Study on Ignition of Thermally Cracked Hydrocarbon Fuel in Scramjet Combustors

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（熱分解を伴う炭化水素燃料のスクラムジェット燃焼器内での点火に関する研究）
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論文内容要約

At Japan Aerospace Exploration Agency (JAXA), a flight experiment of the scramjet engine is explore and a flight test system utilizing a sounding rocket is planned. Downsizing of the fuel tank is importa factor for the realization of the flight test model and hypersonic vehicle. In recent year, much research recent years have focused on scramjet engine using hydrocarbon fuels. Hydrocarbon fuel is selected as t propellant for good packing into the airplane-like vehicle shape becomes in compact size. However, combust the thermally cracked hydrocarbon fuel in a scramjet engine, it is necessary to solve the importa ignition problem in the scramjet engine. Besides, JAXA proposed to use the regenerative cooling system the scramjet engine. The heavy hydrocarbon fuel (e.g., n-dodecane, Jet fuel) inside the fuel tank runs in t cooling passage, consequently, the engine is cooled through the endothermic reactions by the therm cracking. The turbine is driven by thermally cracked component fuel, which has been heated through the cooling passage. After that, the thermally cracked component, which includes various hydrocarbon fuels, was injected into a supersonic crossflow from the orifice. To combust the thermally cracked component in a scramjet engine it is necessary to ignite within a residence time in the order of milliseconds. However, the secure ignition condition by the self-ignition or forced ignition for the thermally cracked component was not clarified from the previous study. The focus of this study was to propose the secure ignition method of specified the thermally cracked component of n-octane and n-dodecane from the autoignition condition or forced ignition condition in the scramjet engine. The overall aim of this dissertation was to propose the ignition model that could be estimated for the self-ignition condition or forced ignition condition of the thermally cracked hydrocarbon fuel.

In chapter 3, five reaction model, which were the USC Mech II model, the GRI Mech 3.0 model, the San Diego model, the KUCRS model, and the JetSurF 2.0 model, were verified by comparison with the ignition experiment data attained in the present ignition experiments and in those by other researchers (Colket et al., Davidson et al.). Ignition experiments of this study were conducted in a shock tube facility at the Kakuda Space Center of JAXA. In this study, a double-diaphragm type shock tube was used. The shock tube driven section was 1800 mm long, the driven section including the visualization window section was 3115 mm long, and the double diaphragm section was 50 mm long. All sections internal diameter was 92.5 mm. In addition, the OH* chemiluminescence emission was recorded to determine the ignition delay time using a photomultiplier tube. Objects of the validation analysis were methane, ethylene, methane-ethylene mixture gas fuel, n-octane, and n-dodecane. From the validation results, the JetSurF 2.0 model predicted the ignition delay time measurements of methane, ethylene, methane-ethylene mixture gas fuel, n-octane, and n-dodecane, very well over the wide range of conditions studied. Therefore, the JetSurF 2.0 model was used in the following part of the present study.

In chapter 4, the self-ignition model within the combustor and cavity in the case of hydrocarbon mixture fuel was developed. The combustor internal conditions, in terms of static temperature, static pressure and so on, were deduced by the one-dimensional flow-approach. In addition, the residence time in the combustor and cavity were estimated. The self-ignition characteristics of hydrocarbon mixture fuel were investigated by use of self-ignition model. Moreover, the self-ignition limit at the combustor and cavity in the scramjet engine was investigated. All ignition study was performed in the flight Mach number 4 to 8 conditions. Firstly, self-ignition characteristics of the methane-ethylene mixture gas fuel was numerically investigated. From the results, on the high-temperature side, at the methane-ethylene ratio of 50/50 or more, the change in the ignition delay time was small even if the ethylene ratio was increased. Next, the self-ignition characteristics of the thermally cracked component of n-octane and n-dodecane was numerically investigated. the thermally cracked components had shorter ignition delay time than un-decomposed component (n-octane and n-dodecane). Among the thermally cracked components, thermally cracked component No. 3 (decomposition ratio of 11.1% for n-octane, and decomposition ratio of 16.6% for n-dodecane) had shortest ignition delay time in the three kinds of thermally cracked components. Under the condition of equivalence ratio of 0.2 and 1.0, there was no self-ignition condition for n-octane, n-dodecane, and thermally cracked component to ignite withing the combustor and cavity residence time. Therefore, the forced ignition method was required to ignite the thermally cracked components. Thus, the forced ignition method using a plasma jet torch and micro-burner torch was investigated in the next chapter.

In chapter 5, the forced ignition model within the cavity in the case of hydrocarbon mixture fuel was developed. The torch gas temperature and torch gas concentration (radical, and unburned hydrogen) of the plasma jet (PJ) torch (feedstock of oxygen) and the micro-burner torch (hydrogen and oxygen) were theoretically estimated. Moreover, the temperature within the cavity at the time of torch gas injection and torch gas concentration within the cavity were theoretically estimated. From the previous chapter results, forced ignition within the cavity under non-self-ignition conditions of hydrocarbon mixture fuel was investigated. The ignition delay times with the PJ torch and the micro-burner torch at the input power of 2.0 kW in the case of methane-ethylene mixture gas fuel (36/64%) and the thermally cracked components of n-octane and n-dodecane were compared. From the comparison between the PJ torch and the micro-burner torch, the PJ torch and the micro-burner torch had almost identical effect of shortening the ignition delay time even in the case of thermally cracked components. As a result of comparing effects of unburned hydrogen concentration, and radical concentration (H, O, and OH) on the ignition promotion by the micro-burner torch, the effects on ignition promotion were found to be radical (H, O, and OH) > unburned hydrogen. In addition, the validity the forced ignition model in the case of micro-burner torch was investigated from the results of combustion experiments by Kobayashi et al. From the validation results, the forced ignition model of this study could be reproduced the combustion experiment results (step-shaped combustor) with hydrogen fuel. Furthermore, the validity of the forced ignition model developed in this chapter was necessary to investigate from the results of combustion experiments of hydrocarbon mixture fuel.

In chapter 6, firstly, combustion experiments were conducted to investigate effects of fuel supply rate on forced ignition limits and flame holding limits. Next, the effects of torch gas temperature on forced ignition limits were experimentally investigated. Moreover, the effect of cavity residence time on forced ignition was also experimentally investigated using two-types of cavities with different cavity lengths. In order to investigate the forced ignition conditions of the fuel in the cavity, the gas composition in the cavity and the torch injection conditions were determined. Moreover, OH* chemiluminescence was measured to clarify the ignition process in the cavity. The validity of the forced ignition model developed in chapter 5 was evaluated based on the result of combustion experiments. Combustion experiments were conducted in the Combustion Wind Tunnel Facility at the Kakuda Space Center of JAXA. The simulated scramjet combustor flow-path consisted of the constant area section and the diverging section. The constant area section and the diverging section had a rectangular of 51 mm × 94.3 mm at their inlet. The diverging section had a divergent wall of 3 degrees only on the injector-side wall. The length of the constant area section was 560 mm, and the length of the diverging section was 300 mm. At 200 mm downstream from the constant area section inlet, a cavity with the aft wall angle of 35 deg. was installed on one side of the walls termed as the injector-side wall. Open type cavities with length-to-depth ratio (L/D) of 4 and 8 were used. Hydrocarbon mixture fuel (methane-ethylene mixture fuel) was injected directly into the cavity to directly control the equivalence ratio within the cavity. At 5.0 mm downstream from the cavity forward step, a micro-burner torch was installed. This torch igniter was 183 mm in length. The injection orifice diameter of this torch was 1.5 or 2.5 mm. The micro-burner torch consisted of a fuel port, an inner pressure port, and oxygen port, a spark plug port, and a combustion chamber. From the combustion experiment result, by lowering the torch gas temperature, the methane-ethylene mixture gas fuel could not be forcibly ignited in some cases, showing the impact of the torch gas temperature on the forced ignition ability. From the comparison between calculation results of forced ignition limits and experimental results of forced ignition limits, in order to reproduce the experimental results of forced ignition limits using the forced ignition model at the Damköhler number, it was necessary to consider the cavity refresh time, and H_2O contained in the mainstream air. In addition, from the calculation result of the forced ignition model in the case of φ2.0 + 50% He torch, the fuel could be ignited within the residence time of shear layer even if the fuel couldn't be ignited within the residence of the cavity. Therefore, it was necessary to investigate the forced ignition by the residence time in the shear layer.

This thesis results were provided an ignition model (self-ignition model and forced ignition model) and a clear ignition method in the scramjet engine. Thus, this thesis results are encouraging and should be validated in a more experiment conditions, which were mainstream conditions (e.g., total temperature, Mach number), fuel (e.g., thermally cracked component of n-dodecane), and cavity shape (e.g., length-to-depth (L/D)).