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Effects of fuel properties on self-ignition and flame-holding performances in SCRAM jet combustor for *n*-alkane fuels

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Abstract

Combustion characteristics of liquid hydrocarbon fuels are studied in a model combustor of SCRAM jet engines. The Mach number and total pressure of main flow in the combustor are 2.0 and 0.38 MPa, respectively, and the total temperature is varied from 1800 to 2400 K. Five kinds of *n*-alkane fuels such as *n*-heptane, *n*-octane, *n*-decane, *n*-tridecane and *n*-hexadecane are employed in experiments. Fuels are injected with a carrier nitrogen gas perpendicular to the mail flow in the combustor and the self-ignition behavior is investigated. The results show that the liquid fuels with lower carbon number have better self-ignition performance. This suggests that physical properties of liquid fuels such as volatility have a dominant effect on the self-ignition. The flame-holding behavior is investigated with the addition of pilot hydrogen to carrier nitrogen gas. The critical equivalence ratio at which the stable combustion keeps after cut-off of the pilot hydrogen is obtained. The relationship between the critical equivalence ratio and carbon number of fuel shows that fuels with the carbon numbers from 8 to 10 have the best flame-holding performance among the tested fuels. These experimental results can be expressed qualitatively by the simplified analysis with the concept of physical and chemical induction times.

Keywords: SCRAM jet; Liquid hydrocarbon fuel; Self-ignition; Flame-holding; Supersonic flow

1. Introduction

The application of liquid hydrogen to the hypersonic propulsion systems such as a supersonic combustion ramjet (SCRAM jet) engine has been expected in the viewpoint of its high-energy content, fast reactions, and excellent cooling capabilities. On the other hand, liquid hydrocarbon fuels, which have been commonly used in aero engines, are recently gathering increasing attention as a candidate for scramjet engine fuel. Although the use of hydrocarbon fuels results in the decrease in the specific impulse for the propulsion system, they are attractive for their high volumetric energy density which leads

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to competitive fuel storage size, higher safety and reliability, and are much easier to handle than cryogenic hydrogen fuel.

However, liquid hydrocarbon fuels have lower combustion and cooling performances, which are main barriers for their application to SCRAM jet engines. In order to overcome these problems, some studies have been previously conducted [1–6]. The improvement of combustion characteristics has been tried by using the combustor with a cavity [1,2]. The ignition has been enhanced using pilot hydrogen [3], and the atomization and mixing behavior have been improved by the injection of liquid fuel and gas mixtures [4]. The thermal cracking behavior of hydrocarbon fuels has been studied in the view point of cooling performance [5] and the combustion tests have been conducted in the supersonic flow using pyrolyzed fuels [6]. It is noted that the jet fuels such as kerosene employed in previous studies consist of various kinds of hydrocarbon and their composition is different from each other. It is also probable that the chemical composition which has a dominant effect on the combustion behavior is dependent on the ambient condition in the combustor, which leads to some difficulties for the better understanding of basic combustion behavior.

The objective of present study is to investigate basically the combustion characteristics of single component hydrocarbon fuels in the combustor for SCRAM jet engines. The results obtained here are also expected to be useful for the understanding of the combustion characteristics for multi-component fuels such as jet fuels and for the determination of the composition in a surrogate fuel in a practical point of view. The attention is paid to *n*-alkane fuels which are main composition of practical jet fuels. The effects of fuel properties on the self-ignition and flame-holding performances are explored experimentally and discussed with the qualitative analysis.

2. Experimental apparatus

2.1. Test fuels

Five kinds of *n*-alkane liquid fuel such as *n*-heptane (n-C_7H_{16}), *n*-octane (n-C_8H_{18}), *n*-decane (n-$C_{10}H_{22}$), *n*-tridecane (n-$C_{13}H_{28}$) and *n*-hexadecane (n-$C_{16}H_{34}$) are tested in experiments. The main properties of these fuels are shown in Table 1. It is generally known that the molar weight, boiling point and specific gravity increase monotonically with carbon number for n-alkane fuels. The specific heat, heating value and stoichiometric fuel air ratio are almost independent on carbon number, which are not shown in the table. In this paper, experimental results are analyzed and discussed with carbon number of the fuel.

2.2. Wind tunnel facility

The experiments are conducted at the blow down wind tunnel in University of Tokyo [1]. A vitiation heater is used in which lean mixture of hydrogen and air is burned to raise the enthalpy of the main flow to a desired level. Additional oxygen is added so that the mole fraction of the vitiated gas becomes 21% (volume). The hot gas is then accelerated by a two-dimensional Laval nozzle and is introduced into the model combustor, which is directly connected to the nozzle. The designed Mach number of the nozzle is 2.0 and the cross section of the exit is a rectangular shape with 30 mm × 36 mm. The total pressure of main flow P_o is about 0.38 MPa, and the total temperature is varied from 1800 to 2400 K by changing the amount of injected hydrogen in the vitiated heater. The main flow includes about 25% of water vapor which is formed by the lean hydrogen combustion and the calculated heat capacity ratio of the main flow is about 1.3. As it has been reported [7] that the combustion behavior in the combustor is affected by the water vapor and radical species formed in the vitiated heater, the quantitative discussion seems not to be suitable.

2.3. Model combustor

Configuration of the model combustor is shown in Fig. 1, which simulates a combustor of a SCRAM jet engine. The overall length of the combustor is 400 mm and the cross section at the entrance of combustor is rectangular with height of 36 mm and width of 30 mm. At 50 mm downstream of the entrance, a cavity with depth of 12 mm and length of 60 mm is placed on the bottom wall. A ramp of 30° is set on the downstream end of the cavity. It is expected that such a cavity acts as a closed cavity and that the existence of injected fuel inside the cavity is to be expected [4,8]. The main flow path broadens by 2° at downstream of the exit of cavity to prevent the thermal choking by the heat release of combustion. The exit of combustor is connected to a diffuser and the combustion gas is exhausted to the atmosphere. A quartz window for optical access can be installed on the side wall of the combustor to observe fuel injection and combustion behaviors.

The 23 static pressure holes with the diameter of 1 mm are set on the top wall of the combustor to measure the static pressure P_w distribution along the main flow. Each hole is connected to the pressure transducer and its electric signal is recorded with the sampling frequency of 500 Hz. The *x*-axis is set along the main flow and its origin is located at the entrance of cavity.

The fuel injector is installed on the bottom wall at 32 mm downstream of the entrance of combustor. As shown in Fig. 1, it consists of two circular