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Review

Optimum operation states and parametric selection criteria of an updated alkali metal thermal electric converter

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ABSTRACT

The cycle model of an alkali metal thermal electric converter (AMTEC) is updated, where the relation between the thickness of the electrolyte and the other parameters of the AMTEC is established. The effects of thickness of the electrolyte on the performance of the AMTEC are discussed. The operation states of the AMTEC are optimized. The maximum efficiency and power output density of the AMTEC are calculated. The selective criteria of the thickness of the electrolyte and other parameters are optimally provided. Moreover, it is expounded that the proportional coefficient related to the thickness of the electrolyte is closely dependent on electrolyte materials. The effects of this coefficient on the efficiency and power output density of the AMTEC are further discussed, and consequently, the rational range of the coefficient is determined.

1. Introduction

Alkali metal thermal electric converters (AMTECs) are a class of thermoelectric devices mainly made of an β''-alumina solid electrolyte (BASE) membrane [1–3]. AMTECs have exhibited some advantages such as the absence of moving parts [3], no noise or vibration [4], reliability [5], competitive manufacturing costs [6], and good compatibility with many heat and fuel sources including the external combustion, the waste heat produced in high-temperature fuel cells [7–9], concentrated solar [6,10], or nuclear reactor [3]. These advantages make AMTECs be suitable for aerospace, military, and domestic applications [11].

In recent decades, many authors carried out theoretical and experimental researches and got some important results. For example, Lee et al. [12] obtained simulation results for the best position and shape of the radiation shield and revealed that the maximum power was generated when a stainless steel shield was installed in between the BASE tube and the condenser. Seog et al. [13] studied the performance of the AMTEC under some conditions such as the number of coatings consisting of Mo/TiN, ranging from 1 to 3 times, and heat treatment temperatures of 1073–1373 K, and obtained the result that the converter yielded a maximum power of 9.99 W for the sample coated 3 times and heat-treated temperature at 1173 K. Kim et al. [14] reported that a single cell composed of Mo/TiN powder (Mo 1.0 mol%) shows high performance and exhibits a low area specific resistance at 973 K. Kim et al. [15] found that the electrode made of the Mo/TiN composite powder has high electrical conductivities of 1000 S/cm at 573 K and 260 S/cm at 973 K, and high-temperature stability. Lodhi and Ahmad [16] described that the optimization of thickness of electrodes can improve the efficiency and power output by 28% and 14.8%, respectively. Ryan et al. [17] indicated that the lifetime of an AMTEC electrode depends on the surface self-diffusion coefficient of the electrode material under differently operating conditions, and it may be advantageous to use somewhat lower platinum-tungsten ratios in order to attain longer lifetimes at higher temperatures. Chen et al. [18] studied the influence of microstructure, relative density, content of β'' phase and performance of β''-Al_2O_3 electrolyte by adjusting the doping amount of TiO_2 and the sintering temperature. Merrill et al. [19] discussed the test results of two major design iterations of the PX series cells and expounded that the continued improvements for the cell design can continually increase electric power output and conversion efficiency. Underwood et al. [20] proposed a concept that incorporates internal series connecting of cells and sodium supply as a vapor. Carlson et al. [21] reported that their experiment provided the first opportunity to test AMTEC cell performance in a true system configuration. Borkowski et al. [22] reported that a major PX cell design challenge is to optimize the power and efficiency of the cell, and these design optimization issues are greatly dependent on the placement of the evaporation zone. In addition, the existing test and analytic results indicated the magnitude of the power transfer to the evaporation zone and the effect of this power transfer on the performance of the cell [22]. Lodhi et al. [23] investigated the factors contributing to this power loss. These analyses showed that the β''-alumina degradation manifests itself as an increase in its ionic resistance which reduces power output. Some

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Nomenclature

B	temperature-independent charge-exchange coefficient, A $K^{1/2}$ Pa^{-1} m^{-2}
c_P	average molar specific heat, J g^{-1} K^{-1}
D	thickness of BASE, m
F	Faraday constant, C mol^{-1}
G	geometric factor for pressure losses
J	current density, A m^{-2}
L	latent heat of evaporation of sodium, J g^{-1}
M	molecular weight of sodium, g mol^{-1}
P	power output density, W m^{-2}
p_x	working fluid pressure, Pa
p_x^{oc}	working fluid pressure in open state, Pa
P_η	power output density at maximum efficiency, W m^{-2}
R	gas constant, J mol^{-1} K^{-1}
R_B	ionic BASE resistance, Ωm^2
T_1	high-temperature, K
T_2	low-temperature, K
V	voltage output, V
V_{oc}	open-circuit voltage, V
Z	geometric factor for radiation losses

Greek symbols

η	efficiency
η_P	efficiency at maximum power output density
λ	proportional coefficient, m^2
σ	Stefan-Boltzmann radiation constant, W m^{-2} K^{-4}
ζ_x	charge-exchange polarization over potentials, V

Subscripts

x	a (anode), c (cathode)
P	state of maximum power output density
η	state of maximum efficiency

Abbreviations

AMTEC	alkali metal thermal electric converters
BASE	β''-alumina solid electrolyte

suggestions, using β-alumina instead of β''-alumina and keeping the electrode current density below a certain critical value, may help to reduce the rate of power degradation and extend the useful and functional time of the cell. Lodhi et al. [24] dealt with the factors responsible for this degradation and discussed in detail the simulation model used to study and predict the performance of the cell as a function of time. It is shown that the β-alumina solid electrolyte is a major cause of this degradation, and a model to simulate its performance is developed and compared with available experimental data to establish the role of the electrolyte. In these researches, the main focus is on the effect of the position and shape for radiation shield, electrode material, thickness of electrodes, lifetime of AMTEC electrodes, and time-dependent degradation behavior on the power output and efficiency of the AMTEC. However, the relation between the efficiency and the power output is rarely discussed. On the other hand, the effects of the thickness of the BASE on the systemic performance are never expounded deeply. These problems urgently need to be discussed and solved in the further investigation of AMTECs.

In the present paper, we will analytically derive the expression of the thickness of the BASE associated with other parameters and comprehensively reveal the optimum relation between the power output density and the efficiency. The concrete contents are arranged as follows. In Section 2, the working principles of an AMTEC are briefly described. In Section 3, the relation between the voltage output of the AMTEC and the thickness of the BASE is derived. In Section 4, the optimum operation states of the AMTEC are discussed in detail. The optimum selection criterion of the thickness of the BASE is supplied. In Section 5, the effects of several parameters on the performance of the AMTEC are further discussed. Finally, some important conclusions are summarized.

2. The model description of an alkali metal thermal electric converter

The diagram of an AMTEC is shown in Fig. 1 [20], where a closed vessel is divided into two regions by a separator made of the BASE and a pump. At the high-temperature T_1 and high-pressure p_a region, T_1 is in the range of 900–1300 K and p_a is in the range of 20–100 k Pa. At the low-temperature T_2 and low-pressure p_c region, T_2 is in the range of 400–800 K and p_c < 100 Pa [16]. The vapor sodium fills the upper region, which is in contact with an external high-temperature heat source. The lower region contacted with a heat sink contains mostly sodium vapor and a small amount of condensed liquid sodium. The critical material in the operation of the AMTEC is the BASE, which is commercially available as a dense micro-crystalline sintered ceramic ($Na_{5/3}Li_{1/3}Al_{32/3}O_{17}$). The BASE conducts only sodium ions but not neutral sodium or electrons. One thin porous electrode is sprayed and plated on the inside wall (high-pressure region) of the BASE and acts as the anode and another thin porous electrode is sprayed and plated on the outside wall (low-pressure region) of the BASE and acts as the cathode. Electrodes connected with current collectors provide a path

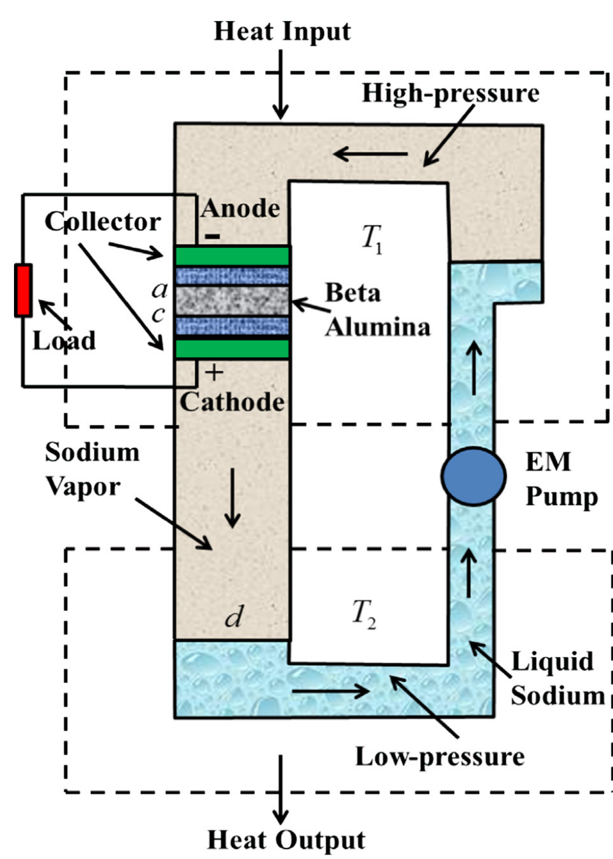

Fig. 1. The schematic diagram of an AMTEC.