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Automatic detection device for the absorption length of water measured by reflection cavity

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Water serves as a key medium for the water Cherenkov detector, and the water absorption length significantly affects the efficiency of the detectors. The water absorption length represents the distance traveled by 1/e of light intensity attenuation due to the absorption of photons in water, representing the cleanliness of the water. It is a great challenge to measure or monitor the water attenuation length accurately at home and abroad. A method, like the integrating cavity ring-down spectroscopy is described in this paper, which could reveal the water absorption length and the reflectivity of the material at the same time. Based on it, an automatic detection device was designed and installed. A cylindrical cavity covered with highly reflective materials on the inner wall was employed to load the water. A cover is designed which can be controlled by a stepper motor to change the depth of water in the reflective chamber by moving the position of the cover, and at the same time sealing the reflective chamber by using the variable air pressure of the tires. The light provided by a pulse-twinkled LED was injected into the cavity, and the data was recorded by a fast photomultiplier tube(PMT). Finally, the collected waveforms of PMT at different water depths of the cavity were analyzed to get the absorption length of water and the reflectivity of the inner wall.

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1. Introduction

When high-energy cosmic rays and gamma rays enter the atmosphere, they cause a chain reaction of particles known as the extended air shower[1]. These showers' features can be used to determine the kind, energy, and direction of the primordial cosmic ray particle[2]. The relativistic particles in the shower emit Cherenkov light as they travel through some medium such as water. The water Cherenkov detectors contain some tanks filled with water observe the Cherenkov light produced by particles from the shower as they pass through the water. Many large organizations have built water Cherenkov detectors globally, such as the High-Altitude Water Cherenkov Gamma-ray Observatory(HAWC), the Cosmic Ray Research Institute of the University of Tokyo in Japan[3], and China's Large High Altitude Air Shower Observatory (LHAASO)[4]. The measurement of water absorption length is important for these experiments because it significantly affects the efficiency of the detectors.

In this paper, we describe our experiment to measure water absorption length with reflective cavity. The cylindrical cavity with high-reflectivity diffuse reflective material is designed and filled with water as the detection medium. There is a PMT on the upper surface of the reflection cavity. When the continuous pulse of light from the LED enters the water, the photons are reflected by the diffuse reflective material some times and received by the PMT. It is necessary to change the different depths of the water, and by analyzing and processing the waveforms of the signals obtained from the different depths of the water, the exact value of the water attenuation length can be known. An automatic device was designed to simplify the above experimental process. The designed automatic device is integrated from the hardware side, and the individual modules are controlled with the LabVIEW program. Automation is significant for the process of measuring the water absorption length. As the equipment matures, it will enable all-day water quality monitoring and has the potential to play a better role in the areas of water quality and air pollution.

2. Method

Water as the key detection medium of the water Cherenkov detector array directly affects the efficiency of the detector. The greater the water decay length indicates better water quality. The international measurement of water absorption length is divided into two methods. One is the direct measurement method, by measuring the attenuation of the optical signal at different water levels to determine the attenuation length of water[5]. The second is the indirect measurement method, that is, through the amount associated with the attenuation length to invert the value of the water attenuation length. Although the direct measurement method is straightforward, the signal attenuation of light in water is very small, and the experiment requires effective detection of small signals and control of errors within a very small range, which is difficult to achieve for the measurement[6]. The integrating cavity technique is, however, considerably simpler to implement. An integrating cavity is essentially a closed container with a very high diffuse reflectance on its interior wall.

The device designed in this paper is a cylindrical reflective chamber with a double layer of PE reflective material on the inner wall, which has a reflectivity of 95%. A PMT and LED are installed on the top of the reflective chamber, and the collected signal waveform is displayed and collected by an oscilloscope. According to the entire absorption effect in the reflective cavity, we define λ_m as the effective attenuation length of photons in the reflective cavity, τ as the effective absorption time, and x as the propagation distance of photons in the tank[7]. The effective attenuation length λ_m is obtained by multiplying the time τ and the speed of photon propagation through the water.The decay process of the number of photons N_0 in the reflecting cavity can be expressed as $N_0 \times e^{(-\frac{x}{\lambda})} \times f^{\frac{x}{L}}$ and $N_0 \times e^{-\frac{x}{\lambda_m}}$, respectively. Let the two equations be equal and transform mathematically to get $\lambda_m = 1/\left(\frac{1}{\lambda} - \frac{\ln(f)}{L}\right)$. The average reflection step of a photon (L) is determined by the shape and structure of the reflective cavity[8], so the water attenuation length (λ) and the reflectivity of the material (f) can be obtained from these two equations. In the experiments of this paper, the desired λ and f can be obtained by varying the height of the cylindrical reflection cavity.

3. Design and Experiment

3.1 System overview

A system overview of the device is shown in Figure 1. The whole system can be divided into three modules to realize automatic control. The automated lift module allows the volume of the reflective chamber to be changed by varying the height. The lid is connected to the lifting table through an adapter plate, the motion controller is connected to the lifting table through a serial line, and the motion controller is finally connected to the host computer, which is visualized and controlled by a LabVIEW program. Inflating the tires on the side of the lid to a suitable air pressure makes the reflective material affixed to the bottom of the lid more extended and flat, and also provides better shading. Once the inlet and outlet water are automated and controlled, it saves a lot of time and effort. These three modules are independent of each other and closely related and play a vital role in the experiments of this paper.

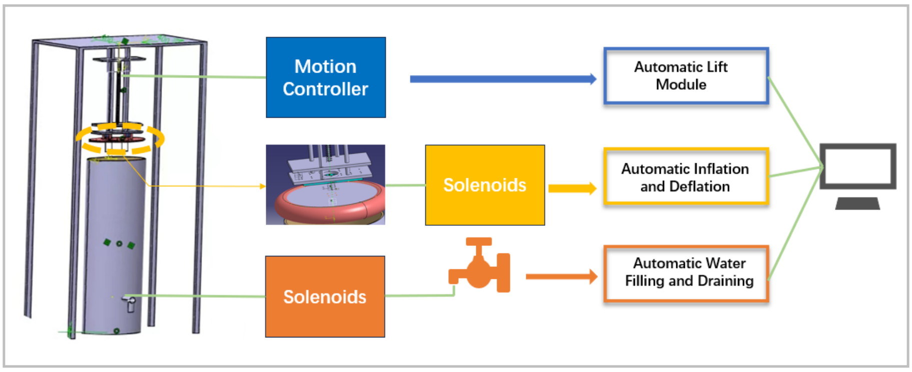

Figure 1: The system consists of three parts, from top to bottom, the automatic lifting module, the automatic filling and deflating module, and the automatic filling and deflating module. The green line indicates the connection. The motion controller and the lift table are connected with serial lines, the tires are connected to the solenoid valve with air pipes, and the bottom valve of the bucket is connected to the solenoid valve and the water inlet faucet with water pipes. The three modules are connected to a serial server to connect to the host computer.

On the far left is the main body of the device, which contains an aluminum frame (support frame), a lifting device, a lid, and a stainless steel cylindrical barrel. The frame of the automation equipment is assembled from several individual aluminum profiles, which are easy to install and disassemble. The frame built by the aluminum profiles has crossbeams above and below fixed to the support frame by corner pieces to ensure the stability of the overall frame. A stepper motor is attached to the top of the frame, and the stepper motor is fixed to the bucket lid by an adapter plate. The two grooves on the upper surface of the lid are placed at the PMT and LED respectively, and the gap between the grooves and the PMT and LED is filled by sponge foam. The rotating groove on the side wall of the lid is fitted with a tire to ensure the tightness of the lid to the inner wall of the barrel. The aluminum profile is surrounded by a double layer of black cloth to form an optical dark room. This shields the outside light from entering the reflective chamber and interfering with the experiment.

3.2 Seal design and error analysis

The water attenuation lengths corresponding to different light leakage areas in the outermost circle of a 50 cm diameter drum were simulated by simulation. As shown in Table 1, when the tire is inflated with a gap of 0.1mm difference from the barrel edge, the difference between the actual and theoretical values of the water absorption length obtained from the fitting is so small that it hardly affects the results of the experiment.

Table 1: Water attenuation length errors corresponding to different light leakage diameters obtained from simulations

The outermost radius of light leakage	theoretical value	actual value	inaccuracies	area of light leakage
0	20	19.95	0.25%	0
0.1 mm	20	20.03	0.15%	1.57 cm^2
0.2 mm	20	20.17	0.85%	3.14 cm^2
0.5 mm	20	20.56	2.8%	7.85 cm^2
1 mm	20	21.45	7.3%	15.7 cm^2
2 mm	20	24.08	20.4%	31.4 cm^2

This simulation shows that light leakage has a huge impact on the experimental results and thus needs to be considered. So photons are required to be spilled as little as possible or confined within the slit. Considering the change of volume, thus a device with gas sealing is designed to realize the photon not leaking. Sealing the lid is relatively simple. Install tires in the side notches of the lid, and inflate the tires to the proper air pressure to support the reflective material affixed to the lid so that it extends flat. At the same time, a circle of threaded holes is designed on the top of the cover to hold the excess reflective material in place. The automatic inflation and deflation process requires a fixed air pressure each time the tire is inflated. So the digital display vehicle inflator pump is used, which can realize the automatic filling and stopping detection.

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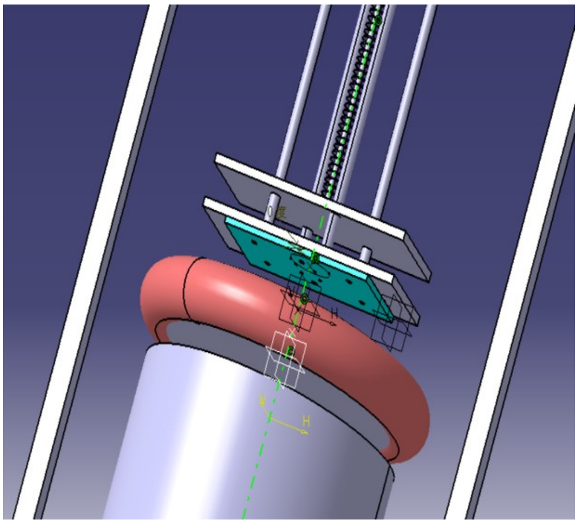

Figure 2: The detail of the sealing lid

3.3 Communication system

The communication system is shown in Figure 3. Relay 1 and Relay 2 are connected to the host computer by a serial server and fed into LabVIEW for control by the program. Meanwhile, the motion controller is also connected to the COM port of the host computer to be controlled by the LabVIEW program. During water filling, the photoelectric contact liquid level sensor continuously detects the liquid level position, and when the liquid level is detected it generates a switching signal that is uploaded to the host computer through the serial port server, and the water inlet solenoid valve is closed by the LabVIEW program.

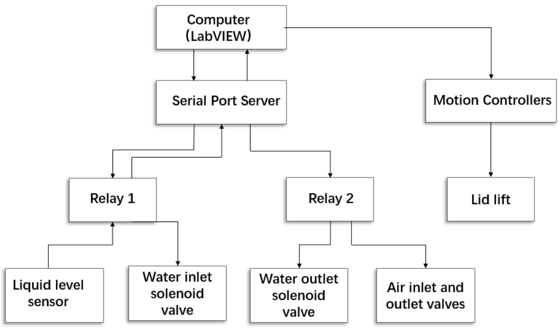

Figure 3: Communication system

The hardware of the automatic water attenuation length measurement system is divided into two parts, the first part is the basic circuit hardware with AC 220V to DC 24V switching power supply, AC 220V to DC 12V power adapter and relay, and the second part is the selection of the instruments in the device including the water solenoid valves, air valves, level sensors, motion controllers, water pipes and others.

Relay 1 is an IO control module serial relay with 4 switching inputs and 2 outputs, the communication interface is RS485, and the operating voltage is 24v DC. The input of relay 1 is whether the liquid level sensor touches the liquid level, and the output of the two states is used to control the switch of the water inlet solenoid valve. Relay 2 is equivalent to a switch in the circuit, controlling the solenoid valve on and off, and also operates at 24 V DC voltage and uses RS485 communication. When filling stainless steel drums with water, the liquid level needs to be measured in real-time for feedback, and the selection of the liquid level sensor becomes particularly important.

3.4 Experimental procedure

The flow chart of the automated water attenuation length measurement device is shown in Figure 4.

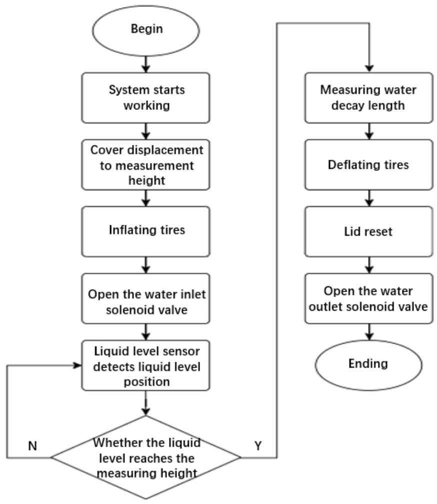

Figure 4: Flow chart of automatic water attenuation length measurement device

Before the equipment starts working, utilize the adapter plate to secure the stepper motor and cover together. When the equipment starts to work, the lift of the lid is first controlled by the LabVIEW program, and after controlling the displacement of the lid to the desired experimental height, the air inlet valve is opened to fill the tires to the set air pressure. Then open the water inlet solenoid valve to fill the stainless steel cylindrical drum with water, the liquid level sensor continuously monitors the liquid level position during the filling process. When the liquid level sensor touches the water, close the water inlet solenoid valve to stop water injection. After letting the water in the stainless steel bucket stand for a while, the experiment was started. LED continuously emits pulsed light, and the photons enter the water and undergo a series of reactions before being received by the PMT, which displays the received signals on an oscilloscope and acquires them as .txt files for subsequent data analysis. After the data is collected, open the air outlet valve to expel the gas in the tire and then reset the cap to the starting position. Finally, open the outlet solenoid valve to drain the water. The experiment needs to measure the experimental data of different water depths, so the above process needs to be repeated several times to get multiple sets of data of different water depths for data analysis and processing to get the desired water attenuation length. In fact, before measuring the water attenuation length, it is necessary to flush the reflective chamber with water several times, which removes impurities and ensures the consistency of the measured medium under multiple measurements.

4. Preliminary experimental results

The time distribution of photons hitting the PMT from each simulation was fitted with the formula $N_0 \times e^{-\frac{t}{\tau}}$, and the effective attenuation length was obtained by multiplying τ by the velocity of the photon. The wavelength of the LED in the experiment is 560 nm, the inner wall of the stainless steel cavity is completely covered by PE material with 95% reflectivity, and the height and diameter of the stainless steel cylindrical cavity are already known. Therefore, according to $\lambda_m = 1/\left(\frac{1}{\lambda} - \frac{\ln(f)}{L}\right)$, the attenuation length of the water can be deduced from the effective attenuation length obtained from the fit. The graph below shows the effective attenuation length measured with distilled water at a depth of 40 cm.

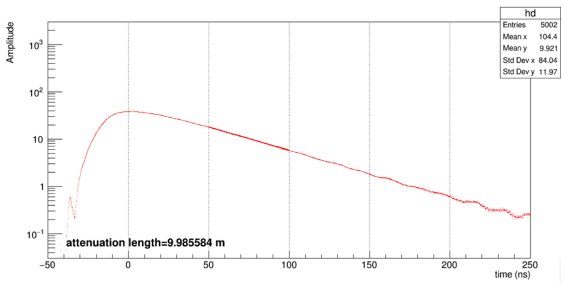

Figure 5: Fitted water attenuation length at a water depth of 40 cm (Fitting interval from 50 ns to 100 ns)

As can be seen from Figure 5, at first the intensity of the signal increases with time, but it is completely randomized when the photons are reflected many times in the reflective cavity. After the average step size of the photons stabilizes, the signal of the PMT starts to show an exponential decay with time. The starting time of the fitting interval is chosen to be 50 ns because it takes some time for the photons to be completely randomized after entering the reflective cavity. A fitting interval of 50 ns to 100 ns was chosen in the figure to obtain the effective decay length. The effective attenuation length is 9.47 m at 30 cm water depth and 10.02 m at 50 cm water depth.The results for the different fitting intervals are being further analyzed.

5. Conclusion

This article presents an automated hardware design of each module in an experimental setup for measuring the absorption length of water based on a reflective cavity. This greatly simplifies the experimental operation, the experiment can also be repeated to reduce the experimental error, as well as to improve the efficiency of the analysis. There are some errors in the value of the water absorption length, and we will continue to deepen the study of the factors affecting the water absorption length and continue to analyze and improve the error of the experiment.

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