocarbons, with cycloalkanes comprising 30.50 wt.%, alkanes 20.06 wt.%, and

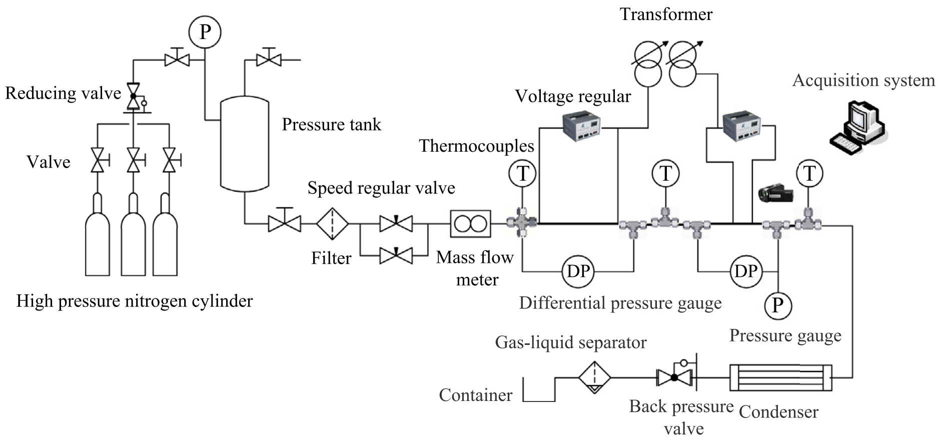

Fig. 1. Schematic diagram of experimental system.