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Leak test for liners of muon detectors of LHAASO

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Muon detector (MD) is water Cherenkov detector in Large High Altitude Air Shower Observatory (LHAASO) experiment. The liner is applied to seal 44 tons of ultra-pure water, which is the major detection media of MD. The liner must protect the water from contamination and inhibit bacteriological activities. The MD conducts a long duration mission (20 years), so any small leak would have severe consequences. The purpose of this paper is to introduce leak test for liners of MDs. A new method of SF_6 tracer gas leak test is proposed by using a SF_6 quantitative determination leak detector with high concentration sensitivity (0.01ppm). This method has quick response time and high sensitivity to detect small leak. Since 2018, 300 MDs have been installed, and no leakage has been found till now.

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1. Introduction

The Large High Altitude Air Shower Observatory (LHAASO)[1] is a large hybrid extensive air shower(EAS) array with an area of about 1km^2 at an altitude of 4410m a.s.l. in Sichuan Province, China. LHAASO consists of a Kilometer-square Array (KM2A), a water Cherenkov Detector Array (WCDA) and a Wide-field Cherenkov telescope Array (WFCTA), and its aim is to study the spectrum, the composition and the anisotropy of cosmic rays in the energy range between 10^{12} and 10^{18}eV, as well as to act simultaneously as a wide aperture, continuously-operated gamma ray telescope in the energy range between $10^{11}$and 10^{15}eV. The experiment will be able of continuously surveying the TeV sky for steady and transient sources from 100 GeV to 1 PeV, thus opening for the first time the 100-1000 TeV range to the direct observations of the high energy cosmic ray sources[2].

The whole KM2A array is composed of 5195 electromagnetic detectors (EDs) and 1171 muon detectors (MDs). KM2A focuses on γ-ray astronomy above 20TeV and cosmic ray physics in the knee region [3]. EDs can accurately measure the arrival time and density of the second particles of primary cosmic ray or γ-ray induced shower. MDs are covered by an overburden of 2.5m soil, and detect the muons, which are used for primary component discrimination between γ-ray and cosmic ray background, or among different cosmic ray nuclei. Due to the powerful γ/p discrimination ability, the sensitivity of KM2A for γ-ray source is much improved at energy above 20 TeV and is $\sim$ 1% of the Crab nebula flux in the energy range of 50 -100 TeV for one year observation[2], which will be crucial to identify cosmic ray Pevatron sources[3].

The MD is water Cherenkov detector. The liner which forms a cylinder with diameter of 6.8m $\times$ height of 1.2m is used to enclose ultra-pure water. An 8-inch PMT sits at top center of the liner and is optically coupled to a high transparent window using an optical coupling compound. The liner is mechanically supported by the MD tank and surrounded with the thermal layer. The liner is made of multi-layer as below (Fig. 1): the inner layer is a composite film of two sheets of DuPont Tyvek 1082D and a sheet of PE, which has an excellent diffuse reflectivity of Cherenkov light; one middle layer is two independent sheets of LDPE, which seals the ultra-pure water; the other middle layer is two independent sheets of EVOH, which is an excellent oxygen barrier; the outer layer is PE woven cloth, which protects the whole inner layers.

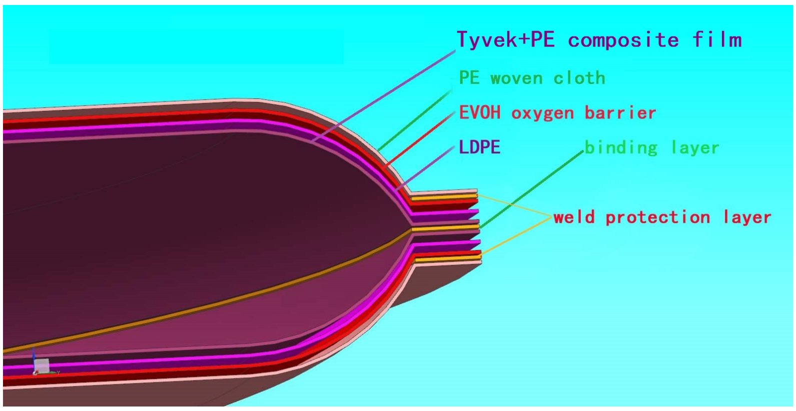

Figure 1: The components of the liner

The liner is applied to seal 44 tons of ultra-pure water, which is the major detection media of MD. In order to keep a long attenuation length for Cherenkov light, the liner must protect the water from contamination and inhibit bacteriological activities. During the data taking, any small leak would have severe consequences and may lead to failure of muon detection. Before installation, each liner must be strictly checked to identify leaks as early and reliably as possible.

2. Leak rate calculation

The liner provides a 20 year seal for 44 tons of ultra-pure water, high reflectivity of Cherenkov light. The sealing requirement is that the water level declines no less than 10% of the total height in ten years, then the water leak rate can be obtained as below:

$$Q_w = \frac{\Delta V}{\Delta t} \tag{2.1}$$

where ΔV is the total volume of water leakage ($4.356m^3$), Δt is 10 years. The average maximum allowable leak rate Q_w is $1.38 \times 10^{-5} L/s$. The leak rates scale inversely with the dynamical viscosity of the gas or liquid, from Hagen-Poiseuille equation, an air leak rate is larger by the factor $\sim$ 56 than that of water when it is measured near atmospheric pressure, thus Q_{air} is $7.728 \times 10^{-4} L/s$.

The gas leak rate is usually defined as below:

$$Q_g = V\frac{\Delta P}{\Delta t} \tag{2.2}$$

where V is the volume of the system, ΔP is the gas pressure loss of the system. Δt is the leak test time. If the volume of the liner remains unchanged, according to the ideal gas law, the gas pressure is directly proportional to the number on moles of gas. At the beginning the difference of the gas pressure inside and outside of the liner is 12KPa, the maximum allowable gas leak rate Q_g is $1.66 Pa \cdot L/s$ from the formula 2.2, .

The liner volume V is $43.56m^3$, $Q_g = 1.66 Pa \cdot L/s$, if the leak test time Δt is $24 hours$, then the pressure difference ΔP is 3.29Pa. The gas pressure can vary $\sim$100Pa because of the air temperature variation in a day, so the temperature variation could easily mask the effects of a small leak, and the pressure decay test method is not suitable to find very small leakages.

3. Leak test

Sulfur hexafluoride (SF_6) is widely used as a tracer gas because of its detectability at low concentrations. This attribute of SF_6 allows the quantification of both small-scale flows, such as leakage, and large-scale flows, such as atmospheric currents. SF_6's high detection sensitivity also facilitates greater usage efficiency and lower operating cost for tracer deployments by reducing quantity requirements[4].

There are two ways to carry out leak test with tracer gas: external detection of tracer gas escaping from leaks of a filled system (inside-out method), and internal detection of tracer gas entering a system to be tested from leaks (outside-in method). The inside-out methods can be executed with atmospheric sniffing or with vacuum chamber detection, while the outside-in method is generally implemented by putting the system to be tested in a room containing the tracer gas or, very rarely, spraying the tracer gas on the system surface. Because the concentration of SF_6 in the atmosphere is very small, about 3.2 parts per trillion by volume (pptv), the inside-out method is adopted and some leak tests are done with liners of small size.

Figure 2: Left : Prototype of the liner. **Middle :** Bag with single LDPE film. **Right :** SF_6 gas leak detector.

The bag with a leak of $\sim$ 0.1mm size is placed in an enclosed room, the SF_6 concentration of the room is the same as that in the atmosphere, then the bag is pressurized with the tracer gas SF_6. Within 30 minutes, SF_6 is detected by the gas sensor. The leak tests are repeated several times and all the measurements are in good agreement. Fig. 2 shows the bags and the gas leak detector. The gas leak detector has high accuracy, sensitivity (0.01ppm), and stability, and the response is instantaneous with quick recovery from exposure to high concentration of tracer gas.

In the "inside-out" leak test, assuming that the concentration of the tracer gas in the test system C_{tg} remains the same[1], the rough estimate of the leak concentration is

$$C = \frac{Q \times \Delta t \times C_{tg}}{V} \tag{3.1}$$

where Q is the leak rate of the test system, Δt is the time of the leak test, V is the volume of the sealed outside space. For MD liner, according to the leak rate calculation in section 2, the maximum allowable Q_{air} is $7.728 \times 10^{-4} L/s$, the allowable concentration standard ($<$ 9.5ppm) is obtained under these test conditions : the volume of the sealed cover is about 20000L; the volume of the liner filled with air and gas of SF_6 is about 2500L, in the liner the concentration of SF_6 is 12%; the leak test time Δt is 30 minutes.

The leak test procedures are:

1. Check the environmental conditions and check the SF_6 concentration in the test room, temperature and so on.
2. Put the liner in the sealed cover and check the SF_6 concentration in the sealed cover.
3. Fill the liner with air and SF_6 gas, and check the SF_6 concentration in the sealed cover.
4. Record the SF_6 concentration in the sealed cover every ten minutes, and monitor the concentration over time.

Fig. 3 left shows the liner is placed in a sealed cover, and Fig. 3 right shows the gas sensor is measuring the concentration of the sealed cover.

[1] If the leak test time is short and the leak is small, this assumption is reasonable.

Figure 3: Left : The liner is placed in a sealed cover. **Right :** The gas sensor is measuring the concentration of the sealed cover.

Table 1: The relationship of the concentration and the readouts of the gas sensor.

unit [ppm]	0.01	0.1	1	10	100	1000
baseline 25	28	38	58	120	159	182

During the test, one liner center flange screws were not tightened, which resulted to the increase of the SF_6 concentration in the sealed cover in a short time, and the leak detector alarmed immediately. Again this accident shows the SF_6 tracer gas leak test is a highly efficient method to find very small leaks.

4. Results

Till May 2019, 468 liners have been tested. The readouts of the gas sensor are shown in Fig. 4. The relationship of the concentration and the readouts of the gas sensor is shown in Tab. 1. Since 2018, 300 MDs have been installed, and no leakage has been found till now.

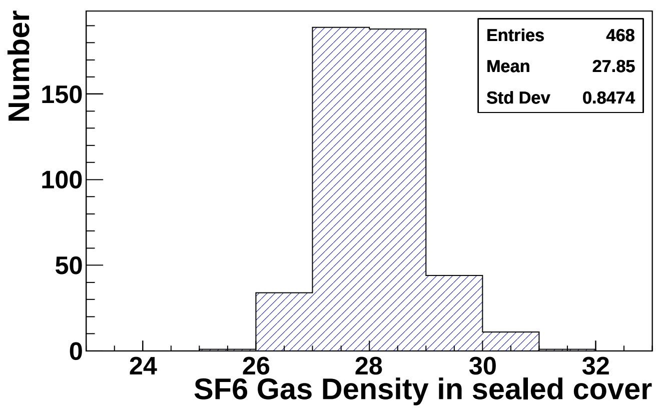

Figure 4: Leak test results

5. Conclusion

A leak test method for MD liner is successfully developed, and it is high precision and sensitivity to detect small leaks.

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