Temperature measurement of cryogenic nitrogen jets at supercritical pressure

H.Tani
Japan Aerospace Exploration Agency, Tsukuba, Ibaraki, 305-8505, Japan,
S.Teramoto[*] T.Toki, S.Yoshida [†] K.Yamaguchi and K.Okamoto
University of Tokyo, Hongo, Tokyo, 113-8656, Japan

I. Introduction

Many of liquid rocket engines used in first stage of launch vehicles operate at a pressure above the critical pressure of oxygen, 5.04 MPa. The cryogenic oxygen injected into a combustion chamber is heated up to several thousand kelvin, therefore the high-density cryogenic oxygen necessarily experiences sudden expansion called "pseudo-boiling"[1] at the pseudo-critical temperature. The pseudo-boiling has large impact on the mixing characteristics, hence a jet injected from a temperature below the pseudo-critical temperature must be distinguished from that injected from a temperature above the pseudo-critical temperature. The former is referred to as "transcritical jet" while the latter is simply called supercritical jet.

Quantitative measurement data of transcritical jets are indispensable both for the better understanding of mixing phenomena and for the validation of numerical methods, but there are only few quantitative experimental data made public.[2]

In this report, axial and radial temperature profiles of a single phase cryogenic nitrogen jet under supercritical pressure are measured, and the influence of pseudo-boiling upon the jet mixing will be discussed.

II. Experimental setup and flow conditions

II.A. Experimental setup

The experimental setup shown in Fig.1 consists of ϕ298mm × 860mm high pressure tank equipped with four optical windows, a 300cm^3 liquid nitrogen reservoir, an injector of which inner diameter is 2 mm, 14.7 MPa gas cylinders and several pressure regulators and valves. A two-axis traversing device is installed downstream of the injector, and axial temperature profile was measured by NETSUSHIN ϕ0.5 platinum resistance temperature sensor. The radial temperature profile where spatial resolution is more important, was measured with ϕ0.25 standard K-type thermocouple. The temperature sensors were calibrated against high-accurate Cernox sensor, and the measurement accuracy of the platinum resistance sensor was evaluated to be ±0.1 K. The uncertainty for the thermocouple is much larger, but it is not quantified at present.

Flow rate of the cryogenic nitrogen was measured at an orifice inserted just upstream of the starting valve. Temperature of the cryogenic nitrogen was controlled using electronic heater installed in the reservoir. The injector is not insulated, but the injector was carefully cooled prior to the injection so that the temperature of the nitrogen at the injector exit was maintained within ±0.4K of the target value.

II.B. Flow conditions

The temperature profiles of cryogenic nitrogen jets were measured at two different flow conditions, transcritical and supercritical conditions. The flow conditions are summarized in Table 1. The ambient

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[*] Associate Professor, Department of Aeronautics & Astronautics

[†] Graduate student, currently Ministry of Defense

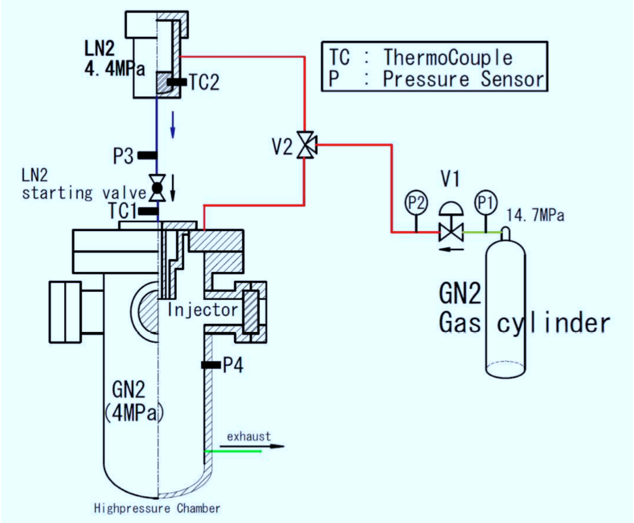

Figure 1. Experimental setup

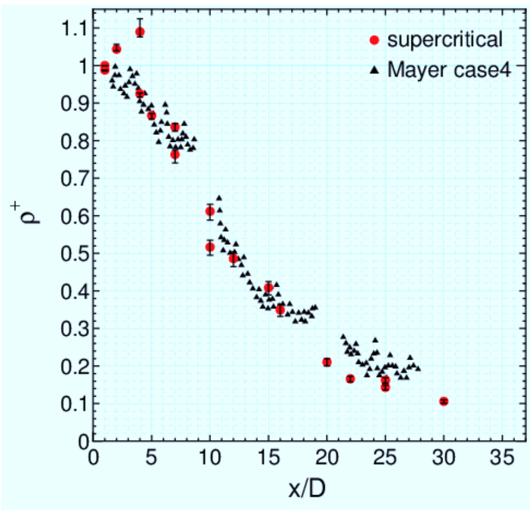

Figure 2. Centerline density profile of a supercritical jet

pressure of 4 MPa corresponds to 1.2 time of the critical pressure of nitrogen, 3.4 MPa. The pseudo-critical temperature at this pressure is approximately 129 K.

Mayer's flow conditions[2] are also shown in Table 1 for reference. Mayer's Case 3 and Case 4 correspond to transcritical and supercritical conditions, respectively. Note that the jet temperature for Mayer's case 3 is very close to the pseudo-critical temperature so that the influence of pseudo-boiling may appear only in a region close to the injector. Present jet temperature of transcritical case is 26 K below the pseudo-critical temperature, so the influence of pseudo-boiling will be observed downstream of the jet core.

Table 1. flow conditions

	present experiment		Mayer et.al[2]	
	transcritical	supercritical	case 3	case 4
Ambient pressure	4.0 MPa		3.97 MPa	3.98 MPa
Jet temperature	103 K	134 K	126.9 K	137 K
Jet Reynolds number	4.3×10^5	1.45×10^5	1.7×10^5	1.6×10^5
Density ratio	14.1	3.9	9.6	3.7

III. Results

Preliminary measured data are plotted in Figs.2 and 3.

Figure 2 is axial profile of centerline non-dimensional density $\left(\rho^* = \dfrac{\rho - \rho_{\text{ambient}}}{\rho_{\text{jet}} - \rho_{\text{ambient}}}\right)$ for supercritical condition. Here, jet densities were evaluated from ambient pressure and the equation of state. The axial density profile decreases almost linearly and it coincides Mayer's case 4 except for slight scatter near $X/D = 5$

The density profile for transcritical jet plotted in Fig.3 right shows different feature. The density profile can be divided into four regions; a region with almost constant density ($0 < X/D < 5$), linear decrease for $5 < X/D < 15$, small density jump near $X/D = 15$ and linear decrease with shallower gradient for $X > 20$. The density jump appears at the position where the local temperature equals to the pseudo-critical temperature, hence it can be correlated to the sudden expansion due to pseudo-boiling.

IV. Summary

Temperature profile of a cryogenic transcritical jet, which has been rarely reported before, is presented in this abstract. The density profile evaluated from the temperature are compared between supercritical and transcritical conditions. Radial profiles as well as physical interpretation for these profiles will be

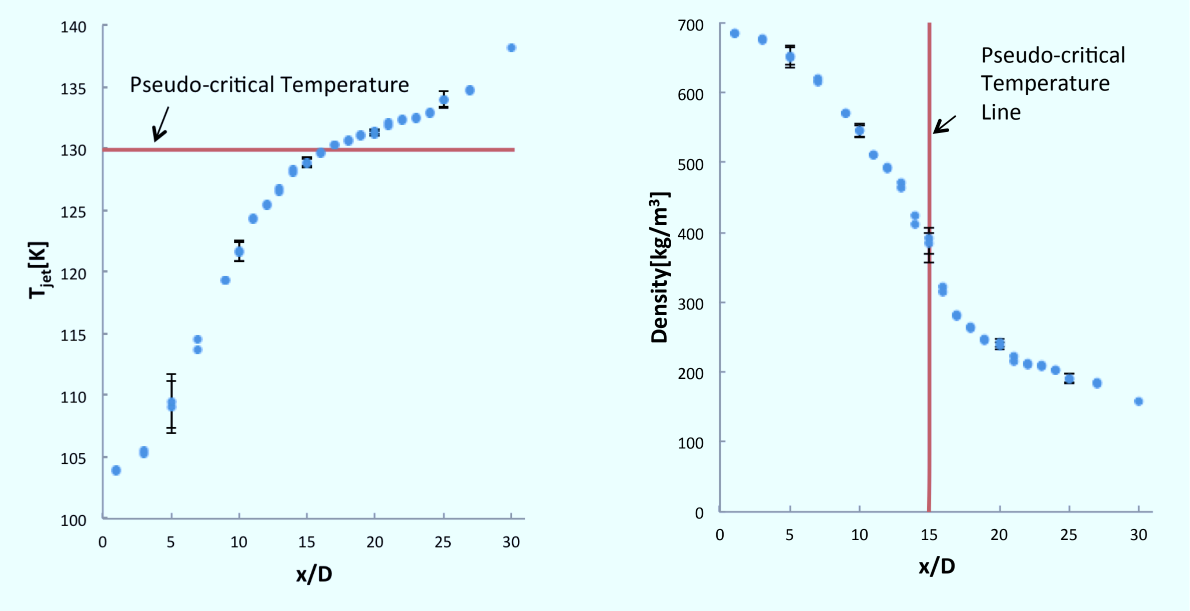

Figure 3. Centerline temperature profiles of a transcritical jet. left:temperature, right:density

discussed in the final paper.

References

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[2]Mayer, W., Schik, A., Schffler, M., & Tamura, H. "Propellant injection in a liquid oxygen/gaseous hydrogen rocket engine". Journal of Propulsion and Power, 16(5), 823-828. (2000)