Concentrated Brine Treatment using New Energy in Coal Mine Evaporation Ponds

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Abstract. Recently, more and more coal mine water is being advanced treated and reused in China. The concentrated brine that results from advanced treatment methods can only be evaporated in an evaporation pond. Because of limited treatment capabilities and winter freezing, evaporation ponds often overflow, causing environment contamination. In this paper, based on analysis of brine water quality and economic-technical feasibility, we present a suitable treatment method for brine in evaporation ponds as electrodialysis using solar energy. In addition, we propose a new system to treat brine in coal mine evaporation ponds, which is powered by solar and wind. The operating efficiency of this treatment system proposed in this paper can meet the concentrated brine treatment demands in most coal mines in western mining areas of China and it places the photovoltaic power generation plates on the surface of the evaporation pond on a fixed floating island, which reduces any risk associated with land acquisition. This system can enhance brine treatment efficiency, requires a reduced evaporation pond area, increases the utilization of coal mine water, and minimizes the risk of environment contamination.

1. Introduction
With environmental protection policies becoming increasingly stringent in China, more and more coal mine water is being advanced treated and reused to realize zero wastewater discharge. After advanced treatment, concentrated brine is evaporated in an evaporation pond. This method can no longer meet the increasing requirements of policy and limited treatment capacity. Therefore, a more efficient, environment-friendly, and low-cost brine treatment technology needs to be developed as soon as possible.

2. Problems with concentrated brine treatment using evaporation ponds in China
2.1. Stricter supervision on evaporation ponds
Since the Tengger desert pollution event was exposed in September 2014, the evaporation pond has gradually become a target for public criticism in China. In May 2015, the Ministry of Environmental Protection published a draft– Guiding Opinions on Strengthening Environmental Protection in Industrial Parks to strictly control the construction of evaporation ponds. Since then, it has been
difficult for new projects using concentrated brine treatment with evaporation ponds to pass the EIA. The Water Pollution Prevention Action Plan (water “ten”) was released in 2015. This enabled the State to strengthen the supervision of industrial wastewater discharge from various aspects and launch a strict accountability system. Therefore, the responsibility for accidents in evaporation ponds such as leakage or overflow is now stringently investigated.

With the progress of mining, water discharge from many coal mines is increasing, and, as a result, the quantities of brine discharged into evaporation ponds after advanced treatment is also increasing. Under strict controls on the construction of new and expansion of existing evaporation ponds, existing treatment capacity must be improved to guarantee safe operation.

2.2. Impact of climate on evaporation pond treatments in China

In the major coal producing areas in West China such as Inner Mongolia, Xinjiang, and Ningxia the coal mine water is often high in total dissolved solid (TDS), and must be advanced treated and desalted before reuse, and evaporation ponds are usually built to treat the concentrated brine. However, the winter is long in these areas and the freeze period lasts for 3–6 months every year. As a result, the surfaces of the evaporation ponds freeze and natural evaporation of the concentrated brine almost stops, which results in overflow and environmental contamination.

3. Water quality characteristics of concentrated brine in evaporation ponds

Coal mine water is mainly from underground water, but it has obvious characteristics of the mining industry due to the mining activities. The main pollution components in coal mine water include the follow eight types [1, 2]: ① suspended solids (mainly coal dust); ② low pH (water in many coal mines is acidic); ③ TDS (including \( \text{SO}_4^{2-} \) and \( \text{Cl}^- \), \( \text{K}^+ \), \( \text{Na}^+ \), \( \text{Ca}^{2+} \), \( \text{Mg}^{2+} \), \( \text{HCO}_3^- \), and other ions); ④ Fe and Mn; ⑤ heavy metals (mainly \( \text{Hg} \), \( \text{Cr} \), \( \text{Cd} \), \( \text{Pb} \), \( \text{Zn} \), and \( \text{As} \)); ⑥ fluoride; ⑦ a small amount of organics; ⑧ radioactive substances. The characteristic components of polluted coal mine water in China are mainly suspended solids, COD, and TDS [1, 2].

Up to now, reverse osmosis has been the most widely used technology in the advanced treatment of coal mine water in China. It is a type of membrane separation technique, which selectively allows water molecules to penetrate an semipermeable membrane under impressed pressure while retaining other solutes in the water. Usually pretreatments such as flocculent precipitation and ultra-filtration are carried out before reverse osmosis. Figure 1 shows a flow diagram of coal mine water advanced treatment in China.

![Figure 1. Flow diagram of the coal mine water advanced treatment process in China](image)

Water quality in coal mines is relatively simple and contains a small amount of organics, therefore almost all other pollution components, except TDS, can be removed during pretreatment. During reverse osmosis itself, the TDS index components are removed. The removal rates can reach above 98% (\( \text{Ca}^{2+} \)), above 94% (\( \text{Cl}^- \)), above 98% (\( \text{SO}_4^{2-} \)), above 95% (hardness), and above 95% (\( \text{Mg}^{2+} \)) [3].
Reverse osmosis techniques usually recycle more than 75% of the fresh water in coal mine water. The remainder is concentrated brine from reverse osmosis, the basic pollution component of which is TDS at a content more than three times that of raw water. According to the investigation of authors, in China, the TDS content in most of concentrated brine from coal mine waters after reverse osmosis is 2,000–6,000 mg/L.

In summary, the water quality characteristics of concentrated brine in coal mine evaporation ponds are: high TDS (mainly SO₄²⁻, Cl⁻, Na⁺, Mg²⁺, Ca²⁺, and HCO₃⁻), a small amount of scale inhibitor, and probably, as the evaporation pond is an open system, a low amount of suspended solids and organic pollutants from external sources.

4. Feasibility analysis on brine treatment using new energy

4.1. Economic feasibility of brine treatment using new energy in coal mines

Currently, relatively mature technologies for brine treatment include evaporation, electrodialysis, high-pressure reverse osmosis, and combinations of these. Although these technologies can effectively treat concentrated brine, their high cost has had serious impact on their popularization and application.

Energy is the highest cost in all treatments. Table 1 shows the TDS in coal mine water from three mines to be 3700, 7905, and 11052 mg/L and the respective energy costs for desalination to be 64%, 45%, and 61% of the total treatment cost. Therefore, reducing the energy cost is the most effective method of reducing the overall cost of concentrated brine treatment in China.

| Coal mine         | Energy cost | Chemicals cost | Maintenance cost | Depreciation cost | Labor cost | Total Unit Energy cost ratio |
|-------------------|-------------|----------------|------------------|-------------------|------------|-------------------------------|
| A mine in Gansu   | 1100        | 200            | 84               | 244               | 88         | 1716 Y/d                      | 64%                          |
| YC Coal Mine      | 1.00        | 0.20           | 0.67             | 0.30              | 0.05       | 2.238 Y/m³                   | 45%                          |
| Qingshuiying Coal Mine | 1.78    | 0.35           | 0.19             | 0.37              | 0.23       | 2.920 Y/m³                   | 61%                          |

Note: data source in this table is from literatures [4-6]

As shown in Figure 2, the major coal producing areas in West China such as Inner Mongolia, Xinjiang, Shanxi, Shaanxi, Ningxia, and Gansu are mostly rich, or relatively rich, in solar radiation and there are large-scale photovoltaic power generation and wind power generation projects in many of these mining areas. Energy costs could be reduced if these rich solar and wind energy resources could be used to power evaporation pond brine treatment systems.

Figure 2. The solar radiation distribution map of China (quoted from Literature [7]).

4.2 Technical feasibility of concentrated brine treatment in coal mines using new energy
Much research has been carried out on seawater desalination powered by solar energy, and many mature application examples exist. As seawater composition is similar to concentrated brine and is even more difficult to treat, we refer and use to relevant research results from this field of study.

Seawater desalination powered by solar energy includes two types, seawater phase transformation powered by solar thermal energy and dialysis powered by solar power generation [8, 9]. The most representative and widely used of all the seawater desalination technologies driven by solar thermal energy is multi-effect distillation (MED). The principle of MED is to evaporate and concentrate raw water by heating, and produce fresh water by condensation[10]. Reverse osmosis (RO) and electrodialysis (ED) are relatively mature technologies among the seawater desalination methods powered by solar power generation. A comparison of desalination technologies can be seen in Table 2.

| Comparative items | MED | RO | ED |
|-------------------|-----|----|----|
| Pretreatment      | Low requirement | High requirement | Medium requirement |
| Applicable salinity | Relatively high salinity. The more saturate, the more economical | Medium and low salinity | Medium salinity |
| Applicable salinity | Good salt-water separation effect, high automation, and stable operation | High technical maturity, small land occupation, high water quality | Low investment, small land occupation, long service life of membrane and simple operation |
| Advantages | High investment, easy for scale formation and corrosion, large land occupation and high steam consumption | High investment, frequent cleaning of membrane and high requirement on inlet water | Low desalination rate, high power consumption and easy for scale formation due to polarization |
| Driving mode | Steam | AC | DC |
| Energy consumption | Steam consumption: 0.3 t/m³ | Power consumption: 1–5 kWh/m³ (raw water) | Power consumption: 2–10 kWh/m³ |

Note: part of the data source in this table is from literature [10].

MED, RO, and ED technologies have their own advantages and disadvantages, and due consideration should be given to the water quality characteristics of the concentrated brine in the evaporation ponds, the environmental characteristics of the mining area, and the costs resulting from technological choices.

Winter generally lasts for 3–6 months in the major coal producing areas in West China. MED technology is greatly influenced by temperature. A low environmental temperature not only influences the heat-collection efficiency of solar energy, but also consumes a large amount of thermal energy while heating the inlet water and keeping the equipment at operating temperatures. Therefore, treatment efficiency cannot be guaranteed if it is dependent on solar heating. The membrane flux in RO also decreases as the temperature drops. By contrast, ED is relatively less influenced by temperature.

Concentrated brine in coal mine evaporation ponds usually has high hardness and a high SO₄²⁻ and Cl content, which easily promotes scale formation, blocking evaporators, and corroding equipment. The organics and suspended solids in concentrated brine mean that RO needs good pretreatment to meet the requirements on inlet water but ED needs only simple multi-medium filtration.

As the salt content of evaporation pond concentrated brine is obviously lower than that of seawater, more water needs to be evaporated during MED treatment, which increases the treatment cost. By comparison, the treatment cost of ED is reduced as the salt content of the inlet water decreases. The power generated by photovoltaic and wind energy is all DC, which can be directly used by ED, but RO equipment must convert DC into AC using an inverter. This consumes a large amount of electrical energy, and increases equipment and maintenance costs. In addition, ED also has advantages in the length of service life and ease of membrane cleaning compared with RO.

In summary, by comparing the water quality, environmental suitability, and cost factors of the three types of technology, it is concluded that electrodialysis using solar energy is a suitable treatment method for concentrated brine in evaporation ponds.
5. Primary design of the treatment system

5.1. System general design

The climate in the major coal producing areas in West China is generally one of high solar radiation intensity during the day and high wind speeds at night. This paper proposes a new treatment system for concentrated brine in coal mine evaporation ponds. The system is powered by solar and wind energy according to local conditions, as shown in Figure 3. This system includes power generation units and a concentrated brine treatment plant.

The power generation units include photovoltaic modules, wind driven generators, the power control system, and energy storage batteries. To reduce land occupation and avoid the risk of land acquisition, this paper creatively places the photovoltaic modules on a floating island device on the surface of evaporation pond. The floating island device is fixed by chains and anchors to the pond banks and is able to support the photovoltaic modules safety and stably. Wind driven generators can be placed on the banks of the evaporation pond or in another wide space. The power control system and energy storage batteries are placed inside the concentrated brine treatment plant.

The concentrated brine treatment plant can be established near the evaporation pond or within the coal mine site. Inside it there are water pumps, a raw water pond, a multi-medium filtration device, an electrodialysis treatment device, and a clean water pond, see flow diagram Figure 4. Following electrodialysis, fresh water from the brine is supplied to the mining area for reuse and the concentrated brine is discharged back to the evaporation pond after being concentrated.

Figure 3. Concentrated brine treatment system powered by solar and wind in coal mine evaporation ponds

Figure 4. Flow diagram of the brine treatment plant
5.2. Estimation of system treatment capacity

For this study, we selected polycrystalline silicon photovoltaic modules of 250Wp with a conversion efficiency of about 15% and module size of 1,650 × 990 × 40 mm. Mining areas in West China are mostly rich in solar energy and the quantity of annual sunlight radiation is 1,500–1,700 kWh/m². The calculations in this paper are based on 1,500 kWh/m², with an annual generating capacity of each module at about 367 kWh and a daily average generating capacity at about 1 kWh. The area covered by coal mine evaporation ponds are mostly dozens mu in Ningxia and Inner Mongolia. Assuming the area of an evaporation pond is 60 mu (40,000 m²), in this paper, under the assumption that the photovoltaic modules are placed at 45°, half the area of the evaporation pond can hold about 11,000 photovoltaic modules, which can generate 11,000 kWh of power.

The salt content of coal mine concentrated brine is much lower than that of seawater and so is the corresponding power consumption of ED. In this paper, we performed our calculations using a power consumption for seawater electrodialysis desalination value of 10 kWh/m³. In an evaporation pond of 60 mu, after being equipped with a concentrated brine treatment system powered by solar and wind as proposed in this paper, the concentrated brine treatment capacity can reach 1,100 m³/d while being powered by photovoltaic power only.

According to Provisions on Prevention and Control of Water in Coal Mines, water inflow in coal mines in West China is higher than 180 m³/h (4,320 m³/d) and they are water-rich mines. Even if all the water inflow was treated with RO, the concentrated brine produced would be only 1,080 m³/d, which is lower than the system treatment capacity.

6. Conclusions

The following conclusions can be drawn:

1. This paper summarizes the water quality characteristics of concentrated brine in coal mine evaporation ponds. We found high-concentration TDS (mainly SO₄²⁻, Cl⁻, Na⁺, Mg²⁺, Ca²⁺, and HCO₃⁻), a small amount of scale inhibitor, and probably, as the evaporation pond is an open system, a small amount of suspended solids and organic pollutants from external sources.

2. In the major coal producing areas of West China, the rich solar and wind energy resources can be used to power concentrated brine treatment systems, which will largely reduce treatment costs.

3. Through comparative study, the most economically rational and technically feasible treatment method for the mining areas in West China was identified as electrodialysis using solar and wind energy.

4. The operating efficiency of the treatment system proposed in this paper can meet the concentrated brine treatment demands in most coal mines in western mining areas and it has the following advantages: ① it places the photovoltaic power generation plates on the surface of the evaporation pond on a fixed floating island, which reduces any risk associated with land acquisition; ② the power generation design, using solar and wind energy, can reduce the climatic effects to the treatment system.

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