Thermocouple as a permanent physics experiment

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Abstract

Following topics are discussed in this paper: thermocouple and its place in lessons, manufacturing a metal thermocouple in school conditions, thermocouple thermometer, detection of thermocouple's small voltages, magnetic field of thermoelectric current, thermoelectric generator as a source of voltage, thermoelectric motor powered by heat from a candle.

Permanent experiment

Every physics teacher uses a wide spectrum of demonstrational experiments in his lessons, ranging from simple, reliable setups to complex, setting-sensitive arrays of devices. If possible, I prefer the first ones. In common lesson experiment is not supposed to occupy teacher's time, but students' time. Therefore, it is supposed to be as simple as possible, with little equipment needed and most of all – it has to be reliable, so it takes place as expected. It has worked well for me to have prepared assembled experiments and do not use the necessary equipment in other experiments. When using assembly kits, I create as many setups as possible, and I do not disassemble them afterwards. That is how "permanent experiments" are made – e.g., an inclined plane with flywheel to demonstrate accelerated motion, assembled optical bench to measure focal length of a lens, assembled RLC circuit to measure impedance and to demonstrate resonance, U-tube for liquids on stand etc. Experiments prepared in this way by one teacher may be used by others in the same office. The only downside is a necessity of space big enough to house all these experiments.

Experiments with thermoelectricity encourage to create such permanent assemblies.

Thermocouple

The thermoelectric effect was discovered in 1821 by Thomas Johann Seebeck – a German scientist living in Estonia. This phenomenon's description may be found in e.g. [1]. Basically, if we insert a metal conductor A (between whose ends there is a temperature difference Δt) between two other identical conductors B, then we measure the voltage at the free ends of the conductors B (see Figure 1). For small temperature differences the measured voltage is directly proportional to the temperature difference Δt: $U = \alpha \Delta t$. Unfortunately gained voltage is very small for common metal conductors, it's of the order of tens microvolts per temperature difference of one degree Celsius. Increasing temperature difference to hundreds of degrees yields higher voltage – this gets to millivolts – arranging thermocouples into series can yield similar results. While using semiconductor

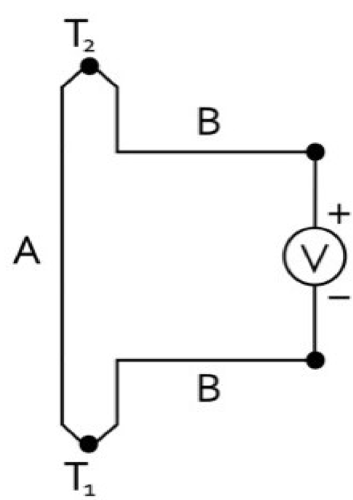

Fig. 1. General diagram of a thermocouple.

thermocouples the options are much better, yet those are, quite unfortunately, usually limited by temperature difference in the order of tens of degrees Celsius. Semiconductor thermoelectric generators TEG capable to withstand higher temperatures are usually expensive.

Tab. 1. Thermoelectric voltage of metals and alloys coupled with platinum at temperature difference of 100 °C in-between cold and hot joint. Retrieved from [3].

material	voltage in mV
nickel-chrome (85% Ni, 15% Cr)	2,55
iron	1,9
brass	1,1
copper	0,75
manganin (86% Cu, 12% Mn, 2% Ni)	0,68
aluminium, magnesium, tin	0,4
platinum	0,00
nickel	−1,55
constantan (55% Cu, 45% Ni)	−3,50

Majority of metal thermocouples works with constantan, which has lower potential then the other metals – as can be seen in table of thermoelectric voltages of metals and alloys coupled with platinum at temperature difference of 100 °C in-between cold and hot joint, see table 1. Thermocouple nickelchrome-nickel creates voltage U = 2,55−(−1,55) mV = =4,1 mV, thermocouple iron-constantan creates voltage U = 1,9−(−3,5) mV = 5,4 mV (both at Δt = 100 °C).

We face two crucial issues while constructing thermocouples: where should we obtain appropriate conductors and how to join them together. I use Fe-Con and Cu-Con thermocouples in my regular experiments. Copper wire is not an issue, striping insulation of phone wires is usually enough and you have got yourself a suitable copper wire. As for iron wire I use common soft binding wire – it cannot be galvanised in any way, nor tin-plated (beekeeping wire is not an option) or zinc-plated. Black binding wire coated with thin iron oxide layer is suitable. Constantan can be bought as resistance wire. Commercial designation tends to be different, and it is necessary to be cautious about the composition of the alloy from which the resistance wire is made. Originally constantan's composition was 55% Cu and 45% Ni, whilst nowadays an alloy marked Thomsen or IZOTAN can be bought (its composition is 55% Cu, 1% Mn, 44% Ni). Important parameter to watch out for is its electrical resistivity which should be approximately 0,49 µΩm. Some of the larger resistors and all rheostats previously made by Metra Blansko are wound with constantan wire. Constantan in resistors and coils is usually insulated either by polyurethane varnish or by thin layer of black oxide (this is common for rheostats). Constantan can be distinguished from chromenickel (that is often used in wire resistors as well) by its non-magnetic properties, whereas copper is ferromagnetic with low Curie temperature.

Quality metal coupling is quite important. They can be joint by twisting them together but that does not last for long and the connection is very imperfect. Soldering them together with tin is a workable solution but it doesn't hold in temperatures above 230 °C, so a mere alcohol stove melts the tin connection. Moreover, alloys with nickel and chrome are difficult to solder (whereas constantan contains a lot of copper and can be easily soldered). Therefore, it is better to have thermocouples soldered together with silver or brass. The best option is to weld the thermocouple – a quite simple, yet effective way how to weld thermocouple's wires together is described in [2].

Welding thermocouples

A robust transformer preferably with taps is required. Ideally 5–15 V / 100 W, without rectification and without fuses in secondary circuit. Important thing is its ability to withstand large short-term current consumption. Furthermore, the following items are required: a stand with holders, a robust carbon rod 6-10 mm in diameter (I use electrode from a carbon arc lamp, yet carbon from big galvanic cell will suffice as well) and a silicone tube, 2 cm long that can be tightly sleeved on the copper rod. Fixate the rod well into the stand with its lower end connected to one of the transformer's terminals using wire with at least 1,5 mm^2 in cross-section. Sleeve the tube in such a way that it is elastically sealed around the carbon rod and there is a 1 cm surplus on its upper end. Then pour several mm of alcohol into the tube. Thermocouple wires are to be cleaned well with sandpaper and twisted together using pliers, so a firm mechanical connection is created. Clean the thermocouple up to 3 cm from the junction with sandpaper as well. Insert it into a bent end of thick copper conductor connected to the other low voltage terminal of the transformer and clench it firmly with pliers. Using goggles (or better yet – a protective face shield) gently connect free end of twisted thermocouple wires, which is held in pliers, to an end of carbon rod that is under surface of alcohol. An arc occurs melting and welding the ends of twisted wires. Welding happens under the surface of alcohol which chemically reacts to created heated oxides and reduces them. A clean smooth weld is created. Unfortunately, a small amount of alcohol splashes into surrounding space and its necessary to be prepared to put out fires. Wires with diameter ranging from 0,2 mm to 1 mm can be welded in this way – it is determined by transformer voltage, overall circuit impedance – you must try it out yourself. Common metals like iron, brass, copper, and constantan are easily welded, whilst nickelchrome is difficult to weld. See result in fig. 2.

Cu-Co thermocouple yields approx. 4,2 mV per 100 °C temperature difference. You can expect temperatures up to 400 °C using alcohol burner and therefore voltages up to 20 mV. We can experimentally verify its polarity – copper has positive potential when coupled with constantan.

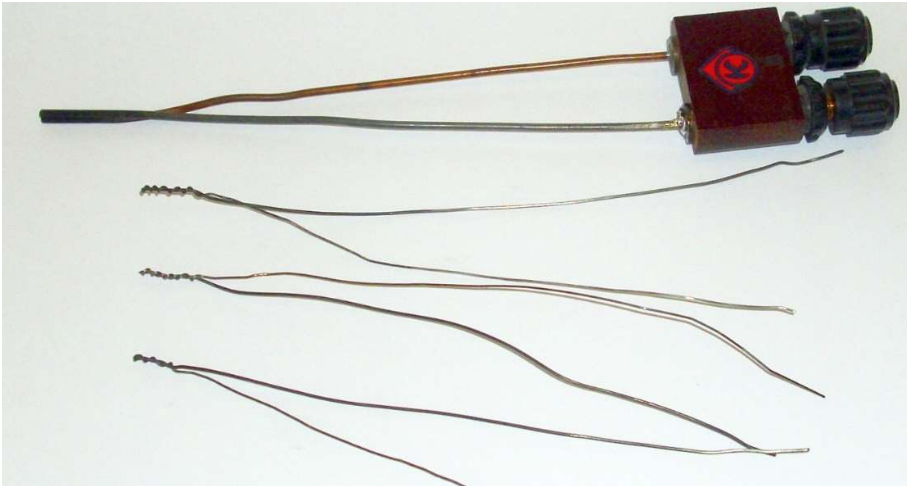

Fig. 2. Cu-Co thermocouple as a physics equipment supplied by Komenius half a century ago and triplet of Fe-Co thermocouples created in school employing described welding technique.

What can be found in teachers' office

Figure 3 shows almost a 100-year-old Fe-Co thermocouple battery. It looks sturdy and twelve thermocouples give hope for higher output power. A lower temperature difference must be accounted for, though, as well as imperfect electrical connection of its parts, which causes measured voltage to be approx. 30-40 mV and a short circuit current around 30 mA when using alcohol burner. Thermocouples are not welded, its constructor was a mechanic, not an electrician. All parts are connected mechanically using rivets and screws which generates a fair amount of transient resistance.

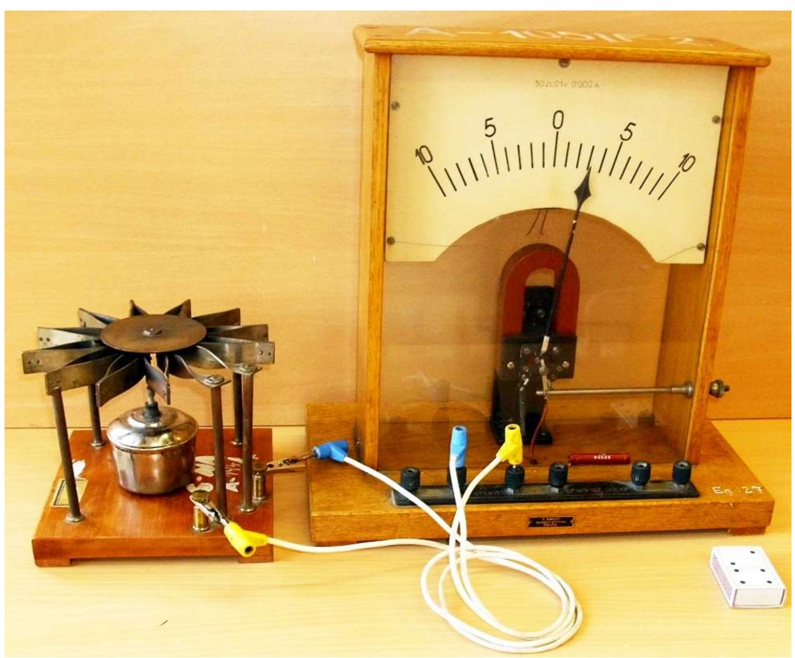

Fig. 3. Battery consisting of twelve Fe-Con thermocouples from 1930 and voltmeter from the same period.

Fe-Con thermocouple on a panel

Very practical and simple physics equipment, typical example of permanent experiment (fig. 4). A thermocouple is connected to a measuring apparatus zeroed onto the centre allowing to show direction of current in the circuit when heating the first or the second coupling. Maximum voltage that the apparatus can display is approx. 6 mV which corresponds to temperature difference of 120 °C. When heated by hand ($\Delta t \approx 10$ °C) the voltmeter pointer slightly moves, when heated by a match set aflame the pointer shows maximum displacement. Thermocouple created from thin wires can be easily heated to a necessary temperature even using a small flame.

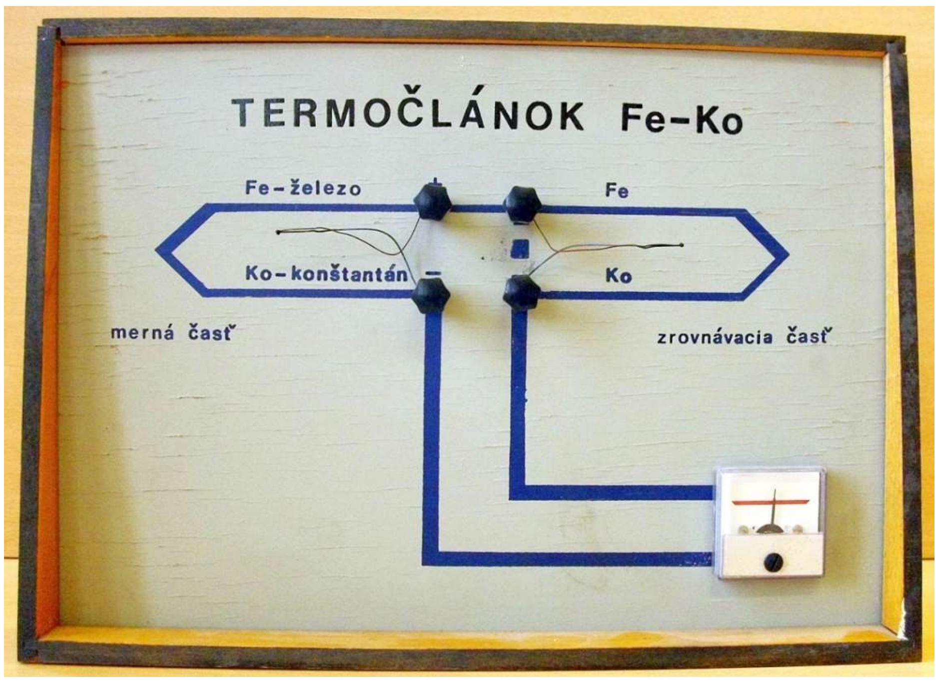

Fig. 4. a pair of thermocouples on a panel is a fitting example of permanent physics experiment. Always ready for action, no adjustments needed.

Temperature thermocouple probes in measuring apparatuses

Thermocouples are usually used as inexpensive measuring probes for digital measuring instruments. Type K in fig. 5 can be used in temperatures ranging from −50 °C to + 350 °C. The upper boundary is dominantly determined by thermal resilience of conductors' insulation and by limited precision due to non-linearity in voltage dependence on temperature difference of junctions. Other than that, alloys of chrome and nickel are very thermally and mechanically resilient and may be used in junctions with temperature up to 1000 °C.

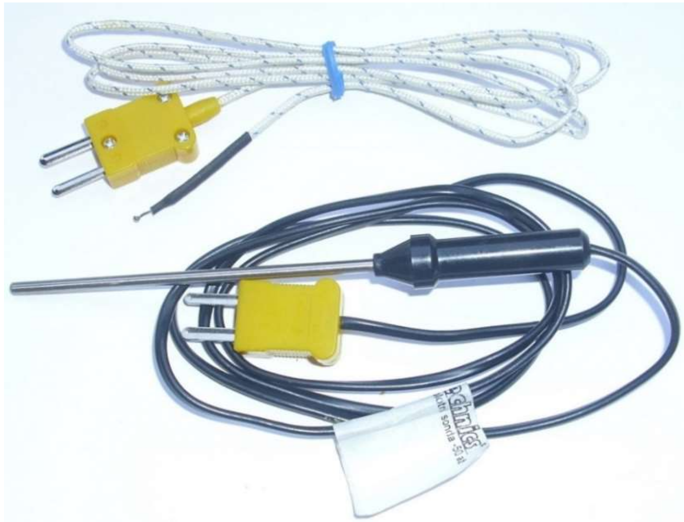

Fig. 5. Thermocouple probes for universal measuring instruments. Type K (chromel–alumel).

Thermoelectric valve

Yet another particularly useful application of thermocouples are thermoelectric valves. Mechanical thermostats employing bimetallic strips to cut-off current to the circuit are quite common. Unfortunately, bimetals aren't very reliable, and their properties deteriorate with number of executed cycles and in quite extreme temperature and corrosive load. This especially manifests when the bimetal is directly exposed to flames – as it is in the case of a gas inlet valve control in gas burners. To avoid a situation in which gas pressure decreases and pilot light is extinguished (it ensures that the gas burner is immediately lit when needed) which sprites into uncontrollable gas leak when the pressure is renewed, it is necessary to have a reliable fuse that releases an inlet valve only when a pilot light is present. Electromagnetic valve powered by a thermocouple ensures that. Providing that the flame is not burning, the thermocouple is not heated, no voltage is being created and the electromagnetic valve (see fig. 6) remains closed.

Fig. 6. Thermocouple in brass tube powers an electromagnet. For the electromagnet to properly function only voltage of approx. 10–20 mV is needed. This voltage ensures that the current flowing through the circuit is in the order of tenths of ampere.

Peltier device

That which cannot be achieved by a single coupling of metals, can be easily achieved by an array of several dozen semiconductor thermocouples. Thermoelectric coolers can be ordinarily bought in electronic components shops. It is an array of thermocouples connected into series which uses the Peltier effect – an effect inverse to the Seebeck effect. If an electrical current flows through metal connected in-between two other conductors, then one joint is being heated while the other one is being cooled. If the whole array is oriented in such way that all warm ends are facing one direction whilst cold ends are facing the other direction you get a Peltier heat pump which can be used to cool thermally sensitive components. And vice versa – if one side of Peltier device is heated and the other one is cooled, we get a thermoelectric voltage source. One such source yields voltages 1-2 V and currents in the order of hundreds miliamps when the temperature difference is approx. 50 °C. Those are not negligible values and Peltier device is rewarding not only as physics experiment, but as a real current source as well. Unfortunately, its surface is covered by very fragile heat conductive ceramics and the device is not exactly mechanically resilient. Furthermore, it corrodes easily when filled with water, yet this disadvantage can be overcome by obtaining Peltier device sealed by silicon to be water-resistant (fig. 7 and 8.).

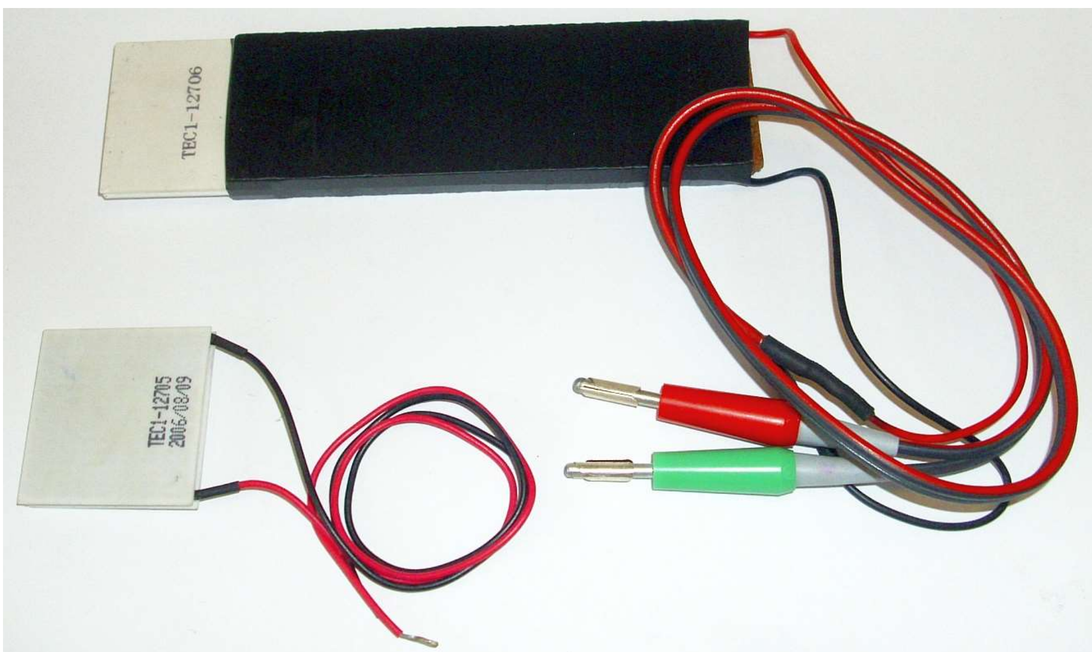

Fig. 7. Peltier device itself (bottom left) and inserted into wooden holder to increase its mechanical resistance (top, with connected outlets).

Fig. 8. Typical permanent experiment, Peltier connected to galvanometer. All that is required for maximum displacement is touch of a finger. Touching other side of the device causes current to change direction and consequently pointer displaces itself in the other direction as well. It is obviously possible to touch the device with a cold object e.g., a piece of ice, which causes current to flow in opposite direction.

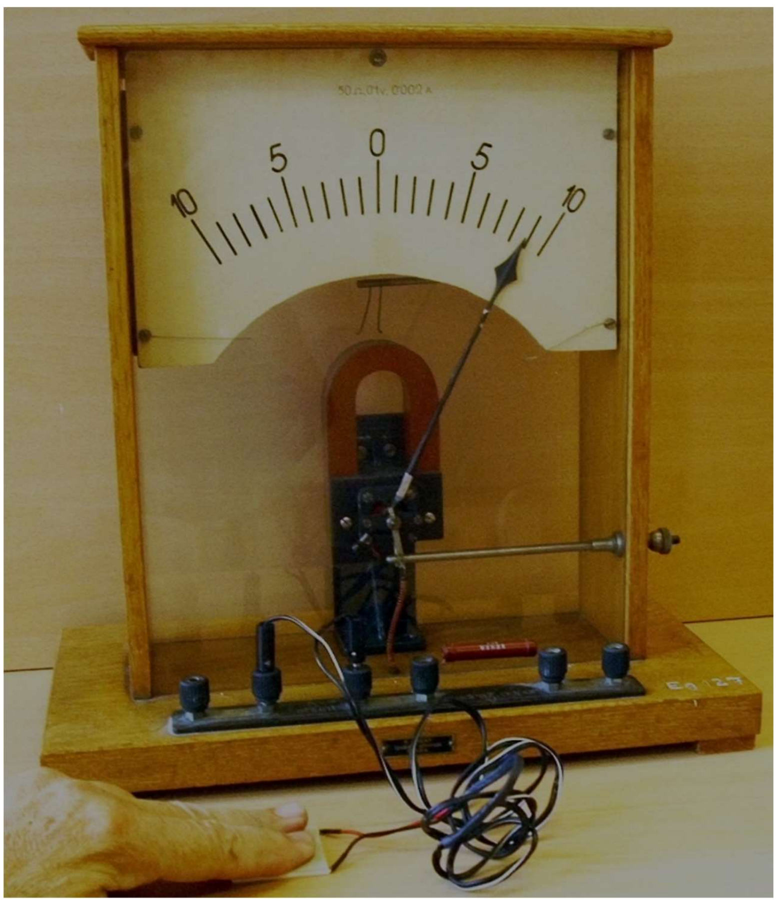

Fig. 9. The same effect, that can be accomplished by a hundred-year-old battery of thermocouples heated by alcohol burner (see fig. 3) can be achieved with one Peltier device heated by two human fingers. Admittedly, the desk was cooled prior to attaching the thermocouple – a tin mug with ice cold water was standing in its place.

Experiments using Peltier devices

Many experiments employing Peltier devices can be carried out. Voltage slightly over 1 V and current in the order of hundreds mA can be easily achieved which allows to power small engine (fig. 10) or light a small light bulb – 1,3 V/100 mA or more common 1,2 V/220 mA are appropriate.

Fig. 10. Peltier device mounted on top of computer passive cooler. Cooler is being cooled by ice cold water in which it is submerged. There are two copper prisms on top, that were originally heated in hot water to temperature of approx. 50 °C. In this arrangement Peltier device yield approx. 1,3 V and current 150 mA.

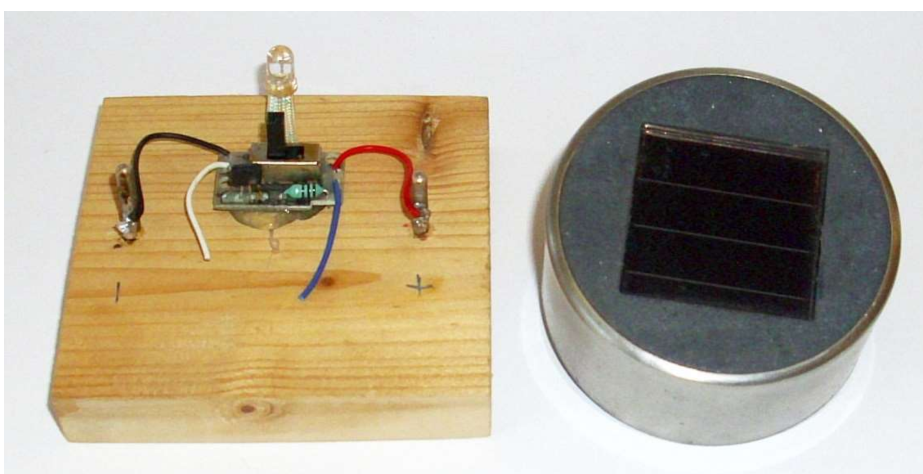

Fig. 11. Charge pump from solar lamp. Free wires were originally connected to a photovoltaic cell. Only approx. 0.9 V is sufficient to light the LED.

Created voltage is not high enough to light a small LED and a converter is required. Simplest solution is to dismantle a retired solar lamp for a simple DC-DC converter, which converts a NiCd cell voltage of 1,2 V to approx. 3 V required for white LED. Such converter works for voltages higher then approx. 0,9 V and is integrated onto printed circuit board with two outlets for photovoltaic cell, two outlets for rechargeable NiCd cell and two outlets for LED – see fig. 11.

Magnetic field of thermoelectric current

Current created by a thermocouple can be used to power an electromagnet (see fig. 6) or to displace a magnetic needle using magnetic field of air-core coil (see fig. 12). It is important for the coil to have a small resistance and a high number of turns. A good compromise is achieved if the coil's resistance is comparable to resistance of the thermocouple while consisting of a hundred of turns. Well-suited for this is a microwave oven transformer primary winding coil – there is microwave oven (output power 1 kW) coil in fig. 12. The coil consists of approximately 220 turns and its resistance is approx. 2 ohms. This coil's advantage is its cavity that is well suited to fit a compass inside and is reinforced by varnishing so it is mechanically stiff. Insert compass into the cavity aligned with north south direction in such manner that the needle lays within the coils plane. All it takes is touch of a finger, heating Peltiers device by several degrees centigrade and the needle noticeably rotates. It is not without interest that those robust coils are winded by aluminium wire.

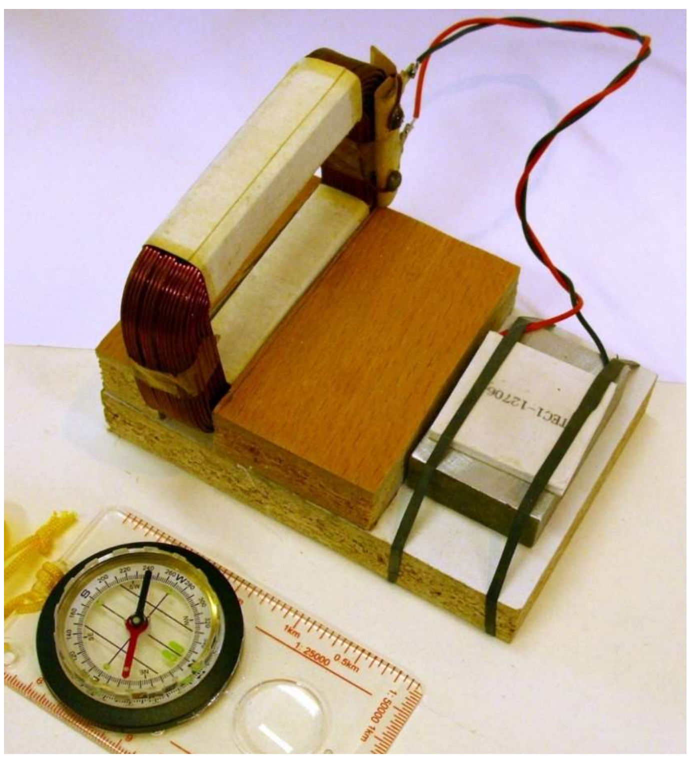

Fig. 12. Peltier device with a coil. Aluminium brick under the thermocouple allows only for small temperature changes to the bottom surface of the couple (due to block's high temperature inertia). Top surface is either heated with fingers or cooled with ice. Magnetic needle rotates to either one side or the other.

Engine made from thermocouples

When we heat a short-circuited thermocouple with small resistance a rather large electrical current flows through it. This can be used to construct an engine. The construction is clearly visible from fig. 13.

Fig. 13. Engine created from thermocouples.

The stator is formed by two strong neodymium magnets, which between them clamp a strong needle inserted into a wooden base. The rotor rests on the tip of the needle. The bearing is made of a brass screw, in the notch for the screwdriver a shallow conical hole is drilled – the friction bearing. The rotor itself is cut from a copper plate. The centre is a circle with a diameter of about 4 cm, from which 16 strips about 0.5 cm wide and 5 cm long run out. The ends of the strips are connected by a thick constantan wire with a diameter of about 1 mm, which comes from a massive rheostat. Thick constantan wires can also be bought in Conrad for about 800 CZK per 100 g, regardless of their cross-section. The wires do not connect directly opposite ends of the strips but take the "shorter route" - there are five more between two ends connected to each other. This saves material, reduces the internal resistance of the thermocouple and, most importantly, creates a hole in the middle large enough to thread the stator magnets through. The constantan wires are connected to the copper sheet by tin soldering. Place a small tea light under the rotor approximately in line with the axis of the magnet. By heating it, a current loop is created which has a magnetic field perpendicular to the stator's magnetic field. A force torque is generated, and the rotor begins to rotate. However, this begins to heat the next closed thermocouple and cool the previous one, still maintaining the force moment required to rotate the rotor. If we move the candle to the other side, the rotor rotates in the opposite direction.

This is another rewarding, stable physics experiment.

Conclusion

This article is not intended to be a precise explanation of thermoelectric phenomena. It is a look at how to arrange the experiments so that the teacher can experiment, showing how the nature works and the use of physical phenomena in practice, make estimates and simple calculations, without going crazy in the process.

References:

[1] https://cs.wikipedia.org/wiki/Termoelektrick%C3%BD_jev

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[3] Šedý V.: *Rozeberte si PC*. BEN – technická literatura, Praha 2001. ISBN 80-7300-016-4