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Feasibility study on thermoelectric device to energy storage system of an electric vehicle

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ABSTRACT

EVs (Electric vehicles) have garnered much of attention over the past few decades as a promising solution to greenhouse gases in transportation. In this paper, a feasibility study is performed applying a TE (thermoelectric) device to the energy storage system of an electric vehicle. By applying a TE device to the Li-family battery system, the effectiveness of the TE device for possible cooling or pre-heating of the battery, or to recover the electrical energy from the waste heat are investigated. Based on the simulated flow field and temperature distribution, the effective locations of thermoelectric devices are identified and installed, and their performances in view of heat recovery or pre-heating during winter and cooling performance during summer are evaluated by simulation. In addition, the results are verified through an experimental setup under a controlled environment of air flow and temperature. Based on the simulation and experiment, the overall effectiveness of cooling or heating, and waste heat recovery quantity is evaluated. It is found that, though the cooling or pre-heating energy is small, the functional benefit to the efficiency and charging/discharging performance of battery system can contribute significantly to sound battery operation, hence to the reliability and overall performance of EVs.

1. Introduction

The transportation sector has been a top contributor to GHG (global greenhouse gas) emissions. EVs (Electric vehicles) have garnered considerable attention over the past few decades as a promising solution to global GHG (global greenhouse gas) emissions. A thermoelectric generator or TEG (thermoelectric generator) is a device that converts waste heat into electricity. Recently, it became very popular as a method of improving fuel economy and total efficiency of either ICE (internal combustion engine) driven vehicles or electric vehicles. According to the U.S. DOE (Department of Energy), about 15% of the total fuel energy of ICE vehicles is consumed to run a car and its auxiliary units, but most of the other energy is transformed into heat during vehicle operation, which consequently and directly contributes to the acceleration of global warming [1]. To deal with this generation of heat, an ATEG (automotive thermoelectric generator) is a device that converts waste heat in ICE vehicle operation into electricity, and many researchers have demonstrated ATEG prototype modules achieving 40%–70% efficiency [2,3]. The lifetime of an ATEG can be 10–20 years without maintenance with low $/W installation cost. The overall vehicle fuel economy improvement has shown a 1–4% increase depending on the vehicle type [4,5].

Thermal management of batteries in EVs and HEVs (hybrid EVs) is essential for effective operation in all weather conditions because the performance and cost of EVs are directly affected by the performance (power and energy capability), lifespan, reliability, charge acceptance, and cost of batteries. Battery temperature typically increases from its initial state with active operation of charging and discharging because of internal heat generation caused by electrochemical reactions and resistance or Joule heating. Thermal management has been emphasized in the design of battery modules and packs when applied to the production of those EVs. Battery temperature affects the available discharge power and energy, as well as the charging range of accepting brake regeneration electrical energy. Battery temperature also influences the lifespan of the battery significantly.

Thus, the objective of thermal management of a battery system is to maintain the operating temperature within a range that is optimized for performance and lifespan. Each battery type works better in a particular temperature range, for example, lead-acid, NiMH (nickel metal hydride), and Li-ion (lithium ion) batteries

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are operated optimally under conditions between 25 and 40 °C, and at these temperatures, they achieve a good balance between performance and lifespan [6–8].

Another objective of the thermal management of battery is to maintain even temperature distribution within a battery pack [9]. The temperature variation from module to module in a pack could cause different charge and discharge behaviors of each module, resulting in electrically unbalanced modules and packs with deteriorated overall performance as an energy storage system. For optimal operation, a temperature variation of less than 5 °C is desirable between modules. The overall heat generation rate from a battery pack during the charging and discharging process determines the required capacity of the cooling system [10]. For example, a Li-ion battery pack with 6 Ah energy storage capacity generates 12 W/cell at 0 °C, 3.5 W/cell at 22–25 °C, and 1.22 W/cell at 40–50 °C when the discharge rate is 5 C, where the C-rate is defined as the nominal current used by the battery divided by 1 h. For cooling purposes, forced air or natural convection process are frequently applied.

In this study, we will examine the effect of cooling by using a thermoelectric generator on a battery pack system. Typical thermoelectric materials with a high Seebeck effect are semiconductors with high electric conductivity and low thermal conductivity. The most common materials are Bi_2Te_3, PbTe, and SiGe, and less frequently used are *n*-type BiSb, and *p*-type TAGS and $FeSi_2$, which also have good thermoelectric properties [4]. Usually the symbol ZT represents the thermoelectric material effectiveness, and a high ZT means that the TEG can convert more heat energy into electric energy. Nissan, GM Chevy, and BMW have tested TEG in their vehicles. The primary challenge of TEG is its relatively low heat-to-electricity conversion efficiency, and research groups are attempting to improve the intrinsic conversion efficiency of thermoelectric materials, even utilizing new nano-crystalline or nanowire materials [11].

Low-temperature heat can be recovered if the cost per watt, $/W, is sufficiently low. With the recent technological developments in the TEG field, the application potential has increased. Several studies are reported to recover low-temperature heat by applying a high Seebeck coefficient of TE material or a new architectural proposal to enhance the recovered heat capacity, like inserting a space inside the TE device [9,11,12]. An extensive study about thermoelectric generators for automotive waste heat recovery systems through numerical modeling, parametric evaluation, and topologies has been reported [2,3]. Fuel cell application of waste heat recovery has been also studied in view of numerical modeling of a thermoelectric generator with a compact plat-fin heat exchanger for high-temperature PEM fuel cell exhaust heat recovery [13].

The maximum power output of the thermoelectric device, W_{max} is expressed as.

$$W_{max} = \frac{((S_p - S_n)\Delta T)^2}{4R}, \tag{1}$$

where ΔT is the temperature difference between the hot side and the cold side, R is the electrical resistance of the thermoelectric device, S is the Seebeck coefficient, and the subscripts p and n denote the p- and n-type thermoelectric semiconductors, respectively [8]. As shown in Eq. (1), large Seebeck coefficients, a large temperature difference, and low electrical resistance are required to obtain high power output.

In this paper, a combined numerical model is developed to investigate the flow and thermal field distribution for an onboard battery system and, thus, to examine a TE device's effect on battery cooling and heating, and waste heat recovery from the battery heat during operation is evaluated considering seasonal ambient temperature change. In addition, a lab-based experimental setup is developed simulating the battery room in an EV, and the effectiveness of the TE device during summer and winter has been verified in terms of cooling, pre-heating of battery start-up, and waste heat recovery. The objective of this research is graphically summarized in Fig 1.

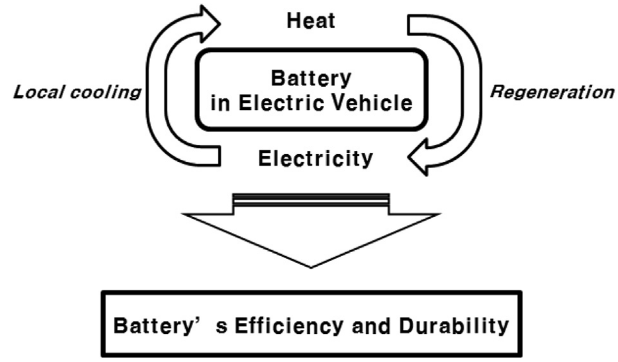

Fig. 1. Battery performance and life extension by applying thermoelectric device for thermal management while generating electric energy for an electric vehicle.

In summer, the battery operating temperature is higher than that required for optimal performance; therefore, cooling is necessary. As the localized temperature rise might cause an unbalance of cell and pack performance, it is necessary to keep uniform temperature distribution. Therefore, in this study, TE devices are placed locally in the possible hot spot area for efficient cooling of battery cells or packs, as conceptually shown in Fig. 2. The TE device does not require additional refrigerant or pumps, nor is it affected by any mechanical vibration environment, which will help the EV operating in the long range.

During the winter season, ambient temperature is lower than the battery or motor/inverter's temperature, the thermoelectric device can be used as a pre-heating device or for waste heat recovery, as in Fig. 2. As shown in Eq. (1), the recovered electrical power by TEG can be used as additional energy so that the overall efficiency can be raised. Additional consideration must be given to the fact that the TEG device can behave as a thermal insulator to the battery cells or packs, so the battery performance might be affected or degraded. Therefore, it is important to have a well-considered and optimized TE configuration based on accurate prediction of efficiency improvement by TEG and efficiency degradation due to a battery temperature increase.

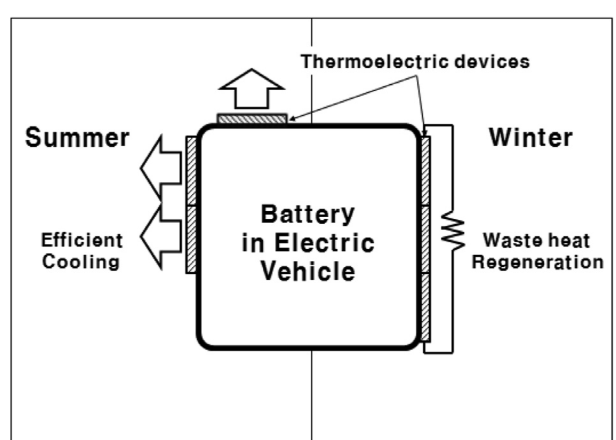

Fig. 2. TE device application concept for different seasonal requirements for an EV battery system.