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A liquid helium temperature target with a 10 K vapor shield for shock compression experiment in the environment condition of 100 Pa

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The shock compression experiment of liquid helium is an available way to gain properties of specimen at high temperatures and pressures. Based on Fluent, a thermal insulation analysis and design of a liquid helium temperature target in the environment condition of 100 Pa for shock compression experiment is performed. Then, a cryogenic target with a 10 K helium vapor shield and a separated vacuum interval is particularly developed. A lowest temperature of 3.63 K and a stable temperature of 3.70 K in the specimen cavity with an accuracy of 0.1 K are obtained by means of continuous flow and vacuum cooling. Both time-consuming and temperature stability are well-suited to the requirements of the shock compression experiment. The results show that the calculated and experimental data well-matched each other. The simulation method may be effective and feasible for the optimal design of the cryogenic target.

numerical computation, cryogenic target, helium vapor shield, helium liquefaction, shock compression

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The equations of state (EOS) of some cryogenic fluids at high pressures and temperatures are very important for the ICF program and the modeling of the giant planets [1–3]. EOS data for dense helium and hydrogen are generally obtained by a shock compression of liquid in the specimen cavity to a high temperature and pressure [4]. The shock compression experiment of liquid helium to 56 GPa has been done by Nellis et al. [2] with a vacuum about 5×10^{-3} Pa around the specimen cavity [5]. In China, Shock compression experiments of gas helium at room temperature have been done by Cai et al. [6]. Based on the Rankine-Hugoniot relation [4], higher final pressure could be generated at initial dense density. In order to carry out shock compression experiments on liquid helium to obtain its properties at high temperatures and pressures, a liquid helium temperature cryogenic target for preparing liquid helium is described in this paper.

According to the requirements of shock compression experiment, the helium reservoir should be designed small and the impact surface or target plate must not be covered. Specially, the vacuum of the target chamber provided is only about 100 Pa for the existed two stage light gas gun, which is much higher than that reported by Nellis [2]. Whereas, an additional heat load caused by the poor vacuum would be appreciable for the specimen cavity and the helium reservoir. Obviously, it will be really hard to have a very small heat load on the specimen cavity to keep the liquefied specimen in liquid state with no or little bubble for the shock compression experiment. Otherwise, it should be necessary to cause a huge investment for the reconstruction of the existent two stage light gas gun to provide a 10^{-3} Pa environment. Although the cryogenic targets based on the existent two stage light gas gun are developed for shock compression of liquid N_2, CO and CO_2 [7,8], they are not suitable for shock compression of helium because the latent heat per unit volume is two orders of magnitude smaller for He than

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nitrogen [2,9]. Therefore, additional thermal insulation for the helium reservoir and the specimen cavity should be provided to offset the heat lose from residual gas conduction.

A new liquid helium temperature cryogenic target with a separated vacuum interval and a 10 K vapor cooled shield is developed for shock compression test device of liquid helium in the environment condition of about 100 Pa. In this case, the poor vacuum condition will certainly lead to an appreciable heat conduction of residual gas and cause some more evaporation of liquid helium in the cryostat. At the same time, the evaporated vapor helium may be able to cool the vapor shield to a temperature as low as 10 K, so as to reduce the shield radiation heat flux to the specimen cavity and liquid helium reservoir to a very low level. As a result, the cryogenic target may be used for efficient cooling in the range of specimen temperatures from 3.6 K to 80 K by means of a heater.

The thermal insulation configuration of the liquid helium temperature cryogenic target is described in detail. Then, a numerical computation of heat losses based on Fluent and the experiments of a liquid helium temperature target are carried out. The results show that the calculated and experimental data well-matched each other.

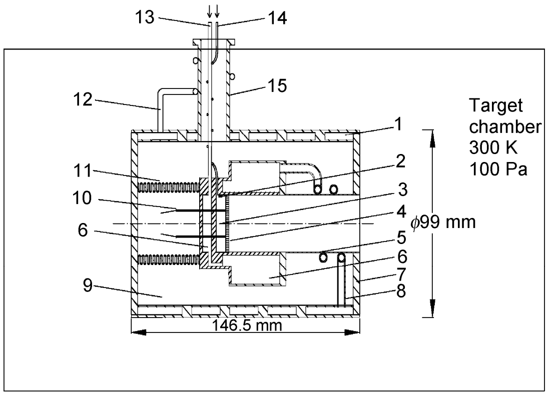

Figure 1 Schematic of cryogenic target. 1, helium vapor shield; 2, diode thermometer; 3, specimen cavity; 4, target plate; 5, neck tube; 6-liquid helium reservoir; 7, shield plate; 8, colied tube; 9, vacuum interval; 10, detector; 11, corrugated tube; 12, gas helium outlet; 13, liquid helium inlet; 14, gas specimen inlet; 15, support tube.

1 Cryogenic target

According to the experimental features of shock compression, technical requirements for cryogenic target should be realized as follows: (1) the cryogenic target should be able to condense the gas helium into liquid and to keep the density of liquid specimen stable and uniform within several minutes; (2) the time of the cooling process should be short; (3) the geometries of cryogenic target should be compact, the target plate must not be covered, and the helium reservoir should be designed as small as possible to avoid risk of high pressure in the target chamber brought by the shock compression of the coolant. In light of the short time for the completion of the shock compression experiment and the small capacity of helium reservoir, the continuous flow vacuum cooling principle is used in cryogenic target process [10,11].

The cryogenic target developed in this study, illustrated in Figure 1, is a cylindrical tank of stainless steel with 99 mm in diameter and 146.5 mm in length. The liquid helium through the inlet tube continuously flows into the helium reservoir of 80 mL capacity, then transforms into cold vapor after absorbing the leaking heat. The sensible heat of vapor helium is firstly utilized to cool the helium vapor shield to about 10 K through the coiled tube, and then the support tube as well.

To minimize heat conduction down to the specimen cavity and helium reservoir, a stainless steel neck tube of 0.5 mm thickness and a stainless steel corrugated tube with 0.15 mm thickness are used. A separated vacuum interval pumped to 10^{-3} Pa by a molecular pump is designed to protect the helium reservoir. Finally, ten layers of aluminum mylars are wrapped outside the helium reservoir and the vapor shield as well as the neck tube and the corrugated tube.

2 Numerical simulation

In general, heat is transferred by conduction, convection and radiation. Eq. (1) is used to calculate conduction heat flux $\dot{Q}_c$

$$\dot{Q}_c = \sum \kappa(T) A \frac{\mathrm{d}T}{\mathrm{d}x}, \tag{1}$$

where κ is thermal conductivity, T is temperature, and A is heat transfer area.

Eq. (2) is used to calculate radiation heat flux $\dot{Q}_r$.

$$\dot{Q}_r = \sigma \bar{\varepsilon} A (T_2^4 - T_1^4), \tag{2}$$

where σ is Stefan-Boltzmann constant and $\bar{\varepsilon}$ is average emissivity.

Eq. (3) is used to calculate thermal conductivity of residual gas

$$\kappa_g = C \cdot \eta \cdot C_v, \tag{3}$$

where C=1.5–2.5, η is viscosity, proportioned to $T^{0.79}$, and C_v is specific heat at constant volume.

A steady state simulation based on Fluent is performed to quantify the heat load of the cryostat and to evaluate the thermal insulation performance of the helium reservoir and specimen cavity [12]. A 2-D axial symmetric model is used and shown in Figure 2.

Boundaries of the computational model are handled as follows:

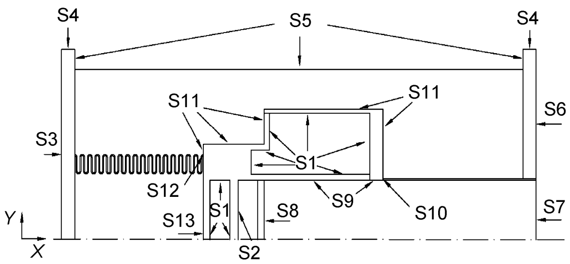

Figure 2 Computational model of cryogenic target. S1, liquid helium reservoir surface 0; S2, spectimen cavity surface; S3, plate 1 surface; S4, adiabatic surface; S5, helium vapor shield surface; S6, plate 2 surface; S7, air surface; S8, target plate surface; S9, liquid helium reservoir surface 1; S10, conunction surface of liquid helium reservoir and neck tube; S11, liquid helium reservoir surface 2; S12, conjunction surface of liquid helium reservoir and corrugated tube; S13, liquid helium reservoir surface3.

(1) The conjunction surface of the shield plate and helium vapor shield is adiabatic. The surface temperature of the target chamber is 300 K and the helium vapor shield temperature is 10 K.

(2) The boiling heat transfer coefficient of liquid helium to the reservoir-wall is programmed by UDF [13] according to Cooper equation about pool boiling [14]:

$$h = 55 p_r^{0.12-0.4343\ln R_p}(-0.4343\ln p_r)^{-0.55} M^{-0.5} q^{0.67}, \quad (4)$$

where M is the helium molecular weight, p_r is relative pressure (p_r=p/p_c), p_c is critical pressure, R_p is average roughness of surface (μm), and q is heat flux density.

(3) The thermal conductivities of solids are defined as a piecewise-linear function of temperature. Table1 gives the thermal conductivity and emissivity of some solids used in the computation. In addition, the emissivity of aluminum mylar and target chamber are 0.011 and 0.21 respectively.

(4) The heat conduction along the corrugated tube wall is handled with one-third of the heat conductivity of stainless steel as its compressed length is one-third of the actual length. The heat conduction from sensors' wires (number: 28, diameter: 0.19 mm and thermal conductivity: 0.048 W/(m^2 K)) is treated such that is counted into corrugated tube as a function of area.

Figure 3 shows the calculated tem perature distribution along *Y*-axis of specimen cavity surface (S2), plate 1 surface (S3) and liquid helium reservoir surface 3 (S13). Table 2 shows the heat flux on liquid helium reservoir. It can be seen that the total heat flux down to the helium reservoir is nearly 29.14 mW, which mainly comes from S10 and S11. Table 3 shows the heat fluxes of the cryogenic target, in which the heat flux of outer shell surface S_{shell} of vapor shield is manually calculated at an outer shell surface temperature 13 K. It can be seen from Table 3 that the total heat flux of the cryogenic target is 2.0926 *W,* which includes latent heat of liquid helium ($\dot{Q}_l$=1.193 W) and sensible heat of vapor helium from 4.3 K to 13 K ($\dot{Q}_s$=0.8996 W).

Table 1 Materials' thermal conductivity and emissivity

Material	Thermal conductivity(W(m^2 K))						Emissivity
	4 K	10 K	40 K	80 K	150 K	300 K	
Copper	1960	4600	1850	590	450	—	0.018
Steel	0.3	0.7	5	8	11	15	0.048
Aluminum	0.261	1.4	77.5	357	634	902	0.011

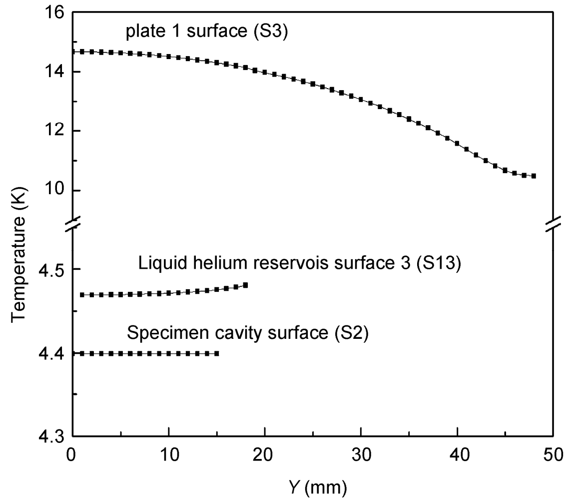

Figure 3 The computational temperature distribution along *Y*-axis for S2, S3 and S13.

Table 2 Heat flux on the liquid helium reservoir (mW)

Surface	S8	S9	S10	S11	S12	S13	Total
Heat flux (mW)	0.3	1.75	13.58	10.89	1.6	1.02	29.14

Table 3 Heat flux on cryogenic target (W)

Surface	S3	S6	S7	S_{shell}	Total
Heat flux (W)	0.2653	0.2393	0.0710	1.5170	2.0926

The rising of the temperature of evaporated helium due to the latent heat load may be calculated by eq. (5)

$$\Delta T = \dot{Q}_s / (\dot{m} \cdot C_p), \quad (5)$$

where C_p is specific heat at constant pressure, $\dot{Q}_s$ denotes sensible heat, and $\dot{m}$ is mass flow rate of evaporated helium,

$$\dot{m} = \frac{\dot{Q}_l}{L}, \quad (6)$$

where $\dot{Q}_l$ denotes the total latent heat down to liquid helium, L is latent heat per kilogram of liquid helium. The calculation points out that the rising of the temperature of evaporated helium is about 5.51 K after absorbing the

0.8996 W heat load. Therefore, the helium vapor shield can be possibly cooled to about 10 K.

Figure 4 shows the computational temperature distributions along *Y*-axis of specimen cavity surface (S2) and target plate surface (S8). The minuscule temperature variation of S2 is very important for keeping stable density and without gasification of liquid specimen. It seems that the thermal insulation design is feasible for the specimen cavity.

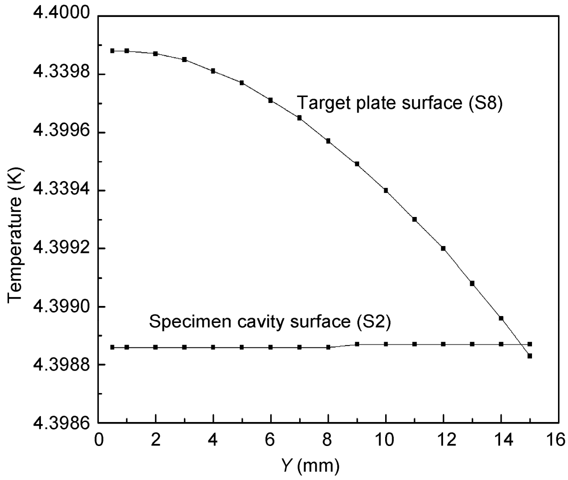

Figure 4 The computational temperature distribution along *Y*-axis for S2 and S8.

3 Experiments

In order to observe practical performance of the cryogenic target system, such as liquefaction ability of the specimen, temperature range and stability, as well as time of the whole cooling process, a cryogenic target experimental system is set up and shown in Figure 5.

The experimental system is composed of a liquid helium Dewar, cryogenic target and target chamber simulator, gas specimen bottle and controller pot, temperature monitor, vacuum pumps and so on. The target chamber simulator is used to simulate the environment of the target chamber. The specimen controller pot is used to purify gas specimen and to control the pressure of the cavity. The vacuum cooling pump is used to reduce the saturation pressure in the liquid helium reservoir when the specimen is cold close to 4.2 K. The negative pressure stabilizer is used to keep a stable flowing of helium gas and a stable pressure in the helium reservoir.

Experiments have been carried out and the results show that the helium specimen reaches a lowest temperature of 3.63 K and stabilizes at 3.70±0.01 K with vacuum cooling. The gas specimen is successfully condensed into liquid. The whole process of the experiment lasts 55 minutes as shown in Figure 6.

Figure 7(a) shows the temperature of the specimen cavity surface (S2, at *Y*=14 mm). We can see that the stable temperature of S2 is 4.42 K. Figure 7(b) shows the temperatures of specimen cavity surface (S2, at *Y*=14 mm), the outer shell surface of the helium vapor shield (at *X*=126.5 mm, *Y*=–9.5 mm and at *X*=15 mm, *Y*=–9.5 mm), and plate 1 surface (S3, at *Y*=35 mm) without vacuum cooling. We can see in Figure 7(b) that the stable temperature of the specimen cavity surface is 4.77 K, while the outer shell helium vapor shield approaches to 10 K or so.

We can see from Figures 3 and 7 that in spite of measured temperature data of specimen cavity surface S2 (4.42 K) and plate 1 surface S3 (13.02 K) are 0.02 K and 0.62 K, higher than the computational results respectively, which may be caused by the unstable cooling process and the Joule

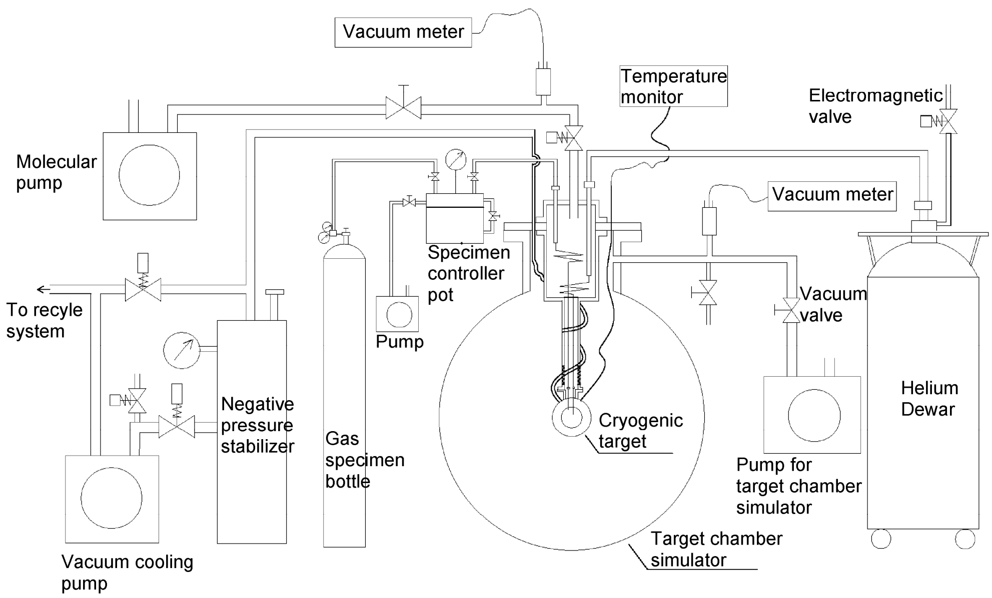

Figure 5 Schematic of cryogenic target experimental system.

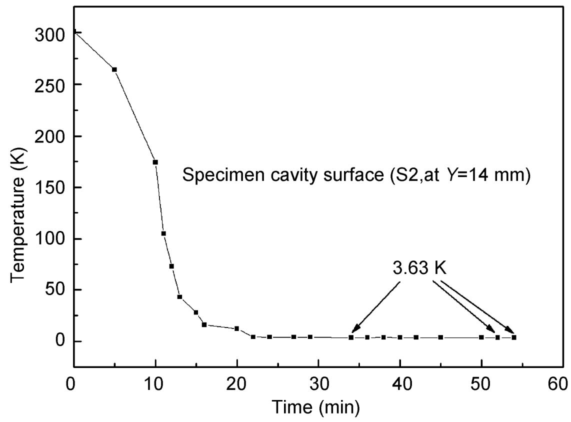

Figure 6 The cooling process of S2 with vacuum cooling.

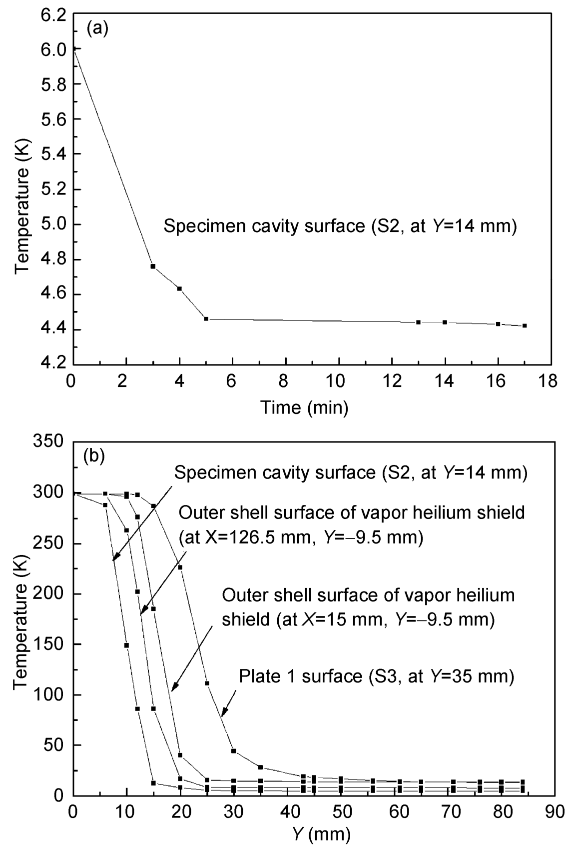

Figure 7 The cooling process of S2, S3, S13 and outer shell of helium vapor shield.

heat of sensor's wires. Generaly speaking, the computational data basically consist with that of the experimental results. Therefore, the calculated results can be effectively used for the design, optimization, and helium mass flow control of the cryogenic target.

4 Conclusions

A self designed liquid helium temperature cryogenic target with a 10 K vapor cold shield has been developed for shock compression experiment at the environment condition of about 100 Pa.

A lowest temperature of 3.63 K and a stable temperature of 3.70±0.01 K in the specimen cavity of the cryogenic target were obtained experimentally. Both the time and the temperature stability are well-suited to the requirements of the shock compression experiment with a relatively low thermal mass of specimen and a restricted geometry.

The comparison result shows that the calculated and experimental data well-matched each other. The simulation method may be effective and feasible for the optimal design of the cryogenic target.

1 Korbeek P J, Schouten J A. Equation of state of fluid helium to very high pressure. J Chem Phys, 1991, 95: 4519–4524
2 Nellis W J, Holmes N C, Mitchell A C, et al. Shock compression of liquid helium to 56 GPa (560 kbar). Phys Rev Lett, 1984, 53: 1248–1251
3 Nellis W J, Ross M, Holmes N C. Temperature Measurements of Shock-Compressed Liquid Hydrogen: Implications for the Interior of Jupiter. Science, 1995, 269: 1249–1252
4 Mitchell A C, Nellis W J. Diagnostic system of the Lawrence Livermore National Laboratory two-stage light-gas gun. Rev Sci Instrum, 1981, 52: 347–359
5 Nellis W J, Mitchell A C, van Thiel M, et al. Equation-of-state data for molecular hydrogen and deuterium at shock pressures in the range 2-76 GPa (20-760 kbar). J Chem Phys, 1983, 79: 1480–1486
6 Cai L C, Chen Q F, Zhang L, et al. Study of equation-of-state of dense helium (in Chinese). J At Mol Phys, 2001, 18: 167–172
7 Sun Y, Chen X M, Chen P S, et al. The structure of cryogenic target on a light-gas gun and technique for preparing liquid CO_2 sampl (in Chinese). Chin J Low Temp Phys, 1997, 19: 150–155
8 Shi S C, Dong S, Huang Y. Study on shock compression of liquids nitrogen and carbon monoxid (in Chinese). Chin J High Pressure Phys, 1999, 13: 295–300
9 Shi S C, Dong S, Huang Y. The experimental technology for shock-compressed liquid gas (in Chinese). Chin J High Pressure Phys, 1999, 13: 211–217
10 Campbell S J, Herbert I R, Warwick C B, et al. A continuous flow cooling unit for ESR experiments over the temperature range 3.7-300 K. J Phys E: Sci Instrum, 1976, 9: 43–446
11 Dostal M, Petera K. Vacuum cooling of liquids: mathematical model. J Food Eng, 2004, 61: 533–539
12 Boukeffa D, Boumaza M, Francois M X, et al. Experimental and numerical analysis of heat losses in a liquid nitrogen cryostat. Appl Therm Eng, 2001, 21: 967–975
13 FLUENT User's Guide, Fluent Inc., 2006
14 Lu Z Q. Two Phase Flow and Boiling Heat Transfer (in Chinese). Beijing: Tsinghua University Press, 2002