pISSN 1229-3008 eISSN 2287-6251
Progress in Superconductivity and Cryogenics
Vol.23, No.1, (2021), pp.7~11
https://doi.org/10.9714/psac.2021.23.1.007

Method applied to evaluate heat leakage of cryogenic vessel for liquid hydrogen

Zhengqing Li*,[a], Shengsheng Yang[a], Xiaojun Wang[a], and Yafei Yuan[b]

[a] *Lanzhou Institute of Physics, Lanzhou, China*
[b] *Fudan University, Shanghai, China*

(Received 16 December 2020; revised or reviewed 29 March 2021; accepted 30 March 2021)

Abstract

Cryogenic vessels are special equipment that requires periodic evaluation of their thermal insulation performance. At the current standard, the test is considered as the loss product or heat leakage of cryogenic vessel, which takes over 72 h to evaluate; consequently, a large amount of working medium is discharged to the environment in the process. However, hydrogen is flammable and explosive, and the discharged gas may be dangerous. If liquid hydrogen is replaced with liquid nitrogen before testing, the operation then becomes complicated, and the loss product or heat leakage cannot respond to the thermal insulation performance of cryogenic vessels for liquid hydrogen. Therefore, a novel method is proposed to evaluate the heat leakage of cryogenic vessels for liquid hydrogen in self-pressurization. In contrast to the current testing methods, the method proposed in this study does not require discharge or exchange of working medium in all test processes. The proposed method is based on one-dimensional heat transfer analysis of cryogenic vessels, which is verified by experiment. When this method is used to predict the heat leakage, the comparison with the experimental data of the standard method shows that the maximum error of heat leakage is less than 5.0%.

Keywords: liquid hydrogen, cryogenic vessel, heat leakage, self-pressurization, loss product

1. INTRODUCTION

Cryogenic liquids, such as liquid hydrogen, liquid nitrogen, and liquefied natural gas, can be stored in cryogenic vessels. Therefore, cryogenic vessels are widely used in various industrial fields. Meanwhile, to mitigate air pollution, hydrogen is used instead of oil and diesel as a fuel for clean-burning natural gas buses, which effectively reduces air pollution in cities [1, 2]. Many buses store hydrogen as a liquid in cryogenic vessels. The cryogenic vessel is a special equipment that maintains a significant temperature difference between internal (cryogenic vessel) and external (environment), this is required to evaluate its thermal insulation performance periodically to ensure its safety. Therefore, relevant management precepts and standards have been published by countries [3-5]. For standard, the test item is considered as loss product or heat leakage, which reflects the thermal insulation performance of cryogenic vessels. However, in the test process, a large amount of working medium is discharged initially to make the pressure of the cryogenic vessel equal to the environment. Thereafter, the related valves are opened for the test system to be in equilibrium for over 48 h. Finally, the loss product is tested for at least 24 h by the flow-rate or weighing method. The whole process wastes a considerable amount of the working medium. Furthermore, the method is unsuitable for application in cryogenic vessels of liquid hydrogen because hydrogen is flammable and explosive, and the discharged gas will form a dangerous source (the concentration of hydrogen explosion is 5 % - 95 %) [4-5]. If liquid hydrogen is replaced with liquid nitrogen before testing, the operation then becomes complicated, and the tested loss product or heat leakage cannot respond to the thermal insulation performance of cryogenic vessels for liquid hydrogen. Considering the aforementioned issues, it is difficult to test the loss product or heat leakage of cryogenic vessels for liquid hydrogen using the standard method. Therefore, a novel method that avoids waste or exchange working medium, wherein heat leakage is also tested correctly, is proposed.

When all valves are closed, the heat leakage of the cryogenic vessel causes a pressure rise called self-pressurization [6-10]. Experimental investigation shows that there is an obvious difference in the rate of pressure rise for a cryogenic vessel at different liquid levels and heat leakage. Several studies have shown that the process of self-pressurization is directly related to the heat leakage of cryogenic vessels; however, these studies were completed under laboratory conditions, where the heat leakage is replaced by hot resistance, and the power is known. Meanwhile, the temperature, pressure, and liquid level can be measured with high accuracy [11-17]. For cryogenic vessels in buses, the heat leakage should be tested; the accuracy of the liquid level gauge is limited. In particular, for the liquid level, the accuracy is 3.0%, which influences the liquid mass that cannot be calculated correctly. Therefore, the purpose of this study is to introduce a method to test the heat leakage of cryogenic

---

* Corresponding author: ahanda-nwpu@163.com

vessels of liquid hydrogen in self-pressurization and ultimately achieve a goal that does not discharge the working medium in the test process or replace it with the working medium. Heat leakage is also calculated correctly.

In the following sections, heat leakage of common cryogenic vessel is tested in self-pressurization, and the equations are established between heat leakage and other physical parameters, such as pressure and temperature. Thereafter, the experiment is completed to verify the method. Finally, the heat leakage is obtained from the calculated final liquid level; thus, solving the limitation of the common liquid level gauge with an accuracy of 3%.

2. PHYSICAL MODEL

Fig. 1 shows the self-pressurization model of cryogenic vessels. The cryogenic vessels have inner shells, outer shells, and accessories. The gap between the two shells is pumped to vacuum, and then filled with thermal insulation materials to enhance thermal insulation performance. During the entire test process, all valves remain in the off-position. Therefore, the pressure of the cryogenic vessel continues to rise, which is measured and recorded by a pressure sensor. The volume is occupied by gas, evaporated liquid, and left liquid.

2.1 One-dimensional heat transfer model

When analyzing heat transfer in self-pressurization, the process is usually considered as a one-dimensional. To establish a mathematical model for heat leakage, the following hypotheses are proposed [6-8]:

(1) Self-pressurization is a quasi-equilibrium process; therefore, the gas and liquid are saturated in the cryogenic vessel.

(2) The temperatures of the gas and liquid are uniformly distributed over the vessels.

(3) There is no exchanged mass between the inside and outside of the vessel because of the self-pressurization test.

Based on the above hypotheses and Fig. 1, the heat leakage of the cryogenic vessel is absorbed by the liquid and gas during self-pressurization, as described in [9-12].

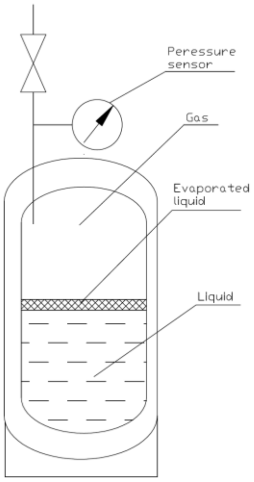

Fig. 1 Cryogenic vessels self-pressurization model

$$\frac{dQ}{dt}=\frac{d}{dt}\left(\rho_l u_l V_l+\rho_v u_v V_v\right) \tag{1}$$

where Q is the heat leakage, ρ_l is the liquid density, ρ_v is the gas density, u_l is the internal energy of the liquid, u_v is the internal energy of the gas, V_l is the liquid volume, and V_v is the gas volume. The internal energy of the liquid and gas can be expanded further as follows:

$$\frac{d\left(\rho_l u_l V_l\right)}{dt}=u_l\frac{d}{dt}\left(\rho_l V_l\right)+\left(\rho_l V_l\right)\frac{du_l}{dt} \tag{2}$$

$$\frac{d\left(\rho_v u_v V_v\right)}{dt}=u_v\frac{d}{dt}\left(\rho_v V_v\right)+\left(\rho_v V_v\right)\frac{du_v}{dt} \tag{3}$$

During the test process, small amount of liquid evaporates into gas, as shown in Fig.1. This is described by Eq. (4).

$$\frac{d\left(\rho_l V_l\right)}{dt}=-M \tag{4}$$

Where, M is the mass of evaporated liquid in unit time. In the test process, the liquid is considered to be incompressible because the density is barely changed in the test; therefore, the liquid density can be regarded as a constant. Thus, Eq. (4) can be rewritten as follows:

$$\rho_l\frac{dV_l}{dt}=-M \tag{5}$$

Meanwhile, the total volume of liquid and gas is constant in the test, as follows:

$$\frac{dV_l}{dt}+\frac{dV_v}{dt}=0 \tag{6}$$

Based on Eq. (6), Eq. (5) can be expressed by the gas volume as follows:

$$\rho_l\frac{dV_v}{dt}=M \tag{7}$$

Combining Eqs. (2) - (7), the energy of the gas and liquid can be expressed as follows:

$$\begin{aligned}&\frac{d}{dt}\left(\rho_l u_l V_l+\rho_v u_v V_v\right)\\&=\left(\rho_l V_l\right)\frac{du_l}{dt}+\left(\rho_v V_v\right)\frac{du_v}{dt}+M\left(u_v-u_l\right)\end{aligned} \tag{8}$$

The latent heat is the difference in enthalpy between the saturated gas and liquid, which is described as follows:

$$L = h_v - h_l \tag{9}$$

The enthalpy can be expressed by internal energy and power of volume as follows:

$$h = u + \frac{p}{\rho} \tag{10}$$

The internal energy can be expressed by specific heat capacity and temperature as follows:

$$du = c_v \cdot dT \tag{11}$$

where, L is the latent heat, p is the pressure, c_v is the specific heat capacity, and T is the temperature.

Based on Eqs. (9) - (11), Eq. (8) can be rewritten as follows:

$$\begin{aligned}\frac{dQ}{dt} &= \left(\rho_l V_l c_{vl} + \rho_v V_v c_{vv}\right)\frac{dT}{dt} \\ &+ M\left[L - p_v\left(\frac{1}{\rho_v} - \frac{1}{\rho_l}\right)\right]\end{aligned} \tag{12}$$

Where p_v is the pressure of the cryogenic vessel measured by the pressure sensor. In Eq. (12), heat leakage consists of the internal energy of the gas and liquid, and the vaporization heat of the evaporated liquid. Based on Eq. (12), the heat leakage can be calculated as follows:

The pressure of cryogenic vessel, p_v, is measured by pressure sensor.

The temperature, T, is determined by pressure because the liquid and gas are saturated.

The evaporated liquid mass, M, is obtained by the difference in the liquid mass between the initial state and final state, which is determined by the volume of gas and liquid measured by the liquid level gauge.

Other parameters of gas and liquid, such as density and specific heat capacity, can be obtained from the properties of saturation obtained from the NIST (National Institute of Standard and Technology) Reference Fluid Properties database.

Therefore, the heat leakage of the cryogenic vessel is calculated using Eq. (12).

3. VALIDATION OF METHOD

To verify that the method is effective and useful, an experiment is carried out as follows:

In this study, the novel method was verified using data from Zhang et al. (2016) and data provided by the Shandong Institute of Special Equipment Inspection and Research. The volume of the cryogenic vessel is 175 L; the working medium is liquid nitrogen because it is difficult to obtain liquid hydrogen, which is forbidden to test in the general laboratory. However, the principle is based on cryogenic vessels for liquid hydrogen. Before the test, the heat leakage was tested using the standard method as follows, Firstly, the valves of cryogenic vessel are opened to discharge gas, which makes the pressure of cryogenic vessel falling and according with atmosphere after the cryogenic vessel is fully filled. Secondly, the test system takes 48 h to stay in heat equilibrium. Thirdly, a flow meter is installed and records the volume or mass of flowing out cryogenic vessel at least 24 h and the total mass of flowing out gas is loss product in a day (kg/day). Finally, the heat leakage equals the loss product multiplied by latent heat of testing medium, which is 4.41 W. The average temperature of the test room was 25 ℃ [17].

TABLE 1
PRESSURE OF CRYOGENIC VESSEL OVER TIME.

Time （h）	Pressure （kPa）	Liquid level (%)
0	275	90.0
24	430	92.5
48	620	95.3

3.1. Experimental data

The test was started after 48 h because the cryogenic vessel was filled. The initial liquid level was 90%. The liquid level gauge is capacitive, and the accuracy was 3.0%. The test data are shown in Table 1.

As shown in Table 1, the pressure change rates are 6.47 kPa/h during 0-24 h, 7.92 kPa/h during 24 - 48 h, and 7.19 kPa/h during 0-48 h. The liquid level always rise in test because the liquid density decreases with increasing pressure.

3.2. Heat leakage calculation

In the calculation, the liquid level gauge cannot accurately measure the liquid interface because of its accuracy limitations. Therefore, there was a large error in the calculation of mass for liquid. Especially for the evaporated mass, this directly influences the heat leakage calculated by Eq. (12). To solve this problem, the final liquid level is not directly measured by a liquid level gauge, which is obtained as follows:

Based on mass conversation, there is no exchange of gas or liquid between the inside and outside of the cryogenic vessel. Therefore, the total mass of gas and liquid is constant and can be expressed as follows:

$$\begin{aligned}&\left(\rho_{l1} Le_1 + \rho_{v1}\left(1 - Le_1\right)\right)V \\ &= \left(\rho_{l2} Le_2 + \rho_{v2}\left(1 - Le_2\right)\right)V\end{aligned} \tag{13}$$

where V is the total volume of the cryogenic vessel, and Le is the liquid level defined as follows:

$$Le = \frac{V_l}{V} \tag{14}$$

Based on Eq. (13), the final liquid level is calculated as follows:

TABLE 2
MEASURED AND CALCULATED LIQUID LEVEL.

Time （h）	Measured liquid level （%）	Calculated liquid level （%）
24	92.5	93.11
48	95.3	96.62

$$Le_2 = \frac{\rho_{l1}-\rho_{v1}}{\rho_{l2}-\rho_{v2}} Le_1 - \frac{\rho_{v2}-\rho_{v1}}{\rho_{l2}-\rho_{v2}} \qquad (15)$$

In the above formula, subscript 1 and subscript 2 represent the initial and final states, respectively. Meanwhile, the final liquid levels are calculated by Eq. (15) as shown in Table 2. To compare measured and calculated liquid levels, their errors are relatively large. For example, during 0 - 24 h, the differences of measured and calculated are 2.5% and 3.11 %. If the heat leakage is calculated with the measured liquid level, a part of heat leakage will be ignored and the total mass does satisfy the mass conservation law. Certainly, there are still errors in calculated liquid levels, because the initial liquid level has measuring error when obtained by liquid level gauge.

Depending on the above analysis, Eq. (12) is expressed by the liquid level as follows:

$$\begin{aligned}\frac{dQ}{dt} &= \left[\rho_{l1} c_{vl1} Le_1 + \rho_{v1} c_{vv1}\left(1-Le_1\right)\right] V \frac{dT}{dt} \\ &+ \frac{\rho_{l1} Le_1 - \rho_{l2} Le_2}{dt}\left[L - p_v\left(\frac{1}{\rho_v}-\frac{1}{\rho_l}\right)\right] V\end{aligned} \qquad (16)$$

In the calculation of heat leakage, Le_1 is measured by the liquid level gauge, and Le_2 is calculated by Eq. (15); other parameters can be obtained from the properties of the saturation liquid; therefore, the heat leakage can be calculated by Eq. (16).

3.3. Results analysis

Based on the data in Table 1 and Table 2, the parameters of gas and liquid are obtained by NIST, and then heat leakage is calculated. The results are shown in Table 3.

The calculated heat leakages were 4.50 W, 4.30 W, and 4.12 W, which should be corrected by Eq. (17) because the temperature difference between internal (cryogenic vessel) and external (environment) is different from the standard condition [3].

$$Q_{co} = Q \times \frac{288 - T_{ca}}{T_a - T_{co}} \qquad (17)$$

TABLE 3
RESULTS OF HEAT LEAKAGE.

time （h）	Heat leakage （W）	Corrected heat leakage （W）
0-24	4.50	4.55
0-48	4.30	4.45
24-48	4.12	4.21

where Q_{co} is the corrected heat leakage, representing the heat leakage tested by the standard method at a standard condition with an atmospheric pressure of 101 kPa and a test room temperature of 288 K; T_a is the average temperature of the environment; T_{ca} is the saturated temperature of the working medium at 101 kPa, which is 77.3 K for liquid nitrogen; and T_{co} is the saturated temperature of the working medium at the test pressure.

The corrected results were 4.55 W, 4.45 W and 4.21 W, as shown in the last column of Table 3. These results are larger than the directly calculated heat leakage because the temperature difference between internal (cryogenic vessel) and external (environment) is less than that in the saturated condition. For example, when the pressure of the cryogenic vessel is 430 kPa, the temperature of is 92.11 K in cryogenic vessel, and the temperature is 298.15 K (25 ℃) at test room; therefore, the temperature difference is 206.04 K. However, under standard conditions, the temperatures internal (cryogenic vessel) and external (environment) are 77.3 K and 288 K, respectively, and the temperature difference is 210.65 K.

Compared with 4.41 W tested by the standard method, the errors of each corrected heat leakage were 3.2%, 0.9%, and 4.5%, and the average error was 2.9%, which is less than 5.0%. Therefore, the heat leakages tested by self-pressurization are consistent and reflect the thermal insulation performance of cryogenic vessels correctly. Furthermore, there is no working medium discharged during the entire test process.

In addition, if a cryogenic vessel is frequently used, it is unnecessary to spend 48 h to make the test system equilibrium. Therefore, the time of equilibrium can be shortened.

4. CONCLUSION

In this study, a method is proposed based on the one-dimensional heat transfer of cryogenic vessels during self-pressurization to evaluate the heat leakage of cryogenic vessels for liquid hydrogen, and an experiment is conducted to verify the method. The conclusions can be summarized as follows:

(1) The self-pressurization method can be used to evaluate the heat leakage of cryogenic vessels for liquid hydrogen in bus because there is no working medium discharged during the entire test process, and the calculated heat leakage correctly reflects the thermal insulation performance.

(2) In the heat leakage calculation process, the final liquid level is directly calculated by the equation of mass conversation to solve the accuracy limitation of the liquid level gauge.

(3) The results of heat leakage are corrected because the temperature difference between the cryogenic liquid and the environment is less than the standard condition in self-pressurization.

REFERENCES

[1] Acar, Canan, Dianer, and Ibrahim, “Review and evaluation of hydrogen production options for better environment,” *J. Clean.*, vol. 218, pp.835-849, 2019.

[2] B. Zohuri, “Cryogenic and liquid hydrogen storage,” In zouhuri, Bahman (Ed.), *Hydrogen energy*, Galaxy Advance Engineering Inc., Albuquerque, pp.121-139, 2019.

[3] “BS ISO 21014 Cryogenic vessels-Cryogenic insulation performance,” *BSI publications*, London, Unite Kingdom, 2006.

[4] J. Wang, Q. Ye, W. Qiu, X. Yi, J. Li, X. Yao, and H. Xue, “Welded Insulated Cylinders,” *Standards Press of China*, Beijing, China, 2009.

[5] L. Wang, B. Han, Y. Ning, A. Yi, H. Zhang, Y. Tan, Q. Huang, F. Tian, J. Yang, and J .Yin, “Periodic inspection and evaluation of cryogenic insulated cylinders,” *Standards Press of China*, Beijing, China, 2017.

[6] S. Gursu, S. Sherif A, T. N. Veziroglu, et al., “Analysis and Optimization of Thermal Stratification and Self-Pressurization Effects in Liquid Hydrogen Storage Systems—Part 1: Model Development,” *Energy Resource Technol.*, vol. 115, pp. 223-225, 1993.

[7] S. Baris and M. Kassemi, “Numerical and experimental comparisons of the self-pressurization behavior of an LH2 tank in normal gravity,” *Cryogenics*, vol. 48, pp. 122-129, 2008.

[8] G. I. Saidal and A. I. Solodov, “Software development for processing test data on product loss by evaporation from cryogenic vessels,” *CHEM PETROL ENG*, pp. 529-532. 2007.

[9] M. Seo and S. Jeong, “Analysis of self-pressurization phenomenon of cryogenic fluid storage tank with thermal diffusion model,” *Cryogenics*, vol. 50, pp. 549-555, 2010.

[10] L. Zhaoci, X. Lie, S. Heng, X. Youming, et al., “Investigation on performances of non-loss storage for cryogenic liquefied gas,” *Cryogenics*, vol. 44, pp. 357–362, 2004.

[11] Q. F. Li, G. B. Chen, X. M. Xie, et al., “Experimental study of self-pressurizing transfer system for cryogenic liquid,” *Proceedings of the 20th International Cryogenic Engineering Conference*, pp. 85-85, 2005.

[12] S. Panchamgam, A. Chatterjee, J. Plawsky, et al., “Comprehensive experimental and theoretical study of fluid flow and heat transfer in amicroscopic evaporating meniscus in a miniature heat exchanger,” *Int. [J] Heat Mass Transfer*., vol. 51, pp. 68–79, 2008.

[13] Jihoon Seok, Dongmin Kim, Changhyeong Lee, Manryeol Kim, Jeongdong Choi, and Seokho Kim, “Development and performance test of a liquid nitrogen circulation pump for HTS power cable,” *Progress in Superconductivity and Cryogenics*, vol. 20, no. 3, pp. 28-33, 2018.

[14] J. I. Hochstein, H. C. Ji, and J. Aydelott, “Prediction of self-pressurization rate of cryogenic propellant tankage,” *Propuls. Power*, vol. 6 (1), pp. 11-17, 1990.

[15] R. Marek and J. Straub, “Analysis of the evaporation coefficient and the condensation coefficient of water,” *Int. [J] Heat Mass Transfer*, vol.44, pp. 39-53, 2001.

[16] S. Barsi and M. Kassemi, “Investigation of Tank Pressurization and Pressure Control—Part II: Numerical Modeling,” *J. THERM SCI. ENG. APPL.*, vol.5, pp. 2-4, 2013.

[17] Z. D. Zhang, Q. Wang, Q. Li, and P. Li, “The relationship of theory self-pressure value and theoretic of welded insulated cylinders,” *Progress of special equipment and saving energy*, 2nd ed., pp. 147-151, 2016.