Emittance of hot bodies (Leslie cube) (Item No.: P2350400)

Curricular Relevance

Area of Expertise: Physics
Education Level: University
Topic: Thermodynamics
Subtopic: Thermal Properties and Processes
Experiment: Emittance of hot bodies (Leslie cube)

Difficulty	Preparation Time	Execution Time	Recommended Group Size
Intermediate	10 Minutes	10 Minutes	2 Students

Additional Requirements:

- Water

Experiment Variations:

Keywords:

Thermal radiation and emittance, Kirchhoff's law of thermal radiation, Leslie's cube, Black and grey body

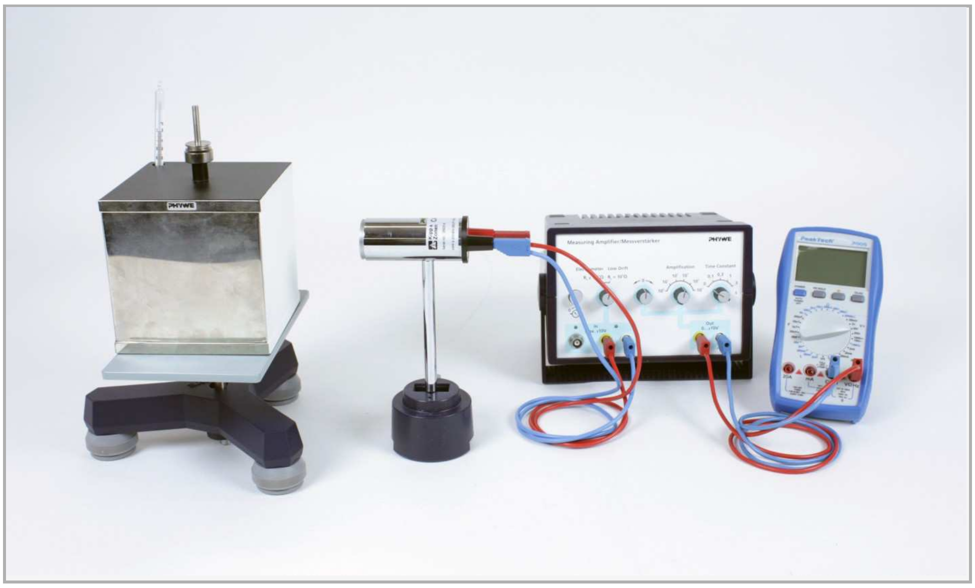
Task and equipment

Introduction

Principle
Thermal radiation can be measured at all surfaces as long as their temperature differs from that of the surrounding. Therefore it applies that the hotter an object is, the more radiation it emits. Also the surface colour influences the behaviour: dark surfaces emit more thermal radiation than light ones. An example for application of this effect is a heat sink (see Fig. on the right) which is often coated with a black layer to emit more thermal radiation.

Educational objective

1. It should be learned in the experiment that all bodies emit thermal radiation, and the intensity of radiation depends on the texture of the object's surface. It should also be found out that a dull surface emits more thermal radiation than a polished surface does.
2. It should be experimentally determined that, according to Kirchhoff's law of thermal radiation, the intensity of the radiation is proportional to the fourth power of the absolute temperature.



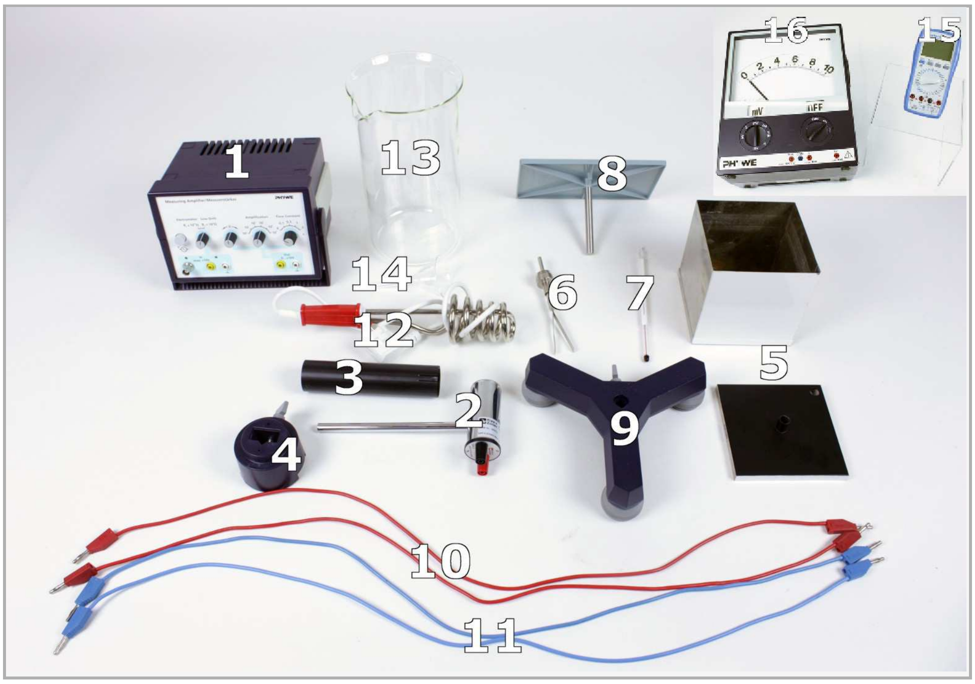
Safety instructions

CAUTION: Do not touch the hot cube with bare hands!

Equipment

Position No.	Material	Order No.	Quantity
1	PHYWE Universal measuring amplifier	13626-93	1
2	Thermopile, Moll type	08479-00	1
3	Shielding tube, for 08479-00	08479-01	1
4	Barrel base PHYWE	02006-55	1
5	Leslie radiation cube	04555-00	1
6	Stirrer for leslie cube	04555-01	1
7	Students thermometer,-10...+110°C, l = 180 mm	38005-02	1
8	Table top on rod	08060-00	1
9	Tripod base PHYWE	02002-55	1
10	Connecting cord, 32 A, 750 mm, red	07362-01	2
11	Connecting cord, 32 A, 750 mm, blue	07362-04	2
12	Immersion heater,1000W,220-250V	04020-93	1
13	Glass beaker DURAN®, tall, 2000 ml	36010-00	1
14	Funnel, glass, top dia. 55 mm	34457-00	1
15	Digital multimeter 2005	07129-00	1
	It is possible to use an alternative voltmeter:		
16	Multimeter ADM 2, demo., analogue (Experiment variant P0454351)	13820-01	1



Task

Set-up and procedure

Set-up

Set up the experiment as shown in Fig. 1:

- Connect the Moll-type thermopile to the input of the measuring amplifier and the voltmeter to the output of the measuring amplifier.
- Set the measuring amplifier to “low drift” mode. This way, a low input impedance is used so that the temperature dependent drifting of the amplifier is low enough to determine voltages in the microvolt range.
- Choose an amplification that is suitable to detect the measured voltage with the voltmeter (10–1000 µV are to be expected as input signal, an amplification of e.g. 10^3 gives output voltages between 10 mV and 1 V).
- Place the Leslie cube in an appropriate distance (3–10 cm) to the thermopile. The cube is set in the centre onto the tabletop that is put in a tripod base. Afterwards, the thermometer and the stirrer are inserted through the respective openings in the cube's lid.

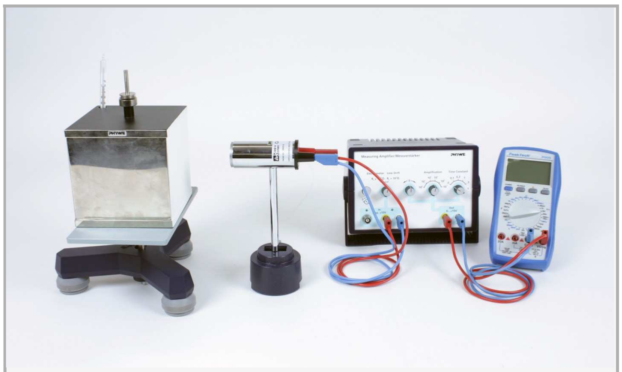


Fig. 1

Notes concerning the set-up:
The experiment's aim is to determine the emittance of hot bodies. Therefore, the radiant intensity of four different cube surfaces is investigated depending on each surface's temperature. Because the expectable thermoelectric voltage is relatively low, these notes should be followed:

- Noise signals (e.g. coming from light sources) should be avoided. It is recommended to darken the lab room. Alternatively, the shielding tube (order no. 08479-01) can be attached to the thermopile to suppress noise.
- The distance between thermopile and cube surface should be kept constant for each series of measurements. Fig. 2 shows exemplary the measured thermoelectric voltage V_{th} for the black surface depending on the distance.
- Because the radiant intensity depends on the temperature of the cube's surface, the water inside the cube should be stirred before each recording to obtain an optimal temperature balance.
- The opening of the thermopile should be aligned perpendicularly to the investigated cube surface. To protect the measured values from interfering influences, the cube should not be touched any more during the measurement series.

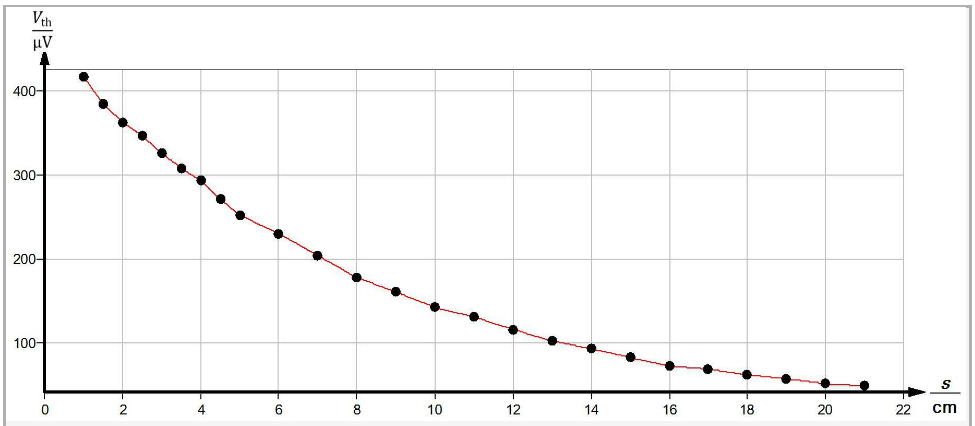


Fig. 2: Distance dependency of the black surface's emittance at a temperature ϑ = 93 °C

Procedure

In this experiment, the (temperature dependent) thermal radiation has to be determined for each of the four cube surfaces, which differ in their textures.

1. Determination of the thermoelectric voltage at a constant temperature:

- At the beginning of the experiment, take the room temperature T_0 that is needed for the evaluation.
- Afterwards, fill the Leslie cube with boiling water. For this purpose, use a large beaker and heat water in it by use of the immersion heater. Use the funnel to transfer the boiling water to the Leslie cube (volume approx. 1.4 l). It is also possible to pour the water directly into the cube when its lid is opened.
- Now measure the thermoelectric voltage V_{th} in a constant distance for all the four surfaces at a stable temperature. For this purpose, record the (amplified) voltage of the voltmeter for the first surface. Afterwards, carefully rotate the tabletop 90° to measure the radiation of the second surface, and so on. **CAUTION:** Do not touch the hot cube with bare hands! Check that the cube is aligned perpendicular to the thermopile. Be aware that the four measurements have to be executed in a short time to keep the cube at an almost steady temperature.

2. Determination of the temperature dependence of the thermoelectric voltage:

- If the water is not hot enough any more (below 90 °C), pour it out of the cube and refill the cube with boiling water. Align the cube's side, whose radiation should be determined first, perpendicular to the thermopile.
- During the cooling of the water, record the voltmeter voltage and the corresponding water temperature for the investigated surface in convenient intervals (e.g. every 5 °C or every 30 s). To maintain a balanced water temperature, use the stirrer regularly.
- After investigating the radiation of the first surface (e.g. the black one), remove the cooled water from the cube. Reposition the cube on the tabletop so that the next surface (e.g. the white one) can be measured. Please regard that the surface is centred on the tabletop and perpendicular to the thermopile, again.
- Proceed as before to measure thermoelectric voltage and temperature of the other three cube surfaces. It is recommended to perform each measurement series in a water temperature range from about 100 °C down to 50 °C (the heat dissipation of the polished surface is quite low).
- We advise to determine the room temperature T_0 before each measurement series, anew.

Note:
It is also possible to collect the data of the temperature dependence measurement in a fast way by recording all four series at once. After each measured value, rotate the tabletop 90° to the next surface as done in the first part of the experiment. This way, only one cooling cycle has to be investigated. Be aware that the accuracy of the measurement could possibly decrease because of the frequent repositioning of the respective surface to the thermopile

Results and evaluation

Results

Theory:
Every hot body emits thermal radiation. The emittance does not only depend on the temperature, but also on the surface texture of the object. Kirchhoff's law of thermal radiation implies that the more radiation a body can absorb, the more it is able to emit. In this experiment, a Leslie cube with four differently textured surfaces is used. Thereby, each surface A (with absolute temperature T) emits radiation with the power

$$P_{\text{surface}} = \epsilon \cdot \sigma \cdot A \cdot T^4,$$

with the emissivity ε as a weighting factor of the respective surface (0 ≤ ε ≤ 1) and σ as the Stefan-Boltzmann constant. Further it has to be considered that the cube also absorbs radiation from its surroundings (with the temperature T_0) with the power

$$P_{\text{ambient}} = \epsilon \cdot \sigma \cdot A \cdot T_0^4.$$

Because of this, not the total emittance is measured in this experiment, but the difference between emitted power P_{surface} and irradiation power P_{ambient}. For the difference ΔP follows:

$$\Delta P = P_{\text{surface}} - P_{\text{ambient}} = \epsilon \cdot \sigma \cdot A \cdot (T^4 - T_0^4).$$

This difference ΔP correlates with the power, which a body with the temperature T releases to its surroundings with temperature T_0 by thermal radiation.
Using a Moll-type thermopile, this thermal radiation can be detected by measuring the thermoelectric voltage drop V_{th} of the thermopile, which is proportional to the radiant power ΔP of the cube and therefore proportional to $T^4 - T_0^4$:

$$V_{\text{th}} \propto T^4 - T_0^4.$$

Results:
Already the first part of the experiment shows that the four different cube surfaces possess a different emittance, although they consist of the same material (brass). The black and the white coated surfaces cause a similarly high thermoelectric voltage, whereas the uncoated sides (dull and polished) show significantly lower values (see Tab. 1). Thus, the texture of the surface has a huge impact on the emitted thermal radiation, even when neglecting the influence of the temperature. Thus, the emissivity ε is an intrinsic property of the body's texture.

Table 1: Comparing the measured data in a distance of 5 cm at T = 366 K and T_0 = 293 K.

surface	**thermoelectric voltage V_{th} / µV**
black	254
white	226
dull	42
polished	26

Evaluation

For a graphic evaluation of the measured data, the thermoelectric voltage has to be plotted against $T^4 - T_0^4$ for each cube surface, respectively. Afterwards, the results can be compared among one another. This diagram shows that for a constant ambient temperature T_0, the emitted radiation increases linear to the fourth power of the absolute surface temperature T for each side of the cube. This means that the higher the surface temperature, the higher the measured voltage using the thermopile is. Fig. 3 illustrates this dependency for all four surfaces. The insights of the first experimental part are hereby confirmed.

Comparing the measurements of the black and the white surface (black and green lines in Fig. 3), one can see that the emittance depends not only on the temperature, but also on the texture of the surface. The determined results reveal that a darker surface radiates with a higher power than a lighter surface does. This finding confirms Kirchhoff's law of thermal radiation, because a black surface absorbs more thermal radiation than a white one does.

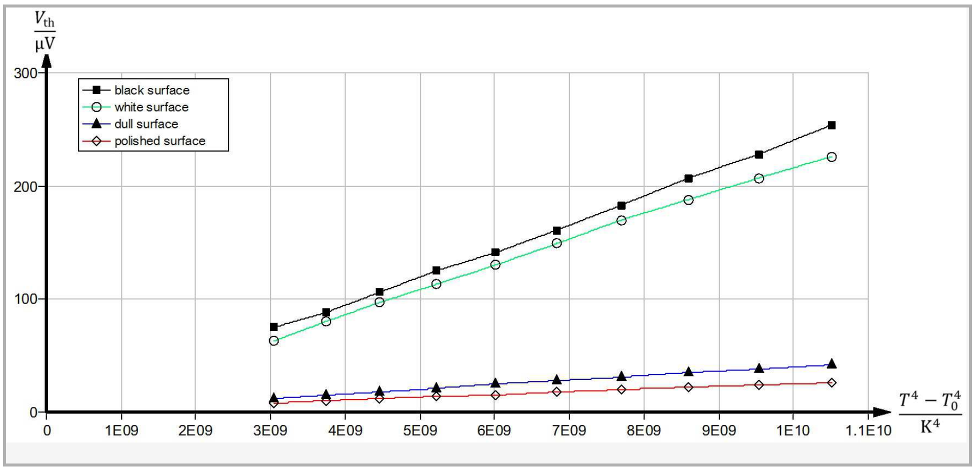


Fig. 3: Diagram of the measured thermoelectric voltage V_{th} as a function of $T^4 - T_0^4$ for all four surfaces in a distance of 5 cm.

But, the emittance of the black surface is very similar to that of the white surface in the investigated temperature range. This can be explained by the fact that bodies emit thermal radiation with a wavelength in the infra-red region for these temperatures. Therefore, the colours of the cube's surfaces (which are in the visible wavelength range) are insignificant for thermal radiation in the investigated temperature range, and there is no considerable difference between the black and the white surface. Nevertheless, the black coated surface shows a slightly increased emittance, because it additionally absorbs more visible light than the white coated surface does, which it emits again according to Kirchhoff's law of thermal radiation.

From investigating and comparing the radiation of the dull and the polished surface (blue and red lines in Fig. 3), it can be derived that a body with a more shiny surface emits less thermal radiation.
These results harmonize with Kirchhoff's law of thermal radiation. According to that, the emittance of the cube's surface is the product of the material specific emissivity and the spectral emittance of a black body. Therefore, emission and absorption of an object are identical. Because the dull surface absorbs more radiation than the polished one, it also emits more than the other.

The results of the measurements lead to the conclusion that all investigated surfaces are so-called grey bodies. A grey body can be recognized by its emittance, which is lower by a certain factor (emissivity ε) compared with a black body (ε = 1). Following the Stefan-Boltzmann law, the radiated power of a black body is proportional to the fourth power of the absolute temperature. Because the measured thermoelectric voltages V_{th} in Fig. 3 also show a linear behaviour when plotted against the fourth power of the absolute temperature, the surfaces of the Leslie cube have to be grey bodies.