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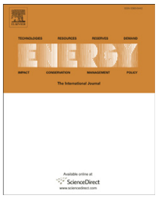

Modelling and analysis of longitudinal thermoelectric energy harvesters considering series-parallel interconnection effect

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ABSTRACT

This work improves the accuracy of longitudinal thermoelectric energy harvesting (LTEH) models introducing the prediction of the interconnection effects. LTEHs are composed of multiple arrays of thermoelectric generators (TEG) electrically arranged in series-parallel configuration. The way that TEG modules are connected strongly affects the electro-thermal outputs of each module and the whole harvester as well. In this paper, a new computational model capable to simulate the electro-thermal dynamics of a longitudinal thermoelectric energy harvester have been developed. It is composed of an array of interconnected TEG modules, which, at the same time, can be disposed thermally and electrically in different series-parallel configurations. The comparison of results between theoretical and experimental data shows great accuracy and the possibility to be used as a simulation tool. The root mean square errors RMSE for electrical power generated and system efficiency are 2.9 mW and 2.15×10^{-4}%. Additionally, the normalized root mean square errors NRMSE are 0.75% and 0.52%.

1. Introduction

Thermoelectric energy harvesting is promising because of its potential utilization in waste heat recovery. The absence of mechanical parts allowing for silent and clean functioning; their small size and light weight properties; their reliability; and their low maintenance are the main features of these devices.

Even with a modest conversion yield, this would have huge benefits. As a consequence, many applications are being imagined for local electricity production by the Seebeck effect, ranging from waste heat recovery in automotive exhaust systems [1–5] to power electronic devices on gas pipelines [6], including waste heat from biomass fired thermal oil heater [7], condensers in thermal systems [8], iron and steel furnaces slag flashing water [9], marine waste incinerators [10], cogeneration systems [11–13] and so on.

Based on Seebeck effect, thermoelectric energy harvesters are composed of many thermoelectric modules, which can produce electrical power from any thermal source. When the heat source comes from a liquid or a gas stream, the longitudinal thermoelectric energy harvester LTEH is the most used topology [14], in which TEG modules are located along the energy flow path with the purpose to convert the maximum amount of thermal energy into electrical power.

Many models describing the electro-thermal behaviour of thermoelectric generators TEGs exist in literature. Gou et al. [15] and Meng et al. [16] presented a theoretic dynamic model of a general thermoelectric generator with finned heat exchangers. However, it does not take into account the electrical interconnection effects of the TEG array, neither the heat losses of the fluid at each stage. Hsiao et al. [17] also analyzed a model of a TE module applied on an automobile exhaust. They provided a scientific methodology with complicated equations on the field of thermoelectric simulations. However, the model cannot be used to simulate the behaviour of a LTEH. It only solves the heat transfer and electrical equations of a single TEG module. Therefore, it does not consider the electrical and thermal losses due to the longitudinal and array configuration.

Wu [18] performed a theoretical analysis on waste-heat thermoelectric power generators. In this study, a real waste-heat thermoelectric generator model was presented based on accounting for both internal and external irreversibility to predict realistic specific power and efficiency. Therefore, this approach gave a much

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more realistic generator specific power and efficiency prediction than does the ideal TEG.

Crane and Jackson investigated thermoelectric waste heat recovery with regards to cross flow heat exchangers [19,20]. A cross flow heat exchanger model was validated against measured performance of advanced cross flow heat exchangers without thermoelectrics. The numerical simulations were compared to experimental data with good agreement between them.

Wang et al. [21] presented a mathematical model of a TEG device using the exhaust gas of vehicles as heat source. The model simulates the impact of relevant factors, including vehicles exhaust mass flow rate, temperature and mass flow rate of different types of cooling fluid, convection heat transfer coefficient, height of PN couple, the ratio of external resistance to internal resistance of the circuit on the output power and efficiency. However, just a few experimental results are provided.

Yu and Zhao [22] developed a numerical model for prediction of performance of a TEG with a parallel-plate heat exchanger. They assumed that the flat thermoelectric modules were held tightly between hot and cold fluids, which had multiple thermocouples with a single layer of p- and n-type semiconductors. The thermocouples along the fluid path were connected electrically in series. A typical energy balance was used to set up the model with the differential equations discretized along the axial direction of the hot fluid. The solution to the numerical model was provided using an iterative method. Simulations were performed to study the effects of the various parameters. An experimental study based on the Yu and Zhao model [22] was performed by Niu, Yu and Wang [23]. A comparison of the experimental results with the numerical model is presented in this work. A two fluid, multi-plate, multi-pass, counter/parallel flow heat exchanger with thermoelectric generators was created for the experimental phase. The data obtained through experimentation shows that the numerical model overpredicts performances of the TEGs over the entire range of data. At lower temperatures, the model displays better agreement with experimental results, but as hot fluid inlet temperatures are increased, the prediction diverges from the measured values. The discrepancy is associated to the lack of accounting for heat losses and the fact that thermoelectric properties are treated as constants.

Xiong et al. [24] developed a numerical model of two-stage thermoelectric energy harvesting system driven by waste heat from the slag water of a blast furnace. This model do consider the longitudinal heat losses of the fluid but do not consider a multiple TEG array, neither the electrical interconnection effect.

Höglom [25] do considered this effect and developed a novel framework for characterization and simulation of thermoelectric generator systems that allows for accurate and efficient prediction of electric and thermal performance. The goal was to develop reduced TE models that can be used to efficiently simulate large system of modules in a CFD analysis. This was achieved by the use of subgrid models that describe the electrical and thermal characteristics of individual modules and an electrical model of the connected system. Although the model allows for heat flow and electrical power output to be predicted with a great accuracy, it needs to be coupled with a third-party CFD software.

Finally, Wang et al. [26] developed a mathematical model of a TEG module with MATLAB software that also introduces the interconnection effect. In this study, the performance of two systems composed of 6 pieces of thermoelectric modules, one in series connection and the other in parallel connection, were simulated and then compared.

A real thermoelectric energy harvester always comprises multiple thermoelectric modules placed with respect to the flow direction. Our model presented in Ref. [27] was created to model this phenomena. It has demonstrated the ability to simulate the electro-thermal behaviour of a LTEH. It treats TEG modules as a whole block and takes into account the fluid heat and temperature reduction at each stage due thermoelectric energy harvesting. This means that each TEG produce less energy as the stage i where TEG is located moves away from the initial stage $i = 1$. All the electro-thermal parameters can be introduced and the number of TEGs per stage and the number of stages that forms the thermoelectric array can be modified. Therefore, the model not only can be used as a simulation tool but also as a design tool.

However, the aforementioned model is valid only for the simulation of LTEHs when an independent load resistance is connected to each TEG. Note that in Fig. 1 of Ref. [27] each TEG is connected to its own independent load resistance R_L. This suppose a limitation because, in practical situations, the array of TEGs that forms a LTEH is wired in series-parallel electrical configuration in order to supply an adequate value of voltage and current to a single load. This means that the electrical power that can be supplied to the load is the sum of the individual electrical power generated by each TEG. An interconnected LTEH with only one load resistance can be shown in Fig. 1.

This electrical interconnection can suppose a global power generation drop of 12% with respect to a not interconnected LTEH. That is because of the temperature mismatch between TEGs located in the same electrical branch [28,29]. Considering that this power loss is very significant and it can increase for larger LTEHs, a complete LTEH model considering electrical interconnection effect is mandatory.

It must be noted that previous models [27,30] presented a great accuracy without considering this phenomenon due to the fact that independent resistances were considered in both model and experiments. In those cases, the effect observed in Refs. [28,29] was not present because TEGs were not electrical interconnected. Hence, electrical series-parallel interconnection of the TEG array was not implemented into the model, as it was the thermal series-parallel configuration.

Thereafter, the aim of this paper is to develop a new computational model capable to simulate the electro-thermal dynamics of a longitudinal thermoelectric energy harvester composed of an array of interconnected TEG modules, which, at the same time, can be disposed thermally and electrically in different series-parallel configurations. The new model incorporates into the recent LTEH model developed in Ref. [27] the electrical interconnection effects occurring in real LTEH systems. Finally, the model is fully analyzed and validated with data obtained from an experimental setup.

2. LTEH modelling

As explained in Section 1, the LTEH is the most used topology when energy recovery comes from a fluid [14]. Generally, it is a device composed of many TEGs placed with respect to the fluid flow direction that converts the waste heat of an element (i.e. liquid or gas) into electricity using the Seebeck Effect. Although LTEHs can be designed in many different ways, generally they are composed of the same basic parts: a hot-side heat exchanger used to capture and increment the heat extraction from the heat source to the TEG modules, a cold-side heat exchanger to remove and transfer excess heat from outer side of the TEG modules to the ambient air, multiple thermoelectric modules that convert the waste heat into useful electrical energy and a support element that permits both the attachment of the aforementioned parts and the compression of TEGs.

2.1. Model description

A TEG device in essence is a thermopile composed of a number