INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 42 (2017) 20835–20842

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Thermoelectric performance using counter-flowing thermal fluids

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ARTICLE INFO

Article history:
Received 18 May 2017
Received in revised form
13 June 2017
Accepted 17 June 2017
Available online 6 July 2017

Keywords:
Thermoelectric generation
Thermoelectric performance
Counter-flowing thermal fluids
Flow rate
Finite-element analysis

ABSTRACT

Counter-flowing thermal fluids are conducive to generate a homogeneous temperature difference on thermoelectric (TE) generator. This study allowed the hot and cold fluids of having constant inlet temperature to flow in the opposite, and examined TE performance of module at different flow rates. The results show that TE performance gradually increases with flow rate in the initial stage of fluid flow, and reaches a transient peak value after the module surfaces are completely covered by thermal fluids, and then tends to be stable. High flow rate leads to larger performance and reduces the time of achieving them. Effect of flow rate on stable performance is slightly more than that of inlet temperature of thermal fluids, which makes regulating the flow rate to be a feasible way to harvest more heat for TE conversion. Module features present a specific trend and provide the supports for the benefit of counter-flowing thermal fluids.

Introduction

Thermoelectric (TE) conversion is bound to be a promising technology for the acquisition and utilization of renewable and recycled resources [1–4], such as inexhaustible solar energy and industrial waste heat, because the thermal feeding can be directly converted into electricity at a junction of two different materials by using a TE generator (TEG) based on the Seebeck effect [5,6], and TEGs can be operated reliably in an isolated place without noise and pollution, and the chemical reactions or mechanical moving parts are no longer needed [7,8]. In essence, TE generation requires a sufficient temperature difference, ΔT, between hot and cold surfaces of TEGs to induce an electromotive force (EMF), and a high ΔT leads to a high EMF, which is attributed to EMF is the sum of the product of the relative Seebeck coefficient and the temperature difference for all p-type and n-type TE elements connected in serial [9], moreover, we had clarified that the homogeneous heat flux throughout a TEG is indispensable to enhance TE performance that is due to the geometry-dependent thermal diffusion becomes uniform [10,11]. Thus as a result, a pair of counter-flowing hot and cold fluids, as shown in Fig. 1 (a), should give rise to a better TE conversion on module, where a high ΔT can be facilitated by the hot fluid, and a homogeneous heat flux can be obtained when the hot fluid is cooled and the cold fluid is heated at the same time by exchanging the heat through the conduction of solid TE module in the process of the thermal fluids flow in the opposite, as depicted in Fig. 1 (b).

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http://dx.doi.org/10.1016/j.ijhydene.2017.06.132

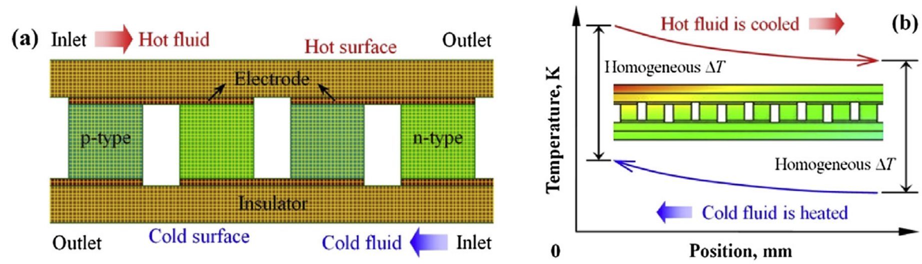

Fig. 1 – TE module using counter-flowing thermal fluids: (a) 3D physical model and (b) temperature difference formation.

The benefits of counter-flowing fluids are widely recognized, but the thermoelectric effects by their flows have been less studied. Our previous work [12] investigated the influence of temperature difference between a pair of counter-flowing hot and cold fluids on the performance of a TE module, including voltage and electric current, as well as output power, input heat and conversion efficiency, and indicated that the transient performance tends to be stable over a period of time after TE module surfaces are completely covered by the thermal fluids, where this delay time is consistent for the different inlet temperature of hot fluid when the inlet temperature of cold fluid and the flow rate of fluids are fixed, and the stable performance increases with the inlet temperature of hot fluid, and that the counter-flowing fluids can simultaneously produce a homogeneous distribution for electric charges and heat flux throughout the entire module composed of the conventional cube-shaped TE elements. This study continued to model a three-dimension (3D) TE module whose surfaces are covered by the counter-flowing hot and cold fluids, and conducted a numerical simulation using finite-volume method in a commercial software environment, Fluent, to clarify the change of module performance with the flow rate of thermal fluids, where fluid dynamics and TE conversion are carried out synchronously, and then the effects of temperature difference and flow rate on TE performance are compared, which illuminates that the regulation of flow rate should be more effective in improving performance of TE module. The uniform thermal diffusion brings about a homogeneous distribution of pressure and enthalpy inside TE module and exhibit a specific trend with flow rate.

Finite-element solution

3D meshed model

Fig. 2 showed a cross-section design of the two cuboid-shaped channels on TE module in order to allow the thermal fluids flow in them and then cover the hot and cold surfaces, where the module surfaces are regarded as the channel floors, and each channel contains two walls and a ceiling to act as the borders of fluid flow. Counter-flowing hot and cold fluids flow into channel via the inlet and exit through the outlet, respectively, and are directly in contact with TE module to provide the required temperature difference for TE conversion. 3D physical model is divided into two computational domains, one is used to calculate the pure flow behavior of thermal fluids, including two channels, and the other is the entire module to implement the simulation on TE process consisting of heat conduction and electric charge transport, and the heat supply from the counter-flowing fluids is considered as the thermal boundary condition. Two computational domains are meshed three-dimensionally by the same size, 0.05 mm, using map mesh method to achieve the sufficient convergence and precision for the repeated finite-element iterations. For simplification, the following assumptions are made in formulating 3D physical model: 1) TE module is adiabatic to the outside, 2) a perfect tight bonding exists among all the component parts of module, 3) the temperature-dependent properties of solid module materials are ignored because no obvious performance change was found in a narrow temperature range [13], 4) the thermal fluids flow in the form of uniform laminar at a fixed flow rate, and the fluid compression and turbulent buoyancy in channel are neglected, thereby no changes in the pressure and volume for them, and 5) the hot and cold fluids are considered as the oil and water, respectively, and the physical properties of high-temperature oil are close to those of water at ambient temperature, so that ensure the one-way flow and the heat transfer of fluids are in a similar situation. TE module is constituted by 18 pairs of cube-shaped elements of p-type and n-type, which are connected together in series using electrode plates, and sandwiched between the insulator layers. The geometric dimensions of 3D physical model as well as the properties of thermal fluids and solid materials are listed in Tables 1–3, respectively.

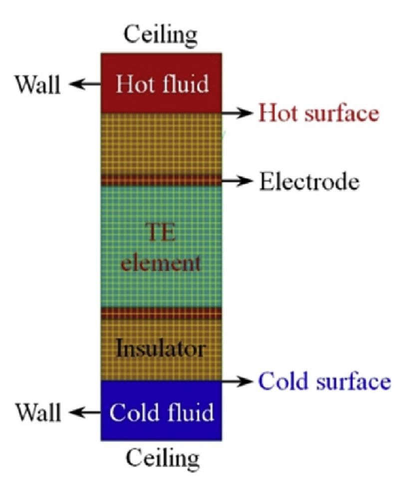

Fig. 2 – Cross-section design of TE module for finite-element analysis.