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A new method fast measure cryogenic vessel heat leakage

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Abstract

Heat leakage is an important parameter to reflect heat insulated performance of cryogenic vessel. According to the current standard requirements, it needs to measure the daily evaporation rate to indicate heat leakage. The test needs-over 24h after cryogenic vessel in heat equilibrium as standard required, therefore test efficiency is poor and new efficient method is required to cut test time. First of all, the volume of instantaneous evaporated gas and heat leakage are calculated by the current standard corresponding to the maximum allowable daily evaporation rate of cryogenic vessel. Depending on the relationship between real daily evaporation rate and maximum allowable daily evaporation rate of cryogenic vessel, we designed a new test method based on the pressure changes over time in cryogenic vessel to determine whether its heat insulated performance meets requirements or not. Secondly, the heat transfer process was analyzed in measurement of cryogenic vessel, and the heat transfer equations of whole system were established. Finally, the test was completed in four hours; meanwhile the heat leakage and daily evaporation rate of cryogenic vessel are calculated basing on test data.

Keywords: cryogenic vessel, heat leakage, evaporation rate, measurement, fast

1. INTRODUCTION

With the wide application of gas in industrial, factories choose cryogenic liquid as the storage of industrial gas. Cryogenic vessel storing industrial gas has the characteristics of large storage capacity in the same volume, low working pressure and high security, compared with the traditional high-pressure gas cylinder. According to the latest standards [1, 2], cryogenic vessel need to test heat insulated performance to ensure their safe use. The measured item is the static evaporation rate(between evaporated gas mass in a day and fulfilled liquid mass in cryogenic vessel) or heat leakage, which is used to test cryogenic vessel heat insulated performance. However, the current test method needs more than 2 days to complete, ineffective and affected the normal production. Therefore, a new measurement method is necessary to cut time, meanwhile, in the process of test we can directly judge heat insulated performance of cryogenic vessels whether meets the standard requirements or not, at the same time, depending on the data of test, the heat leakage and daily evaporation rate of cryogenic vessel were analyzed and calculated.

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2. PHYSICS MODEL

2.1. New test method

As the safe requirements of cryogenic vessels[1, 2], there are different requirements for different cryogenic liquids and volumes in the standard on cryogenic vessel. If the heat leakage is smaller than given value of the standard, we consider heat insulated performance meet the requirements and cryogenic vessel can be continued to use safely. Otherwise it can't continue to use, and we need to further inspect the cryogenic vessel. Before the test, the volume of instantaneous evaporated gas was calculated firstly, because the heat insulated performance is expressed as daily evaporation rate in standard, corresponding to the volume of maximum allowable evaporated gas in cryogenic vessel. Secondly, the heat leakage was calculated by the volume of instantaneous evaporated gas, which is easy to understand and compare. The volumes of maximum allowable evaporated gas are shown in Table 1 for liquid nitrogen and new cryogenic vessel. Finally, the daily evaporation rate of used cryogenic vessel is 1.5 times as high as in new cryogenic vessel in standard.

TABLE I
STANDARD REQUIREMENT FOR DIFFERENT CRYOGENIC VESSELS.

V/L	α /%/d	V_s/L/min	Q_t/kJ/min
100	2.8	1.25	0.596
150	2.5	1.47	0.701
175	2.1	1.64	0.782
200	2.0	1.79	0.854
300	1.9	2.55	1.217
450	1.8	3.62	1.727

In Table 1, V is volume of cryogenic vessel, α is daily evaporation rate, V_s is volume of maximum allowable evaporated gas, Q_t is heat leakage of cryogenic vessel.

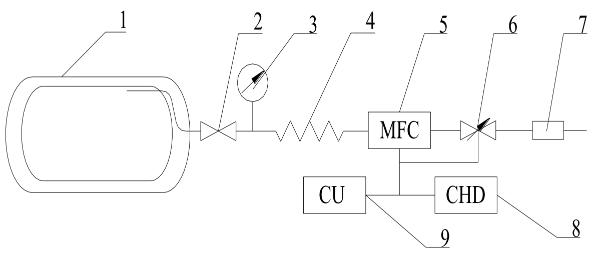
In order to test heat insulated performance of cryogenic vessels we set up the test platform, as shown in Fig.1. Firstly, the volume of flowing out gas (V_s) was monitored by flowmeter, and we regulated valve 6 by a computer in control unite and made the volume of flowing out gas accord with volume of maximum allowable instantaneous evaporated gas in cryogenic vessel as shown in Table 1. Secondly, we recorded and observed cryogenic vessel pressure by pressure sensor. Finally, after a period of testing, the pressure may occur in one of the following three situations because the volume of real evaporated gas (V_r) is usually unequal to the volume of flowing out gas (V_s) in heat insulated performance test of cryogenic vessel:

(1) The pressure rising, indicates that volume of real evaporated gas is greater than the volume of flowing out gas in the cryogenic vessel, means volume of real evaporated gas is greater than volume of maximum allowable instantaneous evaporated gas given in the standard ($V_r > V_s$).therefore, the heat insulated performance of cryogenic vessel cannot meet the requirements of the standard.

(2) The pressure keeping, indicates that volume of real evaporated gas is equal to the volume of flowing out gas in the cryogenic vessel , means volume of real evaporated gas is equal to volume of maximum allowable instantaneous evaporated gas given in the standard ($V_r = V_s$), therefore, the heat insulated performance of the cryogenic vessel just meets the requirements of the standard.

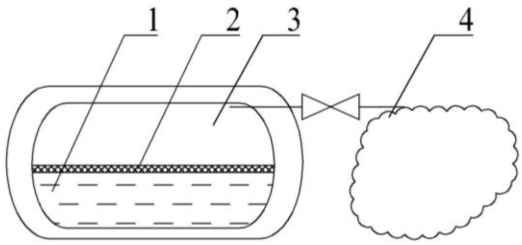
(3) The pressure falling, indicates that volume of real evaporated gas is less than the volume of flowing out gas in the cryogenic vessel , means volume of real evaporated gas is less than the volume of maximum allowable instantaneous evaporated gas given in the standard ($V_r < V_s$), therefore the heat insulated performance of cryogenic vessel meets the requirements of the standard.

Base on above analysis, we can finish test in few hours by this method because cryogenic vessel pressure changes is easily confirmed and tested, at the same time, we need calculate the daily evaporation rate and heat leakage depending on test recorded data.



1-Cryogenic vessel, 2-Valve , 3-Pressure sensor, 4-Vaporization, 5-Flowmeter, 6-Regulating valve , 7-Flame arrestor，8-Gas alarm, 9-Control unite.

Fig. 1. Cryogenic vessel fast measurement platform.



1-Liquid left part，2- Evaporated liquid，3- Gas left part，4- Discharged gas.

Fig. 2. The heat transfer analysis model in the test process.

2.2. Model analysis

In the test process, gas flows out from cryogenic vessel to outside, and the volume of flowing out gas is equal to the value in Table1. In order to analysis heat transfer process of fast measurement test [3-6], the gas and liquid in the cryogenic vessel can be divided into four parts in the whole test, as shown in Fig. 2. (1) The liquid left part from start to end of test; (2) a part of liquid evaporates into gas from start to end of test; (3) the gas left part from start to end of the test; (4) the gas discharged part from start to end of test. The total heat leakage is absorbed by the four parts and can be calculated according to equations (1-5) [4-6].

The mass conservation equation of cryogenic vessel is as follows:

$$\frac{dm_v}{dt} + \frac{dm_l}{dt} + \frac{dm_{out}}{dt} = 0 \quad (1)$$

$$\frac{d}{dt}(\rho_v V_v) + \dot{m}_{out} = -\frac{d}{dt}\left[\rho_l \left(V - V_v\right)\right] = \frac{d}{dt}(\rho_l V_v) = M \quad (2)$$

Where m_v is mass of gas, m_l is mass of liquid, m_{out} is mass of discharged gas, ρ_v is density of gas, ρ_l is density of liquid, V_v is volume of gas, V is storage volume of cryogenic vessel, M is a rate change of liquid mass, $dm_{out}/dt = \dot{m}_{out}$ is mass of flowing out in unit time .

The energy equations for gas and liquid in the process of fast measurement are follows:

$$\frac{d}{dt}(\rho_v V_v e_v) = Q_{vl} + Q_{wv} - \dot{m}_{out} h_g + M\left(e_v + \frac{p_v}{\rho_v}\right) - p_v \frac{dV_v}{dt} \quad (3)$$

$$\frac{d}{dt}(\rho_l V_l e_l) = -Q_{vl} + Q_{wl} - M\left(e_v + \frac{p_v}{\rho_v}\right) - p_v \frac{dV_l}{dt} \quad (4)$$

Where e_v is internal energy of gas, e_l is internal energy of liquid, h_g is enthalpy of discharged gas, p_v is the saturated vapor pressure, Q_{vl} is gas absorbed heat by interface, Q_{wv} is gas absorbed heat from the wall of cryogenic vessel, V_l is volume of liquid，Q_{wl} is liquid absorbed heat from the wall of cryogenic vessel. Combining (3) and (4), energy equation in the process of fast measurement is as follow:

$$\left(\rho_s V_v c_{vv} + \rho_l V_l c_{vl}\right)\frac{dT}{dt} + M\left[L - p_v\left(\frac{1}{\rho_v} - \frac{1}{\rho_l}\right)\right] = Q_t - \dot{m}_{out}(h_g - e_v) \quad (5)$$

Where c_{vv} is gas specific heat, c_{vl} is liquid specific heat, T is temperature, and $Q_t = Q_{wl} + Q_{wv}$ is total heat leakage [8-14]. In the test, we made an assumption that liquid and gas were saturated in cryogenic vessel in test process, so the pressure and temperature were given by the Clausius-Clapeyron equation.

$$\frac{\partial T_s}{\partial p_v} = \frac{R_G T_s^2}{Lmp_v} \quad (6)$$

Where R_G is ideal gas constant, L is latent heat, and m is molar mass. Combining (5) and (6) we get equation as follows:

$$\left(\rho_s V_v c_{vv} + \rho_l V_l c_{vl}\right)\frac{R_G T_s^2}{Lmp_v}\frac{dp_v}{dt} = Q_t - \dot{m}_{out}(h_g - e_v) - M\left[L - p_v\left(\frac{1}{\rho_v} - \frac{1}{\rho_l}\right)\right] \quad (7)$$

According to (7), dp_v/dt is cryogenic vessel pressure over time. If $dp_v/dt < 0$, it means cryogenic vessel pressure falling in test (V_r<V_s), indicating the heat leak is smaller than standard requirement.

If $dp_v/dt = 0$, it means cryogenic vessel pressure keeping in test (V_r=V_s), indicating the heat leak is equal to standard requirement.

If $dp_v/dt > 0$, it means cryogenic vessel pressure rising in test (V_r>V_s), indicating the heat leak is larger than standard requirement. We can judge whether heat insulated performance of cryogenic meet standard requirement or not by pressure over time and calculate the heat leakage by equation (7).

3. HEAT LEAKAGE TEST AND CALCULATION

3.1. Heat Leakage Test

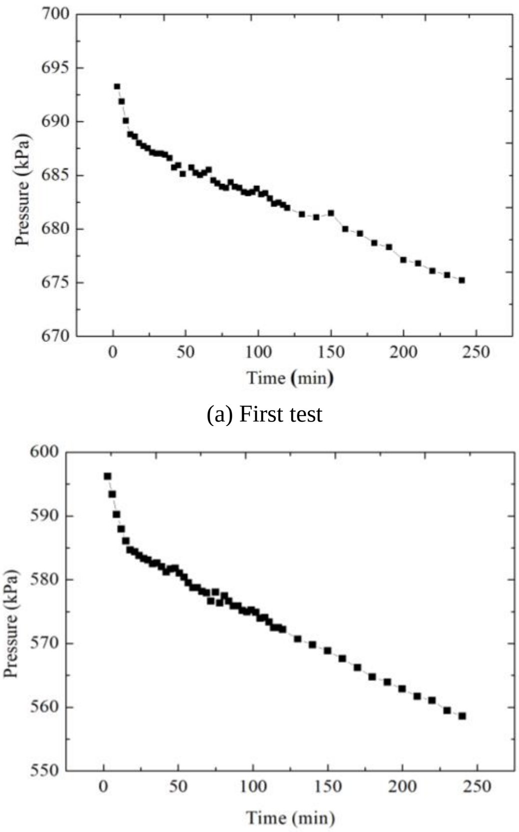
The test platform was built as shown in Fig 1. A 175L cryogenic vessel was selected for the test. The daily evaporation rate is 2.05%/d, and heat leakage is 0.76kJ/min with standard method.

The test process of standard method as follow steps: Firstly, the valve 2 and 6 are fully opened at least 24h. The gas is discharged and the pressure in cryogenic vessel is falling and according with atmosphere. Secondly, a flowmeter records the volume of flowing out cryogenic vessel（L/min）at least 24h. The total mass of flowing out gas is evaporation gas in a day（kg/day）. Finally, the daily evaporation rate is calculated, that is the ratio between mass of flowing out gas in a day and total mass in cryogenic vessel after full filled.

The test environment temperature was 6℃, and the local atmospheric pressure was 84.8kPa. The cryogenic liquid is liquid nitrogen. We carried out twice test. Firstly, the initial pressure is near 700kPa and the liquid level is 50%; secondly, the initial pressure is near 600kPa and the liquid level is 10%. Since the cryogenic vessel has been used for more than 3 years, the heat leakage or daily evaporation rate of the cryogenic vessel is no more than 1.5 times of the standard requirement in Table 1. We get the flow volume rate in the whole test process is 2.46L/min; and the accuracy of the flowmeter is 1.0%. The pressure over time is shown in Fig.3(a) and Fig.3(b) in test.

3.2. Test analysis

The twice test last 4 hours. The valve 6 is regulated so that the volume of flowing out gas in the cryogenic vessel is consistent with standard maximum allowable evaporation rate. As shown in Fig.3(a) and Fig.3(b), the pressure in the cryogenic vessel is always falling, therefore we can determine that the heat leakage or daily evaporation rate of the cryogenic vessel is less than the required value of the standard, so the heat insulated performance meets the requirements. At the same time, through the observation of Fig.3(a) and Fig.3(b), the slope is different between initial phase and final phase, the reason is that test system is not equilibrium in initial phase. Therefore, the pressure in the initial phase drops rapidly. In calculating the heat leakage of cryogenic vessel, we should select the phase after test system stability. According to the Fig.3(a) and Fig.3(b), the test data of 120min~240min can be selected as the calculation parameters[7]. Based on energy conservation, mass conservation equation above, heat leakage was calculated by equations (8-13).



(a) First test

(b) Second test

Fig. 3. Pressure over time in twice test.

$$\left(\rho_s V_v c_{vv} + \rho_l V_l c_{vl}\right) dT + M\left[L - p_v\left(\frac{1}{\rho_v} - \frac{1}{\rho_l}\right)\right] dt = \left[Q_t - \dot{m}_{out}(h_g - e_v)\right] dt \quad (8)$$

$$V_{v1} + V_{l1} = V \quad (9)$$

$$V_{v2} + V_{l2} = V \quad (10)$$

$$\rho_{v1} V_{v1} + \rho_{l1} V_{l1} = m_t \quad (11)$$

$$\rho_{v2} V_{v2} + \rho_{l2} V_{l2} + m_{out} = m_t \quad (12)$$

$$\rho_{l1} V_{l1} - \rho_{l2} V_{l2} = M_t \quad (13)$$

Equations (8)-(13) are respectively energy equation, volume equation, and mass conservation equation of cryogenic vessel. Subscribe 1 represents initial state, and subscribe 2 represents final state. Heat leakages of cryogenic vessel are calculated in twice test, as shown in Table 2.

TABLE Ⅱ
FAST MEASUREMENT METHOD CALCULATED RESULTS.

Item	First test	Second test
Initial pressure （kPa）	680	570
Instantaneous volume flow （SLPM）	2.46	2.46
Initial mass of gas（kg）	2.48	3.69
Initial mass of liquid（kg）	60.69	13.27
Final mass of gas（kg）	2.47	3.60
Final mass of liquid（kg）	60.34	12.99
Accumulated mass（kg）	0.36	0.36
Evaporated mass（kg）	0.35	0.28
Heat leakage（kJ/min）	0.77	0.67
Static evaporation rate （%/d）	2.07	1.80

As shown in Fig.3(a) and Fig.3(b), the slope of pressure over time was close to the constant during the test time of 60min ~ 240min. In Fig.3(a), the pressure falling from 685.032kPa to 675.213kPa, the difference is 9.819kPa, and the slope was 0.055kPa/min. We calculated heat leakage was 0.77kJ/min and daily evaporation rate was 2.07%/d. In Fig.3(b), the pressure falling from 578.706kPa to 558.571kPa, the difference is 20.125kPa and the slope was 0.112kPa/min. We calculated heat leakage was 0.67kJ/min and daily evaporation rate was 1.80%/d as shown in Table 2.

Comparing Fig.3(a) and Fig.3(b), the ratio of slopes is about 1/2, and the ratio of heat leakages is 1.15/1 in twice test, therefore pressure change is more obvious than heat leakage. For further analysis, the slope of Fig.3(a) is smaller than Fig.3(b), but the heat leakage and daily evaporation rate are relatively large respective in Fig.3(a), meaning large amount liquid evaporated in cryogenic vessel, and the corresponding daily evaporation rate, heat leakage and evaporated mass are 2.07%/d, 0.77kJ/min and 0.35kg. In Fig.3(b), the pressure falling rapidly, and the heat leakage and daily evaporation rate is relatively small, meaning small amount liquid evaporated mass in cryogenic vessel, and the corresponding daily evaporation rate, heat leakage and evaporated mass are 1.80%/d, 0.67kJ/min and 0.28kg.

We calculated heat leakages were 0.77kJ/min and 0.67 kJ/min, therefore the errors are 1.0% and 12.2% in twice test, compared with the standard method result 0.76kJ/min. The error is mainly caused by liquid level, temperature and environmental pressure fluctuations and need further detailed analysis. Especially in second test, the real gas temperature is bigger than liquid temperature because the liquid level is 10%.

From above analysis, fast measurement method can judge whether heat insulated performance of cryogenic vessel meet the requirements or not by the pressure over time in four hours, at same time, the heat leakage and daily evaporation rate also can be calculated conveniently.

4. CONCLUSION

Through heat insulated performance of cryogenic vessel analyzed and tested by fast measurement method, the following conclusions can be obtained:

(1) Fast measurement method can judge cryogenic vessel heat insulated performance whether meet the standard requirements or not in few hours depended on pressure over time. If the pressure falling, the heat leakage and daily evaporation rate of cryogenic vessel meet the requirements; otherwise, if the pressure in the cryogenic vessel rises, the heat leakage and daily evaporation rate do not meet the service requirements.

(2) The fast measurement method can realize the measurement within 4 hours, which improves the test efficiency compared with the standard measurement method.

(3) For cryogenic vessels of the same volume, after test system is stable, the slope of pressure over time is large, indicating heat leakage or daily evaporation rate is small, otherwise, heat leakage or static evaporation rate is large.

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