Experiments using thermosensitive sheets

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This paper describes a few experiments using thermosensitive sheets to demonstrate optic and thermodynamic phenomena.

Introduction

Thermosensitive sheets based on liquid crystals that change their colour according to temperature change have lately become a common tool for measurement of human body temperature or aquarium water temperature. It is possible to get even self-adhesive sheets of large dimensions (e.g. 30 cm × 30 cm) for a reasonable price[1]. Advantages of these materials are their sensitivity (full colour scale corresponds to 5 °C difference in temperature), time rate of colour change, and low heat capacity. They are available for temperature measurement from 20 °C to 45 °C. These sheets are ready to become easily accessible tools to demonstrate phenomena connected to material heating processes.

Heat tracker[2]

Put your warm palm on the top of a table and keep it there for 10 or 20 seconds. Then put a thermosensitive sheet of suitable temperature range to this place. In a few moments the sheet will show an image of your hand. Disappearance of this image will be surprisingly slow. To perform this experiment successfully, a few conditions have to be met. First, the temperature in the room should not be too high otherwise the difference of temperature between your hand and the table wouldn't be big enough. Secondly, the thermal conductivity of the table board matters – it should be neither too high nor too low. The influence of thermal conductivity on the experiment can be shown by repeating it using copper board and again using polystyrene foam. None of these would make a sharp, high contrast image of your palm. In the case of a copper board the trace is blurred by copper's high thermal conductivity. For polystyrene foam, its small thermal conductivity coefficient together with its low heat capacity does not allow the material to accumulate enough heat from the hand and transfer it to the sheet. The best results are produced using laminated chipboard; wooden boards or veneered materials are slightly worse.

Choice of the appropriate temperature range of the sheet is crucial for this and all following experiments. We usually measure only slight temperature changes and therefore we have to make sure that the range of expected temperatures is within the range of the sheet's sensitivity. In consideration of common room temperature being a few

[1] http://www.omegaeng.cz
[2] The author of the names of all experiments described here is dr. Pavel Konečný

degrees above 20 °C, the most useful sheets would be those that are sensitive in ranges from 20 ºC to 25 ºC and from 25 ºC to 30 ºC.

Though this demonstration probably won't work in hot summer, it is possible to make an inverse setting. Cool your hand in cold water or ice cubes and then lay it on the desk.

Heat races

This experiment compares the thermal conductivity of different materials. Put rectangular rods of same cross-section side by side and start heating them at one end, e.g. by heating resistors. To make the heating homogenous, you can use a copper rectangular prism to underlay the resistors (see fig. 1). Alternatively you can cool the opposite side of the rods. The temperature distribution will be monitored by a freely laid thermosensitive sheet.

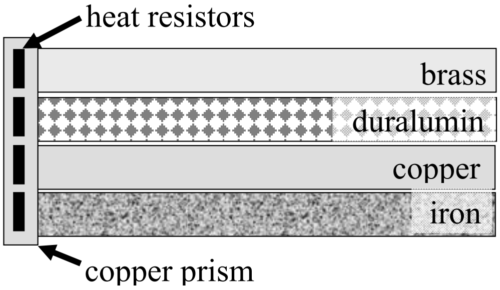

Fig. 1. Experimental setup – rods from different metals

According to heat regime we can distinguish different situations. Three of them will be discussed here.

1) Heating and cooling on opposite sides, negligible heat losses, stabilized state

If we heat and cool opposite sides of the rods simultaneously while heat transfer to the environment is negligible in comparison to heat transfer through the metal rods, the temperature will rise uniformly from one end to another regardless of material thermal conductivity, see fig. 2. The distribution of temperature will be the same in all cases. The condition of negligible losses is being met better, the shorter are the rods, and the bigger is their cross-section and thermal conductivity.

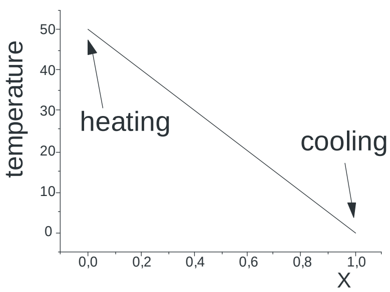

Fig. 2: Temperature distribution with negligible heat losses

2) Heating without cooling, significant heat losses, stabilized state

If heat losses are not negligible, the distribution of temperature is given by the thermal conductivity coefficient (see fig. 3). In an ideal case of a rod so long that its other end is at room temperature, the distribution of temperature is decreasing exponentially according to the formula [1]

$$t = t_o + (t_1 - t_o)\exp\left(-\sqrt{\frac{\alpha P}{\lambda S}}\,x\right),$$

where t_1 is temperature of the heated end, t_o is environment temperature, S is the cross-sectional area, P the lateral surface, α is the coefficient describing the cooling of the rod and λ the coefficient of thermal conductivity.

For a material having high thermal conductivity the point of a given temperature is a farther distance from the heated end of the rod. Also, at any point of the rod the gradient of temperature is lower than for a material having lower thermal conductivity. Both of these features can be visualized easily by the thermosensitive sheet.

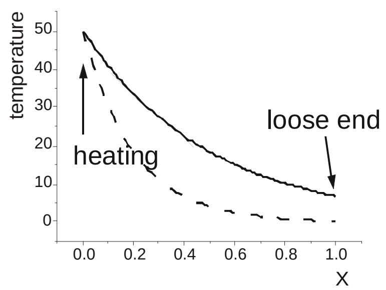

Fig.3: Distribution of temperature in a rod when considering heat losses. Full line – higher thermal conductivity, dashed line – lower thermal conductivity

3) Heating without cooling, non-stabilized state

Both previous cases suppose a stabilized state. However, if the temperature of the individual parts of the system changes in time, the temperature distribution is given not only by the material's thermal conductivity but also by its heat capacity and density. We have to take into account also the heating of each element ΔV according to the equation

$$\Delta T = \frac{Q}{c\rho\Delta V},$$

where Q is supplied heat, c specific heat capacity, and ρ density. It can be derived that the distribution of temperature in the non-stabilized state is given by the quantity

$$\Lambda = \frac{\lambda}{c\rho},$$

called temperature conductivity. When comparing different materials we can get a different result than we would get in a stabilized state; see chart.

material	λ W/(m·K)	ρ kg/m^3	c J/(kg·K)	Λ m^2/s
copper	395	9000	390	$1{,}1\cdot10^{-4}$
duralumin	165	2800	890	$6{,}6\cdot10^{-5}$
iron	60	7800	500	$1{,}5\cdot10^{-5}$

Drawing heat

The thermosensitive sheets can be also used to visualize invisible infrared radiation. This is an alternate method to the use of an amateur camcorder [2]. Let us describe a few possible experimental arrangements.

Infrared shadow of a hand

Place the sheet near to an intense heat source. You can use e.g. a vertically placed electric cooker. In this case the suitable distance between the sheet and heat source would be about 1 m. The infrared radiation heats the sheet and it changes its colour. If we place our hand in front of the sheet, its shadow image appears.

Visualising a heat source

It is possible to visualize an intensive source of heat – an electric cooker – on the sheet directly using a lens. The experimental layout is common for optic demonstrations (see fig. 4).

This experiment is at the edge of thermosensitive sheet capabilities. To make the effect enough clear and convincing we have to obey a few rules.

1) Use a lens having a large diameter and short focal length. Though such lenses suffer from significant spherical aberration, it is not important for our purpose. Due to the thermal conductivity of the sheet we cannot expect a sharp image anyway. We have had good results with a lens having diameter $D = 15$ cm and focal length $f = 25$ cm.

2) A spiral cooker is better that a hotplate cooker. It is necessary to fix the cooker firmly in a vertical position and warm it up to maximum temperature.

3) You can get better results when the object distance is somewhat bigger than the image distance. The image size would be reduced and intensity of the IR radiation would be higher.

4) It is necessary to shield the radiation coming around the lens frame. A suitable lens hood can be made out of cardboard.

5) To make the demonstration convincing it is good to use an object having some kind of inner structure. This is another reason for using a spiral cooker with a hole in the centre. If we shade a part of the cooker by a metal plate (shielding plate on fig. 4)

we can observe this shield also on the image of the cooker. Students can be easily convinced by this demonstration that this is real optical imaging resulting in an inverted image. We can also point out the difference from the previously described shade projection.

6) It is crucial to build the experiment according to the thin lens formula. To fulfil this requirement, use a light source instead of the cooker and find suitable positions of the lens and the sheet. Then swap the light source for the cooker and do the experiment.

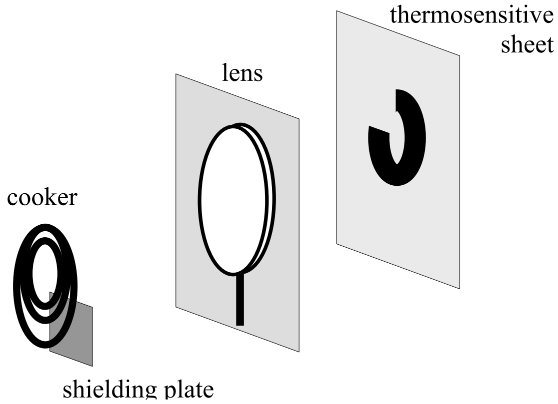

Fig. 4: Projection of a cooker hotplate in IR range by a converging lens

The light-bulb filament in IR range

The image of the cooker hotplate in the previous demonstration is rather low-contrast. Also manipulation with a hot cooker can be source of a risk. There is a different setting to demonstrate the projection of IR rays. The source of heat could be a transparent light-bulb (about 150 W), however we have to filter out the visible light to ensure that only the IR rays form the image on the thermosensitive sheet. The best results are received using a silicone plate polished on both sides – it is non-transparent for visible light but IR rays can pass through [2]. The experiment can still be shown, however, using common absorption filters or even using a black polyethylene sheet.

Focus the image of the light-bulb filament onto a white screen, insert the absorption filter into the track of light and then fix a thermosensitive sheet onto the screen. The image should be formed on the sheet in short time. It is necessary to test in advance whether the IR radiation intensity will be sufficient and possibly reduce the distances between the elements. Using a lens of focal length f = 10 cm and diameter D = 5 cm together with the IR absorbing plate from Si you can get a reasonable image even at image distances up to 50 cm; using a black PE sheet the distances have to be lowered.

References

[1] www.physics.muni.cz/kof/vyuka/prfyz11.pdf
[2] Z. Bochníček, *Amatérská videokamera jako detektor infračerveného záření*. In: Sborník konference Veletrh nápadů učitelů fyziky 10. Ed. Dvořák L. Prometheus Praha 2005. s. 38-42.