

Confirming the laws of radiation with Leslie's cube

Objects of the experiment

- Conducting relative measurements of the radiant intensity of various cube faces as a function of their temperature using a *Moll's* thermopile.
- Graphing the relationship between the radiant intensity and the absolute temperature of the various cube faces.
- Confirming *Kirchhoff's* law of radiation.
- Identifying the individual cube faces as "gray bodies" to confirm the *Stefan-Boltzmann* law in the measured temperature range

Principles

All bodies radiate heat. The intensity of this thermally excited electromagnetic radiation depends on the surface characteristics of the body and increases with the temperature of the body.

In addition, the body also absorbs electromagnetic radiation. The amount of the incident radiation which is absorbed also depends on the characteristics of its surfaces. According to *Kirchhoff*, at a given temperature, the more radiation a body emits, the better it can absorb radiant energy. More precisely,

$$\varepsilon = \alpha \quad (I)$$

where the emissivity ε is defined as the ratio

$$\varepsilon = \frac{M}{M_B} \quad (II)$$

(M : radiant exitance of the body,

M_B : radiant exitance of a black body)

and the absorption factor α is

$$\alpha = \frac{\Phi}{\Phi_0} \quad (III)$$

Φ : radiant power absorbed by body

Φ_0 : total radiant power incident on body

A black body is a body which completely absorbs all incident electromagnetic radiation. It has the maximum possible absorption factor, and thus, at a given temperature, the highest possible emissivity as well. All other bodies absorb and radiate less radiant flux than a black body.

The *Stefan-Boltzmann* law states that the radiant exitance M_B of a black body is given by the relation

$$M_B = \sigma \cdot T^4 \quad (IV)$$

($\sigma = 5.67 \cdot 10^{-8} \frac{W}{m^2 K^4}$: *Stefan-Boltzmann* constant)

The radiation of a black body is not distributed uniformly across all wavelengths, but rather has a characteristic spectral distribution. In the case of gray bodies, the spectral distribution corresponds to that of a black body, but with a lower emissivity ε and absorption factor α . Their radiant exitance is also linearly dependent on the absolute temperature T raised to the fourth power; in other words,

$$M = \varepsilon \cdot \sigma \cdot T^4 \quad (V)$$

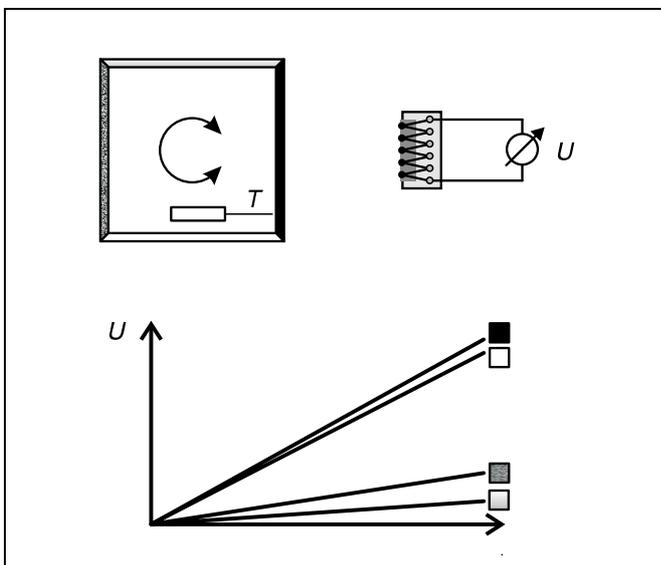
At the same time, the body absorbs radiation from its environment. Thus, we do not measure the total the radiant exitance M , but rather the radiant exitance M' *withdrawn* from the body by radiation. The radiant exitance absorbed from the environment is

$$M_0 = \varepsilon \cdot \sigma \cdot T_0^4 \quad (VI)$$

Thus,

$$M' = \varepsilon \cdot \sigma \cdot (T^4 - T_0^4) \quad (VII)$$

if the temperature of the body is equal to the ambient temperature T_0 then $M' = 0$.



Apparatus

1 Leslie's cube	389 26
1 Stirrer for Leslie's cube	389 28
1 Support for electric oven	555 84
1 Digital thermometer with one input	666 190
1 Temperature sensor, NiCr-Ni	666 193
1 Moll's thermopile	557 36
1 Microvoltmeter	532 13
1 Small optical bench	460 43
1 Large stand base, V-shape	300 01
3 Leybold multiclamps	301 01
1 Immersion heater	303 25
1 Plastic beaker, 1 l	590 06
1 Funnel, 75 mm dia., plastic	665 009

Additionally:

1 Absorbent cloth, 1 sheet of dark cardboard

Leslie's cube has four surfaces with different characteristics, and thus different emissivity values. One surface is metallic matte, one is metallic polished, one is painted white and the fourth is painted black.

In this experiment, the cube is first filled with hot water. The heat radiated by the surfaces is measured as a function of the falling temperature using a Moll's thermopile. The thermopile contains a number of thermocouples connected in series. The measuring points absorb the incident radiation almost completely, while the comparison points are at the ambient temperature. The output voltage of thermopile thus serves as a relative measure of the radiant intensity M' .

Setup*Notes:*

The intensity to be measured is very low; as a result, the measurement is extremely susceptible to interference from environmental influences:

Never touch the thermopile with your hand during the measurement.

Do not work close to the thermopile, and particularly not in front of it.

Avoid drafts and variations in room temperature during the experiment.

Avoid interfering radiation; if necessary, screen the assembly with cardboard.

Darken the room if necessary.

Interference radiation can be caused by:

*direct radiation of body heat on the thermopile,
reflection of radiation at reflecting surfaces (e.g. light-colored clothing),
radiators,
sunlight
and other light sources.*

Fig. 1 shows the experiment setup. The cube is mounted on the electric oven support, which is set up so that it can rotate; this means that the individual cube faces can be easily turned to face the thermopile. Fig. 2 shows the mounting of the electric oven support. The electric oven support can be turned

by slightly loosening the rod of the support at the Leybold multiclamp (a); the Leybold multiclamp (b) prevents the electric oven support and cube from falling.

Electric oven support and Leslie's cube:

- Set up the electric oven support and attach the Leybold multiclamp to the rod of the electric oven support, as shown in Fig. 2.
- If necessary, clean the cube with a damp cloth and plug the stirrer into the center opening on the top face of the cube.

Note: The intensity of the radiant heat decreases with the distance.

- Center the Leslie's cube on the support, so that each side of the cube is at an equal distance s from the thermopile when the electric oven support is turned during the experiment (see Fig. 1).
- Align the black cube face precisely perpendicular to the subsequent position of the thermopile and arrest the electric oven support.

Measuring instruments:*Notes:*

The glass window absorbs long-wave radiation more than short-wave radiation, and thus systematically falsifies the temperature-dependent measurement of radiant intensity.

Allow the microvoltmeter to warm up for at least 10 minutes before starting the experiment.

Switch on the microvoltmeter via the mains switch on the rear of the device.

- Set up the thermopile as shown in Fig. 1, so that the distance s between the rod of the thermopile and the Leslie's cube is about 10 cm; remove the glass window of the thermopile.
- With the rod of the thermopile arrested in place, check the individual distances between each cube face and the thermopile.
- Connect the thermopile to the microvoltmeter as shown in Fig. 1 (measuring range 10^{-4} V); make sure the red socket on the thermopile is connected to the red socket on the microvoltmeter.
- Compensate the offset by pressing the key "auto comp"; if necessary, carry out the fine adjustment using the potentiometer to set the digital display to zero (see Instruction Sheet for the microvoltmeter).
- Connect the NiCr-Ni temperature sensor to the digital thermometer and switch on the instrument (measuring range < 200 °C).

Carrying out the experiment

First:

- Read off the voltage at the microvoltmeter and the room temperature from the digital thermometer and write these values in your experiment log.
- Fill the plastic beaker with about 0.9 l water and boil the water with the immersion heater.
- Fill the hot water into the cube using the plastic funnel. Clean up any spilled water with an absorbent cloth.
- Insert the temperature sensor in the filling opening of the cube.
- Remove the hot immersion heater and plastic beaker from the experiment zone.

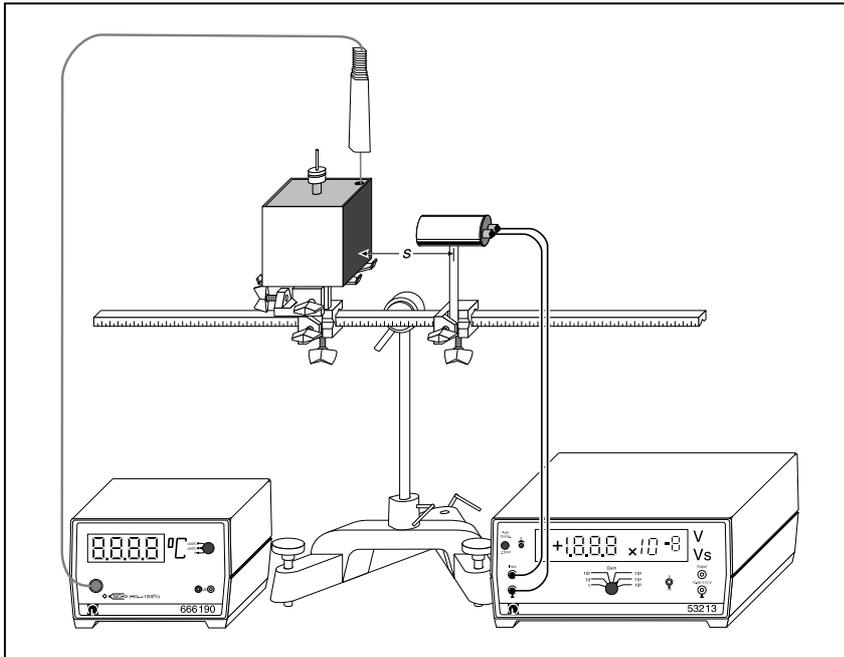


Fig. 1: Experiment setup studying the laws of radiation.

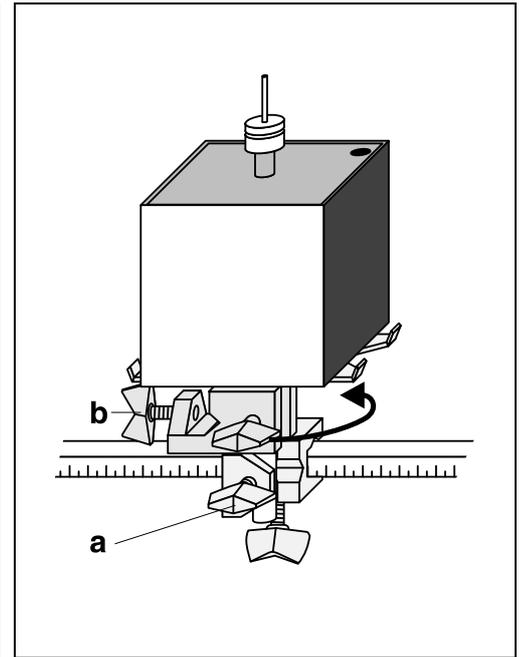


Fig. 2: Mounting the electric oven support for rotation

Notes:

As the temperature equilibrium in the cube is a decisive factor in this experiment, stir the water with the stirrer before each measurement. In the measurement, place the temperature sensor on the inside wall of the cube face currently opposite the thermopile, to measure its temperature as exactly as possible.

Do not allow the cube to slide off-center when turning it on the support, and the respective cube face should be exactly perpendicular to the direction of radiation.

Before reading off the measured values, observe the settling time of the thermopile, which can last up to one minute.

Next:

- Stir the water using the stirrer. Then read off the thermal voltage U and the temperature ϑ for the black cube face (hold the tip of the temperature sensor to the corresponding inside surface) and write these values in your experiment log.
- Loosen the rod of the support slightly by opening Leybold multiclamp (a), turn the white cube face toward the thermopile and reclamp the support.
- Stir the water using the stirrer. Then read off the thermal voltage U and the temperature ϑ for the white cube face (hold the tip of the temperature sensor to the corresponding inside surface) and write these values in your experiment log.
- Measure the values for the polished and matte metal faces in the same way.
- Repeat the measurements for each temperature drop of approx. 5° C.
- When the water reaches a temperature of 40 °C to 50 °C, remove the temperature sensor from the Leslie's cube and dry it off. Then measure the room temperature and write this value in your experiment log.
- Screen the thermopile (e. g. with dark cardboard), check the zero point of the voltmeter and write this value in your experiment log.

Measuring example and evaluation

(See table on page 4.)

Fig. 3 shows the output voltages U of the thermopile as a function of the absolute temperature T of the individual cube faces raised to the fourth power. A straight line has been fit to each set of measurement points for the individual surfaces.

If a check of the zero point of the microvoltmeter or the room temperature show greater deviations, you can correct the measured values in the experiment evaluation.

Fig. 3: Graph of the output voltages U as a function of $T^4 - T_0^4$.

Black squares: black-painted surface
 White squares: white painted surface
 Black circles: matte metal surface
 White circles: polished metal surface

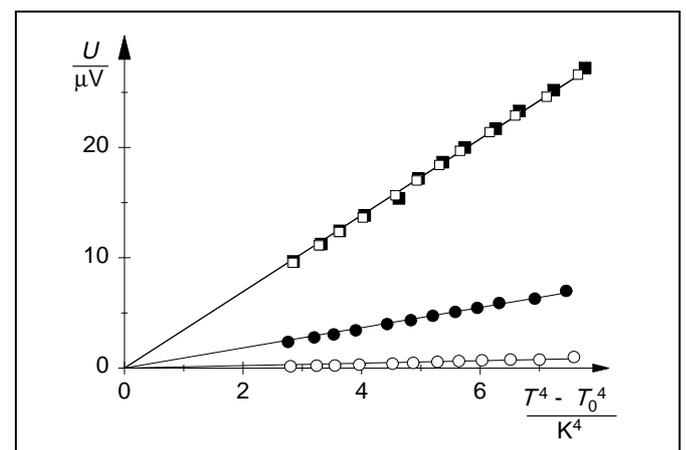


Table 1: Measured values (room temperature $\vartheta_0 = 26.4\text{ }^\circ\text{C}$).

a) Black-painted surface

ϑ $^\circ\text{C}$	T K	$\frac{T^4 - T_0^4}{\text{K}^4}$	$\frac{U}{\mu\text{V}}$
81.5	354.7	7.77	27.2
78.5	351.7	7.24	25.2
75.1	348.3	6.66	23.3
72.7	345.9	6.26	21.7
69.5	342.7	5.74	20.0
67.2	340.4	5.37	18.67
64.6	337.8	4.96	17.20
62.4	335.6	4.63	15.38
58.5	331.7	4.05	13.84
55.6	328.8	3.63	12.44
53.4	326.6	3.32	11.24
50.0	323.2	2.85	9.67

c) Polished metal surface

ϑ $^\circ\text{C}$	T K	$\frac{T^4 - T_0^4}{\text{K}^4}$	$\frac{U}{\mu\text{V}}$
80.4	353.6	7.58	1.00
77.1	350.3	7.00	0.76
74.2	347.4	6.51	0.77
71.3	344.5	6.03	0.70
68.9	342.1	5.64	0.64
66.6	339.8	5.28	0.56
64.0	337.2	4.87	0.47
61.7	334.9	4.52	0.40
57.9	331.1	3.96	0.31
55.0	328.2	3.55	0.23
52.8	326.0	3.24	0.22
49.6	322.8	2.80	0.16

b) White-painted surface

ϑ $^\circ\text{C}$	T K	$\frac{T^4 - T_0^4}{\text{K}^4}$	$\frac{U}{\mu\text{V}}$
80.8	354.0	7.65	26.6
77.8	351.0	7.12	24.6
74.7	347.9	6.59	22.9
72.1	345.3	6.16	21.4
69.0	342.2	5.66	19.7
66.8	340.0	5.31	18.42
64.4	337.6	4.93	17.00
62.0	335.2	4.57	15.66
58.3	331.5	4.02	13.65
55.5	328.7	3.62	12.34
53.1	326.3	3.28	11.13
49.9	323.1	2.84	9.55

d) Matte metal surface

ϑ $^\circ\text{C}$	T K	$\frac{T^4 - T_0^4}{\text{K}^4}$	$\frac{U}{\mu\text{V}}$
79.7	352.9	7.45	7.00
76.6	349.8	6.92	6.29
73.1	346.3	6.32	5.90
70.8	344.0	5.95	5.46
68.5	341.7	5.58	5.09
66.1	339.3	5.20	4.74
63.7	336.9	4.83	4.34
61.1	334.3	4.43	3.99
57.5	330.7	3.90	3.42
54.9	328.1	3.53	3.05
52.5	325.7	3.20	2.78
49.3	322.5	2.76	2.37

Results

The heat emission of a body depends on the characteristics of its surface.

The polished metal surface emits less heat than the matte surface. This agrees with *Kirchhoff's* law of radiation, as a polished (reflecting) surface also absorbs less.

The black-painted and the white-painted surfaces emit the most heat. Although we would suspect a different absorption factor, their emissivity is virtually the same – an apparent contradiction of *Kirchhoff's* law. However, the terms *white* and *black* refer to the visible spectral range, i.e. the wavelength between 400 and 700 nm. In contrast, the intensity maximum

of the emitted thermal radiation is in the wavelength range of about $7\text{ }\mu\text{m}$, a completely different spectral range. Here, the absorptive capacity of the white-painted and black-painted surfaces are virtually identical.

Fig. 3 shows that the measured radiant exitance increases linearly with the absolute temperature raised to the fourth power. Thus, in the measured temperature range the individual cube faces behave like gray bodies.