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Cryogenic Flow from a Coaxial Injector under Low-Pressure In-Space Conditions

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The effect of near-vacuum operating pressure on the evolutionary behavior of cryogenic fluid injected from a single-element coaxial injector has been examined experimentally. The investigated injector simulates one element of the injector array of cryogenic rocket engines under realistic operating conditions. Actual rocket-engine propellants, liquid oxygen and gaseous hydrogen, are simulated by chemically inert and safe to operate liquid nitrogen and helium. This work focuses specifically on the transient evolution of liquid nitrogen jet under in-space conditions. The diagnostic techniques utilized here are high-speed Mie-scattering and Schlieren imaging. The results showed that the behavior of liquid nitrogen jet was significantly affected by the low-pressure conditions as well as the strong heat shielding effect of coaxial helium jet. The cryogenic jet undergoes extraordinary jet expansion at sub-atmospheric pressures. Initial freezing of liquid nitrogen droplets and ligaments was observed close to the injector exit. The heat transfer from the warm surroundings to cold liquid nitrogen jet was reduced significantly in the presence of coaxial gaseous jet, which confined the cold liquid nitrogen jet and prevented its expansion to some extent.

1. Introduction

Cryogenic flows from shear coaxial injectors are one of the most crucial research areas associated with rocket-engine technology for future space propulsion. An important challenge with fuel-oxidizer mixing inside rocket engines is their startup/operation under different low-pressure ambient conditions, such as those found on the moon or mars, or during reentry of the vehicle into earth's atmosphere. Under such conditions the cryogenic oxidizer (LOX) might have two-phase characteristics that alter the fuel-oxidizer equivalence ratio and subsequently the mixing, ignition, and combustion. Therefore, the effects of low operating pressures on fuel and oxidizer flows must be investigated, in order to understand pre-ignition mixing in cryogenic rocket engines under in-space conditions. Although there have been several attempts to analyze and predict the behavior of cryogenic jets under atmospheric and super-atmospheric conditions, there have been no significant efforts on studying the behavior of cryogenic jets under sub-atmospheric in-space conditions. The objective of this research is to analyze the behavior of cryogenic flow from a shear coaxial injector under near-vacuum pressure conditions.

A two-phase binary system has unique properties at various pressures and temperatures. For a given system pressure, the maximum temperature at which a phase equilibrium exists between the liquid and gaseous phases of the system is known as critical mixing temperature. Above this temperature, the system exists under supercritical conditions, and no distinction can be made between liquid and gaseous phases. Figure 1 shows critical mixing lines of common binary systems at various pressures and temperatures. It can be seen that, in general, critical mixing temperature decreases with increase in pressure. The ignition characteristics of propellants also depend heavily on temperature, pressure and fuel-oxidizer equivalence ratio. Furthermore, characterization of the low pressure sub-critical regime provides insight into the problems associated with throttling, in-space ignition and low-thrust mode operation[1,2].

Many efforts have been made during the last few years on cryogenic rocket injectors for improved understanding of the fuel-oxidizer mixing and combustion processes inside rocket engines. Pal et al.[3] and Vingert et al.[4] studied the high-pressure injection and mixing processes of cryogenic propellants under reacting and non-reacting conditions. Mayer et al.[5-8] and Branam et al.[9] studied the mixing and combustion processes of cryogenic propellants under sub-critical and super-critical high pressure conditions

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experimentally using optical diagnostic techniques. They observed the propellant's vaporization, mixing, and combustion at high chamber pressures of up to 10 MPa. They also analyzed the high-pressure injection and mixing processes of cryogenic propellants under non-reacting conditions using LN_2 and He as simulants. In another more recent study, Oschwald et al.[10] investigated the effect of chamber pressure, initial jet temperature and acoustic waves on atomization, mixing, and combustion in LOX/H_2 coaxial rocket injectors. Gautam and Gupta[11-15] studied the flow and evaporation characteristics of cryogenic fluids under atmospheric pressure conditions to gain insight on initial mixing that affects ignition. However, the evaporation, mixing, and ignition behaviors of cryogenic propellants under all operating conditions, i.e., from sub-atmospheric to super-atmospheric conditions are still not well understood. Their prediction requires detailed understanding of the various ongoing complex thermo-chemical processes.

Since rocket engines operate over a large range of operating conditions, i.e., from sub- to super-atmospheric pressures, it is necessary to implement new experimental designs and techniques to quantify the combustion chamber performance. Experimental diagnostic techniques, such as high-speed cinematography and Schlieren imaging have been used to examine the performance characteristics of a single injector. The experimental results can also be used to validate models, in order to obtain performance characteristics at other conditions.

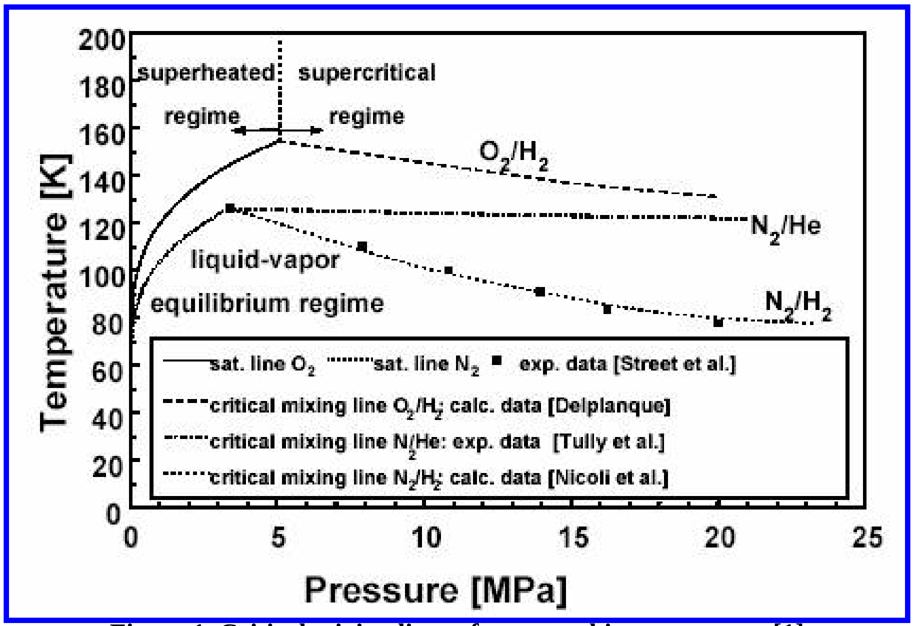

Figure 1. Critical mixing lines of common binary systems, [1]

2. Experimental Setup and Condition

The experimental facility, shown schematically in Figure 2, is used to simulate the flow and mixing behaviors from a coaxial injector that is characteristic of those used in cryogenic rocket engines. The facility consists of a supply system for cryogenic liquid nitrogen and gaseous helium, a single injector, a sealed pressure-tight chamber (2.5 × 2.5 in.), and a large blow-up tank (2500 gallons) at 0.1 atm pressure. The coaxial injector, described in detail in Ref. [14], is used to simulate the cryogenic flow behavior from an actual single element rocket injector. For this research, liquid oxygen (LOX) was simulated with liquid nitrogen (LN_2) flowing through the inner tube of the injector. Gaseous Helium (He) was used to simulate gaseous hydrogen flowing through the outer annulus. The evolutionary behavior of liquid nitrogen flow and its mixing with the coaxial gaseous jet has been examined under transient operating conditions at 0.1 and 1.0 atmosphere pressures.

The flow rate of helium was measured using precision orifices preceded with a digital pressure sensor. The average temperature of helium at the injector exit was measured using a thermocouple, and the velocity was calculated under the assumption of ideal gas density. The flow rate of LN_2 was measured using a liquid turbine flowmeter as described in Ref. [14]. The volumetric flow rate of steady LN_2 jet was fixed at 4.5 GPM for all experiments conducted in this study, with average temperature and density of LN_2 at the injector exit taken as 77 K and 808 kg/m^3, respectively. The measured temperature of LN_2 at the injector exit was found to be very close to this temperature.

The experimental test matrix of the flow conditions examined in this paper is given in Table 1. Two different set of experiments were performed to analyze the effect of pressure on the flow characteristics of cryogenic LN_2 jet in the absence and presence of helium. For the first experimental set, the outlet of the mixing chamber was open to the atmospheric pressure, while for the second set, it was connected to the vacuum tank at 0.1 atmospheres.

Mie-Scattering and Schlieren clips of the full flowfield have been obtained using a high-speed camera at 1024 frames/second with a resolution of 1024 × 512 pixels. The camera responds to the visible wavelengths of the spectrum. The flow images were extracted from the video clips using Photron Fastcam software.

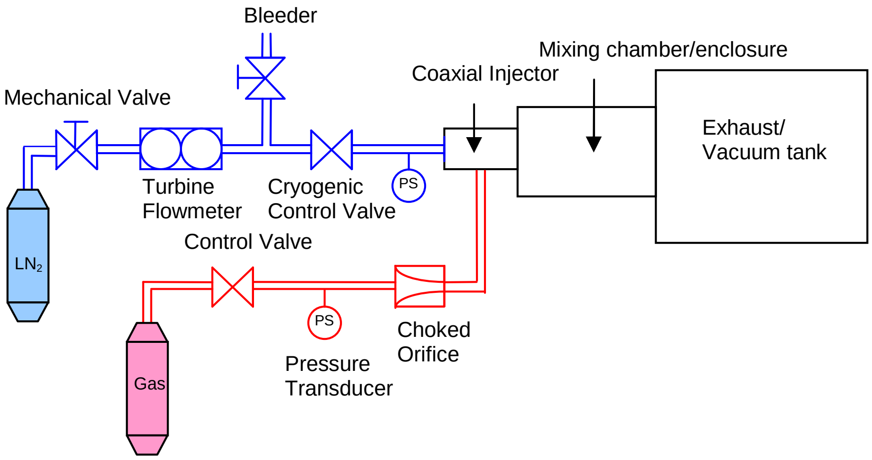

Figure 2. Schematic diagram of the experimental facility

Liquid	Gas	Velocity (liquid/gas)	Density Ratio (gas/liquid)	Momentum Ratio (gas/liquid)	Mass Ratio (gas/liquid)
LN_2	—	5 / 0	—	0	0
LN_2	He	5 / 300	2.3E-04	0.83	1.4E-02

Table 1: Flow inlet conditions examined in experimental sets

3. Results and Discussion

The first set of experiments presented here was performed at atmospheric pressure conditions. Two specific cases were examined for this set as shown in Table 1. In the first case, the evolution of cryogenic liquid nitrogen jet at an average, steady-state velocity of 5 m/s was examined. No gas was fed through the outer tube of the injector for, whereas, for the second case, the evolution of liquid nitrogen jet was examined in the presence of a steady coaxial helium jet at 300 m/s.

Figure 3 shows the evolution of liquid nitrogen jet (no helium), obtained using high-speed cinematography (Mie-scattering) at 1 atm pressure. Time zero in the experiments corresponds to the very first trace of cryogenic jet exiting the injector. The results presented are after the initial puff (0-100 ms)of liquid nitrogen was over, as discussed in the Ref. [14 These images show the effect of heat transfer from the warm injector tubes on the evolutionary behavior of liquid nitrogen jet. Initially (100 ms) the injector tubes are relatively warm, so the liquid nitrogen jet emerges in a two-phase form dominated mostly by the gaseous phase (Figure 3a). As time progresses, the injector walls gradually approach the cryogenic temperature of liquid nitrogen, and the local vapor formation near the walls diminishes. A central liquid flow is observed at approximately 500 ms (Figure 3d).

The Mie-scattering results were concurred by high-speed Schlieren imaging of the same flow. Figure 4 shows the obtained Schlieren images. Since Schlieren highlights density gradients inside the flow, the darker regions in those images correspond to high density or liquid phase, whereas the lighter regions correspond to low density or gaseous phase. As one can see, the Schlieren images confirm the findings of Mie-scattering. Initially, when the injector tubes are warm, most of the liquid nitrogen jet emerges in gaseous form, showing smaller darker regions near the injector exit (Figure 4a). Furthermore, as the flow progresses, the injector walls cool down to cryogenic temperature of liquid nitrogen, and the flow is dominated by the central liquid jet identified by the dark regions in Figures 4c and 4d.

The effect of a coaxial helium jet on the evolution of LN_2 was studied in the second case of the first experimental set, also at 1.0 atm pressure. Figure 5 shows the evolution of liquid nitrogen jet surrounded by a steady coaxial helium jet at 300 m/s, obtained using high-speed cinematography (Mie-scattering). The images of Figure 5 signify the important confinement effect imposed by a coaxial gaseous jet on the central liquid nitrogen jet. As one can see, the central core of the flow appears much brighter in the presence of helium. This is due to the heat-shielding and confinement effects provided by the annular helium jet. Helium hinders the expansion of the liquid nitrogen jet close to the injector exit. Thus, the LN_2 potential core is conserved for a considerable distance downstream.

The effect of having a helium jet at a velocity of 300 m/s is shown in Figure 6 using Schlieren imaging at 1.0 atm pressure. These results confirm the findings of Mie-scattering and previous research.[15] The darker regions of the flow appeared to be less wide as compared to the previous case, confirming the confining and shielding effect of coaxial gaseous jet. For this case, one can also see the formation of vortical structures due to shearing action of the gaseous jet which results in breakup of LN_2 potential core.

The second set of experiments, to be presented here, was performed with the outlet of mixing chamber connected to the vacuum tank, in order to analyze the flow behavior at sub-atmospheric pressures. Such analysis was conducted to study the fuel-oxidizer pre-ignition mixing under different ambient conditions, such as those found on the moon or mars, or during reentry of the vehicle into earth's atmosphere.

Figure 7 shows high-speed cinematography (Mie-scattering) images of the evolution of nitrogen jet at 0.1 atm pressure in the absence of an annular helium jet. These images show both the effects of sub-atmospheric pressure and heat transfer from warm injector tubes. Initially (100 ms), most of the nitrogen jet emerges in gaseous form. One can also notice the extraordinary jet expansion accompanying injection in the low-pressure medium inside the chamber. However, the most crucial observation, to be obtained from these images, is that nitrogen partially solidifies at these low-pressure conditions, as indicated by the emergence of solid particles in Figure 7d. The sudden expansion to 0.1 atm causes some of the droplets and ligaments to freeze, since the triple point of nitrogen is 63.18 K and 0.125 atm. Figure 8 shows a schematic of nitrogen phase diagram, showing that the 0.1-atm operating pressure is below that of triple point.

Figure 9 shows the corresponding Schlieren images of the case analyzed in Figure 7. The Schlieren images confirm the findings of Mie-scattering results. Initially, when the injector tubes are warm, most of the nitrogen jet emerges in gaseous form, showing smaller dark regions near the injector exit. As the time progresses, the flow is dominated by a darker central region. The extraordinary jet expansion, due to vacuum pressures inside the chamber, can also be seen. Figures 9c and 9d also confirm the phenomenon of partial solidification of nitrogen at these extreme pressures, as evidenced by the existence of solid particles.

The effect of introducing a coaxial helium jet was also studied at 0.1 atm pressure. Figure 10 shows the evolution of nitrogen jet in a steady coaxial helium jet at 300 m/s obtained using high-speed cinematography (Mie-scattering) at 0.1 atm pressure. These images signify the important effect of confinement provided by helium on the central nitrogen jet even at lower pressures. The central core of the flow looks much brighter in the presence of helium, as compared to the case of no helium. The coaxial helium jet prevented the expansion of nitrogen close to injector exit. It should be noted, however, that even with confinement of helium the flow looks much wider than the corresponding atmospheric-pressure case. This higher expansion of entire flowfield is due to the vacuum pressures inside the chamber. Solidification of nitrogen can also be seen by the emergence of solid particles in Figure 10d.

Figure 11 shows the Schlieren images of the case analyzed in Figure 10. The Schlieren images strengthen the findings of Mie-scattering results. The confinement and shielding effects of coaxial helium jet can be seen along with the formation of vortical structures due to shearing action between the jets. The solidification of nitrogen droplets and ligaments at this low pressure is also clearly visible. Therefore, it can be concluded that the results presented in this study at near-vacuum conditions show the dramatic change in flow behavior of the cryogenic propellants, thus underlining the importance of studying operation at in-space conditions. Further experiments and detailed analysis are required to study the physics of this problem in detail.

4. Conclusions

The transient evolution of cryogenic nitrogen jet at atmospheric and near-vacuum pressure conditions has been examined experimentally from a single-element coaxial injector. The atmospheric pressure results showed the significant effect of heat transfer from warm injector tubes to the cold liquid nitrogen jet at startup, along with the strong heat shielding and confinement effects of the coaxial gaseous jet on the cryogenic nitrogen jet.

The experiments performed at near-vacuum conditions (0.1 atmospheres) showed a dramatic change in flow behavior of the propellants, thus underlining the importance of studying operation at in-space conditions from the points-of-view of mixing, ignition, and stability. The cryogenic jet undergoes extraordinary expansion at the low pressures inside the chamber. Partial freezing of nitrogen droplets and ligaments is also observed. The heat transfer from warm surroundings to the cold LN_2 jet is reduced significantly in the presence of the gaseous helium jet even at sub-atmospheric pressures.

A combination of various optical diagnostic techniques (Mie-scattering and Schlieren) has allowed us to examine the detailed evolutionary pre-ignition behavior of a cryogenic jet under simulated rocket engine operating conditions. The results from this research provide insightful information on the flow and mixing behavior of cryogenic jet under low pressure in-space conditions. These results will help in the development and validation of advanced computational models under corresponding flow conditions.

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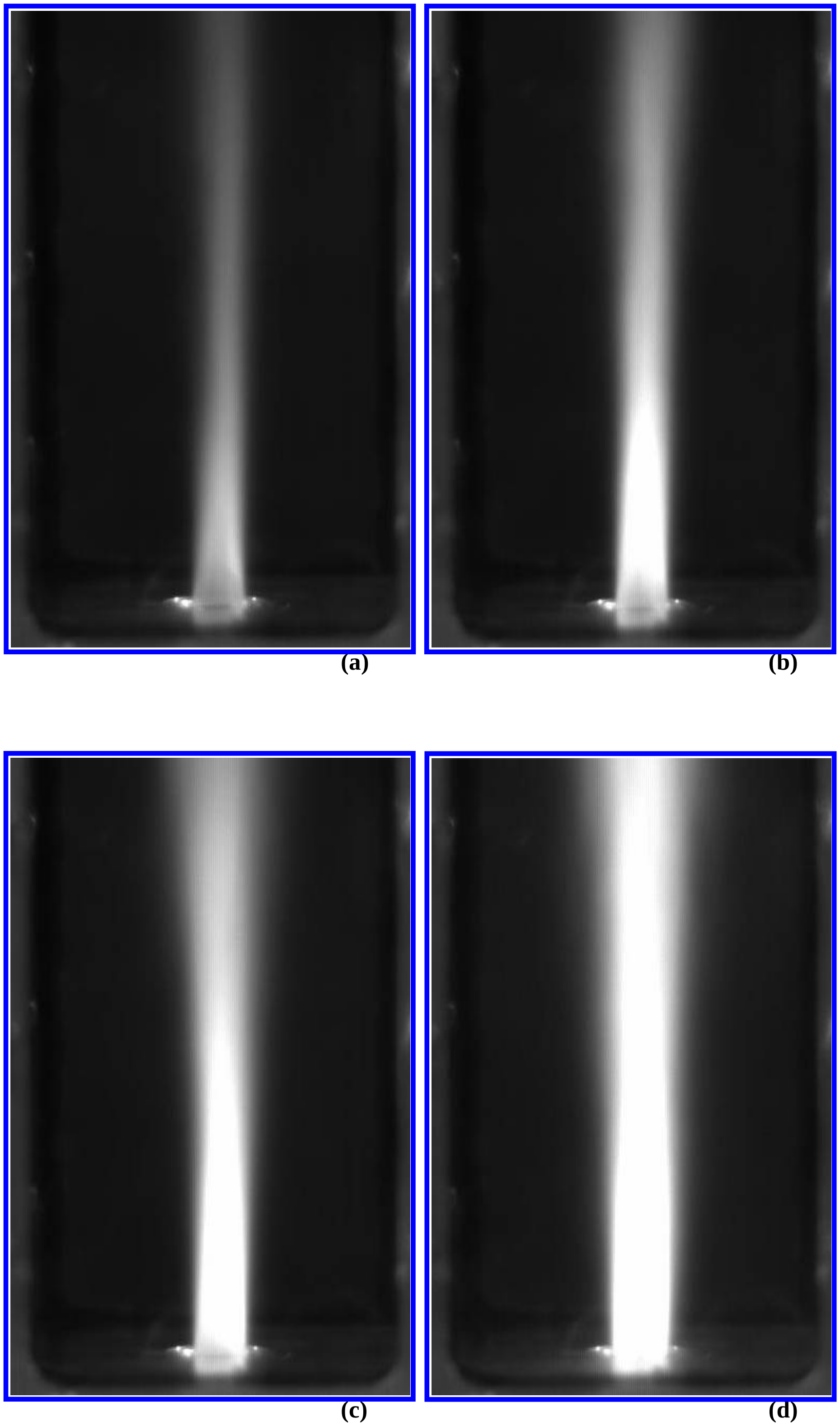

Figure 3. High-speed Mie-scattering images of LN_2 flow at 1.0 atm
a) t = 100 ms; b) t = 200 ms ; c) t = 300 ms; d) t = 500 ms

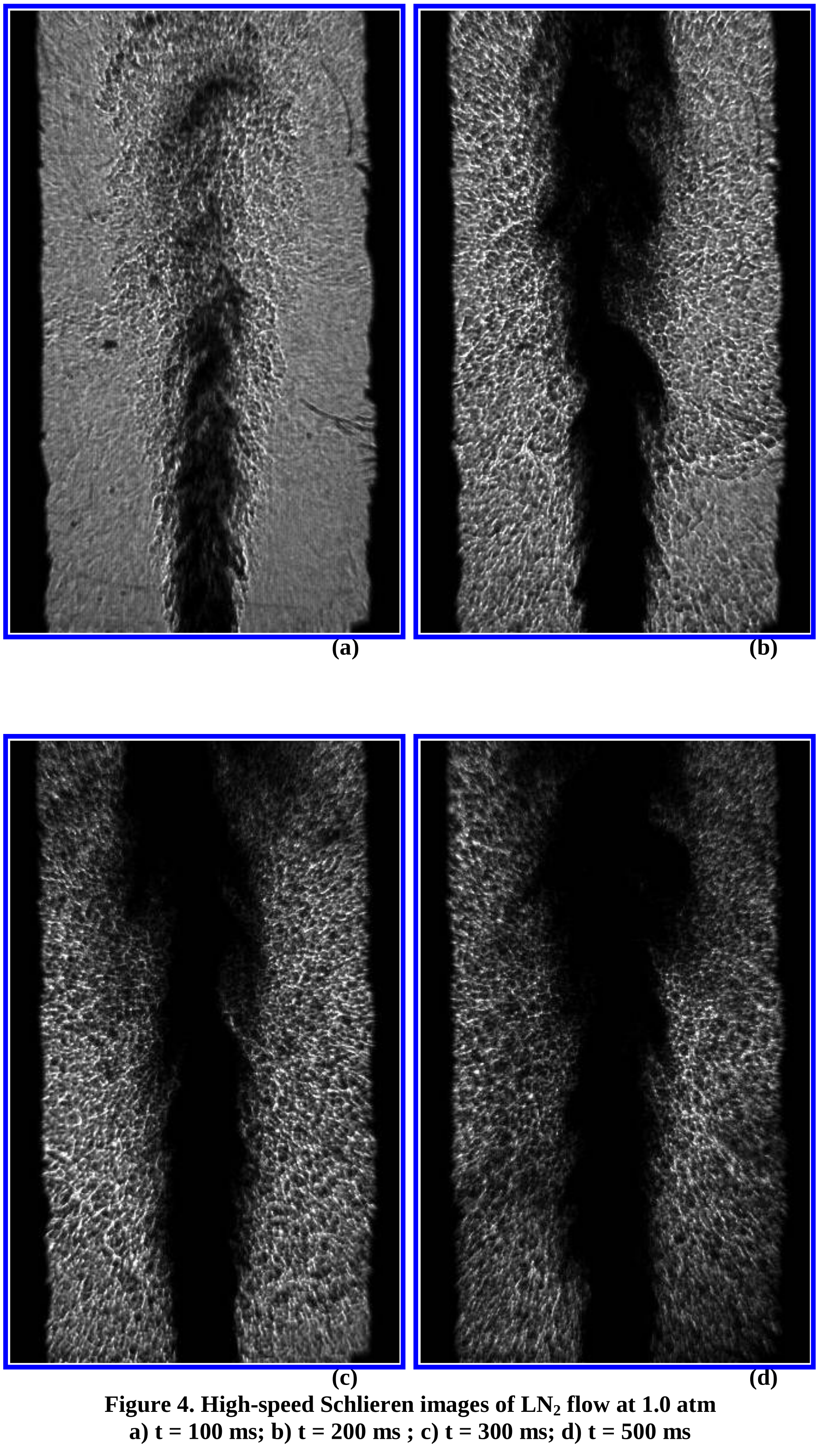

Figure 4. High-speed Schlieren images of LN_2 flow at 1.0 atm
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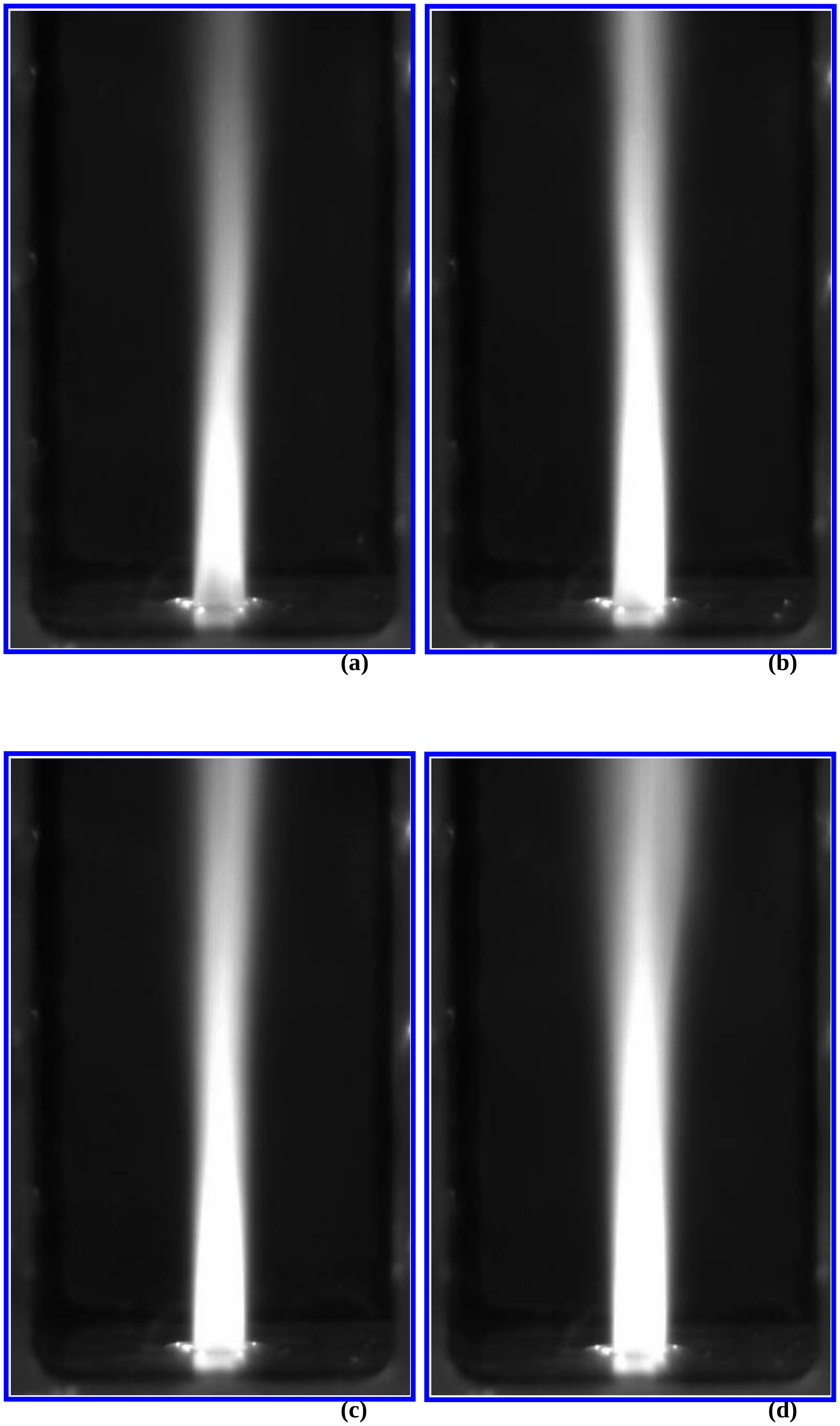

Figure 5. High-speed Mie-scattering images of LN_2/He flow at 1.0 atm a) t = 100 ms; b) t = 200 ms ; c) t = 300 ms; d) t = 500 ms

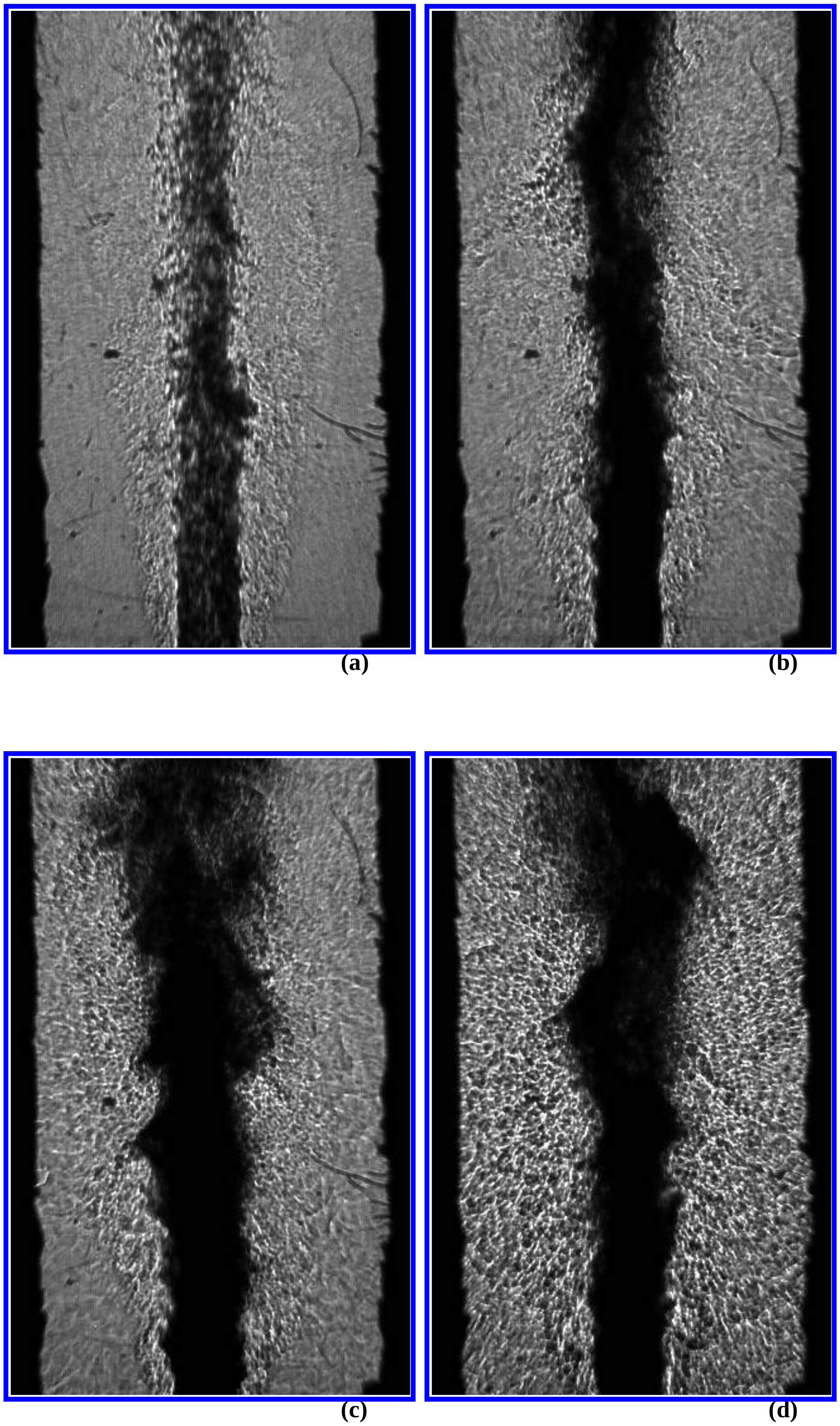

Figure 6. High-speed Schlieren images of LN_2/He flow at 1.0 atm
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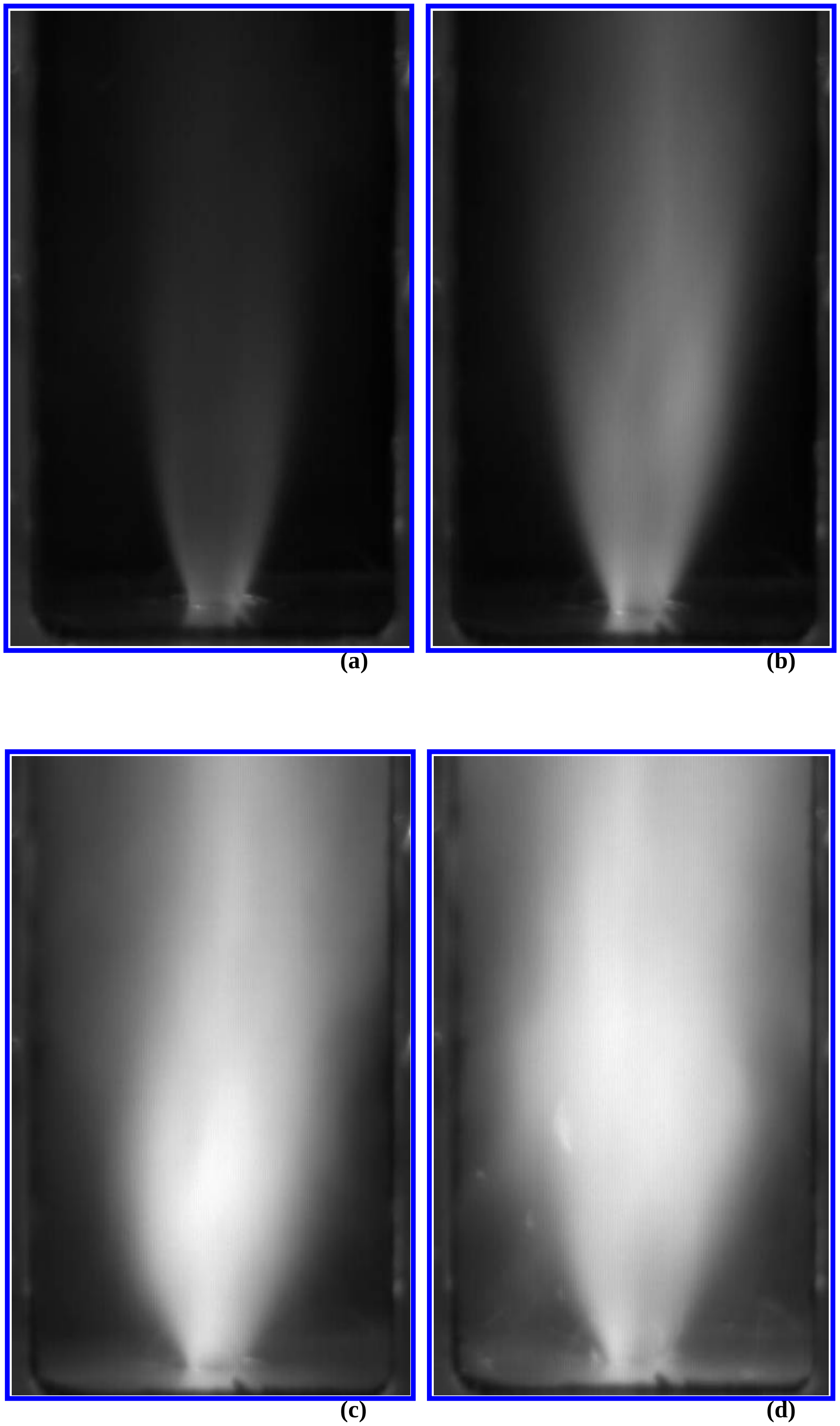


Figure 7. High-speed Mie-scattering images of LN_2 flow at 0.1 atm a) t = 100 ms; b) t = 200 ms ; c) t = 300 ms; d) t = 500 ms

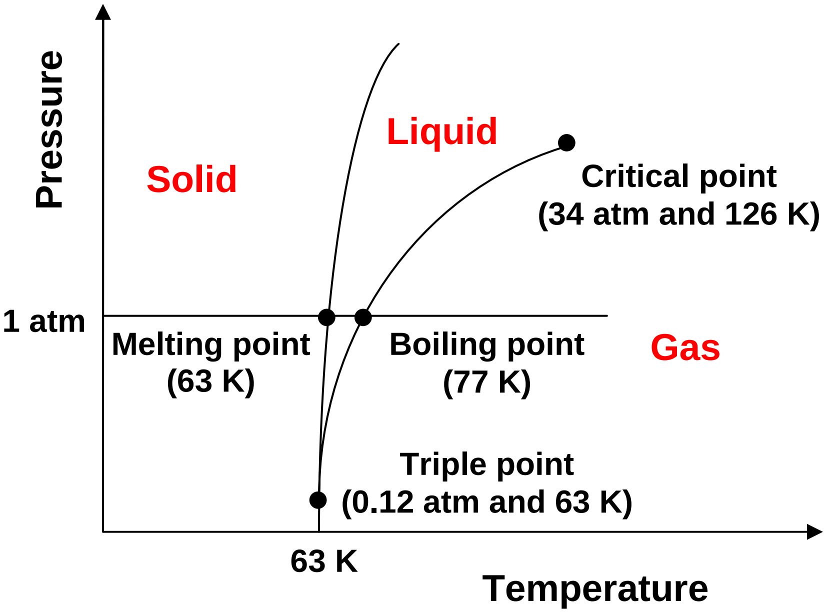
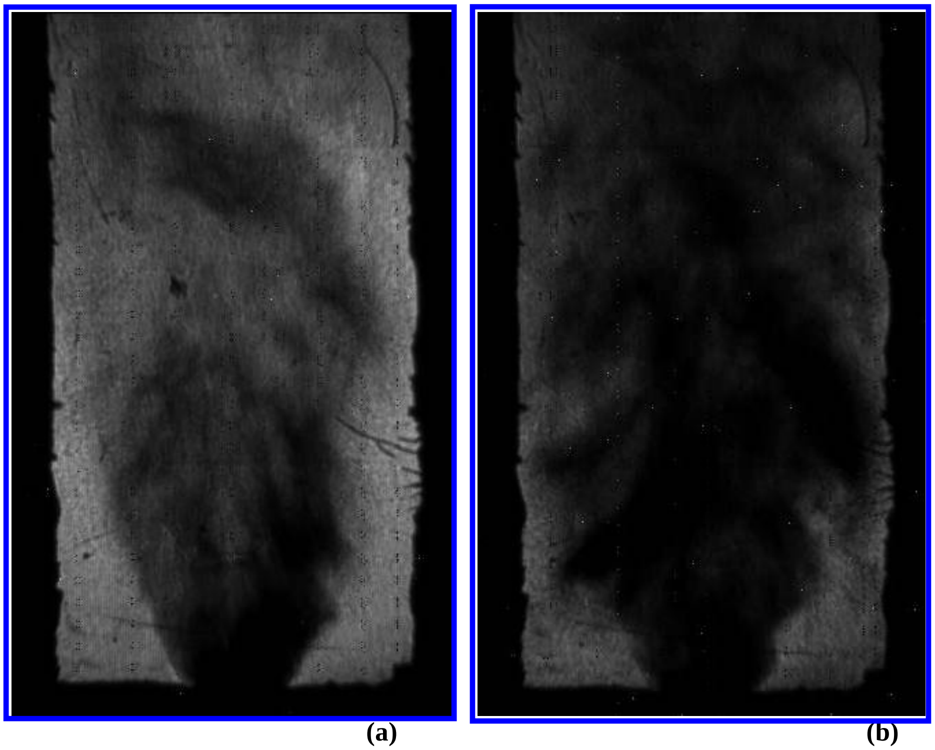
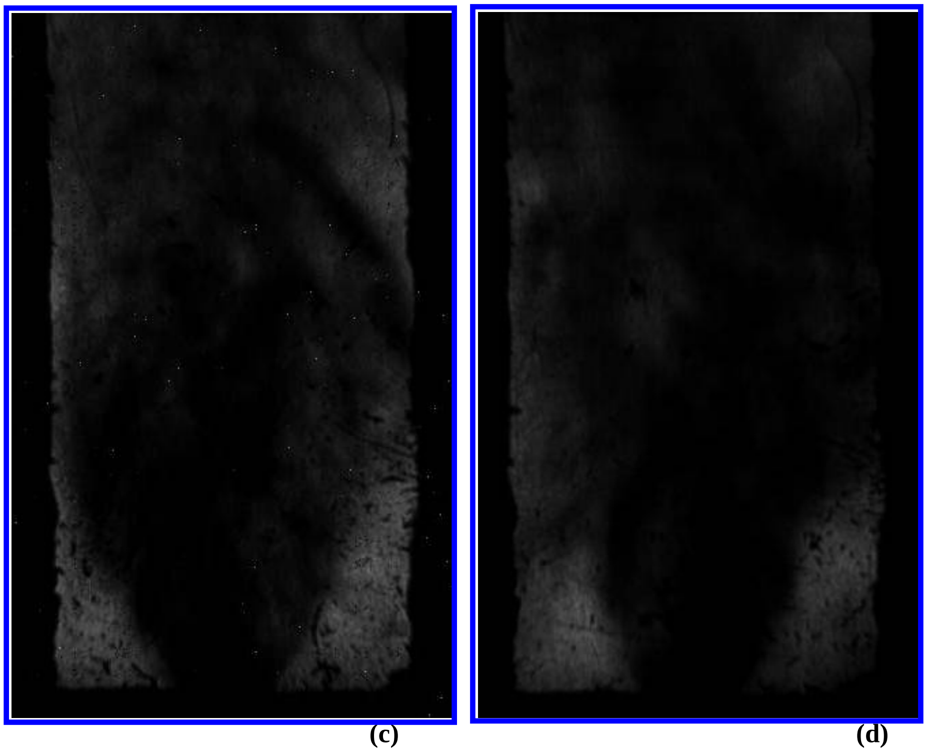


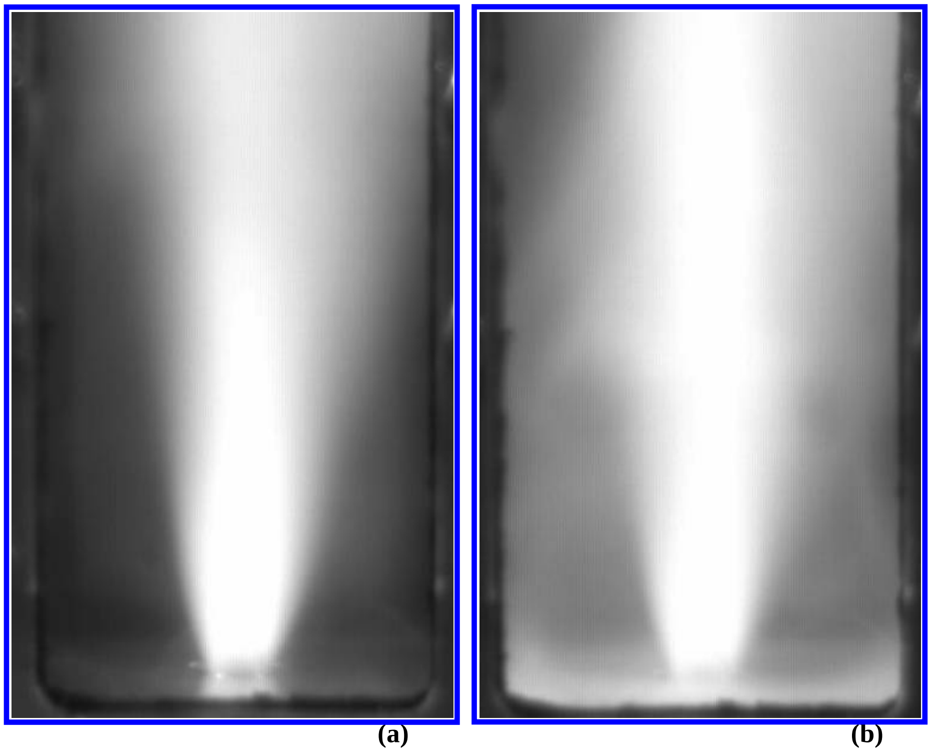
Figure 8. Schematic of nitrogen phase diagram



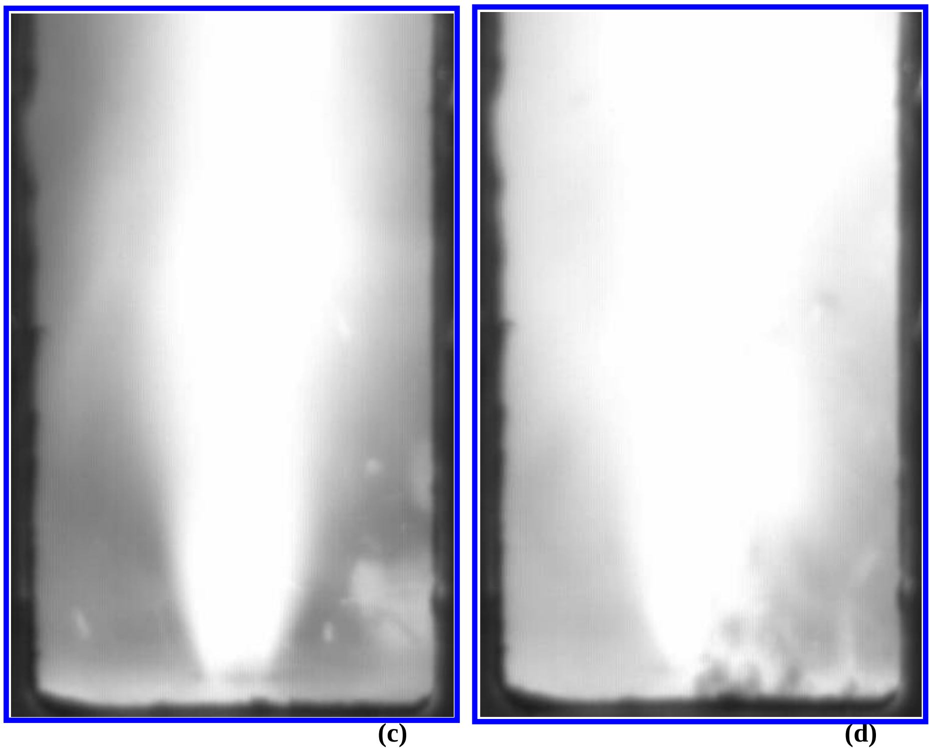


(c) **(d)**

Figure 9. High-speed Schlieren images of LN_2 flow at 0.1 atm
a) t = 100 ms; b) t = 200 ms ; c) t = 300 ms; d) t = 500 ms



(a) **(b)**



(c) **(d)**

Figure 10. High-speed Mie-scattering image of LN_2/He flow at 0.1 atm
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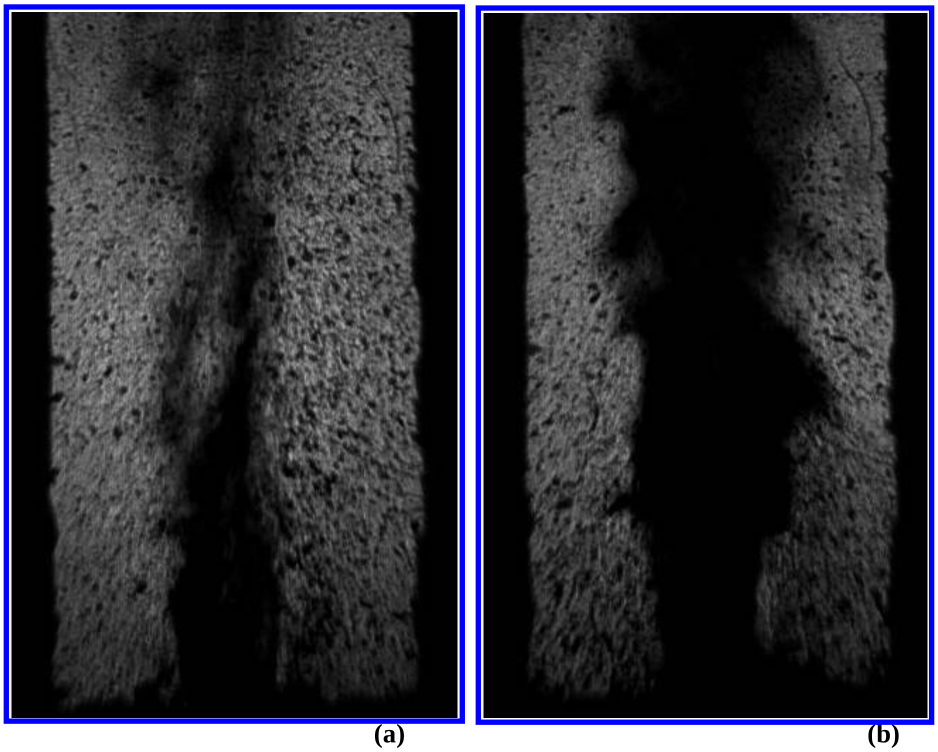
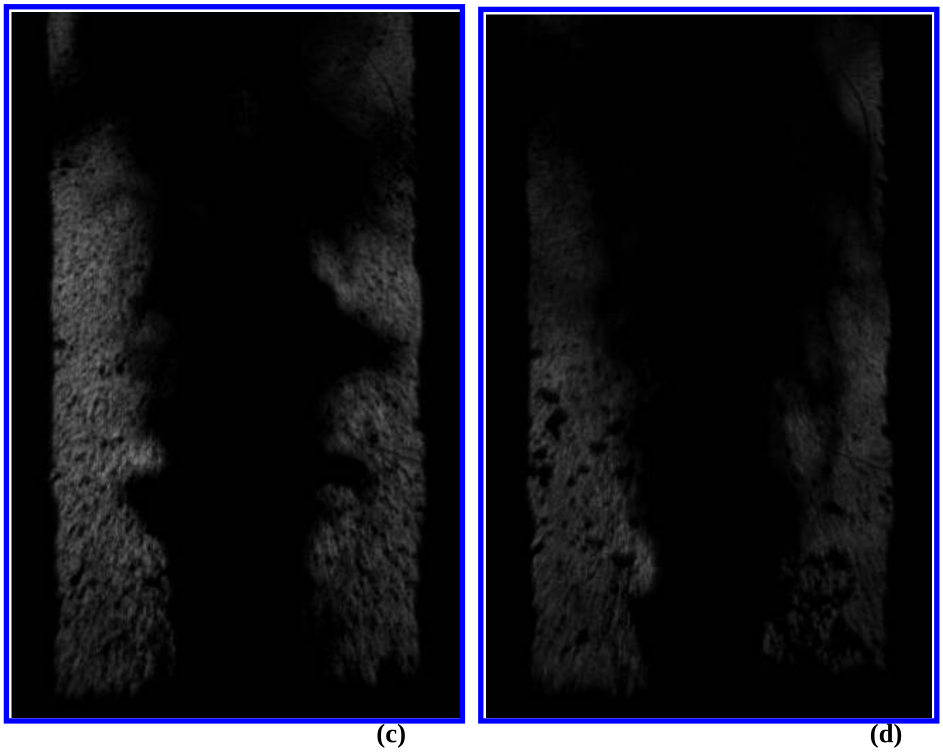


(a) **(b)**



(c) (d)

Figure 11. High-speed Schlieren images of LN_2/He flow at 0.1 atm
a) t = 100 ms; b) t = 200 ms ; c) t = 300 ms; d) t = 500 ms