Turning Heat into Power: The Potential of the Thermoelectric Effect

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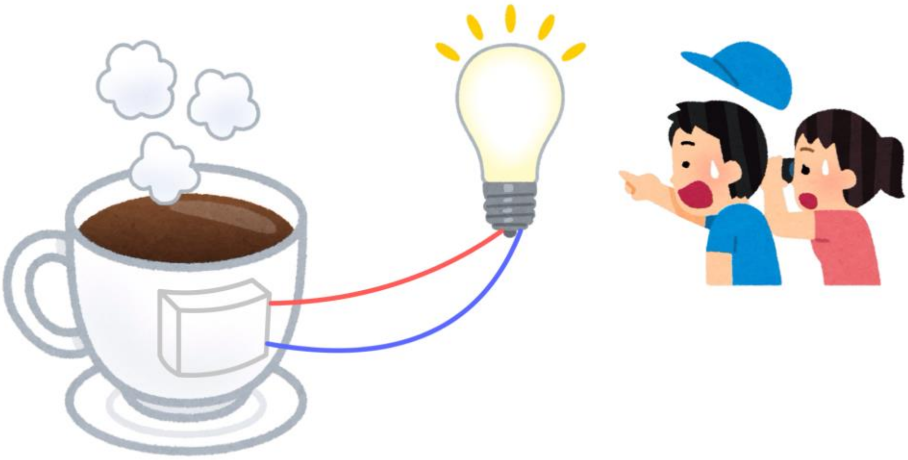

What comes to mind when you hear that the warmth of your morning coffee can light up your room, or the heat radiating from your body can power your smartphone? You would think these are impossible. However, as research on the "thermoelectric effect" progresses and more is learned, this could be possible in the future and this effect could potentially change the world.

So, what is a "thermoelectric effect"? To put it briefly, it refers to a phenomenon in which the mutual conversion of electricity and heat occurs. You learned in your junior high school that if you connect a battery to a piece of metal, the electric current will flow. Also, you have probably experienced a cold drink becoming lukewarm when left in a hot room. This means that the heat current flows from hot to cold places. At first sight, these two phenomena have nothing to do with each other. However, it is known that they are deeply related, and a "thermoelectric effect" is a general term for the mutual effects of heat and electricity.

One of the famous thermoelectric effects is the Seebeck effect, which was discovered by German Physicist Seebeck in 1821. The Seebeck effect refers to the phenomenon in which electric current flows from a hot place to a cold place or in the opposite direction. The reason why this effect occurs is quite simple. From a microscopic perspective, temperature indicates the average speed of particles such as electrons. Particles in a high-temperature region move at a faster speed, allowing them to escape and migrate to regions with lower temperatures. On the other hand, particles in a low-temperature region move slowly and tend to stay in their original place. Thus, the charged particles like electrons are transferred from hot to cold. As you learned in school, electrons have a negative charge, and they move in the opposite direction to the flow of electric current. This means that the electric current flows from cold to hot when the electric carriers are electrons. If the electric carriers have a positive charge, the electric current will flow from hot to cold.

Another thermoelectric effect that has been attracting attention in recent years is the anomalous Nernst effect, which occurs in magnetic materials. In this effect, current flows when a temperature gradient is applied as in the Seebeck effect, but it differs in that the magnetic field bends the direction of the electron and the induced current is perpendicular to the temperature gradient.

So, how might this 200-year idea potentially change the world? Heat is ubiquitous in our lives. Whenever you turn on the light bulb, you will see it gets hotter. Watching YouTube on a smartphone for a long time will make it heat up. Or, in a more industrial situation, only 30% of the energy generated by a nuclear power plant is turned into electricity, while the remaining 70% is discarded as heat. We do not efficiently use these kinds of heat and it is estimated that 10^{19} J of energy is thrown away as waste heat in Japan per year [2]. 10^{19} J is so enormous that it is equivalent to the annual electricity consumption by 500 million households, which is approximately ten times the number of all households in Japan!

Using a device based on the thermoelectric effect, we can extract energy from such a large amount of waste heat. Furthermore, since the thermoelectric effect does not occur by chemical reactions, it generates electricity without emitting carbon dioxide or other toxic gases, which means it does not contribute to environmental problems like global warming. Therefore, power generation by the thermoelectric effect is now attracting attention as a leading candidate for renewable energy.

But most of you have never heard of that kind of nice device and indeed, such things have yet to be put into practical use. The most significant reason for this is the weakness of the electric current. The efficiency of power generation using the thermoelectric effect is about a quarter of that of fossil fuel power generation and it is useless as it is. Thus, many scientists have been searching all along for materials with greater output.

I believe that the key to improving the efficiency of thermoelectric devices and making them more widely used lies in developing a fundamental theory to describe the thermoelectric effect. Constructing a comprehensive theory that can describe the current under the existence of a temperature gradient has not been achieved yet. The pure electric effect is not so difficult, and we can use what is called linear response theory to analyze them from a microscopic point of view. However, once the effect of the temperature gradient is considered, we do not know how to reflect it to the microscopic equation, and we cannot naively use the linear response theory anymore. While some scientists, such as Luttinger, have proposed a way to solve this problem [1], the theory is still under development. So, it is necessary to construct a more sophisticated theory to study the thermoelectric effect in detail. If the theory becomes complete, we will find out what is needed to realize high efficiency and be able to design materials for excellent thermoelectric devices.

You might think creating a theory that can describe the transport under the temperature gradient is so basic and has nothing to do with your daily life. But that is not true. As has been explained, it is essential when designing a highly efficient thermoelectric device. The device could generate energy from large amounts of waste heat, and if it becomes widespread, it will undoubtedly change our world. Imagine drinking your coffee in the morning and using its heat to light up your room or charge your smartphone. This is cool, isn't it? To make these possibilities a reality, it is indispensable to develop a basic theory, to which I would like to contribute. In conclusion, the seemingly useless fundamental research has the potential to change the world, and it is this fact that makes me want to be a scientist.

References

[1] J. M. Luttinger, "Theory of thermal transport coefficient", Phys. Rev. **135**, A1505 (1964)

[2] Ministry for economy, trade and industry, Agency for natural resources and energy, Sogo Enerugi Tokei (Comprehensive energy statistics) [in Japanese], Accessed 30 June 2024, https://www.enecho.meti.go.jp/statistics/total_energy/results.html

I used DeepL, Grammarly, and ChatGPT to improve the language and find grammatical errors.

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