Thermal sensitive foils in physics experiments

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Abstract

The paper describes a set of physics demonstration experiments where thermal sensitive foils are used for the detection of two dimensional distribution of temperature. The method is used for the demonstration of thermal conductivity, temperature change in adiabatic processes, distribution of electromagnetic radiation in a microwave oven and detection of resonant acoustic oscillations in a Rubens' tube.

Introduction

Thermal sensitive foils (TSF) also called reversible temperature labels are commonly used for approximate temperature measurements. They are based on liquid crystal technology and they change colour according to temperature. The change of colour is restricted to a relatively narrow temperature scale, only a few degrees centigrade and that is why they can serve as quite sensitive and fast thermometers. They are also commercially available in large sizes at a convenient price (approx 25 EUR per 12’’ x 12’’ sheet) and they can serve as fast and simple detectors for two dimensional distribution of temperature.

Thermal sensitive foils are primarily intended for the measurement of temperature so their usage in thermodynamic experiments is obvious. But also other physical properties can be transformed into a temperature and detected with TSF [1].

Thermal conductivity 1, heat tracer

This is a very simple experiment which is convenient even for small children. A human hand is placed onto the table for about ten seconds. Immediately after the hand is removed, a TSF is put in the same place on the table. In a short time the TSF reveals a thermal image of the hand, see figure 1.

There are a few requirements that must be fulfilled for the success of this experiment. The temperature of the hand must be significantly higher than the room temperature. A cold hand or very warm weather spoils the result. The temperature range of the foil must be properly selected and only tables made from certain materials are suitable for this experiment, see below.

Although, at the first sight, this experiment looks like it is only just for fun, it has an interesting physical background which also makes it beneficial for higher levels of physics education. The result of the experiment is strongly influenced by the thermal conductivity and heat capacity of the underlying surface. For instance with a metal surface the thermal image is smudged by the high thermal conductivity of metal. On the other hand when a styrofoam plate is used, practically no heating of the TSF can be observed. Very low thermal conductivity and heat capacity decrease the amount of accumulated heat in the styrofoam plate so there is not enough energy to warm the TSF. Thus the medium values of thermal conductivity are the optimal for a successful experiment. Very good results can be obtained with laminated hardboard; pure wood is worse.

In this and the following experiments the correct choice of TSF temperature range is crucial. As stated above the temperature range is quite narrow and during the year, or even during the day, temperatures in the classroom can change significantly. For this reason a set of TSFs with different temperature ranges is necessary to get reliable results. Two foils with ranges 20ºC - 25ºC and 25ºC - 30ºC are the minimal set.

When the room temperature is close to 30ºC the experiment will probably fail. On that occasion a reciprocal arrangement can be tried when we use a cold hand on a warm table. The hand can be cooled down with cold water or a mixture of water and ice.

Figure 1 Heat trace of a human hand.

Thermal conductivity 2, heat race

TSF can be used for an illustrative visualization of thermal conductivity in metals. The foil is fixed onto a metal rod with a rectangular cross section. One end of the rod is heated and the other end can be left free or cooled. This modifies the different boundary conditions for heat conduction.

For the instructive experiment at least two rods of different materials should be employed at the same time to compare different thermal conductivities. For this simple demonstration one end of two rods is heated with a power resistor (figure 2a). In a simpler variant, the rods can be heated with hot water (figure 2b). In both cases the active parts of the rods must be roughly horizontal. In a vertical arrangement heat transfer would be influenced by the convection of air.

(a) (b)

Figure 2 Two metal rods heated with a power resistor (a) or hot water (b).

The time evolution of temperature distribution in a non-stationary state is determined by the so called diffusion equation

$$\frac{\partial t(x,\tau)}{\partial \tau} = D\frac{\partial^2 t(x,\tau)}{\partial x^2}, \qquad (1)$$

where t is temperature, τ time and D diffusion coefficient which is given by the equation

$$D = \frac{\lambda}{c \cdot \rho}, \qquad (2)$$

where λ is the coefficient of thermal conductivity, c specific heat capacity and ρ density. The temperature distribution is not given by the coefficient of thermal conductivity itself, but specific heat and density also play a role. It can be easily understood. The change of the temperature of any volume is not only given by the heat exchange (which is determined by λ), but it is also inversely proportional to the mass heat capacity of this element's volume (given by product $c \cdot \rho$).

In some simple cases the equation (1) can be solved analytically. The experiment depicted in Fig. 2 can by modelled by a semi-infinite rod with one end kept at a constant elevated temperature. In this case the solution of the equation (1) can be expressed as

$$t(x,\tau) = (t_m - t_o)\operatorname{erfc}\left[\frac{x}{2\sqrt{D\tau}}\right] + t_o \qquad (3)$$

where t_m is the temperature at the heated end of the rod and t_o is the ambient temperature, erfc denotes complementary error function. The quantity

$$\Lambda = \sqrt{D\tau} = \sqrt{\frac{\lambda}{\rho c}\tau} \qquad (4)$$

is the so called diffusion length which can serve as a parameter for the qualitative comparison of thermal conductivity of different materials. The ratio of the distances between two points with given temperatures localized in different materials should be equal to the ratio of equivalent diffusion lengths.
The graph of the temperature distribution according to equation (3) is in figure 3. Both curves were calculated for a diffusion time of 60s and for thermal parameters of copper (red line) and steel (grey line). The corresponding diffusion lengths are depicted in the figure. The diffusion length of copper is about three times larger than that of steel (see also table 1).

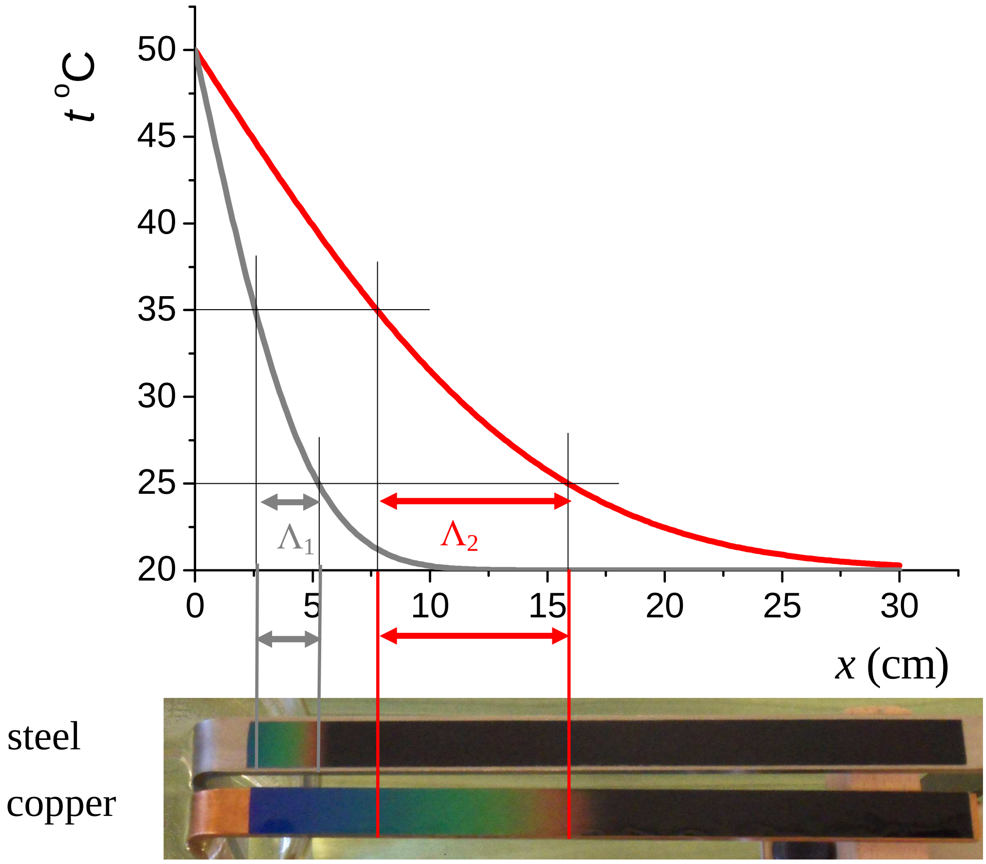


Figure 3 The theoretical temperature distribution in copper (red) and steel (grey) rods compared with the distribution experimentally detected using TSF.

On the lower part of figure 3 is an example of the real temperature distribution on copper and steel rods as visualized by TSF. The highlighted ranges approximately correspond to the same temperature intervals and their lengths have the ratio 1/3 which is in good agreement with the graph in figure 3 and theoretical values from table 1[1].

material	λ **Wm^{-1}K^{-1}**	c **Jkg^{-1}K^{-1}**	ρ **kgm^{-3}**	D **m^{2}s^{-1}**	Λ **cm**
copper	386	383	8940	$1{,}13\cdot10^{-4}$	8,2
iron	80	450	7860	$0{,}23\cdot10^{-4}$	3,7
steel (1% carbon)	43	450	8000	$0{,}12\cdot10^{-4}$	2,7
stainless steel	16	450	8000	$0.044\cdot10^{-4}$	1,6
aluminium	237	896	2700	$0{,}98\cdot10^{-4}$	7,7

Table 1 Thermal properties of selected materials. Diffusion lengths are calculated for time τ = 60s.

[1] The coloured part on TSF does not correspond to the diffusion length labeled above and highlighted temperature ranges on the metal rods do not correspond to the temperature interval 10°C as could be interpreted from figure 3. The equivalent distances should only be compared relatively.

It has to be emphasized that the thermal conductivity strongly depends on the concentration of impurities which are present in the material. The real conductivities of common commercial metallurgical materials can be significantly different from the tabular values of pure metals.

Temperature changes at adiabatic processes

It is well known that in adiabatic compression the temperature of the gas rises and in expansion drops. This can be experimentally proved by direct measurement of the gas temperature. When we use a standard thermometer gauge, the pressure change must be quite large because the heat capacity of air is very low. A TSF thermometer can have a small heat capacity and be sensitive for significantly smaller pressure changes. Moreover this thermometer is very simple and cheap and thus many copies of the experimental equipment can be made and distributed throughout the class.

The temperature changes are detected with a small piece of TSF. Because room temperature is mostly a few degrees above 20ºC, TSF with the temperature range 25ºC - 30ºC is optimal. To obtain the smallest heat capacity it is necessary to remove both the cover paper and sticky tape from back of the foil. A piece of foil is then fixed to a wooden skewer which is glued to a PET bottle cap, see figure 4. The use of a glue gun is recommended for this purpose.
The bottle is sealed with the cap. By rapidly squeezing the bottle by hand the temperature grows due to adiabatic compression and the TSF changes its colour.

The temperature change in this process can be estimated from ideal gas law which leads to the equation

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2} \qquad (5)$$

and from the equation for adiabatic process

$$p_1 V_1^{\kappa} = p_2 V_2^{\kappa}. \qquad (6)$$

Subscripts "1" and "2" denote initial and final state of the gas respectively. From these two equations we easily get

$$T_2 = T_1 \left(\frac{p_2}{p_1} \right)^{\frac{\kappa - 1}{\kappa}}. \qquad (7)$$

By pressing the bottle by hand with the highest possible force, the final pressure in the bottle can reach $1.5 \cdot 10^5$ Pa. In this case an ideal adiabatic process leads to an increase of temperature from 300K up to 337K. The real process is not adiabatic and temperature growth is smaller, but the real temperature change is large enough for TSF to change colour significantly. If the initial temperature of the foil is set to the low end of the TSF temperature range when the colour of the foil should start to turn grey, (e. g. by heating the bottle in the hand) the pressure increase up to $1.15 \cdot 10^5$ Pa is sufficient to change the colour. And this pressure can be reached by a small child.

Figure 4 Equipment required for the demonstration of heating in adiabatic compression.

Distribution of electromagnetic radiation in microwave oven

The inhomogeneous distribution of an electromagnetic field in a microwave oven is frequently demonstrated using absorption in food: chocolate, marshmallow, bread etc. TSF can easily visualize this over a large area and, as opposed to food, usage of the foil is repeatable and free of charge.

When TSF is placed into a microwave oven and the oven is switched on for a few seconds, the foil is heated inhomogeneously because the absorbed energy is proportional to the square of the magnitude of the electric field. Thus the distribution of the electric field, in the cut plane defined by the foil's position, can be visualized, see figure 5.

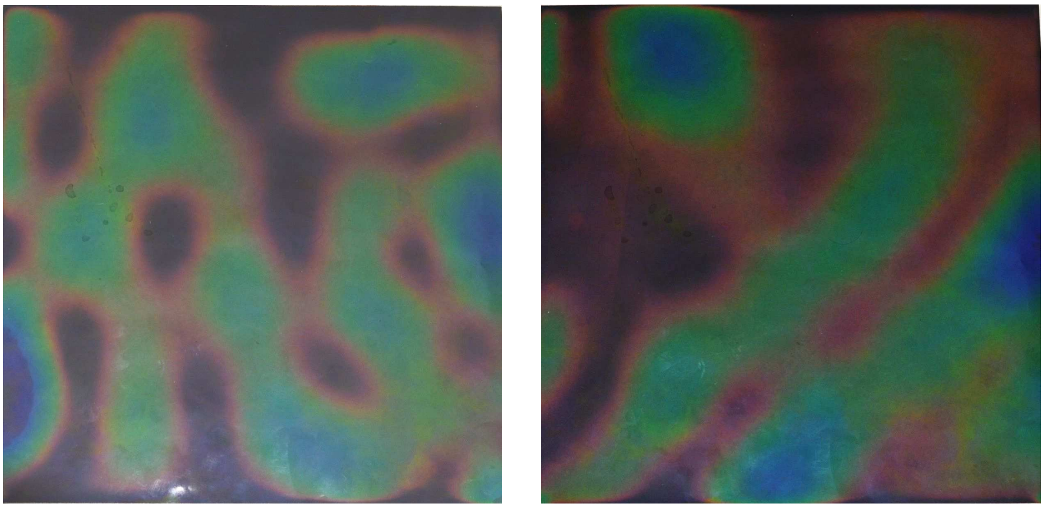


Figure 5 The examples of the distribution of absorbed microwave power in a MW oven.

This experiment is supposed to be a simple method of how to measure the speed of light (microwave radiation in this case, of course). Many such measurements can be found on the internet. This method is based on the assumption that there is a standing wave in a microwave oven cavity and the distance between two detected hot spots must be half of the wavelength. From the known frequency of microwave radiation (usually 2.45 GHz) the speed of light should be easily calculated using the formula

$$c = \lambda f. \tag{8}$$

But this is not correct. The distribution of an electric field in a 3D cavity is rather complicated and the idea of wave resonance in a one dimensional string simply cannot be applied to this case. Figure 6 shows an example of the absorbed power density distribution in (2,4,1) mode corresponding to frequency 2,45 GHz [2,3]. The calculation was based on the resonant cavity approximation and it does not take into account the presence of a waveguide from the magnetron, absorbing media in the oven (food) and the fact that the real electric field is a superposition of different modes. But even in this very simplified case there is no observable distance between spots that are equal to 6 cm as it is predicted from the simple one dimensional model. So this method can provide only a very rough estimation of the speed of light.

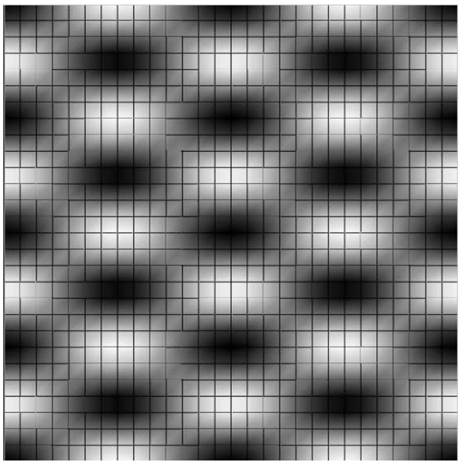


Figure 6 Power density distribution of an electric field in the cavity of a MW oven. Theoretical calculation for (2,4,1) mode. The distance of neighbouring gridlines is 1 cm.

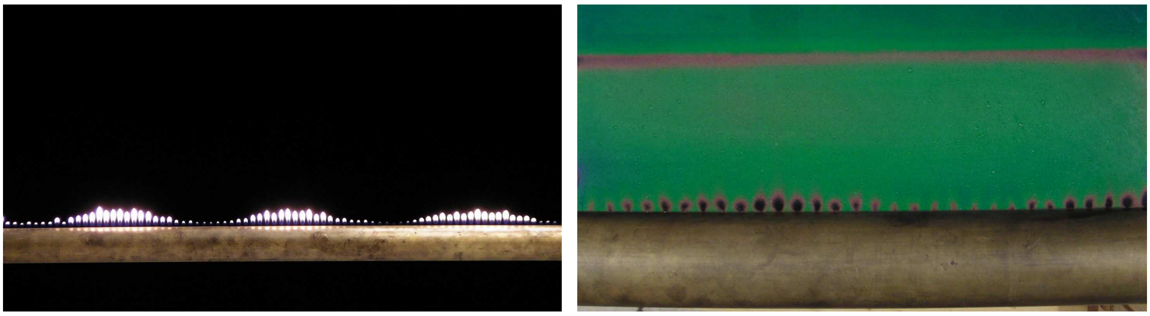
Rubens' tube

A Rubens' tube, also known as a flame tube, is an apparatus which, similar to Kundt's tube, demonstrates acoustic standing waves in a long pipe. The Rubens' tube pipe is filled with a flammable gas which leaks from the perforations along the upper side of the tube. When a standing acoustic wave is created with a loudspeaker attached to one end of the tube, the distribution of the amplitudes of the acoustic pressure is visualized by the flames above the tube’s perforations. The antinodes of acoustic pressure correspond to the maximal height of flames, see figure. 7 (a).

Thermal sensitive foils can visualize standing waves in a Rubens' tube more safely without the use of highly flammable gas. TSF is fixed tangentially along the tube perforations and the experiment can be realized in two ways.

(1) The Rubens' tube is continuously filled with warm air. TSF is preferentially heated in antinodes of acoustic pressure.

(2) TSF is covered with tiny droplets of water. Air stream oscillations are biggest at the antinodes of acoustic pressure and water is predominantly evaporated at these points. The evaporation cools down the TSF and the distribution of nodes and antinodes is revealed, see figure 7 (b).



(a) (b)

Figure 7 The distribution of nodes and antinodes in a Rubens' tube visualized by flames (a) and TSF (b).

Conclusion

Thermal sensitive foils are valuable devices which can be used in demonstration experiments in different fields of physics. The experiments are mostly qualitative but very illustrative and can be employed at all levels of science education, from elementary schools to universities.

References

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[2] Michael Vollmer 2004 Physics of the microwave oven *Phys. Educ.* **39** 74
[3] http://www.wensh.net/archive.php/topic/1527.html