INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 37 (2012) 1385–1398

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High efficiency Thermo-Electric power generator

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ARTICLE INFO

Article history:
Received 29 April 2011
Received in revised form
13 September 2011
Accepted 21 September 2011
Available online 22 October 2011

Keywords:
Thermo-Electric materials
Power generation
Seebeck effect
Thermo-Electric module
Efficiency

ABSTRACT

Thermo-Electric (TE) power generation is an attractive method for the direct conversion of thermal energy into electrical one. Both the TE material properties and the power generator architecture play a fundamental role in the achievement of high energy conversion efficiencies. The paper focuses on the TE module architecture design, as well as on the subcomponents manufacturing and assembly.

Segmented TE power generators, characterized by a counter-current arrangement of the hot and cold gaseous streams, and a catalytic combustion chamber to ignite an air/fuel mixture, were designed and manufactured (SiC monolith heat exchangers, catalysts and supports for the combustion chamber, system housing). As TE materials, commercial Bismuth Telluride cells were adopted. Pd/$NiCrO_4$ and Pt/Al_2O_3 catalysts were investigated to ignite H_2, CH_4 and H_2/CH_4 mixtures, at different gas flow rates and fuel concentrations. The results led to the design of a TE generator architecture providing flexible electrical loads through a modular assembly, with an improved thermal management which enhanced the energy conversion efficiency.

1. Introduction

Thermo-Electric (TE) materials can be used for power generation purposes: when a temperature gradient is imposed across the TE material, a flow of charge carriers (electrons for n-type, and vacancies for p-type semi-conductors) is established, and an electrical voltage is generated to drive an external load. Different commercial TE materials have preferred temperature intervals of operation within which they provide their optimal performance.

The fabrication of TE modules for power generation implies an appropriate shaping of the n- and p-type elements to be assembled together, and the realization of low-resistance and stable electrical contacts: both low-temperature and high-temperature contacts have to be made, according to the two sides of the TE element. Hence, the TE elements are produced by slicing wafers from the ingots and then dicing the wafers into individual elements. A barrier material, for instance, nickel, is usually applied to the sides of the thermo-elements to prevent copper (present in the conductor material) from diffusing into the TE materials. The barrier material is also solder-wettable to insure reliable joints between the thermo-elements and the conductor. The pairs of p- and n- type TE elements are connected electrically in series and thermally in parallel. The TE elements and contacts are then sandwiched between two ceramic plates, as shown in Fig. 1, to provide the TE module with mechanical integrity and electrical insulation, as well as good thermal conduction to the heat sources and the sinks. Finally, heat exchangers are meant to establish the desired temperature gradient: if the heating and cooling media are constituted by gaseous streams, as in the configuration described in this paper, the

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0360-3199/$ – see front matter
doi:10.1016/j.ijhydene.2011.09.125

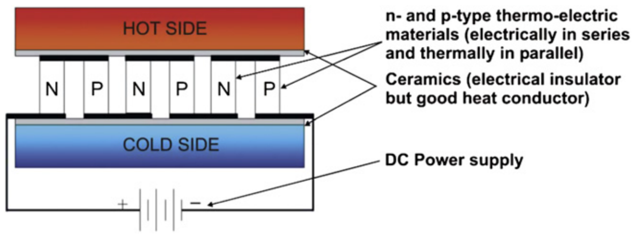

Fig. 1 – TE system for power generation.

heat exchangers assume the shape of finned surfaces or of ceramic flow-through monoliths.

TE energy generation is an attractive method for the direct conversion of thermal energy into electrical energy [1], especially for distributed power generation [2–5] or portable power generation [6–8] when waste heat is available and could be exploited for this purpose. TE generators are compact, quiet, stable and very reliable, but they have found few applications because of their low efficiency (typically less than 5%) and high cost. In the last decade lots of efforts have been spent to develop novel TE materials of increased intrinsic conversion efficiency, but also the design of the system architecture plays a fundamental role to control the thermal exchange and to maximize the conversion performances [1,9,10]. In particular, the effect of heat recovery, the so called "regeneration" or "heat recirculation" [1,10–12], is the key to improve the energy conversion efficiency of TE generators: the heat released at the cold side of TE modules is recovered (Figure 2-A), thus obtaining high energy conversion efficiencies, even employing TE materials with $\langle ZT \rangle \approx 1$ (state-of-the-art materials). The heat can be provided either by an external source, i.e., through the recovery of waste heat as for PEM FCs or vehicle's exhaust gas tailpipes [7,8], or by igniting a specific air/fuel mixture: this operation could be done inside a dedicated combustion chamber [6,13,14], or directly in the hot channel of the module [10,15–18]. Several works demonstrated the capability of combustion in microscale integrated with thermoelectric generators, by employing monoliths as micro-burners [10,13,15,16], 2-D or 3-D Swiss-roll-type combustors [1].

In this work TE generators constituted by TE elements integrated with heat exchangers and with a combustion chamber are presented and analyzed. Theoretical calculations are reported, and related architecture is optimized by means of Computational Fluid-Dynamic simulations (CFD).

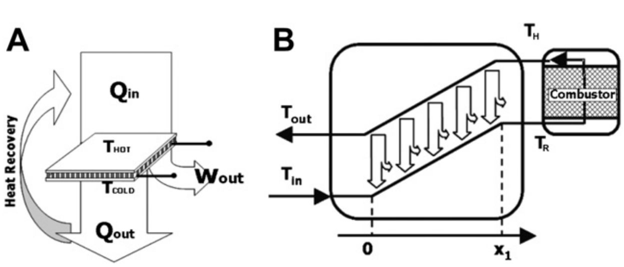

Fig. 2 – Conceptual representation (A) and schematic of a pure counter-current configuration (B) of heat recovery in a TE system.

The paper is outlined as follows: first, section 2 focuses on the theoretical calculation of the TE module energy conversion efficiency, and the consequent implications on the module design. Then, the sub-components of the module are described in section 3, in terms of manufacturing and prototype assembly; an improved module architecture has also been developed, to overcome some technical limitations of the original prototype; it is reported in section 3 as well. Section 4 presents the experimental results of the characterization activity and the performance of the individual sub-components, and of the two TE modules as a whole: the "U-shape" and the "multi-pass" TE generators. Finally, in section 5, conclusions are drawn on the best TE module configuration and its experimental energy conversion efficiency is compared to the maximum theoretical one.

2. Module design

The TE generator taken into account for energy conversion efficiency calculation is characterized by a series of TE elements placed in a counter-current heat exchanger. An air/fuel mixture at room temperature T_{in} is fed to the generator (Figure 2-B), flows in the cold channel where it warms up absorbing heat from the cold side of the TE elements, enters the combustion chamber with the regeneration temperature T_R, and here it burns reaching the temperature T_H. The flue gases from the combustion chamber pass through the hot channel, in counter-current with respect to the inlet air/fuel stream. The flue gases cool down, transferring heat to the hot side of TE elements, and leave the system at relatively low-temperature T_{out}. Such generator can be called "U-shape" TE generator.

The assumed simplifying hypotheses, for calculating the theoretical energy conversion efficiency of the "U-shape" TE generator, are the following:

- no heat transfer along the channels (all the heat is exchanged through the TE elements) and no heat dispersion (perfect insulation);
- the temperature increases/decreases linearly with the gaseous flow direction (x position);
- the temperature profiles of the two gas fluxes are parallel;
- the mass flow rate of the two streams is the same (fuel and air are pre-mixed at the TE module inlet) and their thermal heat capacity remains practically unchanged;
- the temperature difference between the gas and the TE element surface is negligible with respect to the one across the hot and cold sides of the TE element itself;
- the dimensionless figure of merit $\langle ZT \rangle$ of an individual TE material is constant with respect to the temperature.

ΔT is the constant temperature difference between the two fluxes and its value depends on the regeneration capacity of the TE module Φ (i.e., its ability in internally recovering heat from the hot gas stream, and transferring it to the cold one), defined as:

$$\Phi = \frac{T_H - T_{out}}{T_H - T_{in}} \quad (1)$$