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Research Paper

Thermal modeling and efficiency of a dual-stage sodium heat engine

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HIGHLIGHTS

- High-level design of an axisymmetric dual-stage Na-TEC.
- Simplification for conduction and radiation in a corrugated structure.
- Analytic expression for heat loss through a liquid return path.
- Iterative procedure to find efficiency and power from Na-TEC.

ABSTRACT

A thermal design of an axisymmetric dual-stage sodium thermal electrochemical converter (Na-TEC) is presented, where a reduced-order finite-element model is used in conjunction with a Na-TEC thermodynamic model to determine the total parasitic heat loss of this dual-stage design. A number of simplifications are applied in the reduced-order model to decrease the computational time while maintaining acceptable accuracy. These include the use of effective thermal conductivities to account for complex corrugated geometries and apparent surface emissivities to accommodate the effect of radiation shields. Furthermore, a simplified analytical model is developed to account for conduction bypass through the Na-TEC liquid-return path. An iterative procedure between the finite-element and thermodynamic models is described in detail, and the thermal performance of the design proposed herein is analyzed. According to this analysis, a maximum efficiency of 29% and a maximum power output of 125 W can be achieved.

1. Introduction

The sodium thermal electrochemical converter (Na-TEC) is a heat engine that generates electricity through the isothermal expansion of sodium ions through an ion-conducting solid-electrolyte known as β"-alumina. A dual-stage Na-TEC (Fig. 1a) divides the isothermal expansion process into two stages; a first-stage at the evaporator temperature (1150 K) and a second-stage at an intermediate temperature (650 K–1050 K) [1]. This staging takes advantage of regeneration and reheating and improves the thermal management due to a lower average device temperature. This leads to increased practical thermal efficiencies, however at the expense of lowering the theoretical thermodynamic efficiency capable with a single-stage Na-TEC [2]. Several thermal modeling efforts have been previously undertaken for the single-stage Na-TEC. The most extensive of these efforts were the separate 3D models for conduction/radiation, conical evaporator, and sodium vapor flow created for NASA-PX AMTEC cells [3–5]. A more recent effort used an enclosure network to simplify the radiation analysis [6]. Furthermore, parametric analyses on the geometric features and materials of these cells were undertaken to improve thermal efficiency [7,8]. Reduced-order thermal models were also developed for other AMTEC designs (*e.g.,* radial cell) [9].

The thermal management of the dual-stage Na-TEC is the critical challenge in achieving high efficiencies. Therefore, a detailed thermal analysis and design is undertaken herein to estimate the thermal parasitic losses of a dual-stage Na-TEC using a reduced-order finite-element model, similar to models created previously to analyze other electrochemical systems [10–12]. Several engineering simplifications are developed herein to decrease the computational time required for model convergence while maintaining acceptable accuracy, differing from previous approaches to single-stage Na-TEC modeling. First, a high-level design with axisymmetric geometry, including sizes and material selection, is presented. Using a thermal circuit, only conduction losses are initially considered to establish an upper limit for the power and efficiency. These thermodynamic parameters depend most strongly on the thermal resistance between the second-stage electrolyte and the condenser. Radiation is then considered in the interior and exterior of the device in the limit of surface-to-surface exchange. To further reduce computational time, apparent (equivalent) emissivities are used to express the effect of complex geometries having multiple radiating surfaces. A simplified analytical model is also developed to estimate the thermal loss through the liquid-return path between the

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Nomenclature

Roman

t	thickness [m]
P	power [W]
R	thermal resistance [K/W]
T	temperature
Q	heat [W]
k	thermal conductivity [W/m-K]
A_c	cross-section area [m^2]
N	number
h	height of corrugated unit [m]
k_{eff}	effective thermal conductivity [W/m-K]
N_{seg}	number of electrolyte segments
j_1	first-stage current density [A/cm^2]
Nu	Nusselt number
Pe	Peclet number
L	length of liquid-return path [m]
$\dot{m}$	mass flowrate [kg/s]
M	sodium molar mass [22.98 g/mol]
F	Faraday's constant [96485 c/mol]
c_p	constant pressure specific heat [J/g-K]

Greek

ε	surface emissivity
σ	Stefan-Boltzmann constant [5.68×10^{-8} W/m^2-K^4]

Subscript

β	β"-alumina electrolyte
1	first-Stage
2	second-Stage
cond	condenser
evap	evaporator
c	conduction
rad	radiation
Z(i)	i^{th} zone property
a	inner
b	outer
s	stainless steel 316
v	vanadium
spk	spoke
es	external shield (Zone 3)
cs	cylindrical shield (Zone 4)
Na	sodium

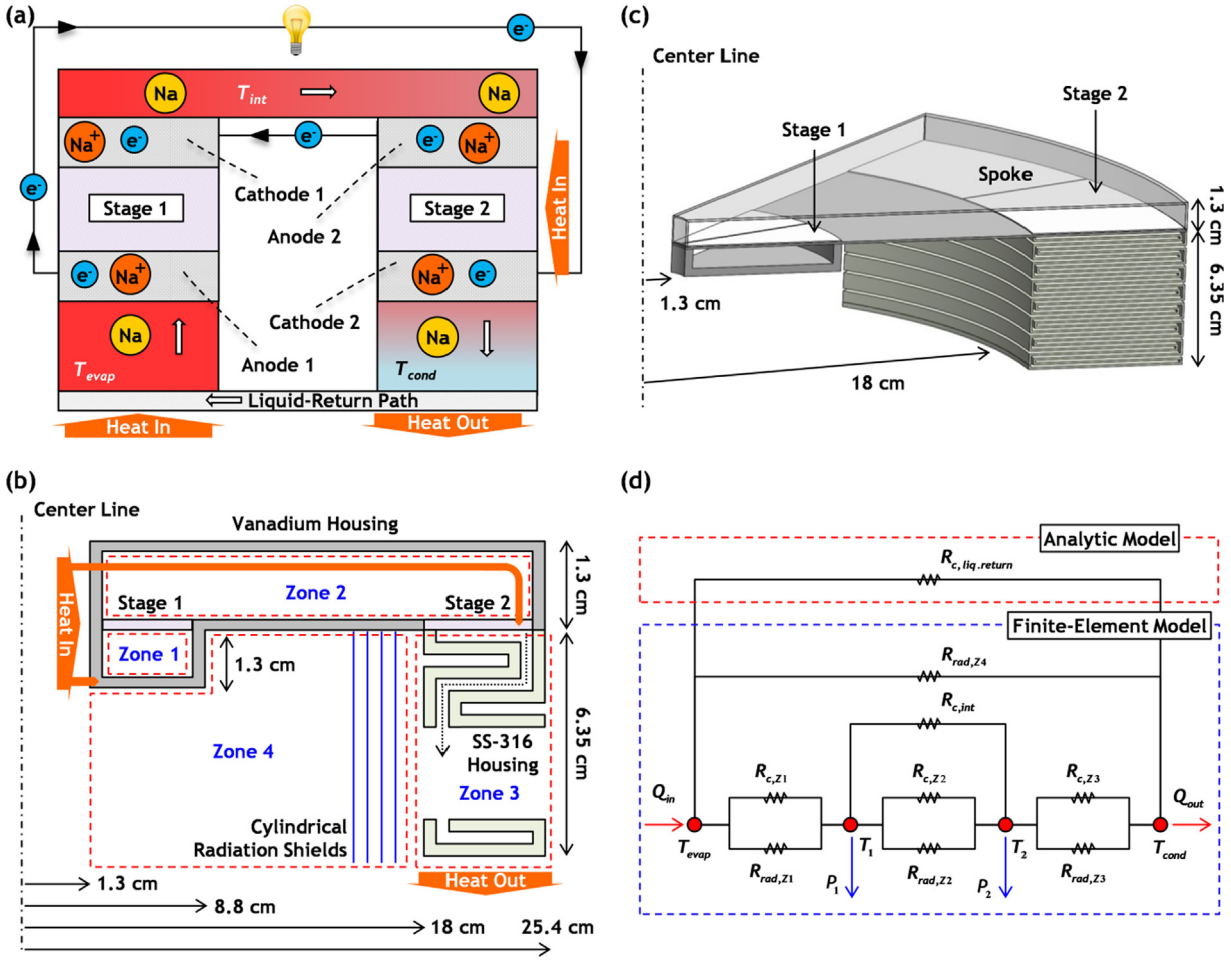

Fig. 1. (a) Schematic illustration of the operation of a dual-stage Na-TEC adopted from Ref. [1]. (b) Axisymmetric geometry of an individual dual-stage module. The corrugated structure in Zone 3 is made of stainless steel 316, while the remainder of the housing is made of vanadium. Zones 1–3 comprise the interior of the device, while Zone 4 is exterior to the device. The heat input to the second-stage (reheat) from (a) is not treated as a separate heat input in this model because this heat comes directly from bypass losses in the first-stage. (c) 3D representation of the dual-stage module design (1/8 piece) with $N = 7$ corrugated units in Zone 3. (d) Equivalent thermal resistance circuit used to calculate the bypass loss.