A process of reverse electrodialysis (RED) coupled with water electrolysis (WE) for air conditioning waste heat recovering: A conceptual design

Yaxiao Li, Dongxiao Yang*
School of Chemistry and Chemical Engineering, Henan Normal University, Xinxiang City, Henan Province, 453007, China
*Corresponding author's e-mail: 2013065@htu.edu.cn;

Abstract. Air conditioning waste heat deserves attention for its abundance, especially for the large-scale industrial and commercial systems. Hydrogen is widely accepted as an ideal energy carrier in the foreseeable future. In this paper, a process combining reverse electrodialysis (RED) and water electrolysis (WE) is proposed to convert the air conditioning waste heat to the hydrogen energy. Based on the assumption of large-scale application of the fuel cell electrical vehicle (FCEV), a conceptual design of the proposed process is investigated. The RED section of the process consumes both the air conditioning waste heat and the solar energy to generate electrical power, while the WE section produces hydrogen by using the electrical power. The concentration of the artificial brine solution for RED is designed to be 4-5 M, and its operating temperature is set to 40 °C. The RED power density in this paper is assumed to be 2.7 W/m². Furthermore, a techno-economic analysis is carried out for the process. Results showed that the proposed process shows potential to become an alternative option for air conditioning waste heat recovery. The conclusion of this paper may be interesting to the researchers in the fields of RED technology and low-grade heat recovery.

1. Introduction
With rapid growth of the population and economy, energy demand increases remarkably. It is estimated that by 2050 the world's population will grow to about 9 billion, which means a huge demand for energy[1]. With the improvement of people's living standard and the development of the industrial technology, various types of air conditioning equipment have been widely used in both people's daily life and the industrial fields. The air conditioning system transfers the heat to the environment, resulting in energy waste. Meanwhile, the thermal pollution caused by the waste heat is also a problem of concern, especially for the large-scale air conditioning system.

However, the air conditioning system produces condensate water during working, which provides opportunity for energy recovery through salinity gradient power generating device.

Currently, the hydrogen energy has been widely regarded as the most promising secondary energy in the 21st century[2-3]. By using electrical power, hydrogen can be generated from water through electrolysis process conveniently.

The process of reverse electrodialysis coupled with water electrolysis device has been investigated by researchers for hydrogen production by utilizing salinity gradient energy from the brine[4]. Tedesco et al. reported a power density of 12 W/m² of cell pair, by using 0.1 M NaCl as dilute and 5 M NaCl as concentrate at 40 °C, which is the highest value so far reported in literature[5]. In their
study, a pilot plant utilizing salinity gradient power was established to generate electricity and results showed that the artificial brine provided much larger power density than the brine treated by saltern[6].

In this work, a conceptual design for a process of RED-WE recovering air conditioning waste heat is investigated. Both the air conditioning waste heat and the solar energy are utilized to evaporate and concentrate the artificial brine solution (outflow from the RED device). In addition, after being heated up to a higher temperature by the air conditioning waste heat, the RED concentrate flow can be driven by thermal convection. In this way, the concentrate can be recycled continuously. The hydrogen produced by the WE section is compressed and stored for the hydrogen fueling station. The energy flow of the proposed process of RED-WE is shown as figure 1.

![Figure 1. The energy flow diagram for the proposed process of RED-WE.](image)

2. Principles

2.1. Air conditioning system
As shown in figure 2, remarkable amount of latent heat has to be transferred during the phase change of the refrigerant. Gaseous refrigerant is compressed by the compressor. Then it is sent to the condenser to be chilled down and condensed to a liquid refrigerant. In the evaporator, the refrigerant evaporates and takes large amount of heat from the air. Then, the refrigerant is compressed again and sent into the condenser for the next cycle.

![Figure 2. Schematic diagram of the air conditioning section.](image)

The heat exchanger is fully exposed to the artificial brine solution (outflow from the RED device). Heat transport occurs because of the temperature difference. The fan of the air-cooled condenser works as a standby, in case RED is not at work.

2.2. RED section
The schematic diagram of the RED device is shown in figure 3. In RED section, there are both the anion exchange membrane(AEM) and the cation exchange membrane(CEM). The two kinds of permeable membranes were placed alternately between the low concentration and the high concentration compartments. For NaCl solution, Na⁺ ions diffuse through the cation exchange membrane towards the cathode. Meanwhile, Cl⁻ ions diffuse through the anion exchange membrane towards the anode. Consequently, the ionic current is formed. Then, this ionic current is converted into electric current at the electrodes placed at the two ends of RED device.
The artificial brine solution cycling system in the RED section is shown in figure 4. The solution is heated up by the heat exchanger of the air conditioning system. Then, the flow of the solution is driven by thermal convection. The concentration of the artificial brine solution is maintained by continuously evaporating in the evaporation tank. In this way, the air conditioning waste heat is converted into the salinity gradient energy. The solar energy can also be utilized in the evaporation process. The replenishment of salt and water is made regularly for the evaporation tank. The condensate water from the air conditioning system is used as part of the make-up water.

2.3. Hydrogen production section
The process of the hydrogen production section is shown as figure 5. In the electrolyzer, water is electrolyzed, generating oxygen and hydrogen. The reaction is shown as below.

\[ 2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2 \]  

(1)
The obtained hydrogen is processed by compressor and then stored in a tank. At the end of the process, the hydrogen is sent to the terminal consumers through dispenser.

Figure 5. Schematic diagram of the hydrogen production section.

3. Feasibility analysis
The proposed process requires large-scale air conditioning (commercial or industrial) waste heat as energy sources, and requires fresh water as low concentration solution for the RED device. Being an energy production section, the process requires the market of hydrogen energy consumption.

Many parts of the low-latitude coastal areas are economically developed areas with large population and developed industry, which means huge energy consumption. Also, many of these places have rivers which can be used as freshwater resources. The rivers flow ceaselessly into the sea, and the fresh water can be utilized. Therefore, the proposed process in this paper is quite suitable for the estuary regions in the low-altitude areas.

4. Process designing
In this paper, a conceptual design is investigated for the proposed process. As shown in figure 2-5, the air conditioning waste heat is utilized to heat up the RED outlet stream, which is diluted slightly after RED process. The concentration of the artificial brine solution is maintained by continuous evaporation. The RED works as the power supply for the WE device. Other power consuming equipment, for example the compressor, is run by the electricity grid. The WE section produces hydrogen gas. After being compressed and stored, the hydrogen is sent to the terminal hydrogen energy consumers. The concentration of the fresh water from rivers is assumed to be 0.03 M. The concentration of the artificial brine solution in this work is assumed to be 4-5 M. In low latitude regions, the river water is generally warm. The temperature of the fresh water is assumed to be 20 °C. The RED power density in this paper is assumed to be 2.7 W/m² of cell pair[6]. The heat exchanger is operated at a temperature of 40 °C. As mentioned above, in case of RED out of working, the air conditioning system can still run with the fan of the air-cooled condenser. The maximum production capacity is 4 kg/h (hydrogen). Due to maintenance and other factors, the actual production capacity is assumed to be 3 kg/h.

The membrane area can be calculated by the following equations.

\[ W = \frac{mq}{\eta} \]  
\[ A = \frac{2W}{3600P_d} \]

Where \( q \) is for the calorific value (1.4x10⁸ J/kg) of hydrogen, \( m \) for the maximum capacity of hydrogen production (kg/h), \( \eta \) for the efficiency(70%) of the electrolyzer, \( W \) for the energy production rate requirement for purpose capacity (J), \( P_d \) for the power density (2.7 W/m² of cell pair), and \( A \) for the membrane area(m²).
According to the data in literature, (fresh water flow rate is 8 l/min; salt water flow rate is 8 l/min; power output up to around 65W)[6], it is assumed that the flow rate of fresh water is 20513 l/min and the flow rate of artificial brine solution is 20513 l/min. The lifespan of the electrolyzer compressor, storage system and dispenser is estimated to be 10 years.

Table 1. Assumptions for the process of RED-WE.

| Item                                      | Value                          |
|-------------------------------------------|--------------------------------|
| Power density                             | 2.7 W / m² of cell pair[6]     |
| Maximum production capacity               | 4 kg/h                         |
| Actual production capacity                | 3 kg/h(26280 kg/year)          |
| Lifespan of the membrane                  | 5 years                        |
| Membrane area                             | 164609 m²                      |
| artificial brine solution flow rate       | 20513 l/min                    |
| Fresh water flow rate                     | 20513 l/min                    |
| Lifespan of the electrolyzer, compressor, storage system and dispenser | 10 years|
| employee                                  | 2 persons                      |

According to the report, the evaporation rate is typically between 5 and 10 l/m²/d[6]. If the evaporation rate can be greatly increased, the size of the evaporation tank will be significantly decreased. In the developed regions, where the cost of land is very high, the size reduction of the evaporation tank is advantageous. In the proposed process, the temperature of the artificial brine solution is greatly increased by utilizing both the air conditioning waste heat and the solar energy. Therefore, evaporation is enhanced effectively.

For the overall process, the energy loss should be considered as follows: (1) The heat loss of the heat exchanger can be reduced by well insulating. (2) The evaporation tank suffers remarkable heat loss, since the temperature of the solution in this process is higher than the environment. The amount of this heat loss depends on the environment temperature, wind and other factors. (3) Nevertheless, the solar energy can be utilized for the evaporation tank. The solar energy is abundant in many parts of the low altitude regions.

5. Economic analysis

5.1. Capital costs

The air conditioning section can work independently. In the industrial or commercial areas, air-conditioning is widely used and is actually indispensable. Therefore, the cost of the air conditioning system is not considered in the economic analysis.

Currently, the membrane is still very expensive, because the mass production of the membrane has not been developed. However, we assume the membrane cost as $10/m², from a view point of the future. Based on this assumption, the cost of RED section is dominated by the membrane cost, while the cost of other parts seems to be negligible. Hence, for the RED section, the calculation can be simplified by considering only the membrane cost.

Capital costs include the cost of membrane, electrolyzer, reciprocating compressor, storage system, and dispenser. The calculation results are shown in the table 2.

Table 2. Capital cost estimation for the process.

| Items                                      | $    |
|--------------------------------------------|------|
| Membrane cost                              | 3292181(10 years) |
| Electrolyzer cost[7]                       | 232942 |
| Reciprocating compressor cost[7]           | 55518 |
| Storage system cost[7]                     | 101372 |
| Dispenser cost                             | 92769 |
| Capital cost                               | 3774782 |
5.2. Operating costs

Apparently, the main power consumption is attributed to the water electrolysis section, and the power consumption of other sections is relatively negligible. Therefore, the power consumption of units other than WE was not considered in this economic analysis for simplicity.

Operating costs include equipment maintenance cost and labour costs. The equipment maintenance cost is estimated to be 6% of the capital cost. The employee fee is assumed to be $10000/year. The calculation results are shown in table 3.

Table 3. Operating cost estimation for the process.

| Items                  | $/one year          |
|------------------------|---------------------|
| Equipment maintenance cost | 226487(10 years)   |
| Labour costs           | 200000(10 years)    |
| Operating cost         | 426487(10 years)    |

The cost constitution is shown as figure 6. As can be seen, the membrane cost accounts for the major part of the hydrogen production cost. The hydrogen production cost is estimated to be $15.99 $/kg. In order to reduce the cost of the proposed process, a novel membrane material with lower cost and higher power density should be developed. Recent development in the membrane research is likely to enhance the potential of the proposed process.

6. Conclusions

This paper presents a RED-WE process for the waste heat recovery of the industrial or commercial air-conditioning. A conceptual design is investigated and an economic analysis is carried out. Results showed that the proposed process can be used as an alternative option for air conditioning waste heat recovery. In order to increase its economical competitiveness, advanced RED technology with higher power density and lower membrane cost should be developed. It should be noted that sustainability is among the advantages of the proposed process.

Acknowledgments

The authors would like to acknowledge the support of Practice Education Research Fund for Professional Master of Henan Normal University in 2019 and Postgraduate Scientific Research Innovation Project of Henan Normal University (No. YL201914).

References

[1] Leiva, E. P. M., Lima, L. C., Cavalcante, F. S. A., Sigal, A., Esteves, N. B., Rodriguez, C. R. (2015) Wind and solar hydrogen for the potential production of ammonia in the state of Ceara-Brazil. Int. J. Hydrogen Energ., 40: 9917-9923.

[2] Ghosh, K. T., M. A. Prelas. (2011) Energy Resources and Systems Volume2: Renewable Resources. Springer Dordrecht.
[3] Yang, C., Wang, M., Peng, B., Lu, J., Zahedi, A. (2013) Building the hydrogen economy in China: Drivers, resources and technologies. Renew. Sustain. Energy Rev. 23: 543-556.

[4] Tufa, R.A., Rugiero, E., Chanda, D., et al. (2016) Salinity gradient power-reverse electrodialysis and alkaline polymer electrolyte water electrolysis for hydrogen production. J. Membrane Sci. 514: 155-164.

[5] Tedesco, M., Brauns, E., Cipollina, A., Micale, G., Modica, P., Russo, G., Helsen, J. (2015) Reverse Electrodialysis with saline waters and concentrated brines: a laboratory investigation towards technology scale-up. J. Membrane Sci. 492: 9-20.

[6] Cipollina, A., Micale, G., Scalici, C., Vaccari, D., Tamburini, A., Tedesco, M. (2016) Performance of the first reverse electrodialysis pilot plant for power production from saline waters and concentrated brines. J. Membrane Sci. 500: 33-45.

[7] Weinert, J.X., Shaojun, L., Ogden, J.M., Jianxin., M. (2007) Hydrogen refueling station costs in Shanghai. Int. J. Hydrogen Energ. 32: 4089-4100.