Optimization of Dimensions and Inner Surface of Water Cherenkov Detector with one Photomultiplier Tube (PMT)

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Abstract: In order to be more precise to find primary cosmic particles directions, nowadays detectors and data analysis for studying secondary particles in extensive air showers have an ongoing progress and water Cherenkov detector is considered as a secondary particle detector. Our aim in this paper is to optimize the size and the inner surface characteristic of a cylindrical water Cherenkov tank with one PMT. By comparing simulation outputs with experiments results, we show that the diffusing inner surface is more practical than the reflective inner surface and we conclude that the optimum height for a diffusing tank with a diameter of 45cm is 60cm.

Keywords: Cosmic rays, Cherenkov detector.

1 Introduction

One way of studying sources of high energy cosmic rays (E>10^{13}eV) is using array of surface detectors for detecting secondary particles in extensive air showers. When high energy cosmic rays enter the atmosphere they produce secondary particles by interacting with air molecules. Secondary particles are detectable by an array of particle detectors. Energy, type and direction of primary particles can be determined by detecting and studying of such secondary particles [1]. Water Cherenkov detector is a kind of detector which is used in surface arrays. In this kind of detector, particles which move faster than light speed in water, emit Cherenkov photons. These photons travel on a so-called Cherenkov cone and the cone vertex angle depends on the refraction index of the medium and the speed of particle, e.g.for relativistic particle passing through the water, the vertex angle of Cherenkov cone is 41°. The water Cherenkov detector is a proper choice for a surface array because of its robustness and low cost. Furthermore, water Cherenkov detectors exhibit a rather uniform exposure up to large zenith angles and are sensitive to charged particles as well as to energetic photons which convert to pairs in the water volume [2]. Their use in surface arrays was proven to be successful in previous experiments such as Haverah Park array [3]. In order to have an affordable array for cosmic rays study, an array of four water Cherenkov detectors each one with one Photomultiplier Tube (PMT) had been made at Sharif University of Technology and 6×10^5 showers had detected by this array [4]. In order to improve count rate we decided to optimize size and inner surface characteristics of the Cherenkov tank for an individual tank at first. In next sections we explain simulation and its results, experimental arrangement, data analysis and concluding remarks respectively.

Parameter limit	Variation in each step
$0 < x < R$	5 cm
$0 < \theta < \frac{\pi}{2}$	$\frac{\pi}{10}$
$0 < \phi < \pi$	$\frac{\pi}{10}$

Table 1: Parameter limits and their variation in each step for particles which enter from upper surface. R is the radius of the tank.

Parameter limits	Variation in each step
$0 < z < H$	5 cm
$0< \theta < \frac{\pi}{2}$	$\frac{\pi}{10}$
$0< \phi < \frac{\pi}{2}$	$\frac{\pi}{10}$

Table 2: Parameter limits and their variation in each step for particles which enter from the wall. H is the height of the tank.

2 simulation

As a first step to estimate optimum size of a Cherenkov tank a primary simulation was performed [5]. After that we decided to simulate Cherenkov tank with more details. In order to simulate a cylindrical tank with diffusing inner surface along with one PMT, placed at the center of the tank's lid, we considered a Cartesian coordinate system with the PMT as its origin. We also assumed that the reflection coefficient of the inner surface is 70%. Charged particles enter the tank from the upper surface and wall of the tank. Since our experiments are performed under two concrete sealing and we want to compare the simulation results with experimental results, we assumed that the charged particles reaching the detector are muons due to small cross section of muons.

Because of azimuthal symmetry of the tank, particles entrance position for the upper surface varies along a radial line of the tank's lid (x axis) and for the wall it varies along a line parallel to z axis. Moreover from each of these positions, particles are entered into the tank with different zenithal and azimuthal angles. The range of each parameter and their variation in each step are shown in tables 1 and 2 respectively for the upper surface and the wall. In the tables R is the radius of the tank and H is the height of the tank.

By entering a charged particle in the tank, Cherenkov cone is formed and Cherenkov photons are distributed uniformly on the cone. Vertex angle of the Cherenkov cone (θ) can be obtained by the following equation:

$$cos\theta = \frac{1}{n\beta}, \quad (1)$$

where $\beta = \frac{v}{c}$ and *n* is the refraction index of the medium (water in this case).

The number of emitted photons on a track length of Δx, which their wavelength λ, lies between λ_1 and λ_2 can be calculated using the formula below [6]:

$$N = 2\pi\Delta x(\frac{1}{\lambda_1} - \frac{1}{\lambda_2})(1 - \frac{1}{n^2\beta^2}), \quad (2)$$

λ_1 and λ_2 are set to be 300nm and 500nm respectively. In each 1cm step of particle's path, Cherenkov photons are emitted and particle's energy is decreased by an amount of 2MeV. 2MeV is the average energy loss of minimum-ionizing particles in water [6]. According to equation 1 and 2, as a result of energy loss and decreasing of β respectively the vertex angle of the Cherenkov cone and number of emitted photons decrease. When particle's energy becomes less than the Cherenkov radiation threshold, we won't follow it anymore. In each 1cm step of photons path, the code checks if one of the following conditions have happened:

1. The photon is absorbed by water.
2. The photon reaches the wall or the bottom of the tank. (it then reflects in a diffusing pattern)
3. The photon reaches the PMT.

Finally the number of Cherenkov photons and the time which they have reached the PMT are recorded.

To determine the PMT's field of view or in another word the optimized diameter of the tank, particles are entered from the upper surface of the tank with different diameters and various heights. Number of detected photons for different diameters are shown in Fig.1. This Fig indicates that the optimum diameter is 40cm. Fig.2 shows the number of detected photons versus height of the tank with diameter 40cm. In this Fig, it can be seen that at the height of 60cm number of detected photons gets a maximum. These results are completely consistent with the earlier simulation.

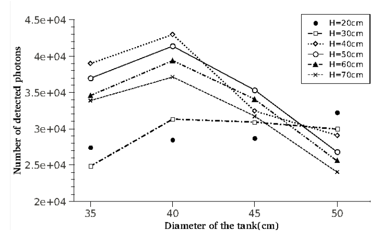

Figure 1: Number of detected photons versus tank diameter for different heights of water.

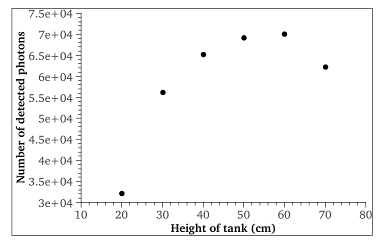

Figure 2: Number of detected photons versus height of the for tank with the diameter of 40cm.

3 Experimental Arrangement

Because of problems in making a cylindrical PVC tank with a diameter of 40cm, we preferred to buy a premade tank with a diameter of 45cm and height of 70cm which was available in market. The inner surface of the tank was optically sealed and covered with white paint which reflects light in a diffusing pattern. The outer surface was painted in black for better optical sealing.

To find the optimum height of the purchased tank we ran the simulation for a tank with a diameter of 45cm. Fig3 shows number of detected photons versus height of the tank. This Fig indicates that the optimum height of the tank with the diameter of 45cm is also 60cm. For further comparison Fig.4 shows number of detected photons when particles enter from the wall of the tank at different heights.

We filled the tank with distilled water and then changed water height from 20cm to 70cm (in each step we increase the water height by 10cm). For studying the characteristic of the inner surface of the tank we covered the inner sur-

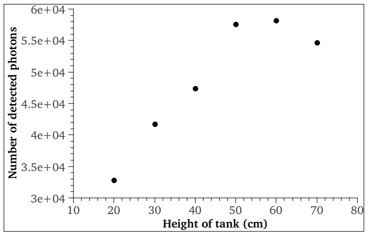

Figure 3: Number of detected photons versus height of the tank for tank with the diameter of 45cm.

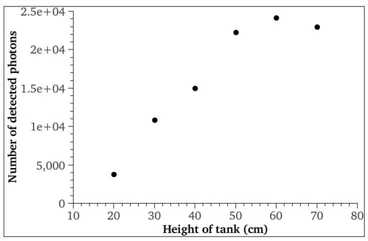

Figure 4: Number of the detected photons when particles enter from the wall of the tank for different heights of the tank.

face with stainless steel sheet which is reflective and we repeated all steps of the experiment for this tank as well. One PMT is placed in the center of the lid and has this capability to be always tangent to the water surface for different height of water. In order to find the optimized height of water in the tank we used the coincidence method. Due to azimuthal symmetry we swept only some parts of the tank surface ,with a small scintillation detector ($10\times10\times1$ cm^3). Fig.5 illustrates these specific parts which was swept with scintillation detector. To record coincidence events (counts) we used the electronic circuit shown in Fig.6. As it can be seen in Fig.6 the generated signals from the Anode of scintillation detector and Cherenkov detector PMTs are connected to a fast discriminator (CAEN N473A) which its threshold was set on 50mV. The output of discriminator channel related to the scintillation detector is sent to ”start” input of a Time to Amplitude Converter (TAC, ORTEC566). Output of the other channel of the discriminator is sent to ”stop” input of TAC by a 18m cable. Finally the output of TAC which was set to a full scale of 200ns is fed into a Multi-Channel Analyzer (MCA) via an Analog to Digital Converter (ADC) unit. To study deposited energy by particles in Cherenkov tank that can be detected by PMT, the amplified PMT's Dynode signal is fed to MCA by ADC.

4 Data analysis

For both reflective and diffusing inner surfaces we changed height of water from 20cm to 70cm. For each water height

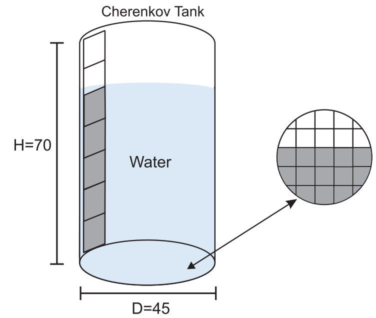

Figure 5: The places that swept by a small scintillation detector.

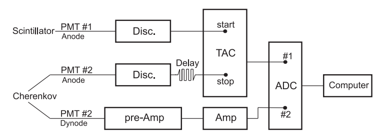

Figure 6: Schematic diagram of the electronic circuit.

we swept the tank with a small scintillation detector. To obtain total count for each specified height of water we carried out the summation on all events of coincidence of individual experiments after noise reduction. Fig.7 shows the total count versus height of water for both inner surfaces. Since the size of error bars for each data point is less than the size of the symbols used for them in all experimental plots, the error bars are omitted in these figures. Fig.7 indicates that for diffusing inner surface, by increasing the water height the total count increases up to 60cm and then becomes flat. By changing the inner surface to reflective, total count doesn't change very much and the maximum deviation of data points related to reflective inner surface from diffusing inner surface data points is about 10%. The events count for each specified height of the water, when the scintillation detector sweeps wall of the tank, is shown in Fig.8 and it is comparable with Fig.4 which is obtained from simulation. These two Figures are in good agreement to each other.

Energy deposited by cosmic rays in Cherenkov detector for each height of water is distributed on 1024 channels. Fig.9 shows the average energy deposited by cosmic rays for different heights of water for both diffusing and reflective inner surfaces. However the average energies deposited for reflective inner surface are usually more than diffusing inner surface but their differences are in error range($\frac{5}{1024}$ which 5 is maximum difference between data points of diffusing and reflective inner surface in Fig.9.)

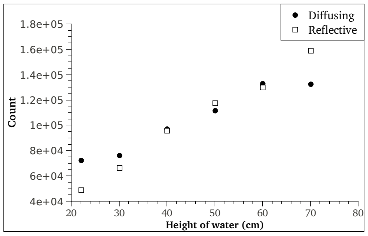

Figure 7: Total count for each specified height of water.

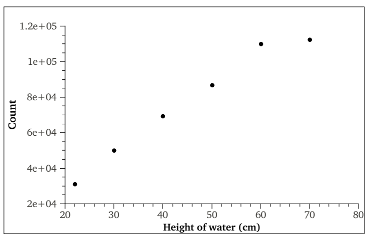

Figure 8: Count for each specified height of water when the scintillation detector sweep the wall of the tank.

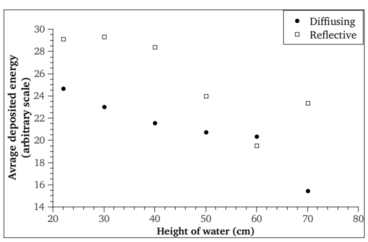

Figure 9: Average energy deposited by cosmic rays in different heights of water.

5 Concluding remarks

Fig.7 and Fig.9 indicate that total count and average energy deposited by particles which were detected by the PMT don't have tangible difference in diffusing and reflective cases. To consider expenses and probability of water contamination in making the inner surface reflective, using the diffusing inner surface is more economical. Fig.1 and Fig.2 show that the optimum dimensions of a Cherenkov tank with on PMT is 60cm in height and 40cm in diameter. But as it mentioned before because of difficulties in making a tank with the diameter of 40cm, we used a tank with a diameter of 45cm which was available in market. From Fig.3 and Fig.7 we conclude that the optimum height of the tank, with the diameter of 45cm and diffusing inner surface, is 60cm. In ALBORZ observatory we will use tanks with these dimensions.

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