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Dynamic characteristics of a cryogenic swirl flow under supercritical conditions

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ABSTRACT

The dynamic characteristics of a cryogenic swirl flow under supercritical conditions were experimentally investigated using a mode decomposition method. Cryogenic liquid nitrogen was injected into a high-pressure chamber through a simplex swirl injector under subcritical to supercritical conditions of nitrogen. High-speed photography with backlight imaging was used to obtain images of the temporally changing flow. The set of images was analyzed by proper orthogonal decomposition (POD) technique. Superposed instability structures and vortex ring structures were found in the instantaneous flow image. The spray angle decreased under supercritical conditions because of the unusual phase change of the injectant inside the injector. Two kinds of modes were deduced by a POD analysis of the flow images. The analysis showed that two types of modes exist: a symmetric/tilted ring-shaped mode and an anti-symmetric-shaped mode. The Kelvin–Helmholtz instability mechanism generated the symmetric mode. The anti-symmetric structure was created by helical instability, which was generated by the instability of the liquid film inside the injector under subcritical conditions. However, under supercritical conditions, the precessing vortex core in the central toroidal recirculation zone determined the unstable behavior of the flow. A spatial and temporal analysis of the POD modes supported this explanation for the instability. Meanwhile, the spatial characteristics of the coherent structures became similar in the downstream region or under supercritical conditions, which implicates the strong influence of the state of the injectant in flow behavior.

1. Introduction

Many types of injectors are used in propulsion or power supply combustion engines for injection and mixing the fuel and oxidizer. In liquid propellant rocket engines, three types of injectors are used: an impinging type, a shear coaxial type and a swirl coaxial type. Among these, swirl type injectors have several advantages in the distribution and mixing of injectants. Accordingly, this type of injector has been studied [1,2] and used in many of the rocket engines developed in Russia [3].

With regard to recently developed liquid propellant rocket engines, the combustion chambers are operated under high temperature and pressure conditions to enhance the performance of the engine; these conditions exceed the critical condition of the propellants. Consequently, the propellants injected in the liquid phase undergo a transcritical process in which phases are changed to a supercritical fluid, rather than a conventional phase change process. Because of the unusual thermophysical characteristics of this supercritical fluid, such as high density and specific heat with near-zero surface tension and viscosity, a classical flow model cannot be adopted to explain the behavior of the injected flow. Therefore, various studies have been conducted both experimentally [4–7] and numerically [8–11] to obtain new flow models. From these studies, it was determined that the behavior of the flow under supercritical conditions is similar to that of a high-density gas.

Serious combustion instability can be induced in the combustion chamber of a liquid rocket engine because of its high-pressure and high-temperature operational conditions. Combustion instability is caused by the coupling of acoustic pressure oscillation and unsteady heat release [12]. This phenomenon drastically increases the amplitude of oscillation and ultimately leads to serious engine failure. Particularly in the most recently developed rocket engines, the high-energy density condition inside the combustion chamber can provide a large amount of energy leading to instability. Therefore, the reduction of instability is extremely important in the development of liquid propellant rocket engines.

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Various factors affect combustion instability: chamber geometry, instability from the propellant feed line, flow instability, and others [12]. Among these, the most significant factor is the geometry of the combustion chamber, which determines the acoustic characteristics of combustion instability. Flow instability can affect the distribution and mixing of the injected propellant. This phenomenon can be related to the disintegration and atomization characteristics of the liquid flow. Thus, numerous studies have been conducted on flow instability in swirl injectors [13–21]. In a simplex swirl injector flow, instabilities in the low-frequency ($\sim 10^2$ Hz) and high-frequency ($\sim 10^3$ Hz) regions are observed simultaneously [18,20], and the similar instability frequencies caused by spray angle oscillation are observed [19]. In addition, several studies have suggested that the internal flow instability of an injector causes instability in the external flow [13,14,16]. In the gas–liquid coaxial injector flow, the self-pulsation frequency is related to the natural frequency of the liquid flow [15].

The dynamic characteristics of cryogenic flows under supercritical conditions have also been investigated. These studies have indicated that two kinds of instability in the cryogenic swirl flow under supercritical conditions exist: a precessing vortex core (PVC) in the central toroidal recirculation zone (CTRZ) and Kelvin–Helmholtz instability caused by shear between the flow and its surroundings [11]. These instability characteristics are similar to those of a liquid swirl flow injected into liquid surroundings [22,23]. The response of the flow to external excitation has also been experimentally [24,25] and numerically [26] investigated. These efforts have revealed that the characteristics of flow instability can affect the response of the flow to external excitation.

For in-depth study of flow instability, mode decomposition methods have been recently applied to the flow field dataset. In particular, the proper orthogonal decomposition (POD) method has been used to investigate the dynamics in various types of flows to obtain coherent flow structures and to determine their roles in flow behavior [11,24,25,27–32]. Although most of these studies used velocity data from the flow field, some of them used flow images [24,25,27,29]. The POD method has already been adopted in investigations of the external behavior of the liquid swirl flow under subcritical conditions [29], jet flow under supercritical conditions [24,25], and the internal flow of the swirl injector under supercritical conditions [11]. Therefore, it is reasonable that this method can be used in a study on swirl flow instability under supercritical conditions.

The main purpose of this study is to conduct an experimental investigation of the instability characteristics of a cryogenic swirl flow, especially to find out the relation between the instability characteristics and the structure of the flow outside the injector. The ambient pressure was changed as the flow was injected into ambient gas under subcritical to supercritical conditions. The coherent structures of the flow were deduced by an analysis of the flow image using the POD method. The spatial and temporal characteristics of the flow and its instability were determined to reveal the instability mechanism that dominated flow behavior.

2. Experimental methods

2.1. Experimental setup and conditions

An experimental system was equipped to inject cryogenic fluid into the surrounding environment under various pressure conditions. A schematic of the experimental setup, which is similar to the system used in previous work [33], is shown in Fig. 1. Liquid nitrogen, at a cryogenic temperature, was selected as the working fluid to simulate liquid oxygen flow in this experiment. Two factors were considered in using liquid nitrogen as the working fluid: the similarities of the critical properties of nitrogen and oxygen and the ease of dealing with nitrogen [6,33]. A cryogenic nitrogen feeding facility, consisting of a run tank, vacuum-insulated feed lines, and a pressurizing system, was used in the experiment. The run tank was filled with liquid nitrogen and pressurized by nitrogen gas. A flowmeter, thermocouples, and pressure transmitters were inserted into the feed lines to check the condition of the flow. The flow was injected into a high-pressure chamber through a swirl type injector. The chamber had six quartz windows for flow visualization and could be pressurized up to 6 MPa by nitrogen gas to control the ambient condition of the injected flow. The inner diameter and height of the chamber were 500 mm and 1000 mm, respectively.

A simplex swirl type injector was mounted inside the chamber to create a cryogenic swirl flow. The injector was a closed-type swirl injector, creating a single hollow-cone-shaped flow. Its geometry was similar to the oxidizer part of the main injector used in an RD-0110 liquid propellant rocket engine [34]. The detailed geometry of the injector is shown in Fig. 2 and Table 1. Because

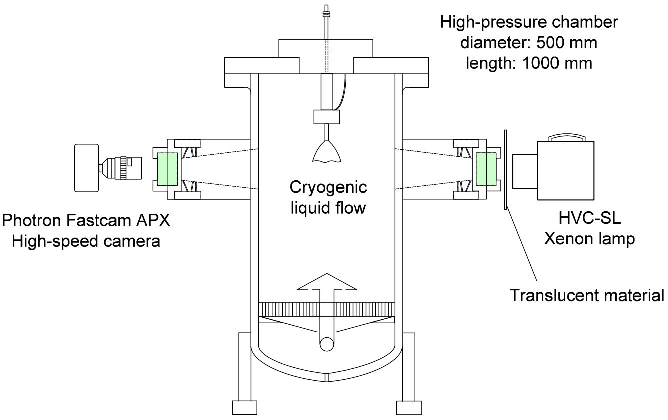

Fig. 1. Schematic of the high-pressure chamber and flow visualization setup.

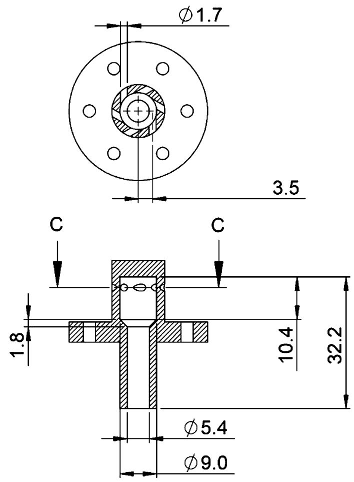

Fig. 2. Schematic of the simplex swirl injector (unit: mm).

Table 1
Injector geometry.

Injector part	Geometry, mm
Swirl arm, R	3.5
Vortex chamber diameter (inner), $D_{c,i}$	9
Nozzle diameter (inner), $D_{o,i}$	5.4
Nozzle diameter (outer), $D_{o,o}$	9
Tangential inlet diameter, D_p	1.7
Number of tangential inlets, n	6
Injector geometrical characteristic parameter $K = 2RD_{o,i}/nD_p^2$	2.2