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Review

Review of thermally regenerative batteries based on redox reaction and distillation for harvesting low-grade heat as electricity

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A B S T R A C T

Low-grade thermal energy (<100 °C) is ubiquitous in nature and human activities, and its enormous reserves and renewability make it significant to convert it into electricity. Thermally regenerative battery (TRB) based on redox reaction and distillation is one of the most promising liquid-based thermoelectric conversion technologies, mainly due to its relatively high power density. In this review, we first summarize the working principle of the general TRB and give the calculation criterion of efficiency, power and energy densities according to whether the initial positive and negative redox couples are consistent. Subsequently, the characteristics of aqueous (such as single metallic, bimetallic and all-soluble) and organic TRBs are analyzed and the latest progress is critically reviewed. The different viewpoints of the temperature required for the thermal regeneration process in the literature are explained from two aspects of theoretical simulation and experimental investigation, then the intrinsic parameters affecting the distillation efficiency are analyzed from the thermodynamic aspect. The application prospects of TRB in wastewater treatment, CO_2 capture and combined cycle are prospected. Finally, the efficiency and power density of different TRBs are compared, and three major challenges (including cycle reversibility, ion cross-contamination and thermal regeneration/electrochemical processes coupling) faced by TRBs and future research directions are presented.

1. Introduction

Low-grade heat (<100 °C) is widely presented in various industrial processes (e.g. steel and glass productions) [1–4], nature (e.g. geothermal [5,6] and solar [7,8] energy), and organisms (e.g. body heat [9,10]), and is characterized by an extremely large quantity and global distribution. The annual emission of waste heat below 100 °C in the world is about 7.3×10^4 TW h, accounting for about 31–34% of the total energy consumption [11]. Consequently, it is gradually considered as a "renewable energy" [12,13]. In addition, the direct discharge of industrial waste heat into the environment will aggravate environmental pollution and greenhouse effect [14,15]. Therefore, the development of advanced low-grade heat utilization technologies to efficiently store and convert this "renewable energy" into electrical power is an important means to improve energy efficiency and mitigate the increasing greenhouse effect.

For many years, organic Rankine cycle (ORC) [16–23] and solid-state thermoelectric generator (TEG) [24–31] have been explored and optimized for thermoelectric conversion. For low temperature heat energy less than 100 °C, it is difficult to find organic working fluid with low boiling point and high vapor pressure to make ORC cycle obtain higher net work and efficiency [23]. Additionally, the operating and investment costs of the overall system are relatively high [32,33]. TEG is mainly based on the Seebeck effect of solid semiconductor materials, which has the advantages of no moving parts, small size, long life and no noise [30]. However, for heat sources with a temperature difference of less than 100 °C, the figure of merit $ZT = [(S^2\sigma)/\kappa]T$ (where S is the Seebeck coefficient, κ is thermal conductivity, and σ is electrical conductivity) is difficult to be higher than 0.2 [29], which limits the application of TEG in low-temperature heat energy utilization. In the past decade, a variety of liquid-based thermoelectrochemical systems or batteries have been proposed and realized the conversion of low temperature thermal energy to electricity or mechanical work with inexpensive material costs, energy storage ability, high thermoelectric conversion efficiency and power density [32,34,35]. On the basis of the working principle, they can be classified as: (1) Thermo-electrochemical cell (TEC) [33,36–41] and thermally-regenerative electrochemical cycle (TREC) [42–49] based on ion Seebeck effect; (2) Thermally regenerative

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