Design and Optimization of Effective Segmented Thermoelectric Generator for Waste Heat Recovery

Energy safety is a vital issue of the global future. Together with developing renewable and eco-friendly energy sources, recovering waste energy is no less of an important issue. It is estimated that 60% of energy converted in most of today’s energy processes nowadays is waste, mainly in the form of heat. Using thermoelectric generators, which convert heat into electricity, is a promising way to recover waste energy. However, the efficiency of thermal-to-electricity converters needs to be improved in order to be widely applied in practice. Despite the fact that significant amount of efforts have been focused on material development, realizing high efficient thermoelectric generators from such well-developed materials is still limited. Moreover, no single thermoelectric material could withstand the wide temperature range required to boost efficiency of TEGs. By segmentation of different TE materials which operate optimally in each temperature range, this study aims at developing high performance segmented TEGs for medium-high (450 – 850 K) temperature application. The research is focused on the challenges in joining and minimizing the contact resistances between different TE materials and with metal electrode.

One-dimensional numerical modeling was employed to design and predict the efficiency of segmented materials built up from most of today’s state-of-the-art thermoelectric materials. Combinations of materials that would deliver the highest conversion efficiency in different temperature ranges of 300 – 700, and 900 – 1100 K are considered. The obtained results reveals that segmented thermoelectric generator comprising of Bi0.6Sb1.4Te3/Ba8Au5.3Ge40.7/PbTe-SrTe/SiGe as p-leg and either segmented Bi2Te3/PbTe/SiGe or Bi2Te3/Ba0.08La0.05Yb0.04Co4Sb12/La3Te4 as n-leg working in 300 – 1100 K temperature range could achieve a maximum efficiency of 18.2 %. In lower working temperature ranges of 300 – 700 and 300 – 900 K, the maximum efficiencies are 13.5 and 16.6 %, respectively for segmented TEGs of p-legBi0.6Sb1.4Te3/TAGS ((AgSbTe)0.15(GeTe)0.85) with n-leg Bi2Te3/PbTe and p-leg Bi0.6Sb1.4Te3/Ba8Au5.3Ge40.7/PbTe-SrTe with n-leg Bi2Te3/PbTe/SiGe. The results could provide a guideline to develop high efficiency segmented thermoelectric generators. Based on these theoretical results, segmentation of half-Heusler alloys and Bi2Te3 materials was selected for further study.

Firstly, the joining between thermoelectric p- and n-type half-Heusler (HH) alloys and silver electrode at hot side was developed. A fast-hot pressing method was introduced to directly join the HH materials with silver interconnecting layer. The method was also compared with the conventional joining method where a third material is used as filler. Microstructures and interfacial chemical evolution at the joining interfaces were investigated using scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). The transport properties of the joint, including thermopower across the interfaces and contact resistance as a function of temperature were studied. With fast hot pressing method, the contact resistance between HH alloys and Ag-electrode could be significantly reduced by about 50 %. Moreover, by avoiding a third filler material, the method limits the formation of new phases at contact interface which might degrade the overall thermoelectric properties. This work is a crucial step to make segmented HH/BiTe TEG.

Then, p- and n-type segmented legs of bismuth tellurides and half-Heusler alloys were built and characterized. Segmentation of bismuth tellurides to half-Heusler/Ag was processed at temperature 493 K, pressure 30 MPa in vacuum using Ag10Sn90 solder as filler. Interface microstructural evolution and thermoelectric properties of segmented legs were then investigated. The contact resistance of the joint as a part of function of temperature was measured from room temperature to 473 K. Numerical modeling was used to evaluate the influence of measured contact resistances on the final power generating properties of the obtained segmented legs and their unicouple. Under working temperature from 323 to 873 K, the obtained p-segmented legs could deliver a power density of 0.3 Wcm-2 and maximum voltage of 115 mV. With the same condition, the power density and maximum voltage generated by n-segmented leg were 0.25 Wcm-2 and 102 mV. These values are significantly smaller than calculation data. The reason is possibly due to the contact resistance between BiTe and electrode at the cold end, thus improvement of the cold side contact was made. At temperature gradient of 498 K, the maximum power density of the improved n-segmented leg was 0.8 Wcm-2, giving a maximum efficiency of 4.5%.