



Heat transfer and cracking performance of endothermic hydrocarbon fuel when it cools a high temperature channel



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ABSTRACT

Jet fuel is used as a coolant before it is burned in the combustor of the aircraft. Insoluble particles and surface deposits can impair engine performance. Jet fuel thermal oxidation test (JFTOT) defines the standard test method for evaluation of the deposit formed through heating fuels in tubes caused by thermal oxidation (<400 °C). At a higher temperature, fuel in the heating process decomposes leading to surface deposits by coking. In this work, we propose a method to evaluate the security of fuel flowing in the tube at high temperatures (>500 °C). The heat transfer and cracking performances of two hydrocarbon fuels which are laboratory modified aviation kerosene (Fuel 1 ($\rho = 0.85 \text{ g/cm}^3$) and Fuel 2 ($\rho = 0.78 \text{ g/cm}^3$)) have been investigated in a heat-exchanger under supercritical conditions ($T = 700\text{--}770 \text{ }^\circ\text{C}$, $p = 2.5\text{--}5.5 \text{ MPa}$, $m = 0.4\text{--}1.0 \text{ g/s}$). The temperature and flow rate in this work are much higher than those in JFTOT. The safe run time (SRT) is used to evaluate the heat transfer security of each fuel. As the temperature increases or the flow rate decreases or the pressure increases, the SRTs of Fuel 1 and Fuel 2 decrease clearly. In general, the heat transfer security of Fuel 1 is better than that of Fuel 2. Moreover, the volumetric heat sink of Fuel 1 is larger than that of Fuel 2. So, the overall performance of Fuel 1 is more excellent when it is used as propellant and coolant for hypersonic aircraft. In consideration of the heat transfer security, heat sink and the required driving force for aircraft, the temperature of fuel at the exit of heat transfer passage should be set as 740 °C, the flow rate of fuel should be 0.6–1.0 g/s, the pressure of heat transfer passage should be 3.5 MPa. Based on these results, we find that the modification of a high density fuel is an effective way to prepare an advanced hydrocarbon fuel.

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1. Introduction

Hypersonic aircrafts have been attracting a great deal of attention in recent years due to its extraordinary importance in military field [1–3]. Aerodynamic heating becomes extremely severe when the flight speed of aircraft reaches or exceeds Mach 5. In the heat protection of the engine of aircraft, the regenerative cooling technology is widely applied by using hydrocarbon fuels both as propellant and coolant [4,5]. Hydrocarbon fuels circulate through the cooling passages located on the hot wall surface to absorb the waste heat before they are injected into the combustion chamber. During the cooling process, the fuels decompose into small molecules through endothermic reactions to absorb more heat than other fuel like hydrogen. However, the coke formation is accompanied with the decomposition of hydrocarbon fuels when the concentration of coke precursor reaches to a certain extent [6]. The deposited coke can reduce heat transfer efficiency, constrict fuel flow system, and block fuel nozzle or filter, finally leading to the shutdown of engine.

In order to ensure the safety and operability of the fuel system, many efforts have been made to study the cracking and coking performance of hydrocarbon fuels under supercritical conditions [7–14]. Huang et al. [15] investigated the endothermic heat-sink of JP-7, JP-8 + 100, JP-10 and *n*-octane for scramjet cooling. It was found that JP-7 had the highest heat sink, while JP-10 had lowest one. Meanwhile, JP-7 had the lower coke formation rate compared with JP-10, which ensured that JP-7 could operate at higher temperature and provide higher cooling ability. Edwards and Huang [16] studied the fuel composition influence on deposition in Jet A-1 and synthetic jet fuel by Fischer-Tropsch process. The results indicated that the deposit formation could be related to aromatic and PAH growth mechanism despite the complexities of the various fuel compositions. Widegren and Bruno [17] found that the thermal stability of hydrocarbon fuel was a function of composition. It was shown that the stability of RP-2 could be suppressed by using feedstock containing a higher proportion of the least stable alkane with tertiary carbons. In contrast, an increase in the proportion of alkane with quaternary carbons was less likely to form coke. According to Liu et al.'s work [18], the coke thickness deposited on the inner face of the tube could be evaluated from the pressure drop along the reactor quantitatively based on the theory of hydromechanics. It revealed the relationship between the blocking degree and coke deposition amount intuitively. Huang et al.

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[19] proposed a coke removal method by the catalytic steam gasification of carbon. The adding of 2 wt% steam into JP-7 with a Cs-catalyst coated reactor was demonstrated to reduce pyrolytic coke deposition successfully. During the test duration of >2 h, the pressure drop increased insignificantly, which ensured the feasibility and the cooling capacity by operating at a higher temperature and increasing run time. Similarly, the co-feeding of kerosene fuel with methanol for controllable decomposition has been carried out by Zhang et al. [20]. The results showed that the presence of methanol promoted the total heat sink, increased ethylene yield, and dramatically reduced coke deposition by the production of hydrogen as dilution agent.

As mentioned above, a lot of researches have been reported about the coke deposition mechanism and its removal. Under a given operating condition, how long a special hydrocarbon fuel can cool the engine safely without blockage is very important. The time here is defined as safe run time (SRT). The influence factor of SRT for a given fuel may be related to temperature, pressure and flow rate. However, no one studied this issue in detail.

In this work, we focus on the SRT and chemistry reaction of two different fuels during their heating process, but the engine dynamic behavior is neglected. The heat transfer security of two fuels, Fuel 1 ($\rho = 0.85 \text{ g/cm}^3$) and Fuel 2 ($\rho = 0.78 \text{ g/cm}^3$), was investigated in a supercritical heat-exchanger. The heat transfer experiments were carried out under different conditions ($T = 700\text{--}770 \text{ }^\circ\text{C}$, $p = 2.5\text{--}3.5 \text{ MPa}$, $m = 0.4\text{--}1.0 \text{ g/s}$). The SRTs and heat sinks of two hydrocarbon fuels are determined, along with other important parameters about cracking process. According to the results, the safe operating conditions of each fuel can be provided to guide its practical application in engines.

2. Experimental section

2.1. Materials

Fuel 1 ($\rho = 0.85 \text{ g/cm}^3$) was prepared in our laboratory with the addition of high density component to the aviation kerosene of China. Some additives like hydrogen donor (tetrahydroquinoline 1%wt), antioxidant (butylated hydroxytoluene 20 mg/L) and metal passivator (dimethyl disulfide 0.01%wt) were also added. Fuel 2 ($\rho = 0.78 \text{ g/cm}^3$) was provided by China National Petroleum Corporation with a further removal of aromatics. Both fuels were checked by a gas chromatograph–mass spectrometer (GC–MS), and the spectra were shown in Fig. 1. The fundamental properties of Fuel 1 and Fuel 2 were listed in Table 1, along with those of JP-7 and JP-8 [21]. The detailed compositions were listed in Tables S1–S2 of Supplementary Material.

Table 1
Fundamental properties of Fuel 1, Fuel 2, JP-7 and JP-8.

Fuel	Formula	Molecular weight	Density/g/cm ³	LHV/MJ·kg ⁻¹
Fuel 1	C _{9.76} H _{18.07}	135.19	0.85	42.54
Fuel 2	C _{11.48} H _{23.83}	161.59	0.78	43.68
JP-7	C ₁₂ H ₂₅	169.33	0.79	43.49
JP-8	C ₁₁ H ₂₁	153.29	0.81	43.22

2.2. Heat transfer experiment

As presented in Fig. 2, the heat transfer experimental apparatus is mainly composed of five systems: a, feeding system; b, electrically heated reaction system; c, cooling system; d, gas–liquid separation system; e, data measurement and acquisition system. An electrically heated GH3128 high temperature nickel alloy tube was used at the test section. Its length was 1000 mm, inner diameter was 1 mm, and the wall thickness was 0.5 mm. The average roughness value of tube surface was 0.821 μm measured by Roughness Measuring Instrument TR300. The fuel temperature was measured by a thermocouple which was inserted into the three-way link at the end of heating tube. The link was designed specially to ensure that the temperature detector could touch the hot fuel directly. The temperature was controlled by changing the input power providing by the DC generator. Before each experiment, nitrogen (N₂) was purged into the tube for 3 min to exhaust the air inside. Then, the sample of fuel was pumped into the heat transfer passage at a given mass flow rate (0.4–1.0 g/s) with a high pressure constant-flow pump (P500, China). The pressure of the system was kept at a target value (2.5–5.5 MPa) constantly by a back valve. A necessary current was provided by a direct current power supply passing through the tube to raise the temperature to a target value (700–770 $^\circ\text{C}$). The fuel completing the mission of heat transfer flowed into the two-stage cooling equipment, and was quenched to the room temperature. Then, the gaseous and liquid products were separated by a gas–liquid separator for further analysis.

It should be noted that the temperature, pressure and flow rate change rapidly all together in the practical engine. CCD (central composite design) method should be used here. However, not all testing point can be carried out successfully in the range of 700–770 $^\circ\text{C}$, 0.4–1 g/s and 2.5–5.5 MPa. To ensure the experiment carried out successfully and safely, we confine the operation condition within the relatively safe region. So, controlling variate method is used instead of CCD. Two parameters were set as constant values, and then the influence of the third parameters could be studied. The effect of temperature on heat transfer experiment was investigated at $p = 3.5 \text{ MPa}$ and $m = 1.0 \text{ g/s}$.

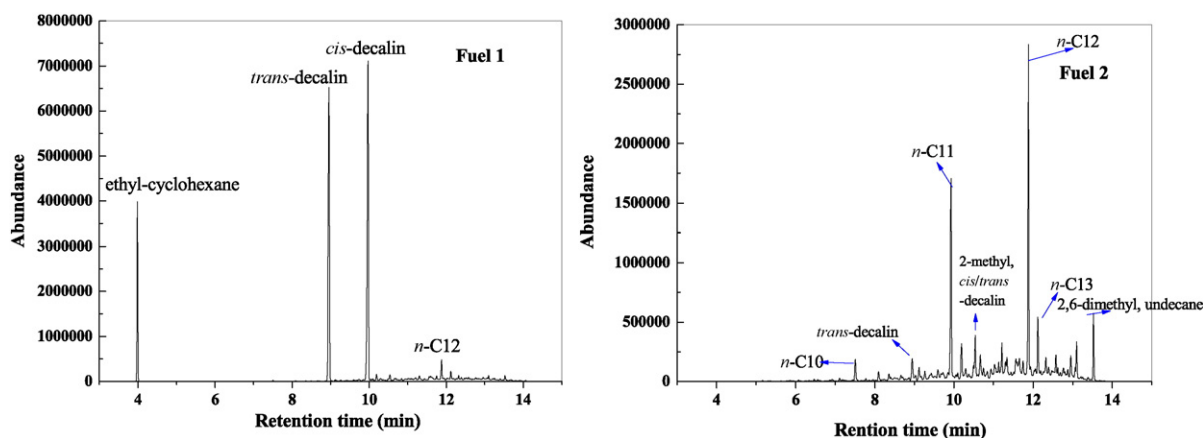


Fig. 1. GC-spectra of Fuel 1 and Fuel 2.

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