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Circulation model for water circulation and purification in a water Cerenkov detector*

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Abstract Owing to its low cost and good transparency, highly purified water is widely used as a medium in large water Cerenkov detector experiments. The water circulation and purification system is usually needed to keep the water in good quality. In this work, a practical circulation model is built to describe the variation of the water resistivity in the circulation process and compared with the data obtained from a prototype experiment. The successful test of the model makes it useful in the future design and optimization of the circulation/purification system.

Key words water Cerenkov detector, mixed-bed, resistivity, circulation

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1 Introduction

There has been a great deal of progress in neutrino physics in the last decade. Many neutrino experiments are on going, including atmospheric neutrino, solar neutrino and reactor neutrino experiments. In these neutrino experiments, the water Cerenkov detector has been or will be chosen by Super-Kamiokande[1], KamLAND[2] and the future Daya Bay experiment.[3;2)] For example, Super-Kamiokande has constructed a 50 kton water Cerenkov detector with a water attenuation length being >100 m. Highly purified water has become an important medium for detecting the particles because of its advantages of low cost, almost 4π coverage, good transparency and high detection efficiency. For the large water Cerenkov detector experiment, one should firstly make the water highly purified and then keep the water in high purity. So a circulation and purification system is needed for these experiments. Because the size of the detector is becoming larger and larger, the cost of the equipment for circulation and purification is getting higher and higher. A useful method is to optimize and design the purification and circulation system for a reasonable cost and size to satisfy the experiment requirements.

For this purpose, we construct a practical model for water circulation and purification. The model includes the influence on pure water quality by substances leaching out from contamination, the circulation speed and water resistivity. The attenuation length is more useful for this modeling but there is no direct correlation between attenuation length and water resistivity; here the water resistivity is used as the index of water quality. In order to verify the model, we construct a prototype system of water circulation and purification. The experimental results are compared with the practical model.

2 Circulation model

We know that Electrical Conductivity (EC) is the reciprocal of resistivity ($\sigma = 1/R$). Pure water isn't a good conductor for electricity. If the Total Dissolved Solids (TDS) in the water increase, the EC of the water will increase, because the electrical current is transported by the ions. The relation between the EC and the TDS can be approximately expressed as the

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2) DayaBay TDR , TDR of the DayaBay experiment, Dec 08, 2007; (DayaBay water systems specifications)

following for the pure water: TDS (mg/l) = 0.5×EC (μS/cm)[1)].

Figure 1 is a sketch plot of the circulation/purification system. There is a water tank with volume V_{tank} and the circulation speed with u (l/h). Water resistance is measured at two different places. One is the place where the water is pumped out of the tank (position 1) and the other one is the place where the water is to be filled into the tank (position 2). The σ_{tank} is the water EC from Position 1 and σ_{p} is the water EC from Position 2. Theoretically, the lowest limit value of the ultrapure water conductivity is 0.055 μS/cm at the temperature of 25 ℃. When the system works properly and continuously, the EC value of the output water, here σ_{p}, stays at a constant value. Depending on the design of the purification system, this value could be different from the theoretical limit.

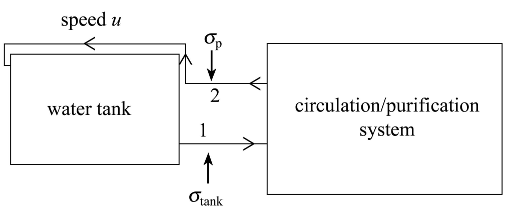

Fig. 1. Circulation diagram.

We all know that water quality will become worse by time evolution as a result of the contact material contamination. The purification system can make water quality better by circulation. We assume that there is k (unit of mg/(l·h)) conductivity particles increased in the tank during 1 hour. When the circulation/purification system works, it can reduce the concentration of TDS. The σ_{tank} will decrease and water resistivity will increase from low resistivity to high resistivity if the reduction rate of contamination by the circulation system is greater than the increase rate of substances leaching out. So we can get the TDS concentration variation of the tank during a short time ($\Delta t \longrightarrow \mathrm{d}t$) as the following:

$$\mathrm{d}(0.5\sigma_{\text{tank}}) = \frac{0.5(\sigma_{\text{p}} - \sigma_{\text{tank}})u\mathrm{d}t}{(V_{\text{tank}})} + k\mathrm{d}t\,. \tag{1}$$

During the working time of purification, the tank EC σ_{tank} is a function of time t, which can be integrated from Eq. (1):

$$\sigma_{\text{tank}} = (\sigma_{\text{p}} + 2k\tau) + (\sigma_0 - (\sigma_{\text{p}} + 2k\tau))\exp\left(-\frac{t}{\tau}\right), \tag{2}$$

$\tau = \dfrac{V_{\text{tank}}}{u}$ is the time needed for circulating one tank volume of water; σ_0 is the water initial EC value. From this we can give the water resistivity in the tank:

$$R_{\text{tank}} = \frac{1}{\sigma_{\text{tank}}} = \frac{1}{(\sigma_{\text{p}} + 2k\tau) + (\sigma_0 - (\sigma_{\text{p}} + 2k\tau))\exp\left(-\frac{t}{\tau}\right)}, \tag{3}$$

In Eq. (3), when time $t \longrightarrow \infty$, the R_{tank} becomes

$$R_{\text{tank}} = \frac{1}{(\sigma_{\text{p}} + 2k\tau)}\,. \tag{4}$$

This means that the water resistivity is finally independent of time, but dependent on the σ_{p}, k and τ values.

When the purification system stops working, this means that the water is only circulated and not purified. The water resistivity will decrease by the material contamination as time goes on. Here we consider the leaching out both from the water tank and circulation system, and assume that k' (unit of mg/(l·h)) is the conductivity particles increased in the tank and circulation system during 1 hour. We want to study the water resistivity variation without the purification system. Eq. (1) becomes

$$\mathrm{d}(0.5\sigma_{\text{tank}}) = k'\mathrm{d}t\,. \tag{5}$$

We get Eq. (6) from the integral of Eq. (5)

$$\sigma_{\text{tank}} = \sigma_0 + 2k't\,. \tag{6}$$

σ_0 is the tank initial EC value. Water resistivity varies with time in tank as shown in Eq. (7):

$$R_{\text{tank}} = \frac{1}{\sigma_{\text{tank}}} = \frac{1}{\sigma_0 + 2k't}\,. \tag{7}$$

3 Experimental results

3.1 Experiment setup

A water tank, dimension 2.8 m × 1.2 m × 1.3 m, with a circulation and purification system has been constructed. It is made of PP (polypropylene) of 1 cm thickness. 4 tons of highly purified water from the IHEP water station fill the tank. The water resistivity from the station outlet is 18 MΩ·cm and its resistivity is decreased to a few MΩ·cm after the water goes through 150 m PVC (poly(vinyl chloride)) pipes into our tank. This is because highly purified water can be very easily polluted by the contact material, such as the PVC pipe and air. The tank is sealed and filled with nitrogen. The pressure inside the tank is about 1.5 cm water equivalent higher than

1) http://www.lenntech.com/water-conductivity.htm

atmospheric pressure to keep the air from coming into the tank.

The circulation system (Fig. 2(a)) is composed of one pump, one 1 μm filter, one ultra-violet (UV) sterilization stage, one cartridge polishing and one 0.22 μm filter, one flowmeter, one conductivity/resistivity cell. Water circulation is powered by the pump of which one can change the rotation speed to control the circulation speed. The 1 μm filter will get rid of the relatively large solids from the water. The UV stage is used to kill the bacteria and decompose organic substance and reduce the total organic carbon (TOC) in the water. A simple switch can control the UV stage on or off which we do not show in Fig. 2(b). The cartridge polishing is the most important part of the system. The cartridge polishing is filled with high quality dowex ion exchange resin to purify the water. It is usually used at the end of the purification system for very high resistivity of the water. Here we use it to simplify the purification, saving the cost of the whole setup. The resistivity of water after purification reaches 16.7 MΩ·cm which satisfies our requirement. The 0.22 μm filter can get rid of relatively small solids and prohibit some of the resin beads escaping from the cartridge polishing into the tank. The flowmeter is used to monitor the circulation speed. The water quality is monitored by the conductivity/resistivity cell with 2% uncertainty.

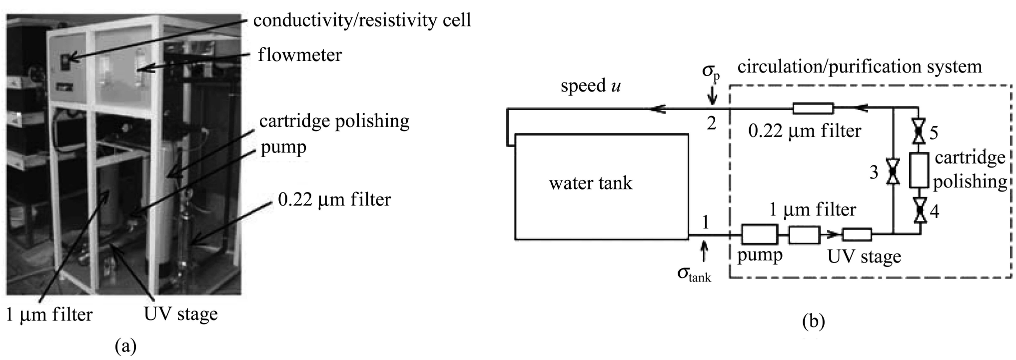

Fig. 2. (a) Circulation and purification system; (b) Circulation diagram.

Figure 2(b) shows the whole circulation process. There are 4 tons of water in the tank (V_{tank}=4000 L). The water is pumped from the water tank and then it goes through the 1 μm filter, UV stage, cartridge polishing, 0.22 μm filter and fills the tank. There are three valves (Positions 3, 4 and 5) to control the purification system on or off. When the valve (Position 3) is off and the valves (Position 4 and 5) are on, the purification system is turned on. When the valve (Position 3) is on and the valves (Position 4 and 5) are off, the purification system is turned off but still keeps the 1 μm filter and UV stage on. We can monitor the σ_{tank} variation by a conductivity/resistivity cell. σ_{p} is measured in our system with a constant value 0.06 μS/cm, corresponding to the water resistivity of 16.7 MΩ·cm.

3.2 Experiment data and model comparison

We have measured the water resistivity at two different circulation speeds for increasing process (purification system on) and decreasing process (purification system off).

When the circulation/purification system starts running, the water initial resistivity is about 3 MΩ·cm. We set the circulation speed at u_1~12 l/min. Experiment data are fitted by Eq. (3) from Sec. 2. The fitting parameters include k, τ and σ_0. The fitting results are shown in Fig. 3. The k value is about 0.8×10^{-3} mg/(l·h). This value indicates the degree of cleanness of the material in the tank. τ=5.2 hours and thus we can calculate the circulation speed is 12.8 l/min, basically consistent with the readout of the flowmeter in the experiment setup.

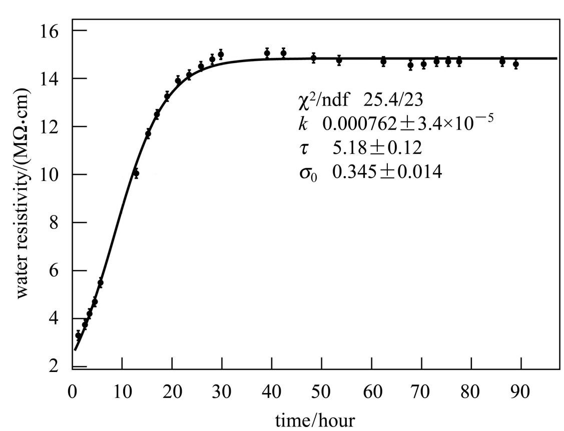

Fig. 3. The increase curve (speed u_1).

The experiment data show that water resistivity can reach a level of about 14.8 MΩ·cm and then stay constant at this value, which is in agreement with the expectation from Function (4). From the initial value 2.5 MΩ·cm to 14.8 MΩ·cm, it takes 25—30 hours, corresponding to 5—6 tank volumes of water change.

We also lower the circulation speed to $u_2{\sim}3$ l/min to cross check the model consistency (Fig. 4). From the fitting results, the k value is also about 0.8×10^{-3} mg/(l·h) which is the same with u_1. The circulation speed is derived to be about 2.8 l/min from the fitting result with τ=24.2 hours. The water resistivity can reach the level of about 10.2 MΩ·cm and then keep this resistivity. From the initial value 3.5 MΩ·cm to 10.2 MΩ·cm, it needs about 120 hours, which corresponds to 5—6 tank volumes of water change too.

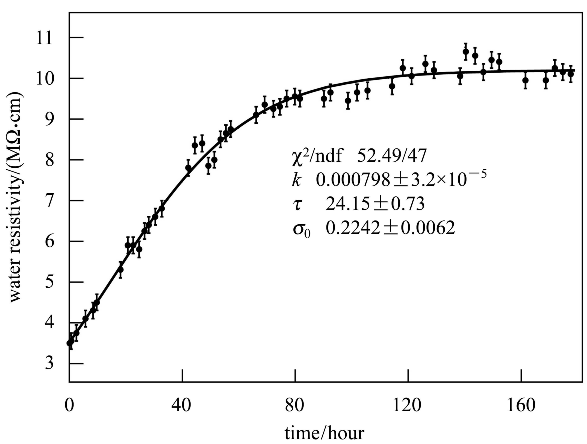

Fig. 4. The increase curve (speed u_2).

Figure 5 and Fig. 6 show the results when the purification system is turned off and the UV stage is also off. The circulation speed is the same as in the increase curve. We use two parameters to fit the data, k' and σ_0. The mean value of k' is 1.3×10^{-3} mg/(l·h) for the decrease curve. This value of decrease curves is larger than the increase. The reason is mainly because k' has included both the tank and the circulation system contamination effect after the UV stage and the mixed-bed are turned off. The material of pipe used in the circulation system is clean PVC. If we consider the relative leaching out rate of the circulation pipe (clean PVC) which is about one order of magnitude over the water tank material (PP)[4], the surface area (about 0.5 m^2) of the water pipe material which is calculated from the water pipe length (about 6—7 m), the measured value k' is reasonable. While in the case of the purification process, the water pipe leaching out is filtered by resin.

Above all, the model describes the circulation/purification process very well. In the case of an increasing curve, the final flat level value of water resistivity is determined by Eq. (4). Decreasing the k value and increasing the circulation speed will increase the water resistivity. For the experiment, we can choose a high circulation speed system and lower the contamination value material if we want to get good quality water. The time from initial value to the flat value (stable state) is mainly determined by τ. It needs 5—6 τ to reach the stable state.

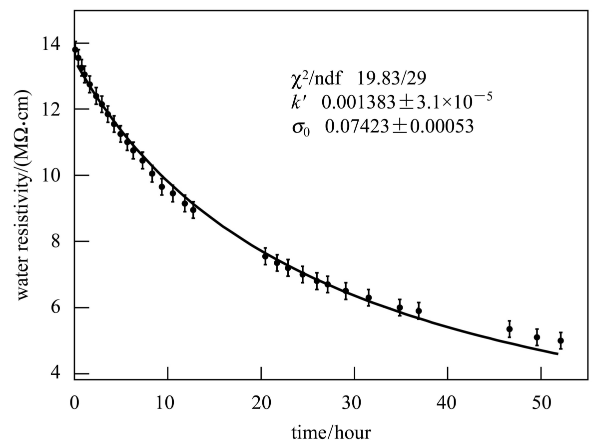

Fig. 5. The decrease curve after the purification system is off (speed u_1).

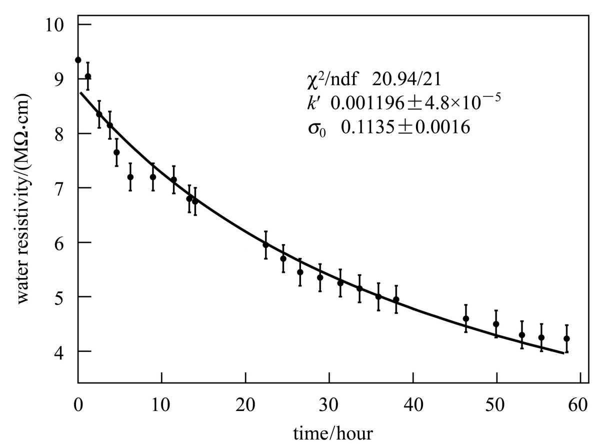

Fig. 6. The decrease curve after the purification system is off (speed u_2).

4 Conclusion

Highly purified water is a good medium for the water Cerenkov detector experiment. The water circulation and purification system is needed to keep the water in good quality for a long time. We have built a practical model describing the evolution of the water resistivity under circulation and purification. The circulation model and experiment data are in good agreement with each other. This model can be used for a large experiment which needs water circulation and purification in the future. It can calculate and estimate the size of the circulation and purification system for an experiment requirement.

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