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Effects of pre-filled gas and spraying condition on ignition of oxygen/kerosene spray combustion

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ABSTRACT

The transient characteristics of kerosene/oxygen spray were investigated using a windowed rocket combustor. In order to investigate the effects of ignition conditions, viz. aerodynamic Weber number and the oxygen fraction of pre-filled gas, on GOx/kerosene ignition, the ignition process was visualized directly using the shadowgraph technique. In addition, the dynamic pressure and global OH* chemiluminescence were measured simultaneously. The transient ignition process was significantly changed by the type of pre-filled gas (nitrogen or oxygen). The nitrogen-filled ignition condition resulted in smooth ignition, while the oxygen-filled ignition condition induced two-step ignition following the sequence of ignition with high-pressure peak, temporary extinction, and re-ignition. The ignition process was less affected by the spraying condition (We_a), except that the change of the spraying condition influenced ignition to steady state transition, such as a combustion chamber pressure overshoot. It was revealed that the oxygen-filled ignition condition caused drastic energy generation at the moment of ignition, producing a high-pressure peak and causing reverse flow of combustion gas through the gaseous oxidizer injector. This resulted in temporary extinction of the initial flame followed by re-ignition. Once the two-step ignition phenomenon occurred, the combustion chamber pressure did not increase to its steady state value during the entire run time (1.5 s). As the oxygen fraction in the pre-filled gas increased because of the increase in oxygen pre-injection time, the ignition delay time decreased and the peak value of global OH* intensity increased exponentially. When the oxygen pre-injection time became more than 14 ms, the ignition process transformed from smooth ignition to two-step ignition, and the peak value of global OH* intensity began increasing, the ignition process was converted from the smooth ignition to the two step ignition.

1. Introduction

A liquid-propellant rocket engine burns fuel with pure oxygen, and its energy generation rate is larger than those of air-breathing engines, which use air as an oxidizer. The combustion pressure of present liquid-propellant rocket engines is in the range of 10–250 bar, and is approximately 5 times higher than that of air-breathing engines. Moreover, for a launch vehicle, liquid-propellant rocket engines need to produce maximum thrust in order to be lifted off and accelerated against gravity. For these reasons, the ignition process of a liquid-propellant rocket engine is accompanied by a violent combustion reaction and a dramatic pressure increase, thus an improper ignition can cause an ignition delay, a high pressure peak or overshoot, which induces a physical failure of the combustor devices and a performance loss. Therefore, the ignition process of liquid-propellant rocket engines should be controlled precisely, as conducted in the following studies using direct visualization methods.

The German Aerospace Center (DLR) reported several results of ignition experiments using Schlieren density gradient imaging and radical chemiluminescence imaging techniques. Schmidt et al. [1] investigated the effects of injection conditions of LOx/GH_2 on a flame propagation velocity and a pressure peak. His results showed that a higher Weber number condition caused the propellant spray to be atomized better, produced a higher pressure peak at the moment of ignition, and discovered that an increase of a gaseous jet (hydrogen) momentum actually accelerated the flame propagation velocity. In addition, they also found that a gaseous momentum lower than 0.8 kg m/s^2 resulted in a blow out of the flame. Rosa et al. [2] investigated on the LOx/GH_2 ignition process under a high altitude condition, and their results were compared with the results of Schmidt et al. [1]. Lux et al. [3] focused on an ignition to flame-stabilization transition of LOx/GCH_4 spray. Their

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observations were conducted by similar methods as those of Schmidt et al. [1]. OH* and CH* chemiluminescence distributions were visualized at high speed, and found that the phase-change of the LOx jet caused a sudden change in the stretching length of the ignition flame as well as a high pressure peak.

There are many fuels used for liquid-propellant rocket engines, such as kerosene, hydrogen, methane, and diverse hypergolic propellants. Kerosene is being widely used as an industrial fuel and aerospace propellant. Compared to cryogenic fuel, Kerosene has better storability, a lower price, and a higher energy density. Most of Russian (former Soviet Union) liquid-propellant rocket engines [4] and recently developed liquid-propellant rocket engines, such as the U.S. SpaceX Merlin series engines and Chinese YF-100, 115 engines use kerosene as a fuel.

Although there are many liquid-propellant rocket engines that use kerosene as a fuel, most kerosene ignition studies used air as an oxidizer and focused on ignition in a gas turbine engine, a SCRAM jet engine, and a detonation engine. But the ignition of oxygen/kerosene spray in a rocket combustor was rarely reported. Spadaccini et al. [5] and Zhukov et al. [6] measured the ignition delay time of an air/kerosene mixture dependent on temperature, pressure, and equivalence ratio using a shock tube. Shepherd et al. [7] investigated the ignition energy of an air/kerosene mixture. Gebel et al. [8] conducted a time-resolved study on a mechanism of flame kernel formation and transient characteristics of radical chemiluminescence at the kerosene ignition process, with air as the oxidizer. As previously introduced, they mainly investigated the effects of the ignition conditions on the ignition process. Because a liquid-propellant rocket engine deals with a highly reactive spray having a high flow rate, the ignition conditions should be controlled precisely. The ignition sequence, which is a representative design factor for stable ignition, affects the oxidizer-to-fuel ratio and the atomization degree before ignition. As an example of the main combustor of a staged combustion rocket engine, oxygen-rich gas and kerosene are mixed and burned. The oxygen-rich gas is supplied from a pre-burner, and the liquid kerosene is supplied through regenerative cooling channels. Thus, the propellants are injected after passing complex devices, and a delay is inevitably induced. To achieve stable ignition, the ignition process should be controlled precisely, which requires information about the effects of the pre-ignition conditions.

In this study, the transient characteristics of a kerosene/oxygen spray were investigated using a windowed rocket combustor. In order to observe the effects of an oxygen fraction in pre-filled gas and a spraying condition, on the ignition process of coaxial GOx/kerosene spray, ignition flow field was visualized using a high speed shadowgraph technique with a high intensity L.E.D. light source. In addition, time-traces of dynamic pressure and global OH* chemiluminescence intensity were measured during the ignition process, and were compared to the visualization results.

2. Experimental setup

2.1. Windowed combustor and combustion facilities

The shear coaxial injector was designed for a high pressure combustion experiment. The injector assembly consisted of two parts – center post and outer body – as shown in Fig. 1(a). The pressure drops at the gas and liquid injectors were determined using metering orifices, which were inserted in the propellant inlet ports of the injector. The geometrical dimensions and the operating conditions are listed in Table 1. When the combustor length was determined by considering literature-suggested L^* (1 m for liquid oxygen/kerosene) of oxygen/kerosene, the combustor length should be 84.6 mm. Since the propellant spray flow of a uni-element subscale combustor is concentrated at the center region, sufficiently long chamber length was required. For that reason, the combustion chamber was designed with a length of 182 mm ($L^* = 2.15$ m).

Table 1
Geometrical dimensions of GOx/kerosene coaxial injector and combustor.

Geometrical dimensions of injector	
Liquid center post I.D., D_L	1.5 mm
Liquid center post O.D., D_P	3.0 mm
Annular gap width, t_{AG}	0.75 mm
Outer body I.D., D_G	4.5 mm
Recess depth, R	2.0 mm
Geometrical dimensions of combustor	
Length from injector to nozzle throat	182 mm
Inner diameter	22 mm
Nozzle throat diameter	6.4 mm

In order to observe the high pressure combustion flow field of the GOx/kerosene spray, the windowed combustor was designed as shown in Fig. 1(b). The inner diameter and the overall length from the injector face plate to the nozzle throat measured 22 mm and 182 mm respectively. The combustor body consisted of three modules; (i) upper module for flame visualization and igniter attachment, (ii) middle module for adjusting combustor length, and (iii) lower module with exhaust nozzle and water cooling channel. The combustion chamber had a normal geometry—a cylindrical shape and convergent/divergent nozzle—except for the cavities on the inside of the quartz windows. Because the cavities had a low depth-to-width ratio (∼0.24), particular flow, such as recirculation, was not observed in the high-speed shadowgraph movie. Therefore, we consider that the windowed combustion chamber had little effect on the ignition characteristics.

The propellants spray was ignited using a motorcycle spark plug (NGK CR9EIX) and a high voltage induction coil, which supplies ignition energy of 198 J. Although the minimum ignition energy for the ignition of kerosene/air mixture at atmospheric temperature and pressure is below 100 J [7], the spark ignition energy supplied in this study was sufficiently higher than the minimum ignition energy to avoid the effect of ignition energy on the ignition transient characteristics. Periodic sparks were generated continuously for 300 ms. The spark frequency was 115 Hz.

The ignition sequence was controlled by a custom-made microcontroller-based controller. The delay times from the transmission of valve opening signal to the actual injection of propellants were measured using high speed imaging near-injector region. 60 ms earlier opening signal for oxidizer main valve allowed simultaneous injection of the oxidizer and fuel jets. The default sequence for a simultaneous oxidizer/fuel injection is illustrated in Fig. 2. The overall runtime was 1.5 s, which was enough time to collect transient characteristics at the point of ignition.

2.2. Visualization and measurement methods

The behavior of the spray flow field at the ignition transition was observed using a shadowgraph imaging technique. The kerosene/oxygen flame emits a high intensity light in the wavelength-range from the visible to the infrared wavelength region (500-3000 nm) by incandescence of carbon particle. In order to get a clear shadowgraph image, we were required to exclude the luminous flame from the shadowgraph image. Since the luminous flame that was observed during the ignition process was more intense than the light from a general halogen lamp, we proposed two solutions to overcome this problem. First was the using of a low pass optical filter, which transmits the light from the halogen lamp (200–600 nm). This solution is appropriate theoretically, but the actual optical filter cannot block the luminous flame light without attenuation of light source intensity. The second solution was to increase the light source intensity to a point that

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