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Solar-driven sodium thermal electrochemical converter coupled to a Brayton heat engine: Parametric optimization

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A novel high-efficiency device comprised of three subsystems, a solar collector, a sodium thermal electrochemical converter, and a non-recuperative Brayton heat engine, is modeled by taking into account the main internal and external irreversibility sources. The model extends previous works in which the heat waste of the electrochemical converter is used as heat input in a Brayton gas turbine to study its performance and feasibility when a solar energy input is added. The operative working temperatures of three subsystems are determined by energy balance equations. The dependence of the efficiency and power output of the overall system on the solar concentration ratio, the current density, the thickness of the electrolyte, and the adiabatic pressure ratio (or temperature ratio) of the Brayton cycle is discussed in detail. The maximum efficiencies and power output densities are calculated and the states of the maximum efficiency-power density are determined under different given solar concentration ratios. The parametric optimum selection criteria of a number of critical parameters of the overall system are provided and the matching problems of the three subsystems are properly addressed. It is found that under a solar concentration around 1350, the maximum efficiency and power output density of the proposed hybrid system can reach, respectively, 29.6% and 1.23×10^5 W/m^2. These values amount approximately 32.7% and 156% compared to those of the solar-driven sodium thermal electrochemical converter system without the bottoming Brayton cycle. The Pareto front obtained from numerical multi-objective and multi-parametric methods endorses previous findings.

1. Introduction

The sunlight is the greatest source of energy in the world compared with the other common energy sources including the natural gas, coal, and oil. It has obvious advantages such as renewable, free, clean, and long term available [1–3]. Solar energy power systems use the heat produced by collectors to drive some power systems such as Brayton-like gas turbines [4–7], Carnot-like heat engines [8–10], thermionic generators [11–13], thermophotovoltaic cells [14–16], and thermoelectric generators [17–20]. The sodium thermal electrochemical converter (Na-TEC) [also named as the alkali-metal thermal electric converter (AMTEC)] is becoming now-days as a useful power system that generates electricity by driving sodium ions [21–24]. For example, Cole et al. [21] described the basic operating principles of the Na-TEC; Underwood et al. [22] proposed a new arrangement incorporating internal cells connected in series; Lodhi et al. [23] studied the influence of the electrode materials on the power output degradation showing a performance of the sodium cell up to 77% when selected materials are used [17,24].

Na-TEC cells are high efficiency devices allowing an appropriate coupling with a variety of heat or fuel sources. In this line, Wu et al. [25] studied an integrating device composed of a parabolic solar collector and a Na-TEC cell; Chivington et al. [26] developed a new conceptual design for a system converting solar energy to electricity with a Na-TEC for spacecraft; Johnson et al. [27] designed and integrated a solar Na-TEC power system with an advanced global positioning satellite; Kotaro [28] studied and analyzed a preliminary design of the solar-driven system with the Na-TEC; Hendricks et al. [29] displayed the crucial aspects of a radial Na-TEC cell

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