Thermal Imaging Experiments as an Inspiration for Problem-based Learning

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Thermal Imaging Experiments as an Inspiration for Problem-based Learning

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In the last decade, a powerful tool has been given to physics teachers to visualize thermodynamic phenomena. Thermal imaging cameras are fascinating devices opening the world of (even small) temperature changes and being able to uncover hidden manifestations of many processes around us. This paper describes a few qualitative thermal imaging experiments prepared primarily for problem-based lessons and repeatedly used with high school or even university students in the Interactive Physics Laboratory[1] at Charles University. These experiments are focused on thermal processes, which often run in unexpected ways (at least for the students), and their explanations typically require a complex insight into physics, so they can be used as a starting point for discussions and activities designed for some level of inquiry.[2]

The belief that using thermal imaging in physics lessons could contribute to deeper students' insight into the nature of thermodynamic processes has led to the publication of various relevant teaching ideas.[3-5] Among other things, these suggestions most often aim at heat transfer mechanisms (conduction, convection, radiation) or temperature-indicated changes in internal energy—e.g., sliding friction or inelastic collisions. All these ideas could serve as an inspiration for teacher demonstrations; however, for students they are more beneficial in their inquiry-based form.[6,7] Thermal imaging experiments are capable of attracting the students' attention, even more so since they show effects invisible to our eyes. This starting point makes thermal imaging cameras generally ideal devices to be manipulated by the students themselves, even though it is still expensive for most schools to buy more than one camera.

Experiment 1: Emissivity and reflected temperature

When using thermal imaging, the teacher as well as the students should be aware of an essential factor that can completely undermine the measurement—the emissivity of the measured surface. The emissivity indicates how much radiation the surface releases in comparison with a blackbody, which represents a theoretical upper limit of emitted energy. The lower the surface emissivity, the more significant the influence of the surrounding objects, the radiation of which could be reflected by the studied surface; we speak about the effect of reflected temperature. This way, the thermal imaging camera could easily detect not only the radiation of the measured body, but also the radiation of surrounding objects, which makes shiny surfaces difficult to study by thermal cameras.

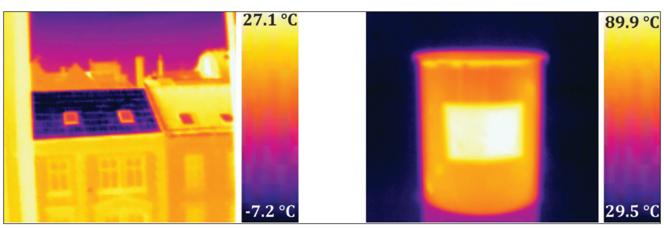

Fig. 1. In the left picture, the dark roof of low emissivity reflects radiation from the atmosphere, i.e., it seems to be much colder than its surroundings. In the right picture, the paper sticker in the middle is the only part of the aluminum container the temperature of which is measured correctly; the rest of the cup has very low emissivity.

Neglecting effects of low emissivity and reflected temperature leads to very strange results that attract students' attention—two examples are shown in Fig. 1. The photo on the left shows a block of houses on a spring afternoon; the roof in the middle is made of low-emissivity polished metal, significantly reflecting the radiation from ice crystals in the atmosphere. This results in an absurdly low temperature measured in this area. The second photo shows a model of this situation in the classroom—there is a paper sticker on a shiny aluminum cup with hot water; the thermal imaging camera only shows a reliable surface temperature for the sticker, while the rest of the cup reflects the radiation from the surrounding room and seems to be colder.

With younger students, these examples could be used to show that shiny surfaces produce strange measurements, without detailed explanations of what emissivity really is.

Experiment 2: Thermal conductivity of a plastic and a metal plate

For this simple experiment two plates of the same size are needed, one made of plastic, the other one made of metal; the metal plate should be covered with dark matte coating to ensure similar emissivity of both surfaces. Students put one hand on the metal plate and the other hand on the plastic one at the same time and leave them motionless for 20 seconds. While the metal plate is almost evenly warmed during that time, the temperature of the plastic plate only increases at the points of contact with the palm (Fig. 2): plastic is a thermal insulator and does not allow for heat distribution in peripheral parts of the plate. The students' explanations of this result are usually satisfactory when they are led to examine the different thermal conductivities λ of two materials. More precisely, the final surface temperature distribution is determined by thermal diffusivity, which also includes the heat capacity c and the density ρ of the material.[8]

However, it is difficult for the students to predict where the overall highest temperature will be measured (after removing the palms). While the criterion of heat capacity points to the "victory" of metal, when taking the thermal conductivities

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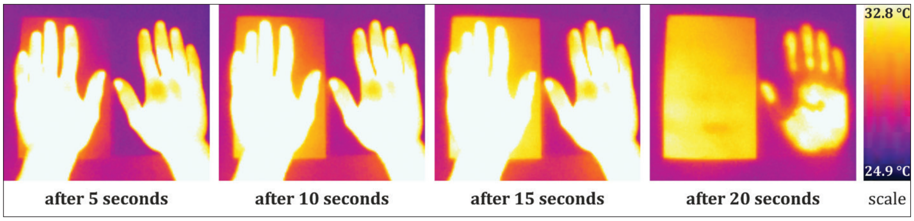

Fig. 2. Temperature distribution observed on the surface of a metal plate (on the left) and a plastic plate (on the right). The time is measured since laying palms on plates.

into consideration, the highest temperature is expected to be somewhere on the plastic plate (which is typically true). Regardless of the actual result, this problem could serve as a starting point for discussion.

Experiment 3: Convection inside the incandescent light bulb

In many texts dealing with light sources, we can find a phrase like "the air is removed from incandescent light bulbs to protect the tungsten filament from oxidation." Among students, this may lead to the impression that there is nearly a perfect vacuum inside incandescent light bulbs, which is generally not true—the vast majority of light bulbs are filled with an inert gas. While quantitative experiments try to measure the pressure in the bulb,[9] thermal imaging offers an elegant way of qualitatively indicating the presence of the gas surrounding the filament. After switching on the light, we only need to watch the bulb with a thermal camera to see that its top is heated more rapidly than its bottom (Fig. 3). Because the filament is approximately in the center of the bulb, the only reasonable explanation is a convective flow of some gas inside.

Once the students explain this phenomenon, they could think about how to support their interpretation. The simplest way is to rotate the bulb around its longitudinal axis—the top and bottom will change places and the gas starts to move in the bulb until the initial state is restored.

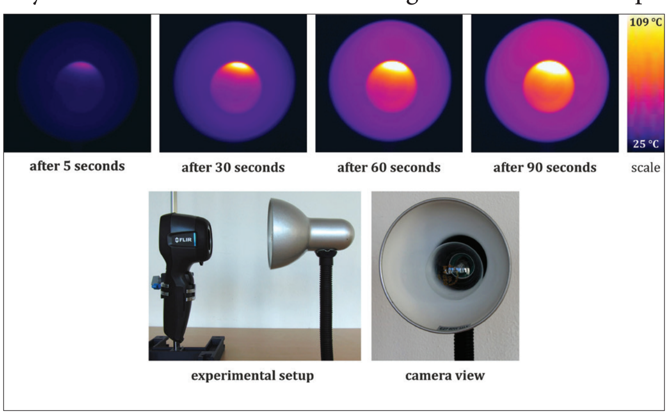

Fig. 3. Due to the convection in the Earth's gravitational field, the temperature rise in the incandescent light bulb is fastest in its upper part; the time is measured since switching on the light. The bottom picture shows the experimental setup consisting of a thermal imaging camera and a table lamp with the bulb inside.

Experiment 4: Evaporative cooling of ethanol and water

The ability to scan the surface makes thermal imaging cameras suitable tools to study evaporative cooling of liquids. In this experiment, two strips of paper were used, one partially dipped in water, the other one in ethanol. In a few seconds, both strips were taken out of the liquids and laid on the table. Since ethanol starts to evaporate more quickly, the "ethanol strip" becomes colder than the "water strip."

However, compared to ethanol, the latent heat of vaporization of water is approximately 2.5× higher and, as such, water should remove 2.5× more energy from the surroundings to evaporate (if we assume comparable masses of liquids), i.e., the water strip should be cooled down more than the other—but the experiment shows the opposite! Thermal imaging provides a solution to this problem; in Fig. 4, there is a time sequence showing the evaporation of ethanol (on the right) and water (on the left). It is evident that ethanol evaporates more vigorously, but for a shorter time; after three minutes, the ethanol strip is dry again and close to the ambient temperature, while the other strip is still being cooled by the continuing evaporation of water. It means that water really removes a greater amount of energy from the paper (in agreement with theory), but in a much longer time; thus, the temperature decrease is more long-lived, and less dramatic than in the case of ethanol.

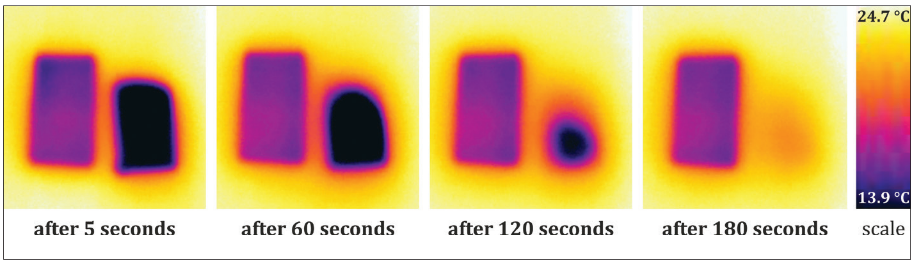

Fig. 4. Two strips of paper were cooled down by the evaporation of liquids. The strip on the right was dipped into ethanol, the other strip into water. After about three minutes, the effect of ethanol evaporation practically disappears. The time is measured since taking the strips out of the liquids.

Experiment 5: Cold writing?

The seemingly crazy section heading above describes an experiment that visualizes temperature changes on the paper during handwriting—a thermal imaging camera observes the tip of an alcohol-based marker when writing a word. Due to the evaporative cooling of the alcohol component of the ink, there is a local decrease in temperature, so written letters are colder than the rest of the paper (Fig. 5). A similar effect can be obtained using an inkjet printer as the portion of ink that is not absorbed by the paper evaporates after printing.

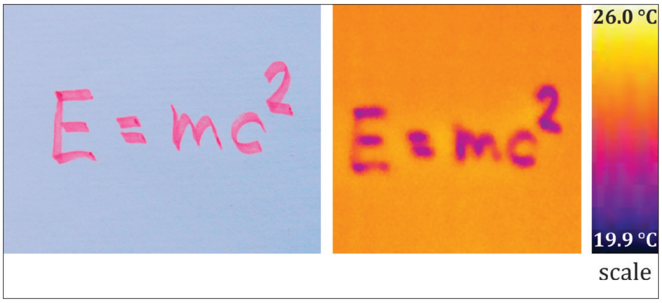

Fig. 5. On the left, there is an equation written by an alcohol-based marker, on the right its IR image a few seconds after writing.

Of course, the use of a graphite pencil does not produce this result; there is no liquid to evaporate. What can be expected in this case is a temperature increase caused by sliding friction; unfortunately, this effect is often too minor to be detected by thermal cameras.

Experiment 6: How can a frozen body heat up its surroundings?

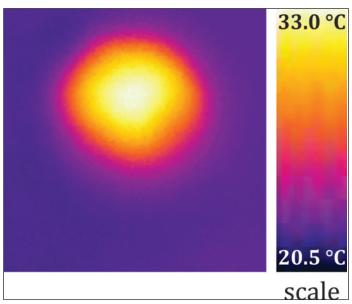

Fig. 6. Temperature increase at the place of impact of the mallet.

When introducing the concept of change in internal energy (related to the first law of thermodynamics), teachers often struggle to explain to students that the transformation of mechanical energy into internal energy, manifesting itself as a change in temperature, occurs in everyday life literally at every turn, during every inelastic collision. Thermal imaging cameras provide evidence of this: detecting the temperature increase during inelastic collisions is described, e.g., by Möllmann and Vollmer.[10] The only equipment needed is a polystyrene plate and a mallet chilled in the freezer for some time before the experiment. Even though the temperature of the mallet is below –20 °C (ideally to be measured at the beginning of the experiment), we observe a temperature increase after striking the plate with the mallet at the place of impact, which is usually surprising for the students. During the impact, the kinetic energy of the mallet is transformed into internal energy, which causes local warming up of both the plate (Fig. 6) and the mallet; moreover, the impact time is too short to allow for the equalization of temperatures between both bodies in contact by thermal conduction.

Experiment 7: Resistors in series and in parallel

Joule heating enables thermal cameras to detect electric current going through a wire, which has wide applications during inspections of electrical equipment. In physics lessons, such a measurement could contribute to students' better understanding of what is happening in simple resistor circuits. In order to perform this experiment, two visually identical resistor sets were prepared, one connected in series ($R_{TOT} \doteq 1.4\ \text{k}\Omega$) and one in parallel ($R_{TOT} \doteq 6\ \Omega$), both consisting of the same resistors. As it will be crucial to compare the surface temperature of the resistors, it is necessary to use resistors of the same size, geometry, and surface treatment.

Joule heating is proportional to the conductor resistance and the square of electric current. After connecting the power supply, the same current goes through resistors arranged in series, so the one with the highest resistance will be heated up the most. However, in parallel the situation is opposite—the current going through each resistor is inversely proportional to its resistance, which means that the temperature increase is the largest for small resistances (Fig. 7). This physically obvious result could be surprising for the students and difficult to explain even if they see the difference in resistor sets arrangement.

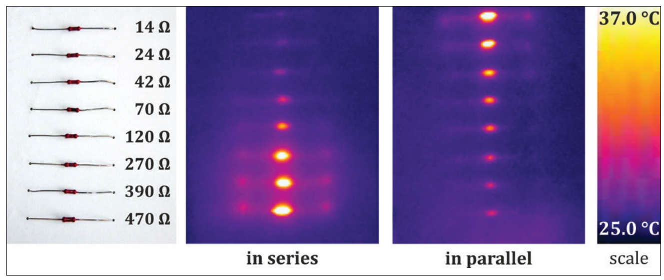

Fig. 7. The real model of a resistor set (on the left) and its IR pictures when the resistors are connected both in series (in the middle, $R_{TOT} \doteq 1.4$ kΩ, $U \doteq 30$ V) and parallel (on the right, $R_{TOT} \doteq 6$ Ω, $U \doteq 3$ V).

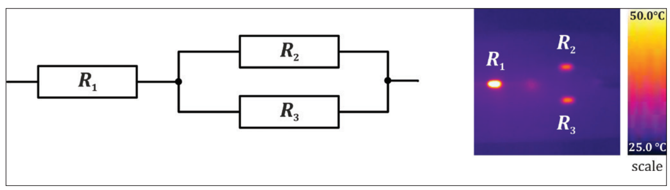

Fig. 8. The simple circuit where $R_1 = R_2 = R_3$. The IR image shows how the current is equally split into two parallel branches. Joule heating is observable also in the node of the circuit due to the contact resistance occurring at this point, which in fact creates the "fourth resistor."[11]

Alternatively, a thermal imaging camera could be used in the role of an ammeter when teaching about Kirchhoff's laws. To demonstrate how the current is divided into branches according to their resistance, even a simple circuit will be sufficient made of three identical resistors arranged as seen in Fig. 8. Resistor R_1 experiences double current compared to the remaining two resistors, which results in its more intensive warming up, whereas R_2 and R_3 change their temperature equally—and more slowly. This way it is possible to build much more complicated circuits made of identical resistors and study currents going through their particular branches.

Summary

The continuously decreasing prices of thermal imaging cameras and special offers for schools allow for their use not only in the construction industry, but more often also in the classroom for educational purposes. The experience from the Interactive Physics Laboratory shows that students' own experimenting with thermal imaging cameras is attractive for them and drives them to solve even more complex problems arising from thermal imaging measurements. Moreover, both operating the thermal cameras and interpreting the thermal images is intuitive for students and does not limit their interest.

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