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Temperature measurement and flow visualization of cryo-compressed hydrogen released into the atmosphere

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ABSTRACT

For assessing the risks of liquid hydrogen pump facilities, we conducted a test in which liquid hydrogen was pressurized to a maximum of 85 MPa and steadily released through a pinhole nozzle. In order to quantitatively evaluate the cooling effect of the released cryogenic hydrogen on the surrounding environment, the temperature of the hydrogen jet was measured while changing the supply pressure and temperature parameters. We applied shadowgraph flow visualization to understand the diffusion mechanism of the low-temperature hydrogen jet escaping the pinhole nozzle. The results showed that no liquid phase appeared during the cryo-compressed hydrogen leakage and that the hydrogen jet temperature could be accurately predicted using the Joule–Thomson expansion equation. The shadowgraph showed that a dense potential core was formed in the hydrogen jet even under a high-temperature condition far from the critical point ($Tr = 2.4$) and was characterized by a supercritical jet. In addition, it was confirmed that the boundary where the hydrogen jet becomes visible exists near the Widom line. Further consideration is required regarding the consistency of these results with the conclusions of existing studies that pseudo-boiling becomes negligible in the region wherein $Pr > 10$.

Introduction

In this paper, we report the results of an experiment conducted to reevaluate the safety standards for high pressure hydrogen handled at a hydrogen supply station for fuel cell vehicles (FCVs). The most likely malfunction of a hydrogen infrastructure is a small hydrogen leak caused by loose threaded joints or damaged sealing materials. Various data have been acquired (hydrogen concentration distribution, blast pressure, flame length, and radiant heat) related to the separation distance by representing the small-scale leakage opening with a circular pinhole of a predetermined diameter (0.2 mm, 1.0 mm, etc.) [1–6]. As a result, an installation of an 82-MPa hydrogen station in 2016 was approved in Japan, and ultrahigh-pressure hydrogen supply to FCVs was started; however, at the moment, the widespread use of FCVs is far behind the electric vehicle (EV). The obstacle to FCV popularization in the future is the costly construction and operation

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Nomenclature

D	diameter of the pinhole, mm
g	Gibbs free energy, kJ/kg
h	enthalpy, kJ/kg
m	mass flow rate, kg/s
P	pressure, MPa
Q	heat input, kJ
ReD	Reynolds number based on the pinhole diameter
T	temperature, K
V	flow velocity in the pinhole
w	axial flow velocity, m/s

Subscripts

1	upstream of the pinhole
2	centerline values at 5 mm downstream from the pinhole exit
3	centerline values at 50 mm downstream from the pinhole exit
a	ambient condition
cr	critical point
r	reduced properties

of hydrogen stands. Currently, the mainstream hydrogen gas boosting system comprises a compressor that requires a large electric power; however, switching to a liquid hydrogen pump boosting system has been considered in order to reduce the required electric power to 1/10th the original requirement. In order to introduce the liquid hydrogen pump into the hydrogen stand, it is necessary to establish new safety standards against the leakage of cryo-compressed hydrogen. When the high-pressure hydrogen is cooled, the leakage flow rate from the pinhole increases, and therefore, it is necessary to increase a separation distance between hydrogen infrastructures and fire handling equipment. Furthermore, the excessive cooling of the surroundings due to the release of liquid hydrogen must also be evaluated. There have been some reports on the effect of leakage and ignition of relatively low-pressure liquid hydrogen. Nakamichi et al. have reported experiments in which liquid hydrogen pressurized to 0.4 MPa is discharged from a nozzle of 0.5–2 mm, and the evaporation distance is examined [7]. Panda measured the flame length and radiant heat while ejecting 0.6-MPa liquid hydrogen from a 0.75–1.25-mm pinhole nozzle [8]. Friedrich et al. have conducted experiments to measure the temperature, velocity, and hydrogen concentration distribution of a hydrogen jet adjusted to a temperature range of 35–65 K and a pressure range of 0.7–3.5 MPa by cooling high-pressure hydrogen gas with liquid hydrogen [9]. Hall et al. conducted experiments to evaluate the influence of liquid hydrogen leakage (60 l/min) from a hydrogen tanker on a large scale [10]. Venetsanos et al. have constructed a numerical calculation model by referring to release experiment data of liquid hydrogen pressurized up to approximately 4 MPa [11]. As described above, in each of the conventional studies that handles liquid hydrogen at a relatively low pressure, there is no experimental example dealing with liquid hydrogen that has been pressurized to the 82-MPa class, which is used in a hydrogen stand for FCVs.

Research has been conducted on rocket engine combustors as a field involving the injection of high-pressure and cryogenic fluids. As the combustion efficiency of the rocket engine depends on how the oxidizer and fuel supplied in the supercritical state are uniformly mix in a short combustor, the injector is a crucial component that is directly linked to engine performance, life, and operation stability. In order to make rocket engine development faster, efforts to improve the precision of rocket engine numerical simulation tools are being actively made. The modeling of injectors is a challenging problem for accurately understanding physical phenomena such as diffusion, mixing, and combustion of cryogenic and supercritical fluids, and several researchers are working on this subject diligently [12]. In order to investigate the performance of coaxial injectors of rocket engines, Branam has revealed the structure of a supercritical nitrogen jet pressurized to 6 MPa using various visualization methods such as Raman imaging and shadowgraph imaging [13,14]. The influence of the axial length and divergence angle of the supercritical jet was investigated using fluid temperature and injection speed as parameters, and the axial density profiles obtained using the Raman measurements were used for the verification of the numerical analysis model [15]. Chehroudi introduced experimental researches on various single jets with and without external excitation and coaxial jets with and/without external excitation in order to understand the phenomenon of supercritical injection into the combustion chamber of a cryogenic hydrogen or oxygen liquid rocket engine [16]. The effect of applying acoustic waves to a jet is reported to be stronger in a subcritical jet than in a supercritical jet. Muthukumaran compared the fluoroketone jet injected into its own supercritical fluid and that injected into another supercritical fluid (nitrogen) and investigated the thermohydrodynamic effect of the mixing behavior [17]. Tani measured the temperature distribution of a supercritical nitrogen jet and investigated the influence of pseudo-vaporization on the propellant mixing in the combustion chamber of a liquid rocket engine. The axial profile of the temperature of the supercritical nitrogen jet shows a tendency to rise monotonously. He confirmed that the rate of temperature change decreases at the position where the local temperature reaches a pseudocritical temperature, which is, the characteristic of pseudo-vaporization [18]. With respect to numerical calculations on supercritical jets, several researches by Müller, etc. have been reported, and good agreement with experiments has been obtained for supercritical and subcritical nitrogen jets [19–22]. These studies have been conducted on the supercritical injection of liquid oxygen, which is important in modeling rocket engine combustors. Hydrogen used for regenerative cooling is not supplied to the injector at a cryogenic temperature, and the jet can be handled almost as an ideal gas. Thus, there are few studies on single injection of hydrogen in the rocket field.

In consideration of the above information, we performed experiments wherein we constantly released liquid hydrogen pressurized to 82 MPa or more from pinholes for the purpose of evaluating the influence of cryo-compressed hydrogen released into the atmosphere. In this paper, we report on some findings obtained from cryo-compressed hydrogen