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Technical Notes

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Observation of Unsteady Cryogenic Flows from a Characteristic Coaxial Rocket Injector

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I. Introduction

CONDITIONS affecting mixing and ignition of cryogenic propellants (usually liquid oxygen and gaseous hydrogen) in liquid-fueled rocket engines have not been widely studied. Mixing between jets of cryogenic liquids and gases have been examined under steady-state conditions in limited studies [1–6]. Although the cryogenic propellants are injected into the rocket engine under steady-state conditions, the initial introduction of propellants into the combustor are far from steady state. For example, during the initial 40 s approximately preceding ignition in some of the rocket engines, the oxygen flow rate through the injector is substantial enough to chill the injector surfaces sufficiently, so that the oxygen present in the injector at ignition is probably two phase [7,8]. Therefore, under realistic engine operating conditions, propellants such as liquid oxygen and gaseous hydrogen initially mix under unsteady conditions to trigger the onset of flow instabilities. The oxygen flow rate is reduced immediately before ignition, due to the closing of the control valve to the start position, but the oxygen flow would remain two phase during this initial period. Hydrogen fuel is in gaseous form under conditions occurring in the injector immediately before ignition. Thus, close examination of the initial transient flow behavior, as well as mixing between two-phase oxygen and gaseous hydrogen flows, is necessary to develop a better understanding of the fate of propellants during the preignition conditions. This will also aid in preventing the ignition failure in cryogenic rocket engines. However, cryogenic oxygen presents substantial experimental and modeling complexities because its state is unknown under realistic engine operating conditions. In this work, the behavior of a liquid nitrogen (LN_2) stream (to simulate the cryogenic liquid oxygen), surrounded by a coannular stream of gaseous helium (to simulate gaseous hydrogen), ejected from a coaxial rocket injector, has been examined starting from the initial exit of the cryogenic fluid from the injector under realistic engine startup conditions. The initial, dynamic interaction of the cryogenic liquid with the surrounding gas has been imaged for the first time to reveal the three-dimensional, two-phase flow behavior of the LN_2 jet. These observations are significant, because instabilities observed at the two-phase boundary during startup will affect the initial mixing and ignition of propellants.

II. Experimental Setup

The experimental facility consisted of a supply system for cryogenic liquid nitrogen and gaseous helium, a single element coaxial injector, an enclosure surrounding the injector, and an exhaust system. A schematic diagram of the injector tubes, along with the injector face plate with dimensions through which the flows emerge, is shown in Fig. 1. The coaxial injector and faceplate geometry is characteristic of those used in many practical engines. The flow conditions used are relevant to some of the rocket engine operating conditions. The flow rate of helium was measured using a choked orifice and a pressure transducer. Because the pressure inside the chamber of a rocket engine is near atmospheric before the engine startup, tests were carried out at normal atmospheric pressure. The enclosure surrounding the flow was removed during tests presented here to gain full optical access, thus aiding high quality of data on flow visualization.

III. Cryogenic Fluid Flow Measurement

The precise measurement of cryogenic fluids is a challenge and is not reported much in the literature. For the present experiments, the flow rate of liquid nitrogen was measured using a high-precision turbine flow meter, designed to handle cryogenic liquids. The challenge here was to ensure that the fluid entering and exiting the turbine flow meter remained in liquid form, because any transformation to gas phase would result in erroneous results on the metered cryogenic flow rate. Therefore, to assure that the measurements were accurate, the flow meter had to be cooled down to LN_2 temperatures, before getting steady-state readings to confirm liquid flow through the flow meter with negligible vapor or two-phase flow formation. The procedure for acquiring true LN_2 flow rate involved first bleeding the LN_2 out through the turbine flow meter at a very low flow rate until the temperature of flow meter reached the LN_2 cryogenic temperature. Once this was achieved, the bleed valve was closed and the fast-response control valve to the injector was opened completely before starting the measurements. This approach assured that the variations in instantaneous LN_2 flow rate under steady-state conditions reduce to less than 5%. The flow rate through the injector was also calculated using Bernoulli's equation by measuring pressures upstream and downstream of the coaxial injector. The difference in measured and calculated average flow velocities at steady state was less than 10% for several different test runs. This difference was expected for a cryogenic fluid because of property variations, chugging instabilities, and a nonideal nature. This procedure allowed one to alleviate the erroneously high apparent flow rates due to an artifact, and determine the true flow rates using two different approaches.

The flows were controlled with solenoid-actuated valves. A high-speed camera, capable of recording up to 10,000 monochrome images per second, was used to record schlieren images of the flow. The resolution of the camera was 1024×1024 pixels to provide the smallest length scale resolution of 0.0066 in. The liquid and gaseous

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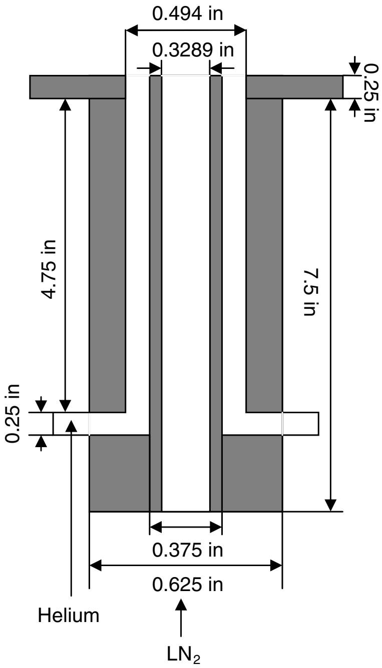

Fig. 1 Injector tubes and faceplate, along with dimensions.

streams, as well as the two-phase regions in the flow, could be examined directly using this technique.

IV. Results

Results obtained at two specific experimental conditions are reported here. In the first case, the flow of liquid nitrogen fed through the inner aperture in the faceplate was controlled to produce an average, steady-state cryogenic fluid velocity of 5 m/s. No gas was fed through the outer tube of the injector. The flow was initiated when a solenoid-operated control valve was opened. The resulting schlieren images, showing the first 8 ms of the experiment, are shown in Fig. 2. Note that *D* in the figure represents the inner diameter of the inner tube in the injector.

Initially, the nitrogen emerged as vapor from the injector, and this is visible in the schlieren image due to the presence of density gradient between the cold nitrogen gas and the surrounding ambient air. During the first few milliseconds, the jet formed a mushroom-shaped structure, indicating that the interface between the flow and the quiescent surroundings was shaped by a starting vortex. After about 7 ms, liquid nitrogen began to emerge, and a dynamically evolving two-phase flow was established. The interface between the cryogenic liquid and the surrounding gas was highly unstable, with the observation of numerous ligaments and smaller droplets, and this is attributed to the Kelvin–Helmholtz instability mechanism. An order of magnitude estimate of the frequencies of vortical structures at the interface showed them to be in the range of 300–3000 Hz. The average length scales of the vortical structures were estimated using the edge detection capabilities of MATLAB; the frequencies were calculated using length scales and liquid jet velocity (frequency = jet velocity/length scale). The higher frequencies were found to be very close to the Kelvin–Helmholtz frequencies of the interface predicted by previous researchers for noncryogenic liquid jets [9,10], and the lower frequencies were of the larger vortical structures that were formed due to the coalescence of smaller vortical structures generated by Kelvin–Helmholtz instabilities.

In the second experiment, a steady stream of liquid nitrogen was allowed to emerge from the injector. The injector system was allowed to cool down to 77 K, at which point the steady mean velocity of liquid nitrogen was 5 m/s. A solenoid valve on the helium line was then opened to allow flow of helium gas with a mean axial velocity of 300 m/s from the outer annulus of the injector. This condition produced a gas-to-liquid momentum ratio of 0.83. The schlieren images obtained for the first 8 ms under these experimental conditions are shown in Fig. 3.

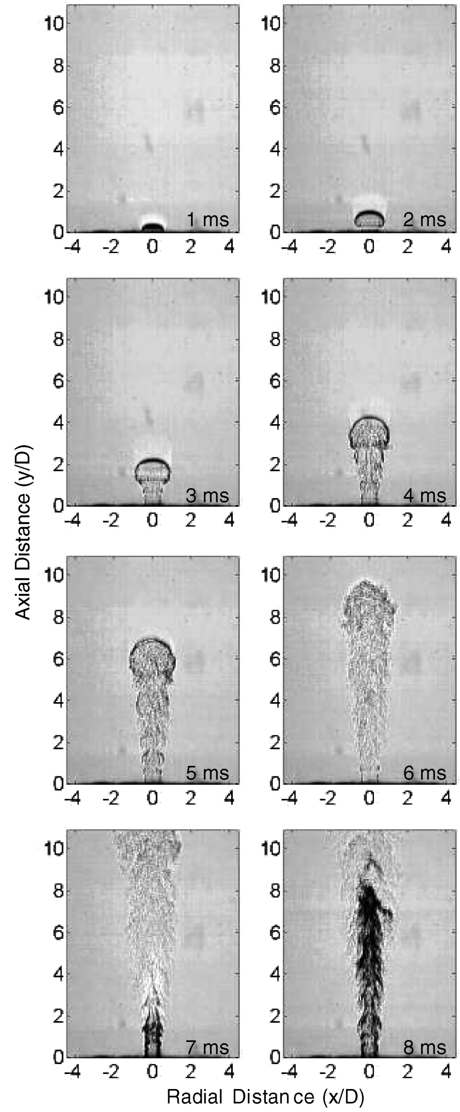

Fig. 2 Liquid nitrogen jet emerging into quiescent air without a surrounding flow of helium; $D = 0.33$ in.

The sheath of helium emerging from the outer annulus was, again, found to form a toroidal vortex during the initial few milliseconds of its emergence. This vortex formation is due to the Rayleigh–Taylor instability mechanism which occurs when a lighter fluid is injected into a denser medium. A more complex interaction between the helium and nitrogen streams was then observed. Momentum was exchanged between the helium and nitrogen streams, in ways that produced distortions of the interface at a variety of length scales. Once again, the frequencies of these length scales were found to be in the range of 300–3000 Hz and support the findings of previous researchers [6,10,11] for cryogenic and noncryogenic coaxial jets. The scales involved affect mixing of propellants before ignition and combustion, and are significant in understanding mechanisms driving unstable phenomena in two-phase systems [12]. The evolutionary behavior of the flow reveals that the flow is unstable at the initial injection of the cryogenic fluid from the rocket injector. These instabilities, once formed, persisted during the entire duration of the experiments (1000 ms), much beyond the initial few milliseconds of the data presented here. Also, once this instability is formed, it may sustain or grow itself in the engine to affect the mixture ratio distribution, ignition, and combustion behavior. These data exemplify the presence of instabilities in rocket engines right from the beginning of engine startup.

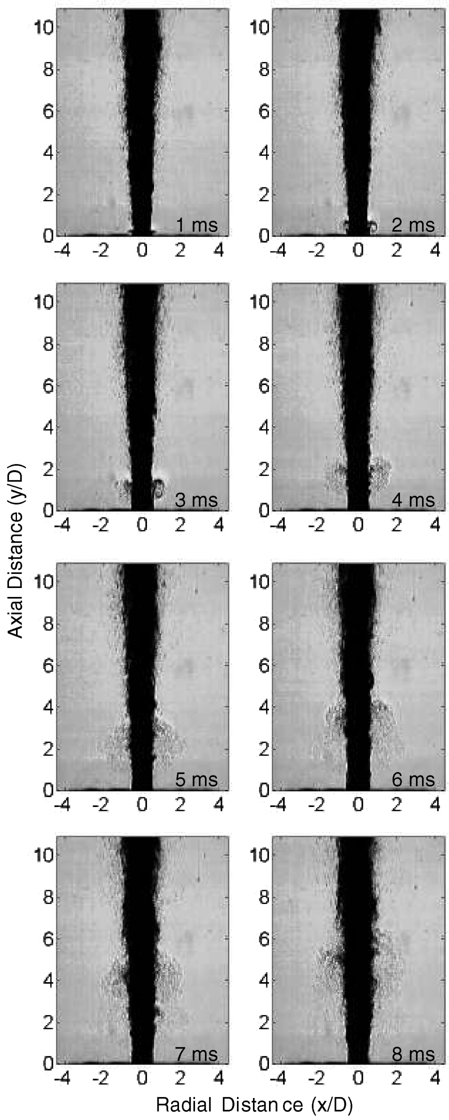

Fig. 3 Annular helium flow emerging around steady stream of liquid nitrogen; $D = 0.33$ in.

V. Conclusions

The unique experimental facility provided here has allowed us to directly visualize and record the interaction of cryogenic liquid streams with surrounding gaseous media under conditions similar to those encountered in liquid-fueled rocket engines during startup. A simple method is presented here to determine the flow rate of cryogenic fluids using a turbine flow meter with good accuracy. This method allowed us to alleviate the large errors associated with measurement of cryogenic fluids due to phase change and chugging instability. A high-speed schlieren technique has been applied to examine the transient behavior of both the liquid and gaseous phases evolved from the two-phase cryogenic flows from the coaxial injector facility. Initial results, showing detailed features on the evolutionary behavior of the flow during the first few milliseconds from the injector exit, have been obtained. Upon initial emergence, the flows were found to form mushroom-shaped vortical structures. These results clearly show that the initial flow from the injector is unsteady, which has an important bearing on the local mixture fraction, and which subsequently will affect the mixture ignition and combustion. Kelvin–Helmholtz instabilities appear to play a significant role in destabilizing interfaces between phases in the flows and in shaping the structures observed. The complex three-dimensional flow structures observed here have clearly revealed the onset of unsteady behavior from the injector exit. These structures may contribute to instabilities in rocket engines.

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