Thermoelectric Generators: Raiders of the Lost Amp

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Abstract

Thermoelectric generators (TEGs) are semiconductor-based devices that harvest heat to produce electricity. The lack of existing measurement standards for TEGs has limited their potential use in a range of industries. NPL has developed a test rig which can provide a reliable way to characterise TEGs at high temperatures. It is hoped that this will form the basis of the very first measurement standard for these devices.

Thermal Energy Harvesting

• Energy harvesting (EH) technologies can recover some ‘lost’ energy in systems.
• Heat is the enemy of mechanical systems.
• > 70% of the energy produced by a car engine is ‘lost’ as heat.
• This waste heat can be harvested by Thermoelectric Generators (TEGs).
• TEGs are solid-state heat engines.
• A temperature difference ‘drives’ the device.
• TEGs have no moving parts.
• They transform heat into electricity.

Thermoelectrics

The term thermoelectricity encompasses three effects - Seebeck, Peltier and Thomson effects.

• The dimensionless figure of merit (\(ZT\)),

\[\alpha = \frac{V}{\Delta T}\]

\(ZT = \alpha^2 a T\)

\(\kappa = \frac{a^2}{L}\)

Where \(\alpha\) - Seebeck coefficient, \(V\) - output voltage, \(\Delta T\) - temperature difference, \(a\) - thermal conductivity, \(\kappa\) - electrical conductivity, \(a^2\kappa\) - power factor.

These factors are influenced by the electrical and thermal properties of the material. In a TEG, the bigger the temperature difference (\(\Delta T\)), the more electrical power you produce.

The best thermoelectric materials are heavily doped semiconductors. Each material has its peak performance at different temperatures. Bismuth telluride (Bi\(_2\)Te\(_3\)) used in commercial TEGs is most efficient at 100 °C.

The Experiment

• NPL work is part of an EU project called NexTEC.
• The test rig – called HELboi – is based on an absolute measurement of heat flow (\(Q_h\)).
• Hot plate (RT – 800 °C).
• Cold plate (liquid nitrogen – 400 °C).
• Vacuum chamber.
• HELboi is measurement suite for both materials and TEGs.

Figure 1: TEG p-n couple under a temperature gradient

Figure 2: Key properties of thermoelectric materials - used in commercial TEGs - as predicted (thermoelectrics/index.html)

Figure 3: A typical thermoelectric generator (TEG) comprising an array of p and n-doped semiconductors connected electrically in series and thermally in parallel, connected to a resistive load.

TEGs have low efficiencies, but are mechanically stable, can be used to reduce CO\(_2\) emissions in vehicles and are suitable for remote locations / autonomous systems.

• Coupling of thermal and electrical properties in TEGs means it is difficult to determine them independently \(\rightarrow\) large uncertainties.
• No existing measurement standards for TEGs \(\rightarrow\) major bottleneck in the mass market uptake of TEGs.

Applications

Thermal Energy harvesting systems can complement power sources to provide
• Hybrid TEG-PV systems
• TEG exhaust heat recovery systems

Figure 4: Thermoelectric generators used by NASA’s Apollo missions

Figure 5: A TEG-based exhaust heat recovery system can produce > 600 W

Figure 6: Hybrid TEG-photovoltaic coupling

Figure 7: TEG-based exhaust heat recovery system can produce > 600 W

Figure 8: HELboi – NPL thermoelectric test rig

The results reported here are for a commercial Bi\(_2\)Te\(_3\) thermoelectric generator (TEG):

• Performance curves – electrical output power
• Heat flow (\(Q_h\)), and TEG conversion efficiency
• The thermal resistance (\(R_{\text{Th}}\)) – NPL Guarded Heat Flow Meter

Where \(E_{\text{h}} = \text{TEG thickness}, \Delta T = \text{temperature difference}, S_p = \text{average Seebeck coefficient}, \alpha = \text{hot side temp}, I = \text{current}, R_{\text{Th}} = \text{TEG DC resistance}.

Figure 9: Measured thermal resistance of a TEG – in open circuit (no load), matched load and with voltage loads removed

Figure 10: Performance power curves and heat exchanged data of the same TEG

Conclusions

• This TEG has a max efficiency of \(\approx 6\%\), with 30 W of thermal power exchanged.
• The power output of the TEG is maximised at \(\Delta T = 170^\circ\ C\).
• This is the first reported measurement of the thermal resistance of any commercial TEG.
• The data’s close fit to the ideal (modelled) performance curve shows that HELboi is a reliable way to characterise TEGs \(\rightarrow\) its output power, heat flow and efficiency

Further work

HELboi will measure the new high temperature (up to 700 °C) TEGs produced by NexTEC project.

An uncertainty budget for HELboi will be the first step to develop a measurement standard for TEGs.

HELboi will characterise TEGs for use in space – the UK is leading Europe’s space nuclear power programme.