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Study on boiling behavior of pressurized liquid nitrogen under rapid depressurization

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Abstract. A project to transport a large amount of liquid hydrogen (LH_2) from Australia to Japan by a cargo carrier is underway. In case of unloading LH_2 from the tank on board to that on land, the pressure of the tank on board should be reduced promptly. However, an optimal depressurization speed to reduce the pressure before unloading LH_2 has not yet been studied. As preliminary studies on boiling behavior of pressurized liquid nitrogen (LN_2) instead of LH_2, transitions of temperature distribution and pressure inside a small tank as well as evaporation rate under rapid depressurization have been measured simultaneously. Experimental results are discussed with parameters of setting pressure, depressurization speed and liquid condition.

1. Introduction

Renewable energy is very attractive to produce CO_2-free hydrogen, which is expected to be the ultimate energy medium for worldwide storage and transportation. Marine transportation of large quantity of liquid hydrogen (LH_2: 20 K) from Australia to Japan by a cargo carrier is desired as a CO_2-free hydrogen energy supply system [1]. Recently, first experiment on LH_2 transportation by ship was carried out successfully inside Osaka bay, Japan to understand the LH_2 sloshing and boil-off characteristics on the sea using magnesium diboride (MgB_2) superconducting level sensors [2], [3].

In case of unloading LH_2 from the tank on board to the stationary tank on land, the pressure of the tank on board should be reduced promptly. However, an optimal depressurization period and speed including boiling behaviors have not yet been studied. Preliminary studies on pressurized liquid nitrogen (LN_2: 77 K) have been made instead of LH_2; transitions of temperature distribution and pressure inside a small LN_2 tank as well as evaporation rate under rapid depressurization have been measured simultaneously. Experimental results of the pressure jump, the inception time of boiling and gross evaporation are discussed with parameters of setting pressure, depressurization speed and liquid condition such as saturation and stratification.

2. Experimental apparatus and method

Figure 1 shows a schematic diagram of experimental apparatus, which mainly consists of an optical cryostat, a high-speed microscope (KEYENCE; VW9000), pressure gauges (NAGANO KEIKI; KJ16), a needle valve/flow control valve (Swagelok; SS-6L-MH), an electromagnetic valve (CKD; AB41-6), a flowmeter (KOFLOC, ACM-1AS), a data logger (KEYENCE; NR-600) and a PC. The optical cryostat is composed of a vacuum jacket, an LN_2 space (10.0 L), an LH_2/LN_2 space (13.6 L), a sample space (3.8 L) and four optical windows having an effective diameter of 50 mm. Figure 2 represents a layout of Pt

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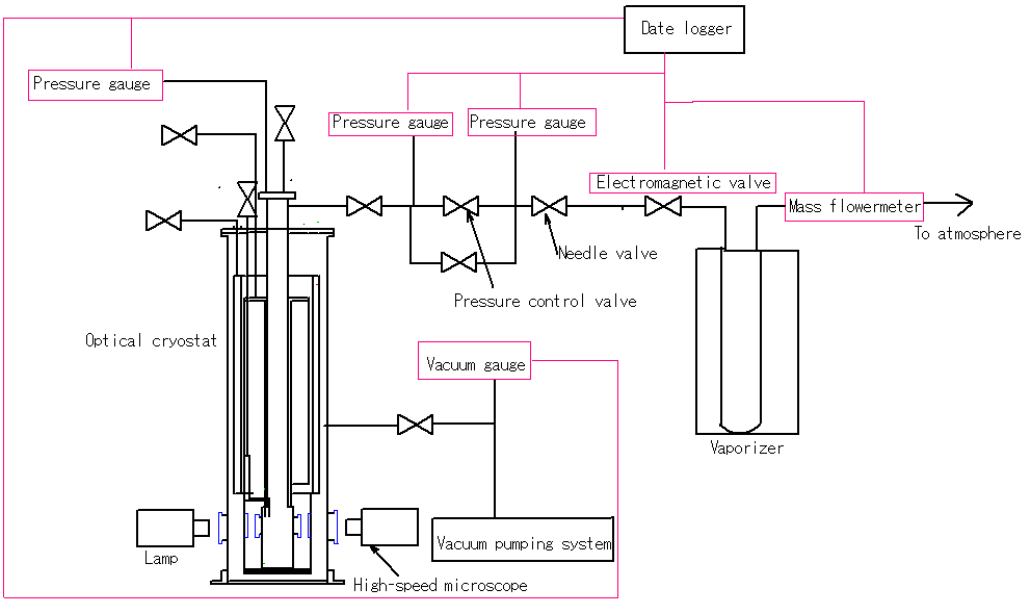

Figure 1 Schematic diagram of experimental apparatus.

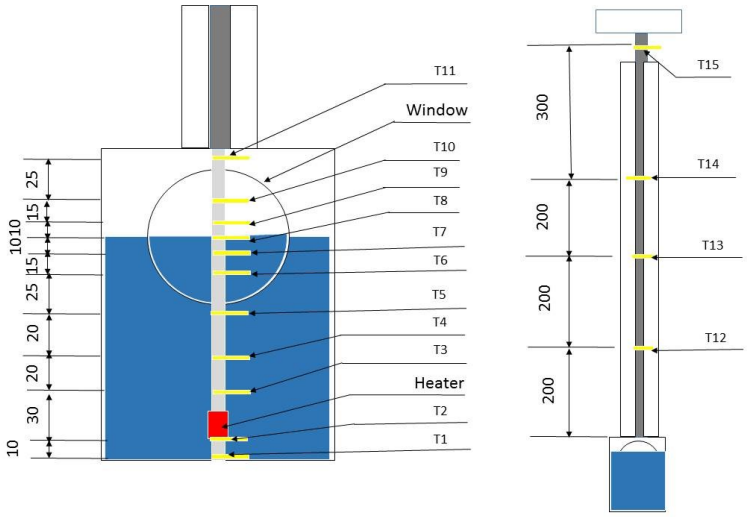

Figure 2 Layout of Pt thermometer inside sample space in unit of mm.

thermometers (HAYASHI DENKO; GR-1205S) inside the sample space. T8 of Pt thermometer was set at the center of the window, which corresponds to the surface of the sample liquid (ca. 1 L).

Table 1 shows experimental conditions of pressurized liquid nitrogen under rapid depressurization as parameters of setting pressure, depressurization speed and liquid condition; setting pressures were 0.2 and 0.4 MPaG, depressurization speeds ranged from high speed to low speed with coefficient of discharge C_V using the needle valve and liquid conditions were saturation and stratification. Transitions of temperature distribution and pressure inside the sample space as well as evaporation rate under rapid depressurization were measured simultaneously, before and after opening the electromagnetic valve at the setting pressure.

Table 1 Experimental conditions of pressurized LN_2 under rapid depressurization.

Test #	Setting press.[MPaG]	Depress. Speed (Cv)	Liquid condition	Test #	Setting press.[MPaG]	Depress. Speed (Cv)	Liquid condition
run 1	0.4	High (0.16)	Satura.	run 6	0.4	High (0.16)	Stratifi.
run 2	0.4	Normal (0.10)	Satura.	run 7	0.4	Low (0.02)	Stratifi.
run 3	0.4	Low (0.02)	Satura.	run 8	0.2	High (0.16)	Stratifi.
run 4	0.2	High (0.16)	Satura.	run 9	0.2	Low (0.02)	Stratifi.
run 5	0.2	Low (0.02)	Satura.				

3. Experimental results

3.1. Temperature distribution and pressure

Figure 3 represents time chart of temperature distribution (T1-T8) and pressure under rapid depressurization of run 1: 0.4 MPaG, high speed (C_V = 0.16) and saturation condition. Saturation temperature was calculated on the basis of the data of pressure. As shown in Fig.3, superheated liquid state that T1-T8 was higher than the saturation temperature was observed under rapid depressurization. Hard boiling was also observed 0.9 s (inception time of boiling) after opening the valve using the high-speed microscope; consequently, the pressure jump was observed under rapid depressurization.

Figure 4 shows time chart of temperature distribution and pressure under rapid depressurization of run 6: 0.4 MPaG, high speed (C_V = 0.16) and stratification condition. As shown in Fig.4, superheated liquid state of T5-T8 was observed under rapid depressurization, on the other hand, subcooled liquid state of T1-T4 was maintained even under rapid depressurization. Soft boiling was observed 2.2 s after opening the valve with small pressure jump.

3.2. Pressure jump

Pressure jump due to rapid boiling was discussed with parameters of depressurization speed, liquid condition and setting pressure. The value of pressure jump was defined as the difference between minimum pressure and recovery pressure. Figure 5 represents the pressure jump due to rapid boiling of

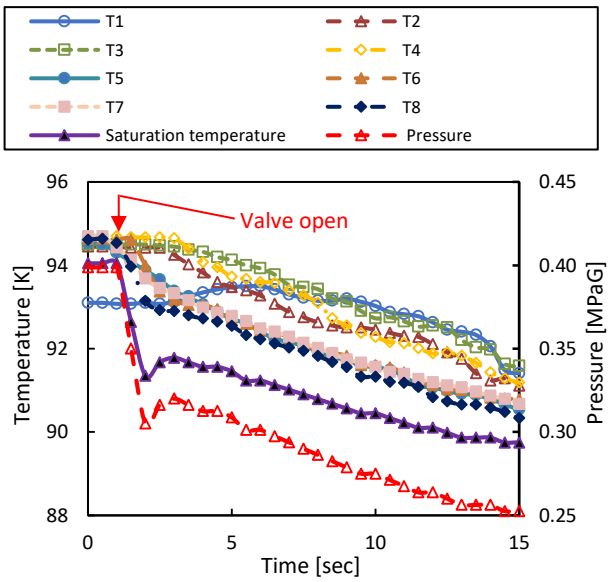

Figure 3 Time chart of temperature distribution and pressure under rapid depressurization of run 1.

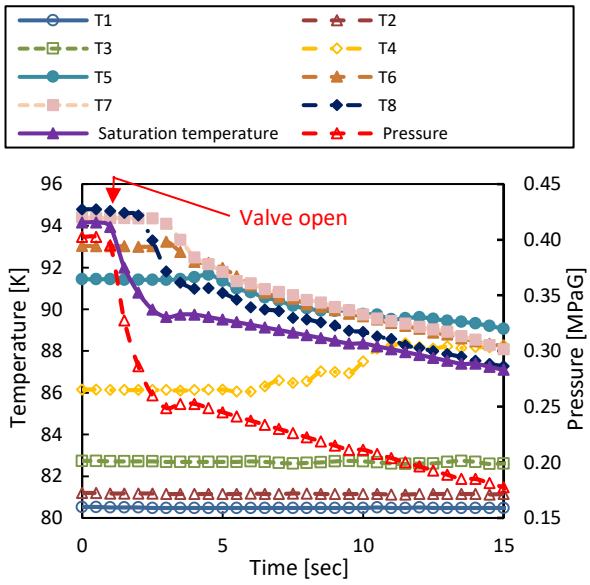

Figure 4 Time chart of temperature distribution and pressure under rapid depressurization of run 6.

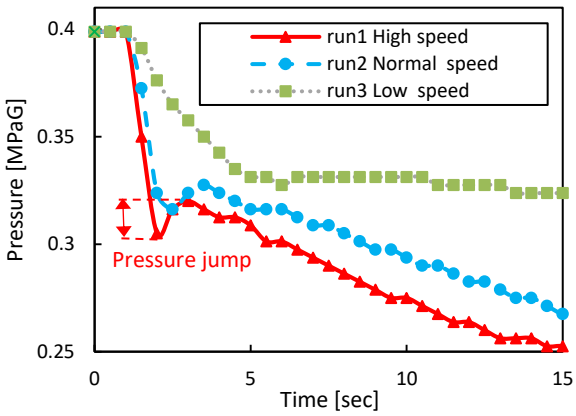

Figure 5 Pressure jump due to rapid boiling of run 1-3 as a parameter of depressurization speed.

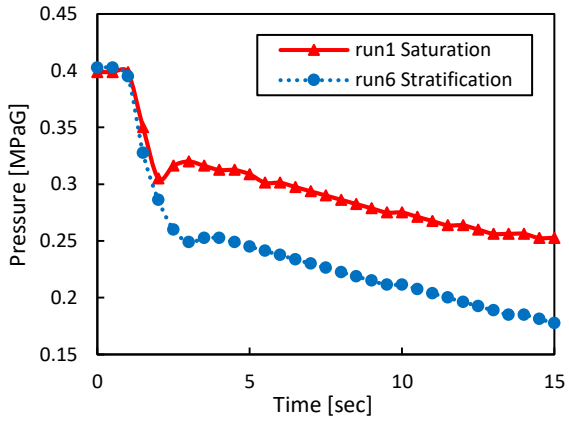

Figure 6 Pressure jump due to rapid boiling of run 1 and 6 as a parameter of liquid condition.

run 1-3 as a parameter of depressurization speed. The values of pressure jump were 0.015, 0.012 and 0.003 MPaG as run 1-3, respectively; the pressure jump decreased with decreasing the depressurization speed. In addition, the inception time of boiling increased with decreasing the depressurization speed. These mean the low depressurization speed corresponds to weak boiling.

Figure 6 shows the pressure jump due to rapid boiling of run 1 and 6 as a parameter of liquid condition. The values of pressure jump were 0.015 and 0.004 MPaG as run 1 and 6, respectively; the pressure jump in stratification condition was smaller than that in saturation condition. In addition, the inception time of boiling in stratification condition was longer than that in saturation condition. These are explained as low enthalpy in stratification condition.

Regarding pressure jump due to boiling of run 1 and 4 as a parameter of setting pressure, the values of pressure jump were 0.015 and 0.026 MPaG as run 1 and 4, respectively. Similarly, the values of pressure jump were 0.004 and 0.038 MPaG as run 6 and 8, respectively; the pressure jump increased with decreasing the setting pressure under both saturation and stratification conditions. While rough calculation has been under way, this is thought to be caused by the suppression of boiling behavior under relatively high pressure.

3.3. Gross evaporation

Evaporation rate was discussed with parameters of depressurization speed, liquid condition and setting pressure. Figure 7 represents time chart of evaporation rate under rapid depressurization of run 1-3 as a parameter of depressurization speed. Gross evaporation was estimated when the pressure arrived at 0.0 MPaG. The values of gross evaporation were 0.204, 0.210 and 0.224 kg as run 1-3, respectively; the gross evaporation increased with decreasing the depressurization speed. While rough calculation has been under way, this phenomenon remains an open question.

Figure 8 represents time chart of evaporation rate under rapid depressurization of run 1 and 6 as a parameter of liquid condition. Similarly, the values of gross evaporation were estimated 0.204 and 0.148 kg as run 1 and 6, respectively; gross evaporation in stratification condition was smaller than that in saturation condition. This is explained as low enthalpy in stratification condition.

Regarding gross evaporation of run 1 and 4 as a parameter of setting pressure, the values of gross evaporation were 0.204 and 0.128 kg as run 1 and 4, respectively; the gross evaporation decreased with decreasing the setting pressure. This is also explained as low enthalpy at low setting pressure.

4. Summary

Transitions of temperature distribution and pressure inside the sample space of pressurized liquid nitrogen as well as evaporation rate under rapid depressurization were measured simultaneously. It was found that the pressure jump and the inception time of boiling were intimately related to the

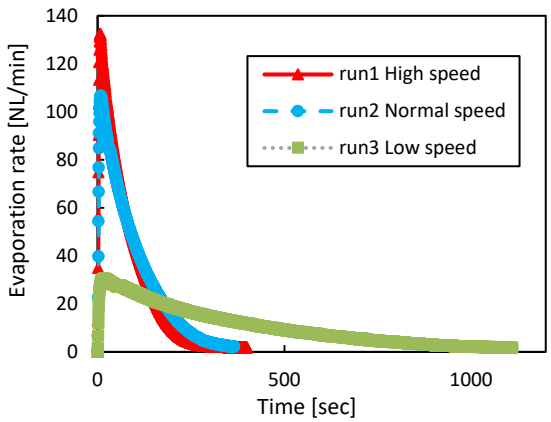

Figure 7 Time chart of evaporation rate under rapid depressurization of run 1-3 as a parameter of depressurization speed.

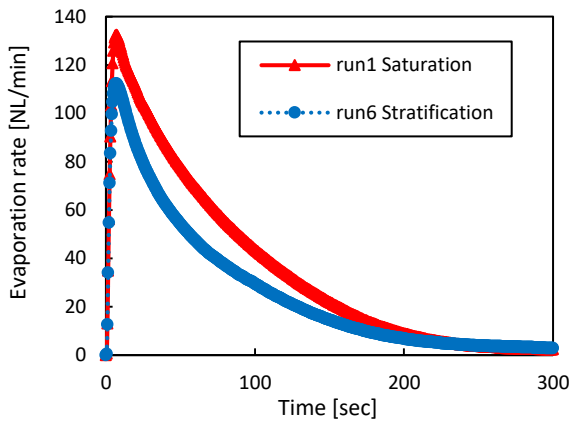

Figure 8 Time chart of evaporation rate under rapid depressurization of run 1 and 6 as a parameter of liquid condition.

depressurization speed and liquid condition such as saturation and stratification. In addition, the gross evaporation in stratification condition was smaller than that in saturation condition, on the other hand, the gross evaporation increased with decreasing the depressurization speed.

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