



Experimental study on effect of pressure on heat sink of n-decane



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HIGHLIGHTS

- The supercritical pyrolysis of n-decane is studied under different pressures.
- Fuel heat sink is calculated by the temperature profiles and pyrolysis products.
- Higher pressure is favor to improve the heat sink at a specific temperature range.
- Operating pressure is critical to the utilization of fuel heat sink.

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ABSTRACT

The heat sink is one of the key indicators of the development of endothermic hydrocarbon fuels, and the total heat sink of endothermic hydrocarbon fuels can be increased by enhancing the chemical heat absorption capacity to meet the cooling requirements for future high-performance aircraft. The supercritical pyrolysis and endothermicity capacity of n-decane (a major component in endothermic hydrocarbon fuels) are studied under different pressures. Experimental results indicate the main gas products are small molecular hydrocarbons (methane, ethane, ethylene, etc.), ethylene and propylene are the most abundant components at current experimental conditions. It is noticed that the influence of pressure on the production of ethylene is greater than that of any others. The increase in pressure increases the conversion of fuel to enhance its endothermicity, but the increase in pressure also decreases the alkene/alkane ratio, which has negative effect on the improvement of the chemical heat sink of fuel. So the influence of pressure on the endothermicity of n-decane is not a simple effect of promotion or inhibition, the regularity is different in different temperature ranges.

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1. Introduction

Thermal management is a significant challenge for engines to power advanced aircrafts, rockets, and missiles engines because fuel has to be utilized as the primary coolant to cool the structure as flight speed increases to high supersonic and hypersonic regime [1,2]. Future aircraft is projected to operate at a high Mach number and be powered by engines operating at high pressure and fuel/air ratio, aerodynamic heating exacerbates the thermal management task.

The heat sink (cooling capacity) of fuel has become one of the key concerns, and scramjet is the one of the advanced aeroengines, which bears the largest heat load. To fulfill the thermal management requirement of aeroengines with high flight Mach numbers, it has been proposed to use hydrocarbon fuel which can provide extra heat sink through endothermic pyrolysis reactions to replace conventional hydrocarbon fuel with heat sink limited by its sensible heat cooling capacity [3].

Improving chemical heat sink is an effective way to enhance the heat-absorbing capacity of fuel because its sensible heat cooling capacity is already determined by its physical properties [4,5]. There are so many factors, such as reaction temperature, residence time, and operating pressure to be studied before a coolant can be taken into consideration during the design of a new heat exchanger. Much works on the effect of fuel temperature and residence time has been performed due to the strong influence on the reaction rate [6–8]. For example, Zhong et al. [9] investigated the thermal cracking and the heat sink capacity of aviation kerosene in a heated tube in a temperature range from 780 to 1050 K, a pressure range 3–4.5 MPa, for a residence time duration of 0.6–3 s. They found the chemical heat sink does not always increase with the temperature of fuel; a maximum endothermicity occurred at a temperature of fuel approximately 900–960 K. The maximum chemical heat sink was approximately 0.5 MJ/kg with a 45% fuel conversion. Edwards [10] demonstrated that the flow reactor residence time was critical for the endothermic property of cracking mixture. The literature [9–11] indicated long residence time would increase the conversion rate of fuel and form products approaching equilibrium products such as light saturated hydrocarbons, and the

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overall reaction became exothermic, and the effect of residence time could be easily characterized by plotting alkene/alkane ratio as a function of residence. In general, shorter residence time corresponds to larger alkene/alkane ratio, thereby causing a more endothermic cracking process.

The effect of reaction pressure on pyrolysis process is also complex. The reaction mechanism under supercritical condition could often show dramatic differences resulting from a lower pressure condition [12]. The change in pressure in flow affects the properties of flow, especially residence time and distribution of pyrolysis products [13,14]. Furthermore, the changes in the properties of the fuel as it cracks could lead to the change in the heat-absorbing capacity of fuel. Endothermic hydrocarbon fuel generally operates under supercritical pressure [15]. The operating pressure is constrained by three factors: the heat transfer capacity of fuel, the fuel injection on the needs of operating pressure, and the pyrolysis character of fuel, and so, it is essential to understand the effect of pressure on the heat sink of fuel.

Ward et al. [13] showed that an increasing pressure would increase the overall conversion rate of flowing, supercritical n-decane and enhances the process in which n-decane converts to (C₅–C₉) n-alkane products instead of decomposing into low molecular weight products (C₁–C₄). A two-dimensional CFD model was developed by using experimentally derived PPDs to predict the formation of pyrolysis products. The experiment aimed at the study of the effect of pressure on flowing, mildly cracked, supercritical n-decane, and the PPD model was limited to mild-cracking reactions (the conversion is lower than 20%) [11]. When the conversion was lower than 20%, the result indicated that as pressure increases the endothermic heat sink increases because an increasing pressure increases the conversion rate on n-decane. Wang et al. [16] studied the cracking of hydrocarbon fuel ZH-100 in a continuous reactor under four different pressures (0.1, 1.5, 2.5 and 3.5 MPa). They found that the contents of ethane and propane generally increased with the increasing pressure, the effect of pressure is more important than that of temperature on the content of light components. Considerable research has been carried out to determine the effect of pressure on the characteristics of hydrocarbon fuel in pyrolysis process, however, the endothermic properties of the fuel are affected by the changes of pyrolysis characteristics caused by the changes in pressure. To our knowledge, few studies on the influences of pressure on the endothermicity were published. Therefore, one of the objectives of this study is to obtain the effect of pressure on the endothermic properties of fuel relevant to practical applications.

Supercritical pyrolysis of n-decane was investigated in heated high-temperature alloy tube at different pressures (3–6 MPa) in a same temperature range from 370 to 940 K. With directly measured wall temperature along the tube, an energy analysis was applied to determine the heat-absorbing capacity and the chemical heat sink of fuel. The gas and liquid pyrolysis products of n-decane were rapidly cooled to room temperature and then separated for the specific measurements using GC–MS. In addition, the fuel conversion rates of n-decane were measured and compared at different conditions. And the effect of pressure and temperature on the chemical heat sink of fuel and cracking were examined and discussed in detail. The experimental facility, the components analysis of pyrolysis products, the analysis methods and measurement of heat sink, and the experimental results will be presented in the following description.

2. Experimental

The composition of practical hydrocarbon fuel is complicated; the major components of jet fuel are straight chain alkanes, branched chain alkanes, cycloalkanes, aromatics, alkenes and

additives. It is difficult to run detailed research on the pyrolysis of fuel. A viable option is to use a surrogate [17]. n-Decane was employed in this paper because it is a typical pure liquid hydrocarbon and a major component in practice fuel with a carbon number and properties similar to those of jet fuel (for example JP-8) [13], in addition, n-decane is often used as a main ingredient in surrogate to investigate the combustion and flow characteristics of the GTL kerosene (an alternative aviation fuel) [18–20]. The critical temperature and critical pressure of n-decane are 617.7 K and 2.11 MPa respectively.

A one-stage fuel heating and cracking system (as shown in Fig. 1) was developed for the experiments. It consisted primarily of a fuel reservoir, a syringe pump, flow meter, a flow tube reactor, an electric heating power and a condenser. The maximum operating pressure of the system was 8 MPa, and the system can heated fuel temperature up to 1000 K. The flow reactor was a thin-walled circular (3 mm o.d. × 1 mm i.d. × 1000 mm in length) high-temperature alloy tube. The type of the high-temperature alloy used in this work is GH3128 (see Table 1) purchased from China Iron & Steel Research Institute Group (Beijing, China). GH3128 is a material suite for the fabrication of aircraft engines with excellent mechanical strength, and anti-oxidation between 650 and 1200 °C. Recently, this GH3128 alloy is often used to reflect the condition of the engine cooling channels [21–25], and these investigations do not reported the effects of surface catalysis. Compared with stainless steel (for example 316 stainless steel), the same elements are contained in these materials. In addition, a number of investigations on pyrolysis of hydrocarbon fuels were carried on in stainless steel tubes [26–29], in their studies, there is no result indicate the surface catalytic effect on the pyrolysis of hydrocarbon fuel. The object of this study is to discuss the effect of pressure on heat sink behavior of n-decane, and the surface catalysis is not investigated. The tube was placed horizontally and heated by direct current at its both ends. The DC power can provided a heating capacity of more than 1 MW/m². Twenty K-type thermocouples with a diameter of 0.1 mm were welded to the surface of the tube to measure the surface temperature distribution along this reactor (a common method [22,30,31]) as shown in Fig. 2(a). The measured surface temperature profiles (uncertainty: ±2 K) were used to calculate the heat loss, the processing method of heat loss.

The oxidation and coking of hydrocarbon caused by the presence of oxygen would influence the pyrolysis significantly [32]. In order to avoid the influence, tests were started by first purging the reactor tube with nitrogen to remove oxygen [16,21,33]. The fuel pressure was regulated with the back pressure regulator to achieve the desired reactor pressures. The mass flow rate of n-decane in the reactor was controlled by the syringe pump and the mass flow rate was kept constant at 1 g/s. The pressure and mass flow rate were measured by MicroMotion CMF 010 mass flow meter (uncertainty: ±0.1%) and Rosemount 3051 transducer (uncertainty: ±0.075%) respectively. As the cracked fuel exited the reactor and was cooled to room temperature, the gas products were analyzed using a gas chromatograph (GC) and the liquid portion of stressed fuel is analyzed by gas chromatograph/mass spectrometry (GC–MS).

3. Pyrolysis and endothermicity analysis

3.1. Analysis composition of cracking products and conversion rate

Cracked fuel comes out from the tube and enters into the condenser, and was sampled from a fluid/gas separator. The volume flow rate of gas products was measured by a gas rotameter, and the fluid products were collected for 60 s.

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