

The Visit of Thermal Imaging World in One Physics Lesson

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Abstract

This paper describes ten simple thermal imaging experiments designed primarily for upper secondary students, but usable with younger pupils as well. The author's primary motivation was to come up with meaningful use of a thermal imaging camera even if the teacher only has a short time to work with it – in the extreme case, only one lesson in each class (if he/she e.g. borrowed the camera from another school or university). Experiments create three logical sequences – interaction of IR with matter, mechanical experiments and thermal properties of matter. In the predict-observe-explain design, the sequences are continuously used in the Interactive Physics Laboratory, which allows the author to add some relevant notes and recommendations derived from authentic experience.

Keywords: infrared radiation, change in internal energy, secondary school, thermal imaging, thermal properties of matter

Introduction

Thermal imaging has recently experienced a considerable development not only in industrial applications, but also in the field of physics education. More and more physics teachers can offer their students thermal imaging cameras as an attractive tool to enter the world of thermal processes, which have remained hidden to our eyes so far. Different authors come up with simple teaching ideas using thermal imaging [e.g. 1-7], and the related research follows [8, 9].

However, despite permanently decreasing prices and the arrival of cheaper smartphone-compatible devices [10], for some secondary schools thermal imaging cameras remain too expensive to be purchased as regular teaching equipment. Some secondary school teachers use their collaboration with universities to borrow at least one camera; the author has even experienced cases where lending took place directly between differently equipped secondary schools. Anyway, teachers get into situations where they have a very limited time to use this special tool, which can lead to the degradation of the thermal imaging camera to just an interesting physics toy – students are watching colourful pictures of their classroom or classmates and the teacher is

satisfied because he/she succeeded in getting students' short-term attention.

The author of this paper has nothing against such an approach; however, he is convinced that the potential of thermal imaging cameras should be fully exploited. Due to the intuitive interpretation of IR images, even only a single physics lesson (let us say 45 minutes) can consist of non-trivial compilation of meaningful experiments, which enrich students' understanding and simultaneously avoid their overloading by new findings. This experience is repeatedly confirmed e.g. in the Interactive Physics Laboratory [11], where students (under the supervision of lecturers) have worked with thermal imaging cameras since 2014; the concept of the Laboratory is described in the text below.

Hands-on experiments in the Interactive Physics Laboratory

The Interactive Physics Laboratory at the Faculty of Mathematics and Physics (Charles University) provides upper secondary school students with a space for conducting hands-on experiments designed in the spirit of structured inquiry. The main goal of the Laboratory is to lead students to maximum autonomy – starting with preparing the apparatuses and continuing by creating hypotheses,

performing measurements, recording and evaluating data and finally formulating results and presenting them to their classmates. Anytime, students can indeed consult these steps with lecturers – students or junior employees of the Department of Physics Education.

Divided into groups of three to four, students spend a total of two hours in the Laboratory working on experimental units that together create a monothematic experimental set; every unit has its own worksheet for recording all findings and results. At present, the Laboratory offers nine experimental sets and welcomes about one thousand students every year.

Thermal imaging cameras have been used regularly in the Laboratory for five years as part of a much more extensive experimental set *Thermodynamics – Qualitative Approach*. More specifically, within this set thermal imaging experiments form three logically arranged sequences which can be used separately and incorporated into common secondary school physics lessons. All the sequences follow the POE (predict-observe-explain) scheme [12] and are primarily designed for upper secondary students; however, the author's experience shows that many experiments are easy to use also with younger pupils. All thermal images in the following text were taken with the FLIRi7 thermal imaging camera.

Sequence A: Interaction of IR with matter

The aim of the sequence is to show that if we focus on reflection, absorption and transmission, the infrared radiation used for thermal imaging, i.e. wavelengths about $10\text{ }\mu\text{m}$, behaves somewhat differently in comparison with visible light and the near-infrared (known e.g. from remote controls).

Reflection

As soon as students are given a thermal imaging camera for the first time, very quickly they find out that objects with smooth surfaces around them reflect thermal radiation. The temperature of such surfaces (e.g. glass, varnished wood or metal objects) can be evaluated incorrectly, because the thermal camera detects not only the radiation of the measured body, but also that emitted by surrounding objects and reflected by the body in the direction of the camera. For low-emissivity surfaces (figure 1) this effect of reflected temperature is dominant and causes the temperature readings produced by the camera could be pointless.

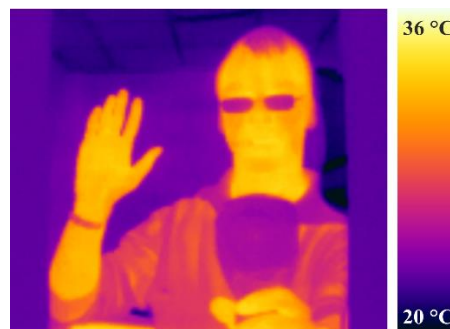


Figure 1. Looking at a low-emissivity aluminium plate, students can see a reflected thermal image of themselves holding a camera

Everybody using thermal imaging should be aware of this limitation and in the Laboratory we work with it intentionally to avoid misinterpretations and students' confusion when performing subsequent experiments. At the very beginning of their work, students should decide in which situations the temperature readings are trustworthy and when we should be cautious.

Transmission

Being familiar with the effect of reflected temperature, students compare different plastic materials (polyethylene, polystyrene, polyethylene terephthalate etc.) according to their ability to transmit thermal radiation. Things of everyday use could be investigated, such as PET bottles, plastic bags or different packaging and foils. Even a short exploration shows that materials transparent for visible light can be opaque in the thermal imaging region and vice versa (figure 2). On that occasion, students also discover and verify that with the increasing thickness of a material its transparency decreases (according to the Lambert-Beer law, which however need not be mentioned).

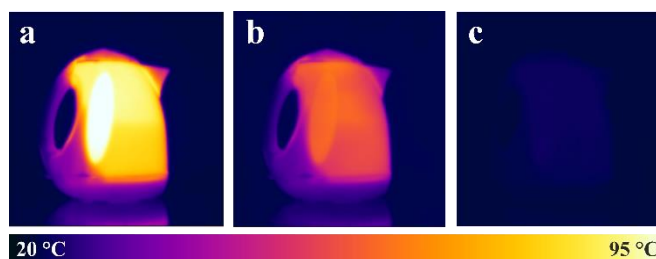


Figure 2. Hot kettle seen (a) directly, (b) through polyethylene packaging opaque in visible light and (c) through a piece of PET bottle transparent in visible light.

Absorption

The effect of partial absorption of radiation is often discussed together with transmission as part of the previous experiment. Students obviously have the experience that radiation can be absorbed, but usually in connection with visible light – they know that black clothing warms up more rapidly than white one when exposed to sunlight. To

demonstrate this, we use a paper with differently coloured printed bars illuminated by an incandescent bulb (= Sun), as described in [5]. The thermal imaging camera instantly shows that black, brown or dark blue bars heat up more than e.g. white or yellow areas. However, this effect (as in the case of sunlight) is caused not only by absorption of visible light, but also by absorption of IR radiation. When students cover a bulb with a visible light filter, which allows for the IR passing through, the experiment leads to the same result – visible light is evidently not necessary to heat up the paper.

After this finding, students sometimes completely change their belief and start to doubt that visible light itself is capable of transmitting energy necessary to warm up other objects. Fortunately, they can confirm that even visible wavelengths have this power – when a monochromatic laser beam impacts a thermally insulating and absorbing surface, it causes a local temperature rise in the impact area. Using a laser pointer as a source and a black matte Styrofoam plate as an impact surface, we are able to prove that both visible light and IR participate in warming up objects through Sun or bulbs.

Sequence B: Mechanical experiments

Teaching mechanics, we often meet the problem that in real processes we almost never observe a thing like mechanical energy conservation because some portion of the initial energy is typically dissipated and partially converted to internal energy, as manifested by a temperature increase of the interacting bodies. Thermal imaging gives a unique opportunity to visualize this (often tiny) temperature increase.

Sliding friction

Frictional heating can be easily visualized by thermal cameras. One of the students sits in a chair and one of his mates drags the loaded chair on the floor; the chair legs will leave thermal traces behind.

Conversion of mechanical energy into internal energy

The following experiment is also well known [7] – hitting a thermally insulating (e.g. Styrofoam) mat with a mallet, the temperature of both objects locally increases due to the transformation of kinetic energy into internal energy. Surprisingly, the explanation of this phenomenon is not intuitive even at the upper secondary level – the author’s experience shows that students often consider the sliding friction to be the key effect again. This is the reason why we emphasize here that in this case no sliding is present, so the influence of frictional heating is irrelevant.

Energy of free fall

The same physics principle is applied also in this experiment, only the single blow with the mallet is replaced by the hit of a freely falling body. Students drop the same object (a metal ball with matte surface appeared to be ideal) from four different heights (50, 100, 150 and 200 cm) and measure the local temperature increase of the Styrofoam plate in the area of its impact. The higher the initial point, i.e. the potential energy of the ball, the more significant temperature growth is detected (figure 3).

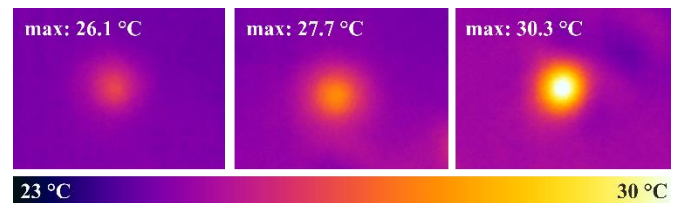


Figure 3. Temperature increase on a Styrofoam plate caused by a metal ball falling from the heights of 50 cm, 100 cm and 200 cm (from the left). The number indicates the maximum temperature in the impacted area.

Note: It is misleading to perform this experiment with a glossy metal sphere (as suggested in [6]), which has a low emissivity and reflects the ambient radiation. Watching their own thermal reflections, students can get the impression that the sphere is “naturally” warmer than its surroundings, so heat simply flows to the mat.

Convection in the liquid

The final experiment of this sequence does not focus on energy transformations but uses thermal imaging to visualise an effect which is present in everyday context countless times but usually remains unnoticed. Students are typically aware of the fact that during heating in a glass or a beaker, liquids increase their temperature primarily at the point of contact with the heat source. The temperature dependence of density then leads to the convective flow in the liquid, which distributes energy into its volume. However, it could be interesting not only for students that this convection is observable even after a long time (dozens of minutes), when the liquid is not heated up any more. After being brought to a boil, water was left in an ambient temperature for half an hour, and then two thermal images of its surface were taken with a ten-second delay (figure 4). Hotter and colder areas can be identified, and as they tend to dynamically move in time, students conclude that there are still convective flows in the liquid that permanently change the temperature distribution (not only) on the water surface.

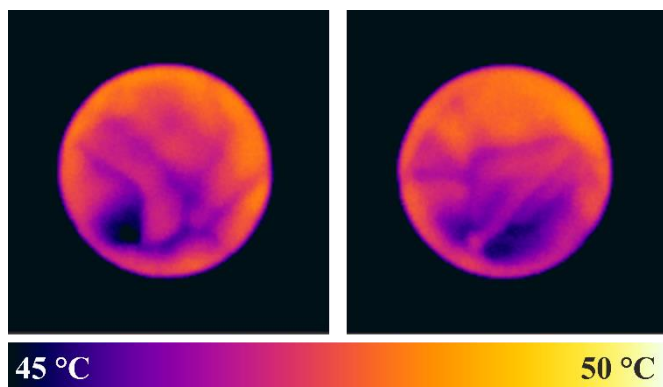


Figure 4. Two images of water surface with a ten-second delay. The temperature distribution apparently changes due to convective flows.

Sequence C: Thermal properties of matter

In a common class, thermal imaging typically does not allow for quantifying thermal constants of matter (specific heat, thermal conductivity, latent heat etc.), but can help to simply compare them for different substances.

Thermal conductivity

Comparing thermal conductivity of thermal insulators and conductors or of two different metals with an IR camera is an evergreen of physics teaching, as e.g. proven in [6-9]. Usually, two objects are heated up and students are expected to make a conclusion as to which one spreads the heat faster and why. In our Laboratory, this experiment is performed in the design described in [7] – plastic and metal plates are warmed up by laying palms and students typically do not struggle to understand and interpret the result they obtain.

However, the author's experience shows that the situation is interpretatively more complicated when both plates are cooled down – in our setup by two cups filled with ice and standing ca. 30 seconds in the centre of both plates (figure 5). The concept of “spreading cold” often occurs, which requires a discussion with students leading them to reformulate their explanation using a physically accepted concept of heat.

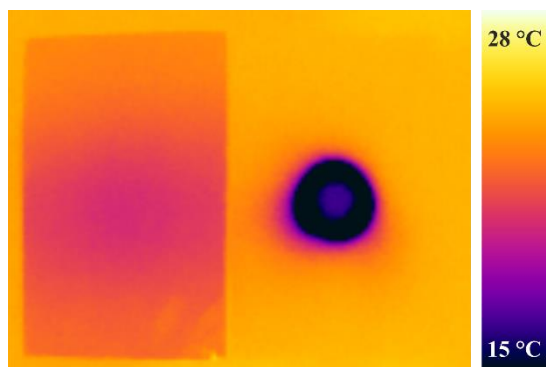


Figure 5. The metal (on the right) and plastic plates immediately after cups with ice were removed.

Note: Students sometimes formulate their observation in a way that “metal is getting hot/cold faster than plastics”, but this description is not correct as it refers to specific heat the difference of which however cannot account for the fact that peripheral parts of metal change their temperature, and peripheral parts of plastics don't.

Specific heat

To avoid the above mentioned (and interfering) influence of thermal conductivity, different specific heat can be simply demonstrated for two commonly used liquids, e.g. water and ethanol. Students fill two identical cups with the same mass of both liquids and put them into a larger container which works as a water bath. After pouring hot water into the container, the liquids in the cups are almost evenly heated and it is obvious that the temperature of ethanol (specific heat ca. $2450 \text{ J kg}^{-1} \text{ K}^{-1}$) rises faster than the water temperature (figure 6).

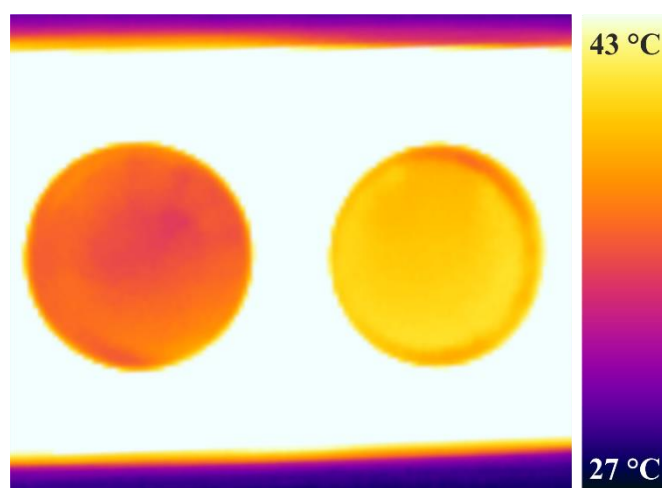


Figure 6. Cups with water (on the left) and ethanol (on the right) heated in a water bath.

Note: Ethanol is much more suitable for comparing with water than vegetable oil which is also considered a liquid of everyday use. However, the high oil viscosity limits convection and without stirring, the temperature at different depths differs significantly.

Latent heat

The last experiment aims at the latent heat of vaporization, which is studied indirectly here through the evaporative cooling effect. At room temperature, students dip one strip of paper in water, another one in ethanol and with thermal imaging camera they observe that the second one becomes colder than the first one.

This finding is often expected by the students, but it contradicts the fact that compared to ethanol, the latent heat of vaporization of water is ca. $2.5\times$ higher, and so water

should remove more energy from the surroundings to evaporate in the same amount. Thermal imaging can clarify even this discrepancy – it shows that ethanol evaporates much faster, but for a shorter time. After a few minutes, the “ethanol strip” becomes dry again, while the “water strip” is still being cooled by the continuing vaporization – in other words, water actually does remove more energy from the paper, but in a significantly longer time.

Conclusion

The paper has described three experimental sequences designed for the use of thermal imaging with upper secondary school students. Even if implemented in a limited time, these experiments give an opportunity to use the non-trivial possibilities of thermal imaging cameras to support students’ understanding of basic thermal phenomena. Experience from the Interactive Physics Laboratory, where the predict-observe-explain (POE) strategy is applied, proves the viability of the suggested experiments and confirms that they can be both attractive and beneficial for students.

Acknowledgements

This work was supported by the Charles University Research Centre, No. UNCE/HUM/024.

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