Astroparticle Physics 35 (2012) 792–796

Contents lists available at SciVerse ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropart

Optimization of dimensions and inner surface of water Cherenkov detector with one photomultiplier tube (PMT) for the Alborz observatory air shower array

S. Mortazavi Moghaddam [a], P. Khalaj [a], M. Bahmanabadi [a,*], D. Purmohammad [b], S. Abdollahi [b]

[a] Department of Physics, Sharif University of Technology, P.O. Box 11155-9161, Tehran, Iran
[b] Science Faculty, Imam Khomeini International University, P.O. Box 11365-9161, Qazvin, Iran

ARTICLE INFO

Article history:
Received 11 July 2011
Received in revised form 18 February 2012
Accepted 10 April 2012
Available online 21 April 2012

Keywords:
Cosmic rays
Cherenkov detector

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 particles 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 in order to use at the Alborz observatory air shower array which consists of 20 plastic scintillation detectors and 10 water Cherenkov detectors. By comparing data gathered by tanks with diffusing and specular reflection inner surfaces, we show that the diffusing inner surface is more practical. Also from simulation and experiments results, we conclude that the optimum height for a diffusing tank with a diameter of 45 cm is 60 cm.

1. Introduction

One way of studying sources of high energy cosmic rays ($E > 10^{13}$ eV) is using an 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 to air molecules which these particles are detected 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, charged particles which move faster than light speed in water, emit Cherenkov photons. These photons travel on a so-called Cherenkov cone with a vertex angle which depends on the speed of light in the medium (c/n) and the speed of particle (v), e.g. for a 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 detecting surface 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 application in surface arrays such as in Haverah Park array have completely succeeded [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 (SUT). This array monitored 6×10^5 showers during its performance within 2005–2006 [4].

The second generation of arrays at the Alborz observatory of SUT is an array consists of 20 plastic scintillation detectors and 10 water Cherenkov detectors. In order to improve count rate in water Cherenkov detectors which will be used in this new array and according to the results of previous array, we decided to optimize size and inner surface characteristics of the Cherenkov tank for an individual detector at first. It is worth noting that in this paper, we report results of PVC and stainless steel sheet as two available materials for covering inner surface of the tank. So although hemispherical PMTs have a bigger acceptance for photons than flat face ones, existing constraint led us to use flat face PMTs. In next sections we explain simulation and its result, experimental setup and data analysis respectively.

2. Simulation

As a first step to estimate optimum size of a Cherenkov tank, a primary simulation was performed [5]. In order to more detailed studies, a cylindrical tank with one PMT placed at the center of the tank's lid was simulated. The position of PMT was chosen as origin of Cartesian coordinate system. We also assumed that the inner surface reflects light in a diffusing pattern with the reflection coefficient of 70%, respect to the reflectivity of Polyvinyl Chloride (PVC) tank which we used in our experiments. All experiments were performed in Cosmic Rays Laboratory at SUT under two concrete ceilings with a thickness about 150 g cm^{-2}. Our previous

* Corresponding author.
E-mail address: bahmanabadi@sina.sharif.edu (M. Bahmanabadi).

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http://dx.doi.org/10.1016/j.astropartphys.2012.04.003

Table 1
Region of the parameters and their variation in each step for particles which are entered from the upper surface. R is the radius of the tank.

Region of the parameters	Variation in each step
$0 < r < R$	5 cm
$0 < \theta < \frac{\pi}{2}$	$\frac{\pi}{10}$
$0 < \phi < \pi$	$\frac{\pi}{10}$

Table 2
Region of the parameters and their variation in each step for particles which are entered from the wall. H is the height of the tank.

Region of the parameters	Variation in each step
$0 < z < H$	5 cm
$0 < \theta < \frac{\pi}{2}$	$\frac{\pi}{10}$
$0 < \phi < \frac{\pi}{2}$	$\frac{\pi}{10}$

experiences showed a drastic decrease of count rate when experiment set-up moved from outdoor to the lab, hence we assume that charged particles reaching the detector are mostly muons.

Muons were injected to the tank from upper surface (lid) and wall of the tank with energy 10^9 eV. This energy was obtained from our previous simulations with CORSIKA code to consider the geographical parameters of Tehran. Because of azimuthal symmetry of the tank, particles entrance position varies along a radial line of the tank's lid (x axis) and for the wall, varies along a line parallel to z axis. Moreover from the various points of these lines, muons are entered into the tank with different zenithal and azimuthal angles. The muon angular distribution in atmosphere is as $I(\theta) = I(0)\cos^n\theta$ with $n \simeq 2$ [6]. The azimuthal angle distribution is also uniform. The range of these parameters and their variation in each step are shown in Tables 1 and 2 respectively for the upper surface and the wall.

By entering a charged particle in the tank, Cherenkov photons emitted on a cone. Vertex angle of the Cherenkov cone, θ, can be obtained by the following equation:

$$cos\theta = \frac{1}{n\beta}, \tag{1}$$

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 by using [7]:

$$N = 2\pi\Delta x\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)\left(1 - \frac{1}{n^2\beta^2}\right). \tag{2}$$

We set λ_1 and λ_2 to be 300 nm and 500 nm respectively. In each 1 cm step of particle's path, Cherenkov photons are emitted and particle's energy is decreased by an amount of 2 MeV which is the average energy loss of minimum-ionizing particles in water [7]. According to Eqs. (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. Cherenkov photons are distributed uniformly on the cone surface in each 1 cm step of particle's path. So we divide the cone to 72 light beams, each beam containing $\frac{N}{72}$ photons. We follow each light beam. In each 1 cm step of photons path in a beam, the following cases is considered by the code:

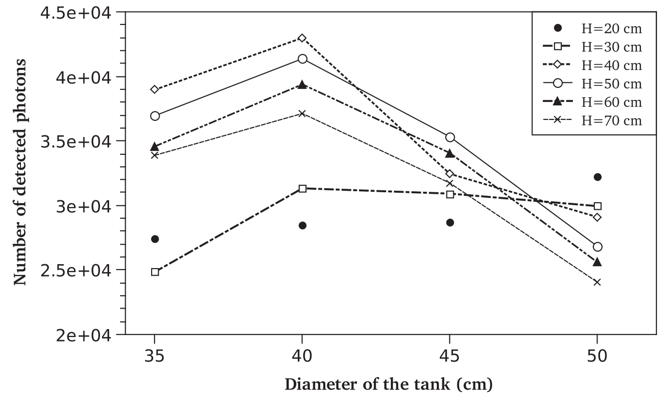

Fig. 1. Number of detected photons versus tank diameter for different heights of the simulated tank, when particles are injected to it only from the upper surface to find optimum diameter for the cherenkov tank with one PMT.

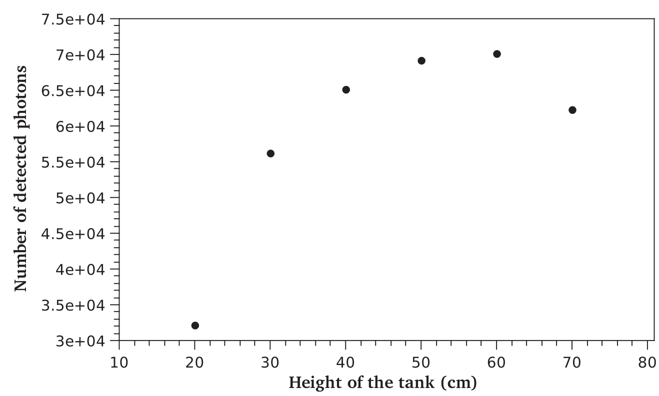

Fig. 2. Number of detected photons versus height of the simulated tank with a diameter of 40 cm, when particles are injected to it from the upper surface and the wall.

(1) Photons absorption of any light beam by water or the inner surface of the tank is checked. Water absorption coefficient in interval 300–500 nm, was assumed 10^{-4} cm^{-1} [8].
(2) Reaching the light beam to the PMT with 5 cm diameter is checked.
(3) To simulate the light beam reflection from the wall or the bottom surface of the tank in a diffusing pattern, the beam is split into other beams in 2π steradians and photons in the incident beam are evenly distributed in these new beams. Then all these new beams are separately followed by the code.

Finally the number of Cherenkov photons which reached to 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 heights. Number of detected photons for different diameters are shown in Fig. 1. This figure indicates that the optimum diameter is 40 cm. Fig. 2 shows the number of detected photons versus height of the tank with diameter of 40 cm. In this figure, it can be seen that at height of 60 cm the number of detected photons gets a maximum. These results are completely consistent with the earlier simulation.

3. Experimental set-up

Because of some problems in making a cylindrical PVC tank with a diameter of 40 cm, we preferred to buy a premade PVC tank with a diameter of 45 cm and height of 70 cm which was available in market. It made us to run the simulation for a tank with diameter 45 cm again which its results will be mentioned in next section. 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 covering.

We filled the tank with distilled water (with conductivity $\sigma = 10 \times 10^{-6}$ S/m) and then changed water height from 20 cm to 70 cm (in each step we increase the water height by 10 cm). One PMT (9813B, 5 cm, QE = 27%, Spectral Response with maximum QE at 380 nm in interval 300–600 nm) is placed in center of the lid so that can be tangent to water surface in different heights. To study the characteristic of the inner surface of the tank, we covered its inner surface with stainless steel sheet which reflects light in a specular pattern and we repeated all steps of the experiment for this tank as well. It is worth noting that reflectivity of both inner surfaces (white painted PVC and stainless steel) in the interval of 300–500 nm is 70% based on results of Diffuse reflectance Spectroscopy (DRS) test. In order to find the optimized height of water in the tank we swept both the wall and the bottom surface of the tank with a small scintillation detector ($10 \times 10 \times 1$ cm^3) by using the coincidence method. Due to azimuthal symmetry, we swept only some parts of the tank surface. Fig. 3 demonstrates these specific parts which was swept with the scintillation detector. To record coincidence events (counts), we used the electronic circuit shown in Fig. 4. As it can be seen in Fig. 4 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 50 mV. The output of discriminator channel related to the scintillation detector is sent to "start" input of a Time to Amplitude Converter (TAC, ORTEC566) and the output of the other channel of the discriminator related to the Cherenkov detector is sent to "stop" input of TAC by a 18 m cable. This set up ensures us that the generated signal by the PMT of Cherenkov detector is related to a particle which passes through the scintillation detector as well. Finally the output of TAC which was set to a full scale of 200 ns is fed into a Multi-Channel Analyzer (MCA) via an Analog to Digital Converter (ADC, KIAN AFROUZ Inc.) 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.

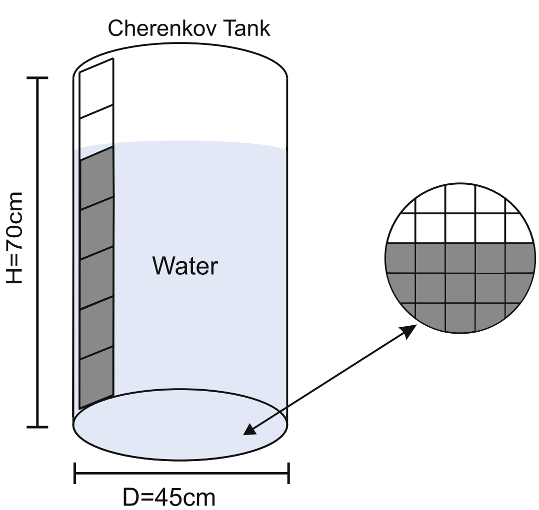

Fig. 3. The swept positions by a small scintillation detector.

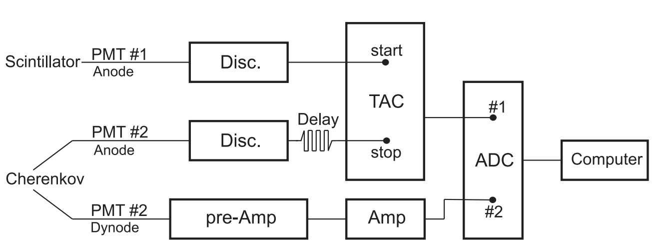

Fig. 4. Schematic diagram of the electronic circuit.

4. Data analysis

To find the optimum height of water in the purchased tank, we ran the simulation again for a tank with a diameter of 45 cm. Fig. 5 shows number of detected photons versus height of the tank. This figure indicates that the optimum height of the tank with the diameter of 45 cm is also 60 cm. For further comparison, number of detected photons for different heights of the tank when particles enter from the wall of the tank, is shown in Fig. 6. The variation of detected photons versus radial distance of entrance point from the origin (r) and also versus vertical distance (z) of entrance point are shown in Figs. 7 and 8.

In experiments for both specular and diffusing inner surfaces, we changed height of water from 20 cm to 70 cm. For each water

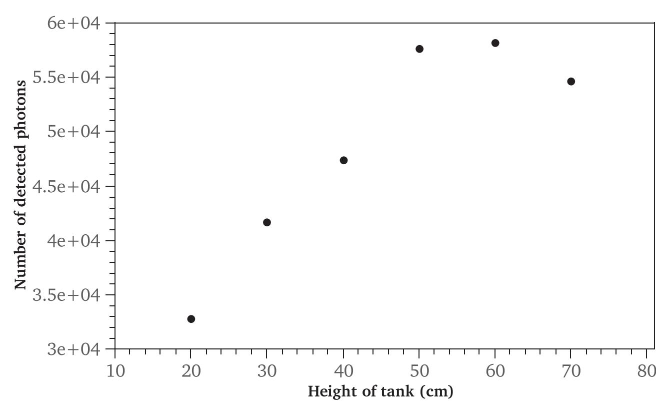

Fig. 5. Number of detected photons versus height of the simulated tank with a diameter of 45 cm, when particles are injected to it from the upper surface and the wall.

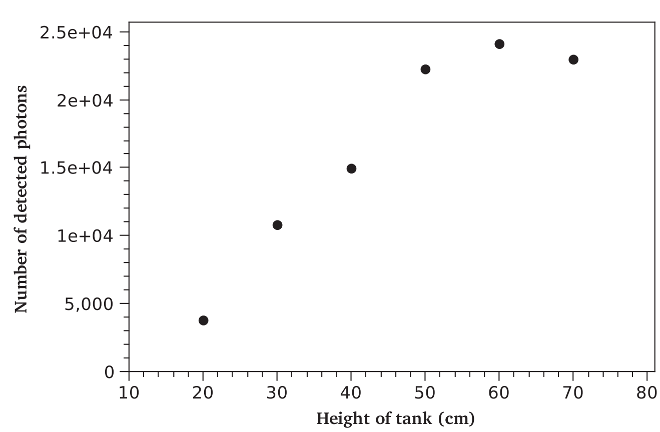

Fig. 6. Number of the detected photons for different heights of tank when particles enter from the wall of the simulated tank with a diameter of 45 cm.

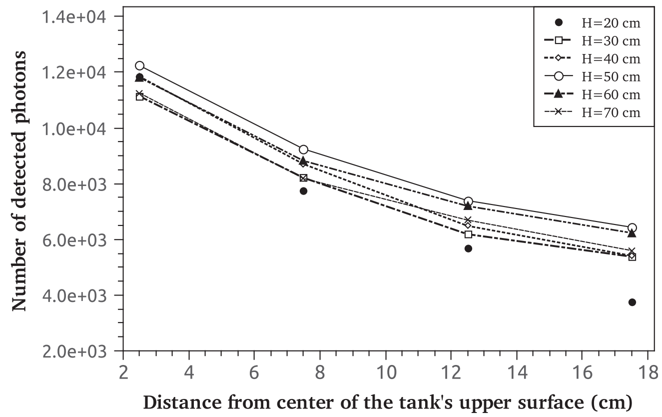

Fig. 7. Number of detected photons versus radial distance of injection point from the origin (r), for simulated particles which enter the tank (with diameter 45 cm) from the upper surface in all zenith and azimuth angels.

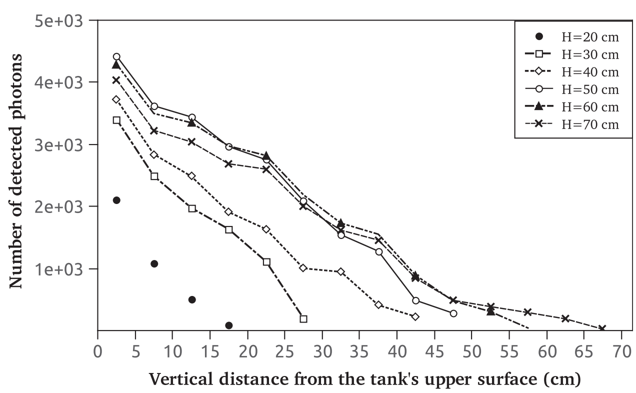

Fig. 8. Number of detected photons versus vertical distance of injection point (z) for simulated particles which enter the tank (with diameter 45 cm) from the wall in all zenith and azimuth angels.

height, we swept the tank with a small scintillation detector. Measured counts by sweeping the bottom surface and so the wall of the tank with the scintillation detector are shown in Figs. 9 and 10 respectively. So to obtain total count for each specified height of water, we carried out a summation on all coincidence events of individual experiments after noise reduction. Fig. 11 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. 11 indicates that for diffusing inner surface, by increasing the water height the total count increases up to 60 cm and after that does not change significantly. By changing the inner surface to specular, total count does not change very much and the maximum deviation of data points related to specular inner surface from diffusing inner surface data

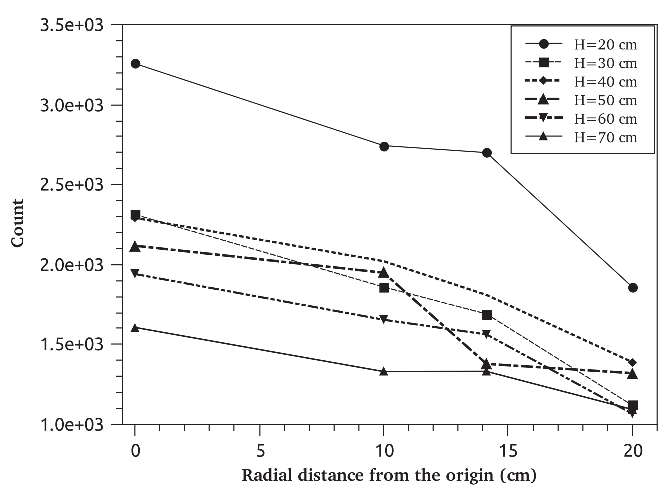

Fig. 9. Measured count versus radial distance of the scintillation detector from the origin (r), when it sweeps the bottom surface.

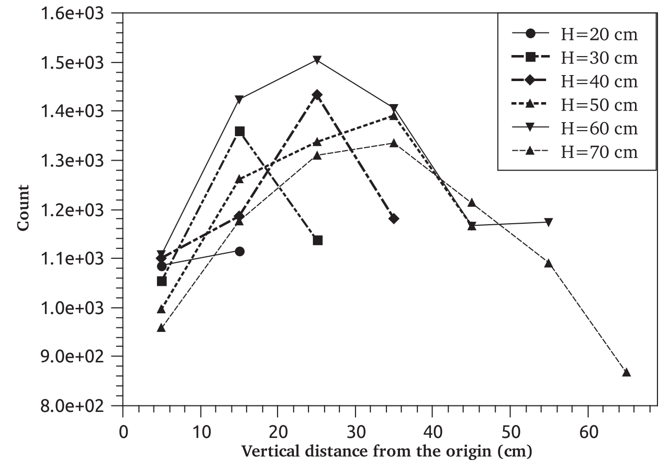

Fig. 10. Measured count versus vertical distance of the scintillation detector from the origin (z), when it sweeps the wall.

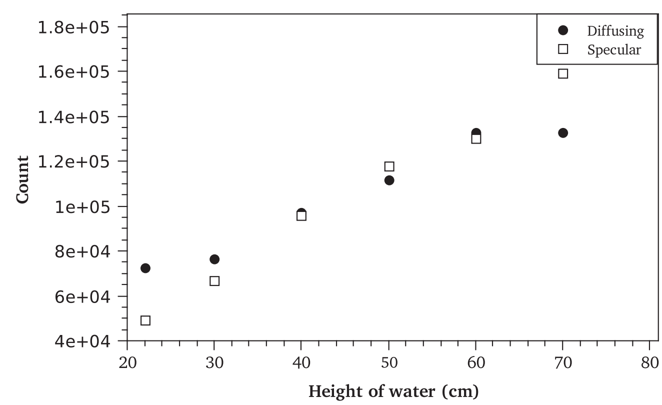

Fig. 11. Total count for each specified height of water.

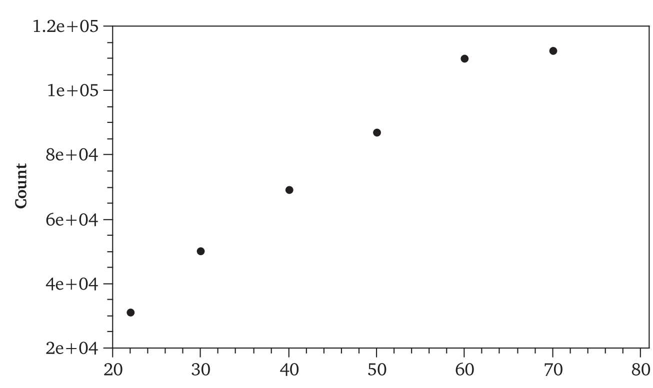

Fig. 12. Count for each specified height of water when the scintillation detector sweeps the wall of the tank.

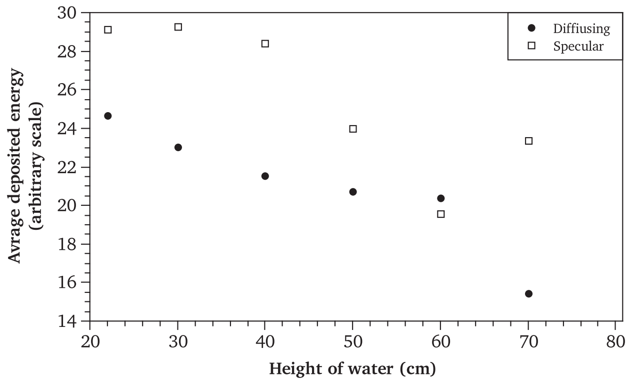

Fig. 13. Average energy deposited by cosmic rays in different heights of water.

points is about 10%. The events count for each specified height of the water, when the scintillation detector sweeps the wall of the tank, is shown in Fig. 12 and it is comparable with Fig. 6 which is obtained from simulation. These two Figures are in good agreement to each other. Pulse height of energy deposited by cosmic rays in Cherenkov detector for each height of water is distributed on 1024 channels by an Analog to Digital Converter (ADC). Fig. 13 shows the average energy deposited by cosmic rays for different heights of water for both diffusing and specular inner surfaces. As Fig. 13 shows maximum of these differences between two inner surface types, is only 7 channels. Hence, however the average energies deposited for specular inner surface are usually more than diffusing inner surface but their differences, because of maximum 7 of 1024 channels, are very small.

5. Conclusion

In the present work, we have determined optimized dimensions of a water Cherenkov detector which will be used at the Alborz observatory air shower array. Our studies show the appropriate dimensions for the these tanks (Figs. 1 and 2) are 60 cm in height and 40 cm in diameter. But as it was mentioned before because of difficulties in making a tank with the diameter of 40 cm, we used a tank with a diameter of 45 cm which was available in market. From Figs. 5 and 11, we conclude that the appropriate height of the tank for Cherenkov detector with one PMT, with the diameter of 45 cm and diffusing inner surface, is 60 cm.

So we have compared results of PVC and stainless steel sheet as two available materials for covering inner surface of a tank. Figs. 11 and 13 indicate that total count and average energy deposited by particles which are detected by the PMT, do not have tangible difference in diffusing and specular cases (PVC and stainless steel sheet) and due to expenses and probability of water contamination in making the specular inner surface, using the diffusing inner surface is more economical.

Acknowledgement

The constructive comments of anonymous referees are gratefully acknowledged by authors.

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