Physics Through the Eyes of Thermography

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Thermal imaging cameras operating in the far infrared range allow the visualization of many physical phenomena that otherwise remain hidden from our eyes – very often, these are phenomena that are manifested by temperature changes on the surfaces of bodies. This ability makes the infrared camera a suitable helper especially when teaching thermodynamics, as has already been described for example in [1] or [2]. This contribution, however, refers to the use of thermography in other areas of physics, where the thermal phenomena are perceived rather as a minor accompanying effect.

Note: The following experiments were performed using a FLIR i7 thermal imaging camera. If monochromatically printed, dark areas in the thermograms correspond to places with low temperature and the light (white) surface corresponds to higher temperature.

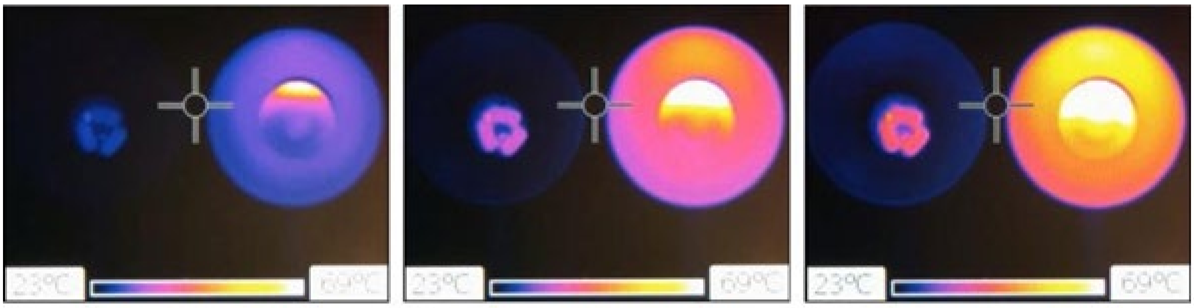
Experiment No. 1: Light Efficiency of a Compact Fluorescent Lamp and a Conventional Light Bulb

Equipment: Thermal imaging camera, classic light bulb and compact fluorescent lamp.

Generally, luminous efficacy *K,* expressing how much luminous flux is produced by the light source per 1 W of its input power, is used to compare the efficiency of light sources.

The values of luminous efficacy can be easily estimated from the data provided by the manufacturers of the light sources on the packaging of their products; in our experiment we will be using a classic light bulb with nominal parameters of 700 lm and 60 W ($K \approx 12$ lm/W) and a compact fluorescent lamp (incorrectly "energy saving lamp") of 700 lm and 13 W ($K \approx 54$ lm/W).

From this comparison, it is clear that a conventional light bulb emits significantly less energy from each watt of its wattage to the light field than a compact fluorescent lamp and so it emits more in the infrared region of the spectrum. This well- known fact is shown in Fig. 1, in which there is always a compact fluorescent lamp in the left part of each image and a conventional light bulb in the right part. While the fluorescent lamp remains relatively cool and its surroundings is virtually not heated at all, the light bulb quickly reaches a high temperature and warms the entire structure of the lamp.



10 seconds after switch-on

30 seconds after switch-on

50 seconds after switch-on

Fig. 1. Compact fluorescent lamp (left) and conventional bulb (right) shortly after switching on

Experiment No.2: Flow Where You Wouldn't Expect It

Equipment: Thermal imaging camera, classic light bulb.

While carefully monitoring the heating of the conventional light bulb in Fig. 1, you can notice the fact that its temperature increases from the top and the lower part is heated last. This can be set as a problem task for students – why does it heat up in such a way? If we repeat the experiment several times, we find that it is not a random phenomenon but rather there is a causal connection. Students are likely to reach the correct explanation in a short time – i.e. the fact that the gas inside the bulb (protective atmosphere of the bulb filament) is heated from the filament and its density decreases and the gas flows to the upper part of the bulb, which thereby increases its temperature. Thus we obtain a textbook example of heat exchange by convection.

If we want to further exploit this issue, we can now invite students to come up with a proposal on how to experimentally confirm this hypothesis – i.e. that there is a convection inside the bulb. The simplest way to do this is to turn the light bulb in the gravitational field in such a way that the lower part of it is at the top and upper part (heated) is at the bottom. The warmest part of the protective atmosphere immediately begins to travel in the opposite direction of gravity, and after a few seconds the original state is restored.

Experiment No. 3: Temperature Changes of the Nasal Mucosa

Equipment: Thermal imaging camera, volunteer.

The primary way the air enters the body of a healthy person is the nasal cavity, in which the incoming air is filtered by ciliary epithelium and thereby freed of dust and contamination. Purely from a physical point of view, the air coming through nasal conchae is humidified and heated before entering the lungs to a temperature close to the internal body temperature. On the other hand, when the air leaves the organism, it is partially cooled so that the body does not lose a large amount of heat by exhaling; the nasal cavity thus serves as a kind of a heat exchanger.

In any case, at normal room temperature, the exhaled air is warmer than the inhaled air, and this is exactly what we will be able to visualize with the help of a thermal imaging camera. More precisely, we will not directly measure the temperature of the flowing air, rather the mucosa of the nasal cavity, which is heated (cooled) by the exhaled (inhaled) air. Fig. 2 shows that during inhale (left), when the air at room temperature enters the nasal cavity, the nostrils are cooled, while during exhale (right), when heated air leaves the body, this phenomenon does not occur.

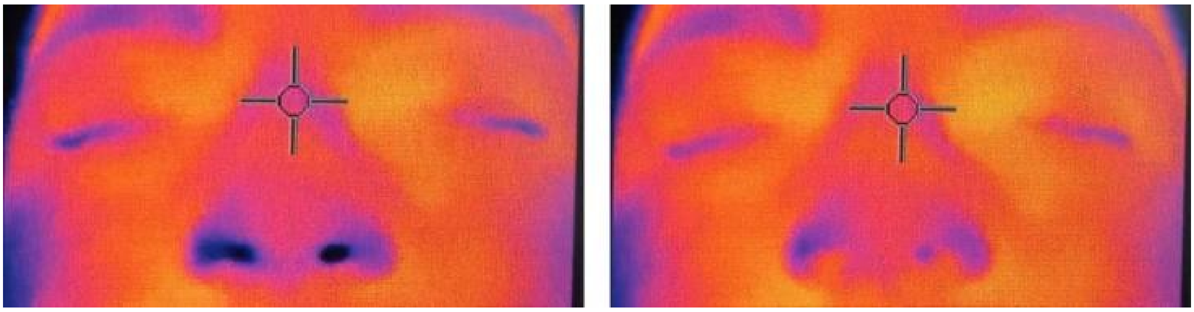
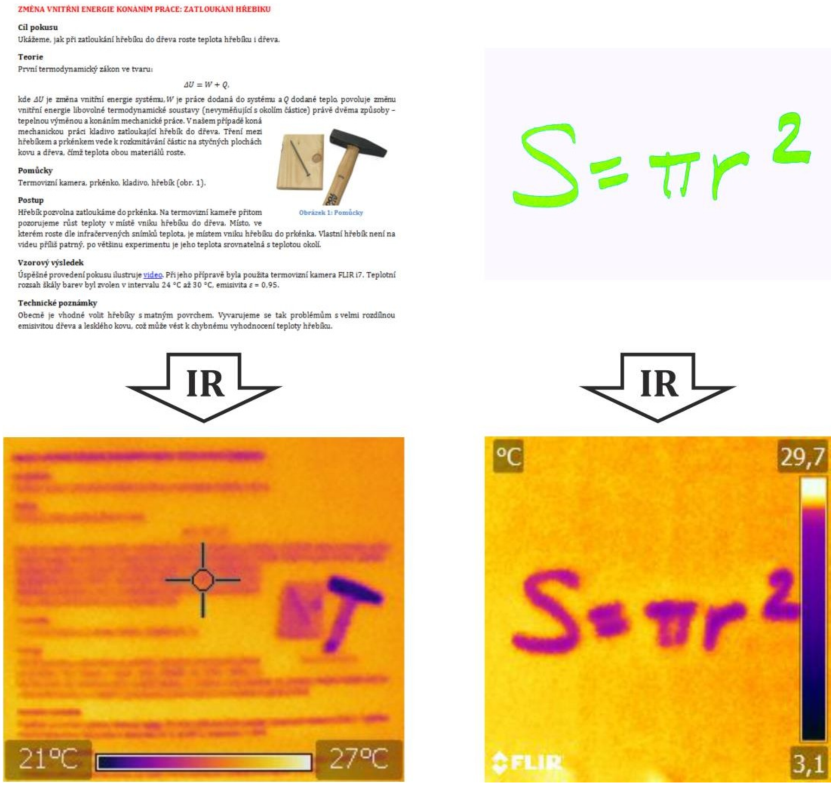


Figure 2. Temperature changes of nasal mucosa - inhale on the left, exhale on the right

Experiment No. 4: Latent Heat of Vaporization

Equipment: Thermal imaging camera, alcohol-based highlighter, inkjet printer.

As liquid evaporates from the surface of an object, particles with the highest kinetic energy leave the liquid; the average energy of the remaining particles therefore decreases and the surface at which evaporation takes place is cooled. From a macroscopic point of view, we say that the liquid draws the latent heat of vaporization from the surface.



ZMĚNA VNITŘNÍ ENERGIE KONÁNÍM PRÁCE: ZATLOUKÁNÍ HŘEBÍKU

Cíl pokusu

Ukážeme, jak při zatloukání hřebíku do dřeva roste teplota hřebíku i dřeva.

Teorie

První termodynamický zákon ve tvaru:

$$\Delta U = W + Q,$$

kde ΔU je změna vnitřní energie systému, W je práce dodaná do systému a Q dodané teplo, povoluje změnu vnitřní energie libovolné termodynamické soustavy (nevyměňující s okolím částice) právě dvěma způsoby – tepelnou výměnou a konáním mechanické práce. V našem případě koná mechanickou práci kladivo zatloukající hřebík do dřeva. Tření mezi hřebíkem a prkénkem vede k rozkmitávání částic na styčných plochách kovu a dřeva, čímž teplota obou materiálů roste.

Obrázek 1: Pomůcky

Pomůcky

Termovizní kamera, prkénko, kladivo, hřebík (obr. 1).

Postup

Hřebík pozvolna zatloukáme do prkénka. Na termovizní kameře přitom pozorujeme růst teploty v místě vniku hřebíku do dřeva. Místo, ve kterém roste dle infračervených snímků teplota, je místem vniku hřebíku do prkénka. Vlastní hřebík není na videu příliš patrný, po většinu experimentu je jeho teplota srovnatelná s teplotou okolí.

Vzorový výsledek

Úspěšné provedení pokusu ilustruje video. Při jeho přípravě byla použita termovizní kamera FLIR i7. Teplotní rozsah škály barev byl zvolen v intervalu 24 °C až 30 °C, emisivita $\varepsilon = 0{,}95$.

Technické poznámky

Obecně je vhodné volit hřebíky s matným povrchem. Vyvarujeme se tak problémům s velmi rozdílnou emisivitou dřeva a lesklého kovu, což může vést k chybnému vyhodnocení teploty hřebíku.

Fig. 3. Evaporation of the ink on a printed page to the left, evaporation from a highlighter trace to the right

Using a thermal imaging camera, we can easily show that this happens even in situations where we might not expect it – Fig. 3 shows a text written with a highlighter (right) and a text printed on an inkjet printer (left). In both cases, it is clear that the areas covered with ink are colder than the rest of the paper due to the evaporation of the solvents contained.

Experiment No. 5: Joule Heating Seen with Our Own Eyes

Equipment: Thermal imaging camera, suitable set of resistors, flat battery.

When electric current I passes through a conductor with a resistance R for time t, the internal energy of the conductor increases by $Q_\mathrm{J} = RI^2 t$, where Q_J is Joule heating. Externally, this increase in internal energy is manifested by the heating of the conductor, which can be easily detected by the thermal imaging camera.

For the purposes of the following experiment, two identical sets of resistors were made – one with resistors connected in series (total resistance about 760 Ω) and one with resistors connected in parallel (total resistance 1.7 Ω). In Fig. 4, the sets are captured in such a way that the resistance of the resistors increases downwards.

When connected in parallel, the voltage on all resistors is the same and current can be derived from Ohm’s Law. Joule heating is therefore given as $Q_J = \frac{U^2 t}{R}$. The most Joule heating will be manifested on the “upper” resistors with the lowest resistance. In serial connection, the current on all resistors is the same and the most Joule heating is thus manifested in the “lower” resistors with the highest resistance – those are therefore heated the most.

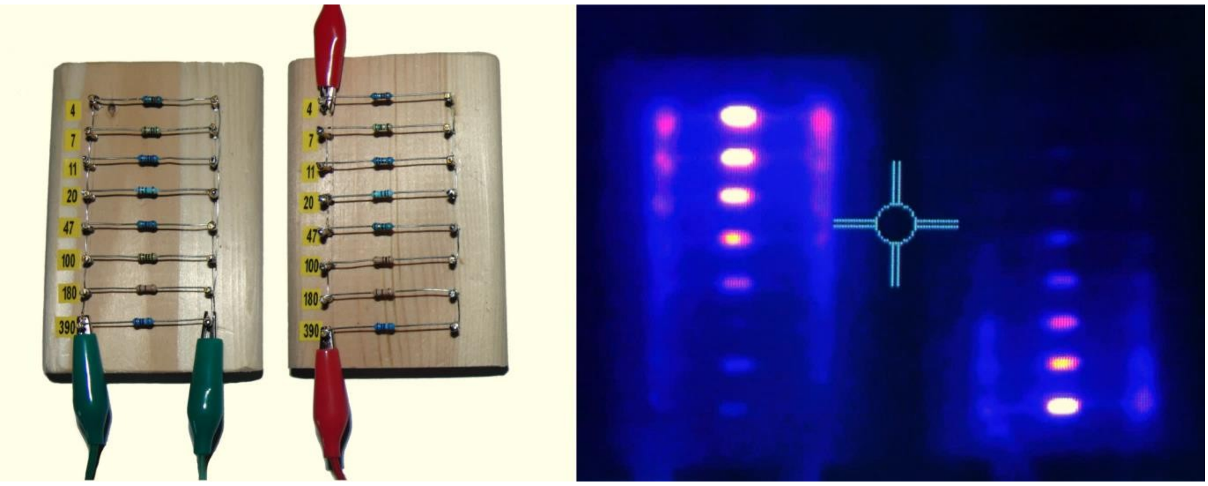


Fig. 4. Resistor sets and their thermal image; parallel connection to the left, serial connection to the right.

Experiment No. 6: Thermal Imaging Camera Instead of Ammeter?

Equipment: Thermal imaging camera, 10 Ω and 100 Ω resistors, 4.5 V flat battery.

Experiment 5 can be extended by additional experiments. By combining resistors, it is possible to connect different schemes and monitor the heating of individual components with passing current. In this contribution, we prepared two connections A and B (Fig. 5 left), to which a 4.5 V flat battery was connected in both cases. The resulting thermograms can be seen in Fig. 5 on the right.

In case of diagram A, the current is divided evenly into each branch of the circuit – resistors 2 and 3 are heated approximately the same, while resistor 1, with current twice as large warms up much more.

In the case of diagram B, the current in the lower branch of the circuit is only one tenth of the upper branch and Joule heating which develops in the lower branch is also tenth in this comparison, resistor 6 is therefore virtually not heated at all, while resistors 4 and 5, with almost all of the current of the circuit heat up more or less the same.

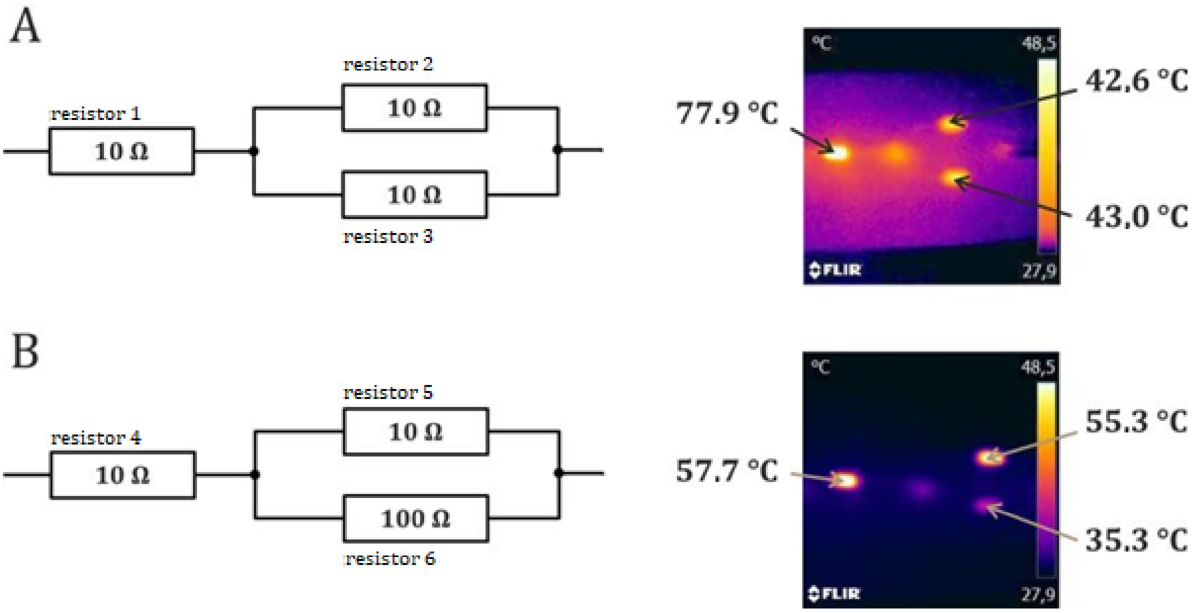


Figure 5. Sample result for experiment No. 6

Where to find more materials and advice

All of the above experiments are described in more detail and documented in the electronic *Collection of Physical Experiments* [3]. A document [4] which briefly summarizes the principles of working with a thermal imaging camera and gives recommendations on what to avoid when working with it in teaching is also part of these experiments.

Literature

[1] Kácovský, P. *In the Footsteps of Heat with Thermal Imaging Camera.* In: Proceedings of Physics Teachers Invention Fair 19. Ed.: Vochozka, V., Bednář, V., Kéhar, O., Randa, M. University of West Bohemia in Pilsen, 2014, p. 69–73.

[2] Kácovský, P. *Experiments with Thermal Imaging Camera*. In: Proceedings of a seminar How to Cajole Students into Physics? 2. Ed.: Seifert. JČMF Prague 2015.

[3] http://fyzikalnipokusy.cz/cs

[4] https://physicstasks.eu/media/01584/Experimentujeme_s_termovizni_kamerou.pdf