Untapped potential

Thermoelectric energy converters generate power from waste heat

Dr. Wolf Eckhard Müller

A refrigerator is supposed to cool – and so it does. It also produces heat – which it needn't. After all it's a refrigerator, not an oven. But like an oven, it is also an energy user. If only it could make use of its own wasted heat, it would require considerably less energy to run. And refrigeration is by no means the only process that wastes energy; many processes generate heat as an unintended side effect. This waste heat, however, can be exploited – using materials that convert heat into electrical energy. Thermoelectric generators are a key to tapping this potential. For example, devices with low energy requirements can be made to run on self-sufficient power supplies. Thermoelectric generators are also suitable for high-temperature environments. Scientists at DLR are currently searching for new ways of producing electricity from wasted process heat, and they have also been developing new thermoelectric materials. In the analysis, simulation and design of segmented thermoelectric generators, DLR is at the forefront of research.

Is it possible to make heat flow upstream along a temperature gradient, i.e. from a cooler source to a warmer sink, without the noisy power unit of a fridge or freezer, and without pipes or refrigerant? Can a solid body be caused to release electrical energy simply by heating it on one side? It may sound like science fiction, but in fact these two ideas are physically entirely feasible. This is aptly demonstrated at the DLR Institute of Materials Research. In a small-scale demonstration system, a thermoelectric module is mounted on a block of metal. If you place your hand on the ceramic plate at the top of the module and press either the blue or red button, a significant temperature drop or rise can be felt within seconds. The two buttons simply control the direction of the electrical current flowing through the module.

This thermal response is made possible by a phenomenon in solid-state physics known as the Peltier effect, which couples thermal energy with electrical energy. The Institute of Materials Research is developing materials that take advantage of this effect. The electric current is made to pull along an accompanying heat flow, with such force that it surpasses even large temperature differences – much like water being pumped uphill. The temperature rise that is felt when you press the red button is markedly higher than if it were generated by the well-known Joule heating process used by most electrical heaters. Today's Peltier devices can generate temperature differences of 60 °C or more. Special cascaded component arrangements in experimental setups operating against room temperature have even achieved a cooling down to minus 120 degrees Celsius.

Current pumps heat

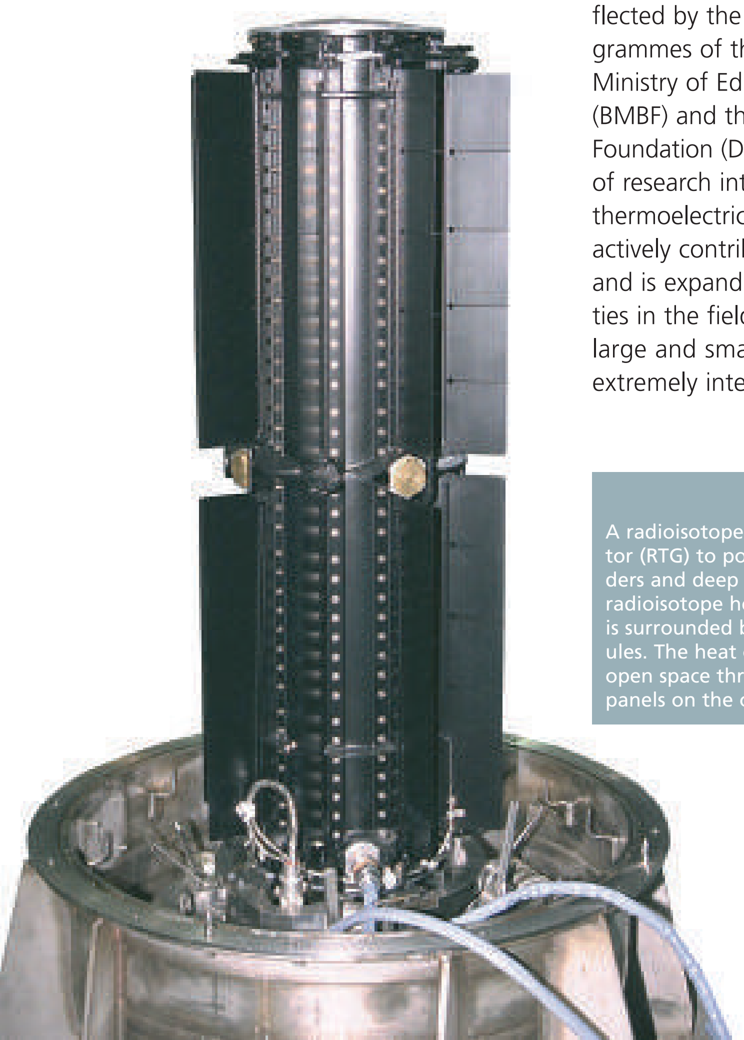
In 1834, the French physicist Jean Charles Athanase Peltier discovered an interesting effect. When current flows between two conductors with different properties, this changes the heat transport. Effectively, the current flow causes a temperature change at the contact points between the conductors. This is known as the Peltier effect.

Heat turns into electricity

The Seebeck effect works similar to the Peltier effect in reverse. A temperature difference causes an electrical voltage. When two different types of metallic conductors or semiconductors form a circuit and their connection points are kept at different temperatures, this causes the diverging thermal forces to generate an electric current. This phenomenon was discovered in 1821 by the Baltic German physicist Thomas Johann Seebeck.

The Voyager probe, which explored remote areas of the solar system, was powered by thermoelectric generators mounted on the base

The demonstration system's second experiment also relies on the coupling of heat and electricity. As soon as the thermoelectric module is exposed to the light from a powerful lamp, the multimeter connected to the module displays a current of around one ampere. This gives some idea of the electrical energies that can potentially be generated through external heat sources. The thermoelectric principle at work here is the Seebeck effect which can be understood as a kind of reversal of the Peltier effect. In this case, the heat flow pulls along the electrical current and the electrons are slipping down from the hot to the cold side since their energy depends on temperature; when the module is exposed to a temperature gradient, the flow of heat through the thermoelectric material creates an electrical current.



Components that function like this are known as thermoelectric generators. Although their efficiency level is still comparably low, they are more advantageous in some applications than other energy conversion methods.

Beside the total power output, the main technological parameters of a thermoelectric generator are the efficiency of the thermoelectric conversion, the achievable flow density of the electrical power, and the specific output per volume or mass. This last parameter is particularly important for mobile systems. A big advantage of thermoelectric energy conversion is that it doesn't involve mechanically moving parts; this makes it more reliable and guarantees noiseless, maintenance-free operation.

In Germany, and hopefully in the future in Europe, research and development into thermoelectric materials and systems is booming. This is reflected by the new funding Programmes of the Federal German Ministry of Education and Research (BMBF) and the German Research Foundation (DFG). Thanks to its years of research into high-temperature thermoelectric generators, DLR is actively contributing to this process and is expanding its research capacities in the field. Internationally, both large and small enterprises are extremely interested in thermoelectrics, and companies across Germany are also following technological developments closely. Vehicle manufacturers, automotive suppliers, development providers and companies in the chemicals, energy, heating, fuel-cell and solar industries are all beginning to establish their own research teams. DLR is finding very cooperative industrial partners in these areas for the development of thermoelectric materials and systems.

A radioisotope thermoelectric generator (RTG) to power lunar/planetary landers and deep space probes. The radioisotope heat source on the interior is surrounded by thermoelectric modules. The heat current is dissipated into open space through the dark radiator panels on the outside of the generator.

The enormous amount of heat being lost from power plants, factories, transport and households is crying out for a meaningful exploitation. In many energy systems – such as cars – the direct conversion of heat flows into electrical currents can reduce fuel consumption and thus make them more environmentally friendly. Thermoelectrics have already proved themselves in numerous space missions, producing electricity reliably and over long periods of time. Products based on Peltier coolers are already wide-spread, being used in such things as car and camping cool boxes, transport containers for perishable goods such as pharmaceuticals or biological products, coolers for electrical circuits, temperature stabilisers for optical detectors, and even temperature regulators for the transport of art works.

Across the world, the utilisation of industrial waste heat (average temperatures up to 400-500 °C) is advancing rapidly. Waste heat is becoming an economically viable source of energy. Special technologies can even make use of waste heat as hot as 600-700 °C and higher. When exposed to large temperature differences, modern thermoelectric generators can achieve

DLR is developing unique measurement technologies for thermoelectric materials and modules. This is the measuring column of a test rig for assessing the efficiency factor and other component properties in real-world conditions.

efficiency factors of ten percent and more as already shown in the laboratory. Experimental technologies for space flight have already produced efficiency factors of up to 14 percent. New nanomaterials and prototypes of segmented elements are even promising efficiencies of 17-20 percent and higher. With such performance levels, thermoelectric technology is of interest well beyond the niche and specialist applications it has traditionally been restricted to, and can contribute significantly to the reduction of carbon-dioxide emissions.

Thermoelectric generators are particularly effective when they are combined with renewable energy sources. Self-sufficient power supplies used for environmental measurement technology, telecommunications and navigation technology have been proposed which are based on thermoelectrics combined with photovoltaics. Such hybrid systems may manage to reliably provide electricity even in the harshest conditions – and are much more economical than conventional generator systems. Solar thermal collectors can be fitted with thermoelectric generators to produce electricity for immediate use. Developers are currently working on converting waste heat from high-temperature fuel cells to power internal consumers in the cell's energy system, which will increase overall system efficiency. Biomass boilers and heat pumps that are fitted with thermoelectric generators can be run self-sufficiently, making them completely independent from the power supply grid. Auxiliary heaters in vehicles that are fitted with thermoelectric generators can assist the on-board electrical system and even charge the battery.

In the serial production of commercial thermoelectric modules, the only thermoelectric materials currently available are special tellurium compounds. For state-of-the-art modules based on bismuth telluride, the highest operating temperature that can be achieved is 250 °C. However, the technological possibilities of thermoelectric materials are by no means exhausted – nor are their potential real-world applications. Across the globe, intensive research is going on into high-efficiency converter materials, thermoelectric modules and mid-temperature systems.

The key to most of the envisioned systems lies in the development of highly efficient and long-term stable thermoelectric materials and in the innovative contacting of these materials. Currently favoured materials include chalcogenides, skutterudites, silicides, and clathrates. The electrical contacting of these materials and their integration into real-world thermoelectric generator modules still represent big challenges. An important tool to aid development in this field is the numerical simulation of materials, components and systems. Innovative technologies for measuring the properties of thermoelectric materials and systems are crucial to further progress. At the DLR Institute of Materials Research in Cologne, innovative new thermoelectric generators for temperatures of 400 °C and above are currently in development. This is a major project, and DLR is backing it with its experience and expertise gathered over 15 years of continuous research. DLR is well recognised in Europe for its groundbreaking work in the areas of automated functional characterisation and the numerical design of thermoelectric materials, modules and segmented generators.

The industrial sector is waiting for applicable research results that can be implemented as technology. It has already been demonstrated that thermoelectric generators can be successfully integrated into existing energy systems fairly quickly. What is needed now are improved materials that are commercially available – and the thermoelectric generator modules to match.

Author:
Dr. Eckhard Müller is the Head of Thermoelectric Materials and Systems at the DLR Institute of Materials Research.