



# The Design and Validation of a Zero Boil-Off LAr System for CDEX-10 Experiment

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## Abstract

The China Dark Matter Experiment (CDEX) is an experiment of detecting light weakly interacting massive particles by using the p-type point contact germanium (pPCGe) detector. The underground laboratory of the CDEX is situated in Jinping Mountain in Sichuan province of China. In this experiment, a 1200-L liquid argon (LAr) scintillator is employed as anti-coincidence veto detector to maximally rule out the background radiation, and to provide a stable low-temperature surrounding for the pPCGe detector. A self-circulation argon liquefaction system with three Pulse Tube Refrigerators is developed to satisfy the zero boil-off condition of the LAr detector; bubbles formed during system operation are prevented by LAr sub-cooling condition. Meanwhile, an actively cooled LAr shield outside the LAr detector is used to prevent the external heat radiation from propagating inside to keep the required 1.0 K temperature gradient inside the LAr detector. The structure of the cryogenic system and the testing results of this cryogenic system by using liquid nitrogen are presented in the paper. The testing results indicate that the cryogenic system satisfies the dark matter experiment requirements.

**Keywords** Liquid argon · Dark matter · Zero boil-off · Pulse tube refrigerator

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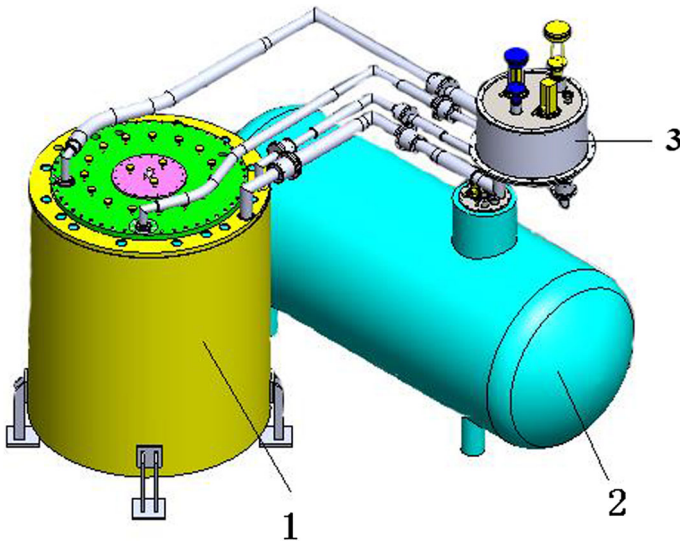
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## 1 Introduction

Various astronomical and cosmological evidences stemming from the gravity observation indicate the existence of the dark matter and suggest that it contributes about a quarter of the mass of the universe [1, 2]. The direct evidence of the dark matter is still not available because it does not participate in the other three fundamental interactions (electromagnetic interaction, weak interaction and strong interaction) except gravity interaction. In the current theoretical study of the dark matter, the WIMPs are one of the most desirable candidates [3]. The basic idea of WIMPs detection is through the detection of the charged elastic scattering productions of WIMPs and the ordinary matter. However, the extremely low interaction cross section of the WIMPs with the ordinary matter puts an extraordinarily strict requirement of the background exclusion ability, which makes the dark matter detection one of the most challenging problems in astronomy and particle physics [4]. China Jinping Underground Laboratory (CJPL) is one of the deepest underground laboratories in the world, with 2400 m thickness of the low-background-radiation rock covering it. The less than  $61.7 \text{ year/m}^2$  cosmic ray flux [5] makes the CJPL an ideal place for searching the dark matter. The CDEX project established in 2009 [6, 7] is focusing on searching light WIMPs with pPCGe detectors [8, 9] in the CJPL. The development of the CJPL and the progress of the CEDX project are remarkable in recent years [10–12]. The upgrade CDEX project CDEX-10 consists of a 10 kg pPCGe detector array and a LAr detector. The LAr detector serves as an active shielding detector and provides the low-temperature-work surrounding for the pPCGe detector array.

The noble liquids, such as argon and xenon, are widely used as targets in the WIMPs detection because of their relatively high density, high light yield due to passing charged particles. Many liquid argon and xenon detectors are now under operation or in construction [13–15]. The LAr detector is not the direct target of the WIMPs detection in CDEX-10; instead, it provides the low-temperature working condition for the pPCGe and the photomultiplier tubes (PMTs). The light collected by the PMTs from the LAr due to the charged particles can be used as an anti-coincidence veto signal to further select out the background events. The key technology of the associated cryogenic system is satisfying the requirements of the long-period operation of the LAr detector at the liquid argon temperature (87.3 K) and keeping the temperature gradient of the LAr within 1 K. This requirement is due to the temperature dependence of the PMT scintillation detection system; a stable low-temperature working condition produces fewer gas bubbles which will cause less vibration for the signal readout and hence reduce the noise for the detector system. To achieve this target, a number of techniques have been used to fulfill such stringent requirements and to maintain the constant liquid level of the argon [16]. A self-circulation argon liquefaction system with three Pulse Tube Refrigerators (PTRs) is designed to achieve the zero boil-off condition and to keep the stable long-period operation of the experiment. To prevent the formation of gas bubbles, the sub-cooled LAr is used due to its large density and the relatively large hydrostatic pressure occurring with increased depth below the LAr surface. Besides, large convective motion and the pool-boiling of the LAr are avoided by a cryogenic system which reduces the environmental heat leaking to the cryogen;



**Fig. 1** The cartoon illustration of the cryogenic system of CEDX-10. 1—The cryostat; 2—the LAr storage tank; 3—the cooling system (Color figure online)

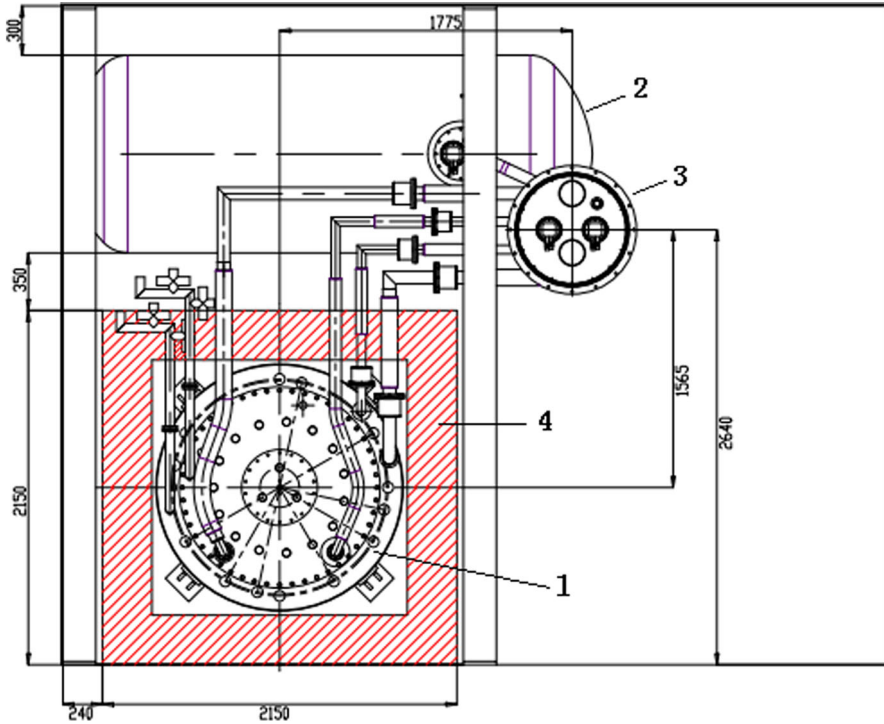
what is more, an actively cooled LAr shield surrounding the cryostat is used to prevent the external heat radiation.

## 2 Description of the Cryogenic System

The very weak deposited energy (below 1 keV) from the nuclear recoil generated by the direct collision between the WIMPs and the nucleus of the germanium can be captured by the sensitive cryogenic detectors. The background radiation, such as the cosmic ray, can generate very similar signals as the recoils in the cryogenic detectors, which becomes a big challenge of this experiment. The cryogenic system will be finally operated in CJPL to reduce the background radiation from the cosmic rays. The whole system will be set in a special PE room and then be shielded by a lead chamber to reduce the neutron and gamma background from the surrounding. The materials of the shields, the stainless steel of the inner cylinder of the LAr Dewar and a 30-mm layer of copper with high purity wrapping the inner cylinder are deliberately selected; so, the background radiation coming from the shields and the apparatus are reduced to a very low level and can be evaluated from the measurements of the selection process.

### 2.1 The Cryogenic System

The CDEX-10 cryostat system is a bath-type cryostat cooled by liquid argon in which the pPCGe array is completely immersed. A cartoon and a CAD drawing of the cryostat system are shown in Fig. 1 [16] and Fig. 2, respectively. The basic constituents of the cryogenic system are the cryostat, the LAr storage tank and the cooling system. The

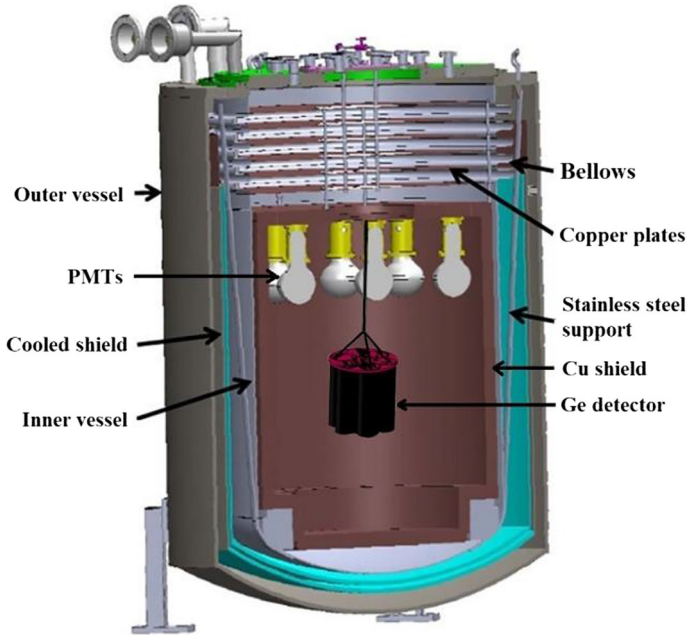


**Fig. 2** A CAD drawing of the top view of the CDEX-10 setup. 1—The cryostat; 2—the LAr storage tank; 3—the cooling system; 4—the shield with Cu and Pb (Color figure online)

equipment will be finally mounted in CJPL with dimensions of 6 m \* 4 m \* 3.6 m (length \* width \* height).

## 2.2 The Cryostat

The basic components of the cryostat are shown in Fig. 3, consisting of an outer vessel, cooled shield, an inner vessel and service tower and piping to make a closed thermo-siphon loop. The dimensions are introduced in Table 1. The total mass of the cryostat system is about 6 t after filling with LAr. The Cu shields and the inner vessel are hung vertically by six stainless steel supports because of its excellent tolerance of the stretch and the thermal performance at low temperatures. A big bellow is installed to compensate the thermal contraction and reduce the heat conduction from the room temperature flange. Five layers of copper plates are installed on the top of the inner tank to prevent the convection of argon. The cooled shield wrapped with 40 layers of superinsulation is designed as an interlayer that surrounds the inner tank except the top and acts as an active-cooled LAr shield technique for the inner vessel. Liquid argon is filled in the interlayer. Then, the temperature of the thermal shield and the inner tank is the same; so, the heat radiation from the outer tank to the inner tank can be reduced maximally.



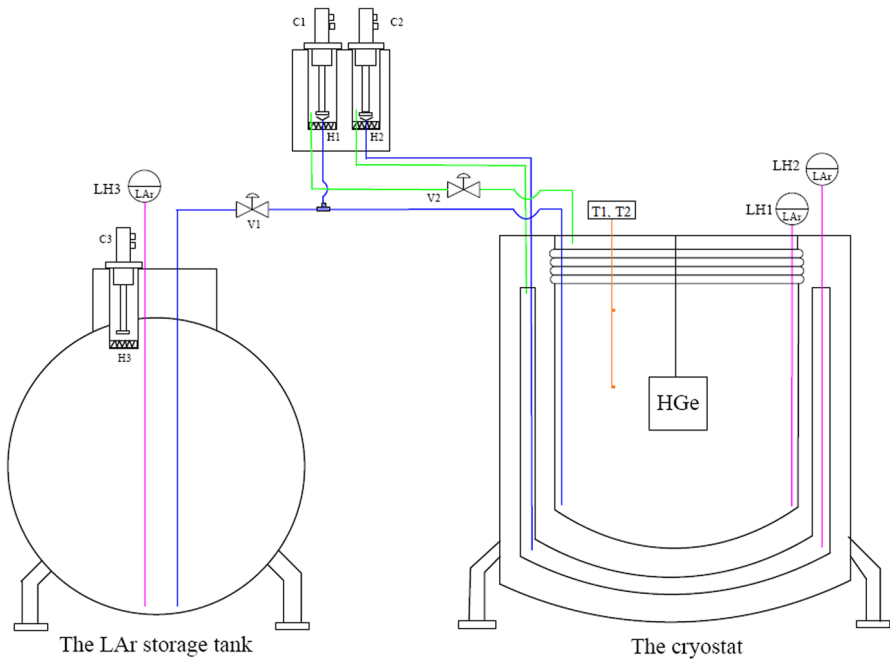
**Fig. 3** The cutaway view of the cryostat (Color figure online)

**Table 1** Parameters of the LAr cryostat components

Items	Diameter (mm)	Height (mm)	Thickness (mm)	Weight (kg)	Material
Inner vessel	1100	1740	6	302	304 L
Outer vessel	1550	2050	15	1398	304 L
Outer tube of cooled shield	1386	1473	6	878	304 L
Inner tube of cooled shield	1348	1445	6		
Cu shield	1100	1300	30	1520	High-purity copper

All materials used for the cryostat must pass a very stringent test on their intrinsic radioactive impact. The inner vessel, outer vessel and cooled shield are made of 304 L stainless steel, the radioactivity of materials in the stainless steel to be  $<0.00124$  Bq/kg for  $^{238}\text{U}$ ,  $<0.006$  Bq/kg for  $^{232}\text{Th}$ ,  $<0.013$  for  $^{40}\text{K}$ ,  $<0.002$  for  $^{60}\text{Co}$  [17]. A Cu shield at the inside wall of the inner vessel will stop radiation from the steel, the copper purity up to 99.995%, and the radioactivity caused by other impurities can be neglected. Table 1 summarizes the detailed dimensions of the components of the cryostat system.

The inner pressure of the LAr Dewar is 0.15 MPa, which is determined by the pressure tolerance of the glass surface of the PMT used to collect the light generated in the ionization–recombination process due to the recoils inside the LAr. The LAr height should at least be 1.3 m to totally immerse the pPCGe array. There is still a



**Fig. 4** Simplified flow scheme of the cryogenic system. *C1*—the cooler for the inner vessel; *C2*—the cooler for the cooled shield; *C3*—the cooler for the storage tank; *T1* and *T2*—the temperature sensor for the inner vessel (upper is *T1* and lower is *T2*); *LH1*, *LH2* and *LH3*—the LAr level for the inner vessel, the cooled shield and the storage tank, respectively; *V1* and *V2*—the cryogenic valve in the transport line; *H1*, *H2* and *H3*—the heaters on the *C1*, *C2* and *C3*, respectively (Color figure online)

room with height 400 mm above the LAr filling with argon gas. This gaseous space serves as a thermal barrier between the LAr and the cover of the inner vessel. Two groups of temperature gauge with each group including two sensors are mounted in the inner vessel to monitor the temperature. One group is mounted at the center plane of the pPCGe. The temperature is labeled as *T1*. The other one is mounted about 4 cm above the LAr surface to monitor the temperature *T2* close to the PMT. The gauge positions are illustrated in Fig. 4 in the orange color.

The expected temperature of *T1* and *T2* should be at 83.8 K within an error of 1 K in the stable operation state. The key issue in the operation of the cryostat system is the solidification of the LAr because the temperature difference between the liquid and the solid phase is only 3.29 K which makes the phase transition from the liquid phase to the solid phase hard to control. The solidification of the LAr due to the overcooling could result in permanent damage of the PMTs. So, the precise measurements and careful control of the temperature of the cryostat system become necessary in avoiding the rapid temperature variation in the whole system. The cold head temperature is kept constant at around 87.38 K by using a heater attached on the cold head. At this temperature, the argon vapor pressure is 1.02 bar, a sub-cooling condition is provided with 1.5 K below the equilibrium temperature, and gas bubbles formation will be prevented.

### 2.3 The Cooling System

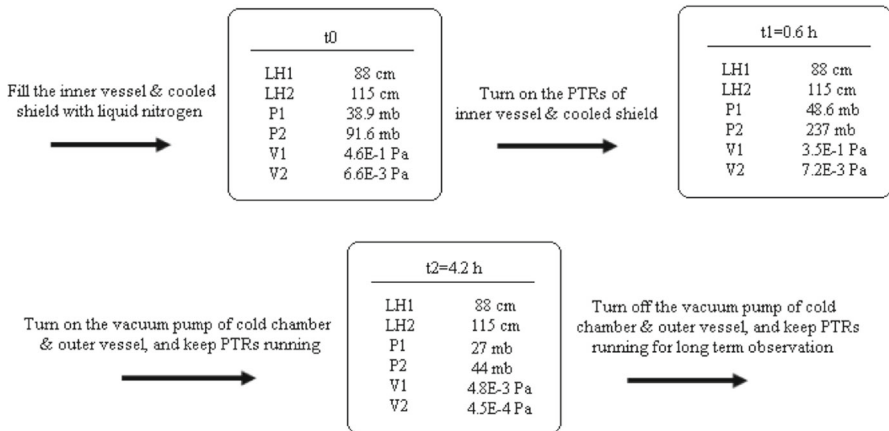
The cooling system is based on three Pulse Tube Refrigerators (PTRs) to form the argon recycling system. There are two PTRs housed in a cold chamber, used to achieve the zero boil-off condition of the cryostat. One of the PTRs is connected to the inner vessel, and the other one is connected to the cooling shield as shown in Fig. 4. The cooling power is about 90 W at 80 K driven by a 6-kW helium compressor to meet the heat load. The cryocooler of the cooling system is installed outside the inner chamber to reduce the risk of contaminating the circuits and the LAr in the inner vessel during the annual maintenance work on the refrigerator. The evaporated argon gas is guided into the re-condenser connected to the cold stage of the pulse tube cryocooler through a valve on top of the inner vessel, and then, the LAr flows through a tube to the stainless steel vessel after being liquefied. The vibration induced by these PTRs is also an energy source. So, the PTRs are installed outside the inner chamber. The stainless steel bellow in the transport line is also used to reduce the vibration and to balance the thermal contractions.

### 2.4 Heat Loads

In order to realize a zero boil-off mechanism, it is a key objective to minimize the environmental heat leak and thus minimize active cooling power requirements. The steady-state heat loads of the cryostat, both radiative and conductive, are driven by the temperature difference between the vacuum vessel and the inner vessel. One important source of the heat is the radiation propagating from the laboratory to the inner vessel. In this experiment, after the liquid argon was filled into the cooled shield of the cryostat, the active-cooled LAr shield technique can intercept the heat radiation about 10 W. The bellow pipe is employed to further reduce the heat flow from the room to the inner vessel. The total heat loads to the PTRs are summarized in Table 2.

**Table 2** Heat loads to the first and second stages of PTRs

	C1 (W)	C2 (W)
Radiation via superinsulation or the top of the inner vessel	0.60	10.70
Heat conduction via support rods	0.20	0.15
Heat conduction via the bellow wall and the vapor column	16.50	0
Heat conduction via signal cables	10.90	2.50
Heat transfer via cryogenic pipes	5.20	6.50
Heat transfer valves	2.50	2.50
Heat transfer via PMTs	2.00	0
Others	4.50	3.65
Total	42.40	26.00
A safety factor	1.5	1.5
The calculated heat loads	63.75	39



**Fig. 5** Operation flowchart of the cryogenic system. LH1—the liquid level of inner vessel; LH2—the liquid level of cooled shield;  $P_1$ —the pressure of inner vessel;  $P_2$ —the pressure of cooled shield;  $V_1$ —the vacuum degree of cold chamber;  $V_2$ —the vacuum degree of outer vessel

### 2.4.1 The LAr Storage Tank

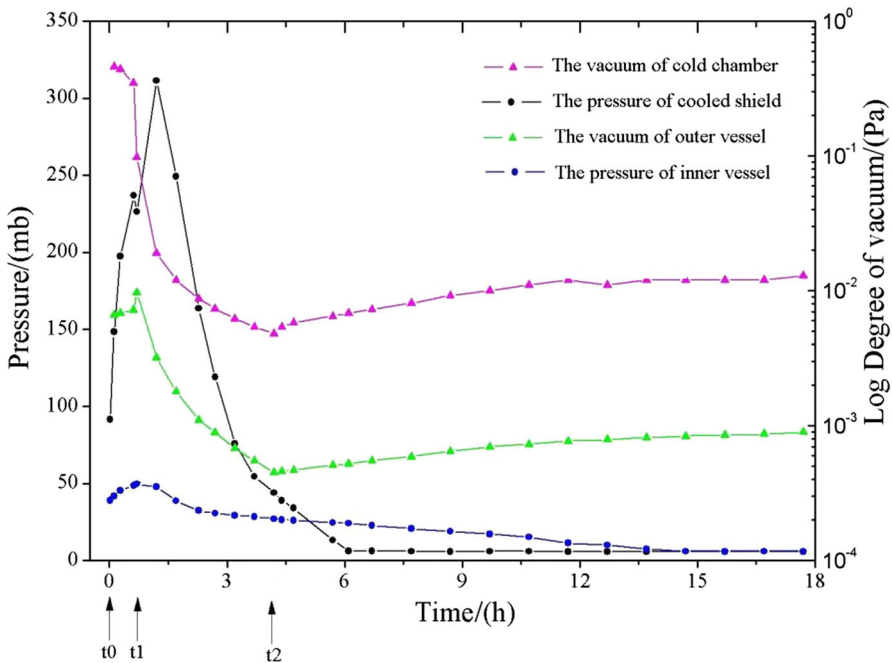
The purpose of the LAr storage tank is to store about 2000 L liquid argon and keep the pressure inside the tank at 1.02 bar. The estimated heat load of the storage tank is about 82 W with a safety factor of 1.5, including the radiation via 40 layers of superinsulation, the conduction heat leakage through the signal cables, etc. The LAr storage tank is for temporally storing the LAr from the cryostat system when the detectors in cryostat system are in maintenance; meanwhile, it also serves as a quick recovery tank in emergency.

## 3 The Performance of the Cryogenic System

The liquid nitrogen is used in the stability test of the whole cryogenic system considering its low price and property which is similar to the LAr. Such extremely low temperature is a great challenge for the stable operation for a long term. The performance of the cryogenic system under such ultimate temperature condition can provide criteria to us for evaluating the stability of the system. Figure 5 shows our main operation in the test.

In the test, the inner vessel and cooled shield have been filled with liquid nitrogen to the height of 88 cm and 115 cm, respectively. The valves which connect the inner vessel and cooled shield are kept open in the whole filling process for safety. After the filling process (the time is labeled as  $t_0$  in Figs. 5, 6), the vacuum degrees of cold chamber and outer vessel are 4.6E-1 Pa and 6.6E-3 Pa and the temperature of  $T_1$  and  $T_2$  are  $-196 \text{ }^\circ\text{C}$  (77 K). The pressure of both inner vessel and cooled shield increased as soon as we turned off the valves after the filling process because of the evaporation of liquid nitrogen. The inconspicuous decrease in the vacuum of the cold chamber and outer vessel is attributed to the cooling of the inside surrounding. The

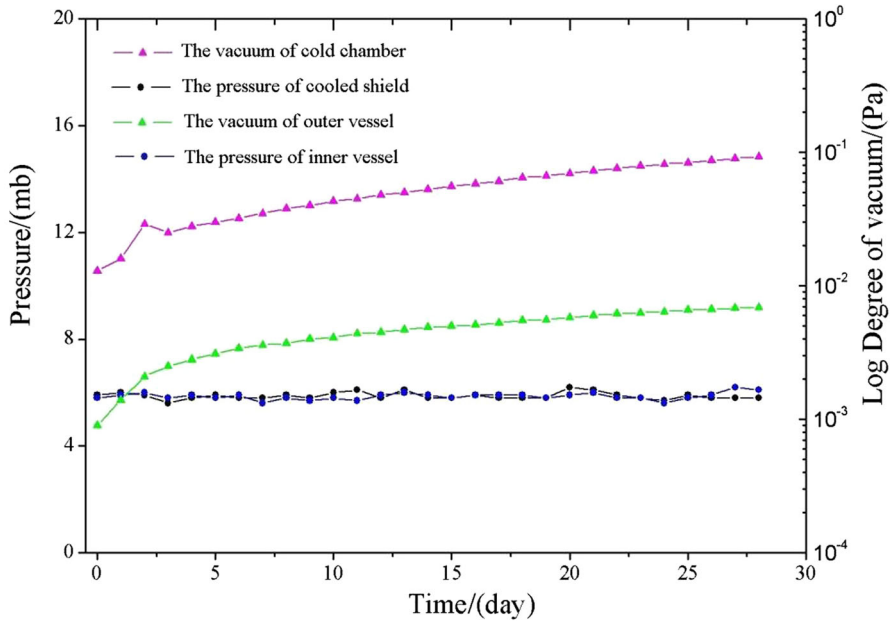




**Fig. 6** Testing performance of CDEX-10 cryogenic system. In this figure,  $t_1 = 36$  min,  $t_2 = 4.2$  h (Color figure online)

PTRs of inner vessel and cooled shield are turned on after turning off the valves, and then, the cooling system comes into operation. The pressure values of the inner vessel and cooled shield are recorded as 48.6 mb and 237 mb after 36 min, which does not satisfy the requirements of the design. So, the outer vessel and cold chamber are vacuumed simultaneously to study the influence of the vacuum degrees of the outer vessel and the cold chamber to the pressure of the inner vessel and the cooled shield we vacuumed. The change in the pressure of these four parts is shown in Fig. 6. The better vacuum of the outer vessel and the cold chamber is due to the vacuum system. The decreases in the pressure of the inner vessel and the cooled shield, which reduces the heat exchange between inner vessel, cooled shield and outer surrounding, were attributed to the vacuum increase in the outer vessel and the cooled chamber. So, it makes sense to believe that the vacuum degrees of the cold chamber and the outer vessel play key roles in making the cryogenic system stable.

The vacuum system is turned off after running the whole system for 4.2 h. The change in the pressure is shown in Fig. 7. From the tendency of the pressure change, we believe that the stability of the cryogenic system is as good as expected. The pressures of the cooled shield and the inner vessel are maintained at about 6 mb during the test. The vacuum degrees of the cold chamber and the outer vessel deteriorate uniformly. The liquid levels of the inner vessel and the cooled shield are the same in the testing period. The temperatures of  $T_1$  and  $T_2$  are stable in the test.



**Fig. 7** Pressure and vacuum change in CDEX-10 cryogenic system in long-term operation (Color figure online)



**Fig. 8** The cryogenic system of CDEX-10 (Color figure online)

The cryogenic system has been operated continuously in a stable state for 29 days. Figure 7 shows that the pressure values of the cooled shield and the inner vessel are maintained at about 6 mb. The change in the vacuum degrees of the cold chamber and the outer vessel is  $2.0 \times 10^{-3}$  Pa/day and  $3.0 \times 10^{-4}$  Pa/day, respectively. The liquid levels of the inner vessel and the cooled shield are stable in the 29 days running. The temperatures of  $T_1$  and  $T_2$  remain at  $-196$  °C after the filling process (labeled as  $t_0$  in Fig. 6). So, we believe that the system satisfies the experimental requirements of

the pressure and the temperature. Further tests using liquid argon as the medium are necessary in the future.

## 4 Conclusion

A reliable and stable cryogenic system has tremendous significance to the CDEX-10 experiment since the variation of the temperature or the pressure around the detectors can be reflected to the change of the light yield of liquid argon and the change of the gain factor of the PMTs. In other words, a stable and accurate zero boil-off LAr system is fundamental and necessary for CDEX-10; otherwise, it will spoil the accuracy of the experimental results. Figure 8 shows the photograph of the cryogenic system in Sichuan University. As can be seen from the test, the whole system can successfully fulfill the requirement of the dark matter searching design criteria that can keep the liquid nitrogen temperature at  $-196\text{ }^{\circ}\text{C}$  and stable within 1 K during the long-period operation, also the pressure of cooled shield and inner vessel maintained at about 6 mb. Further improvement in the cryogenic system will depend on the suggestions of the operators in the further experiments in the underground laboratory.

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