

Stefan-Boltzmann law: measuring the radiant intensity of a “black body” as a function of temperature

Objects of the experiment

- Conducting relative measurements of the radiant intensity of an electric oven with the black body accessory in the temperature range from 300–750 K using a *Moll's* thermopile.
- Graphing the relationship between the radiant intensity and the absolute temperature to confirm the *Stefan-Boltzmann* law.

Principles

All bodies radiate heat. The intensity of this thermally excited electromagnetic radiation increases with the temperature of the body, and is also dependent on the surface of this body. At a given wavelength, the more heat a body radiates, the better it can absorb this radiation.

A body which completely absorbs heat radiation of all wavelengths is called a *black body*. It was *Kirchhoff* who first proposed using a cavity as a virtually ideal black body. The black body has the greatest absorption factor, and thus, at a given temperature and wavelength, the highest possible emissivity as well.

The *Stefan-Boltzmann* law states that the total emitted radiation of a black body increases proportionally to the absolute temperature T raised to the fourth power. More precisely, the radiant exitance M , i.e. the total power radiated on one side of the surface with reference to the area of the radiating surface, is defined as

$$M = \sigma T^4 \quad (I)$$

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

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

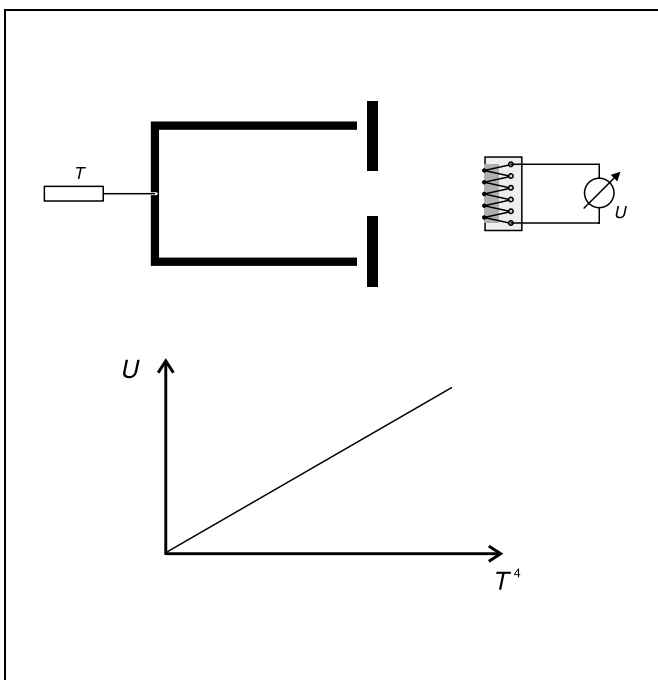
$$M_0 = \sigma T_0^4 \quad (II)$$

Therefore, it follows that

$$M' = \sigma (T^4 - T_0^4) \quad (III)$$

In this experiment, an electric oven with a black body accessory is used as the “black body”. The black body accessory consists of a burnished brass cylinder and a screen. The brass cylinder, which is sealed at one end, is slid into the electric oven and heated to the desired temperature. The screen, which can be water-cooled if necessary, is arranged in front of the electric oven, so that essentially only the thermal radiation of the burnished cylinder is measured, and not the outer wall of the hot oven. An NiCr-Ni temperature sensor is used to measure the temperature at the brass cylinder.

The thermal radiation is measured using a *Moll's* thermopile to which a microvoltmeter is connected. 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. We can thus take the output voltage of the thermopile as a relative measure of the radiant exitance M' .



Apparatus

1 Electric furnace, 230 V	555 81
1 Black body accessory	389 43
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
4 Leybold multiclips	301 01
1 Universal clamp S	666 555
Connecting leads	
<i>Additionally recommended:</i>	
1 Immersion pump for liquids	306 98
2 Silicone tubing, i.d. 7×1.5 mm, 1 m	667 194
1 Water vessel, approx. 10 l	

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.

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.

Fig. 1 shows the experiment setup.

When using water cooling:

- Attach the silicone tubing to the immersion pump and the screen so that the inflow is at the bottom hose nipple and the outflow is at the top hose nipple of the screen.
- Fill the water vessel with water and attach the immersion pump to the rim of the water vessel e.g. using the mounting clamp so that the inlet opening is completely submerged and the maximum immersion depth of 17 cm is not exceeded (see Fig. 2; refer to the Instruction Sheet for a description of another mounting possibility).

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.

Then:

- Set up the electric oven, the screen of the black body accessory and the thermopile as shown in Fig. 1 so that the rod of the thermopile is about 15 cm in front of the opening of the electric oven. The screen of the black body accessory should be positioned about 5 – 10 mm in front of the electric oven, with the metal side facing the thermopile.

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

- Remove the glass window of the thermopile.
- Connect the NiCr-Ni temperature sensor to the digital thermometer and insert it in the small central hole in the burnished brass cylinder as far as it will go.
- Mount the temperature sensor in place with the universal clamp S and switch on the digital thermometer (measuring range > 200 °C).
- Align the openings of the electric oven, the screen of the black body accessory and the thermopile so that the radiant heat is directly incident on the opening of the thermopile.
- If you are using water cooling, switch on the immersion pump now.
- 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).

Safety notes

Danger of burns: the outer wall of the electric oven can exceed 200 °C.

- Avoid burning your skin on the hot electric oven.
- Only operate the electric oven on its support.
- Read the Instruction Sheet for the electric oven carefully, and observe all instructions.

Water which penetrates the motor of the immersion pump can cause a short-circuit.

- Do not exceed an immersion depth of 17 cm.
- Do not rest the wet immersion pump on its head after operation.
- Read the Instruction Sheet for the immersion pump carefully, and observe all instructions.

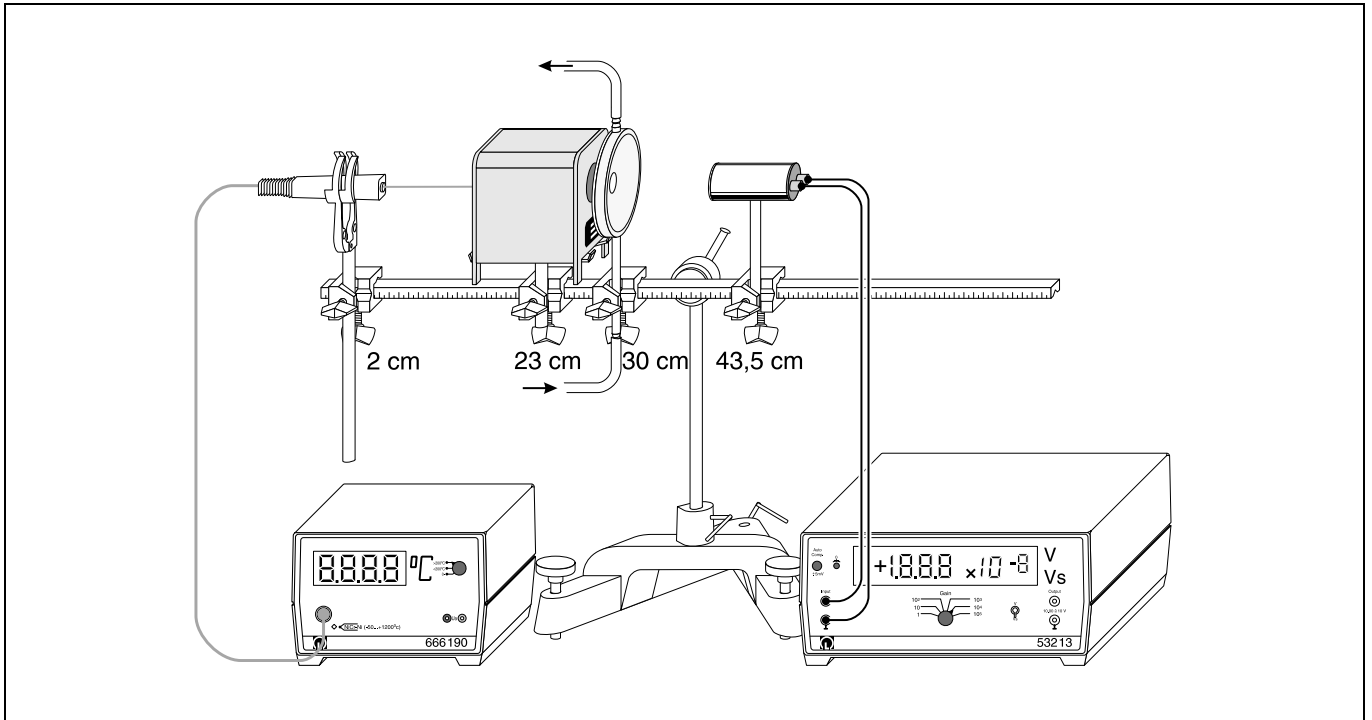
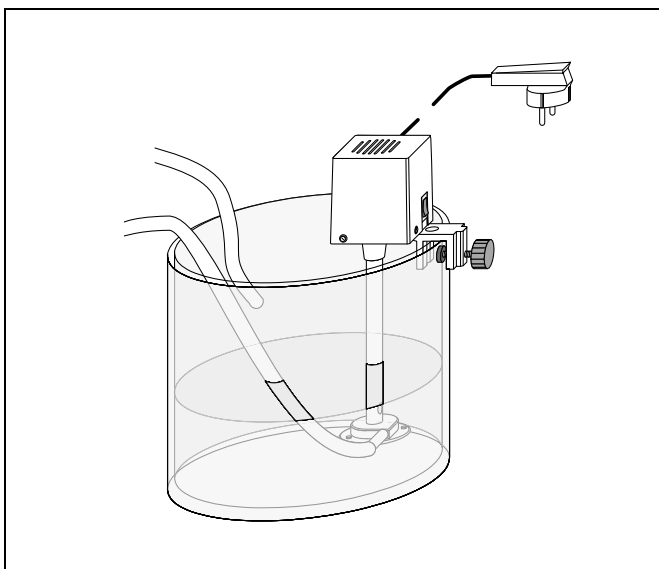


Fig. 1: Experiment setup for confirming the law of radiation according to Stefan and Boltzmann. The position data refer to the left side of the Leybold multiclamps on the small optical bench

Fig. 2: Setup example for mounting the immersion pump on the water vessel



Carrying out the experiment

First:

- Measure the temperature ϑ of the brass cylinder and the initial output voltage U of the thermopile and write these values in your experiment log.

Then:

- Switch on the electric oven; for each temperature increase of 25 °C, write the measured values ϑ and U in your experiment log.

When the temperature reaches a level between 400 °C and 500 °C:

- Switch off the electric oven; for each temperature decrease of 25 °C, write the measured values ϑ and U in your experiment log.
- When the temperature reaches a level between 100 °C and room temperature, remove the temperature sensor from the electric oven, measure the room temperature and write this value in your experiment log.
- Screen the thermopile with dark cardboard, check the zero point of the voltmeter and write this value in your experiment log.

Measuring example and evaluation

Table 1: Measured values for heating and cooling

ϑ °C	T K	$\frac{T^4 - T_0^4}{K^4}$	$\frac{U_{\uparrow}}{mV}$	$\frac{U_{\downarrow}}{mV}$
24	297	0	0	0
50	323	0.31	0.06	0.06
75	348	0.69	0.14	0.14
100	373	1.16	0.24	0.24
125	398	1.73	0.36	0.36
150	423	2.42	0.52	0.51
175	448	3.25	0.70	0.68
200	473	4.23	0.91	0.89
225	498	5.37	1.16	1.13
250	523	6.70	1.43	1.41
275	548	8.24	1.75	1.72
300	573	10.00	2.11	2.07
325	598	12.01	2.50	2.46
350	623	14.29	2.93	2.90
375	648	16.85	3.42	3.38
400	673	19.74	3.95	3.92
425	698	22.96	4.53	4.50
450	723	26.55	5.17	5.17

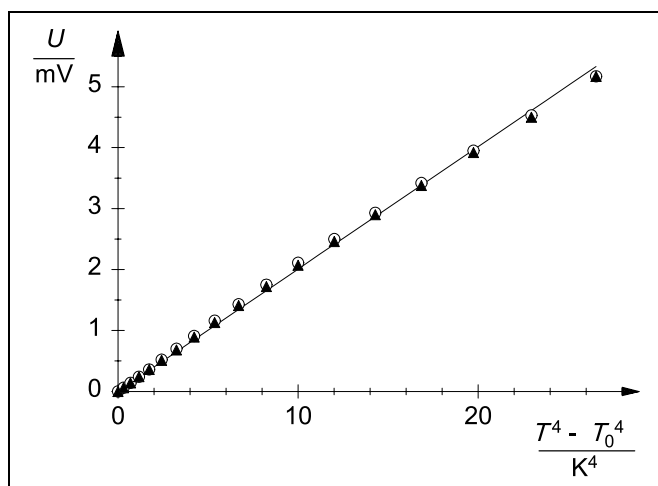


Fig. 3: Graph of the output voltage U as a function of $T^4 - T_0^4$. The circles correspond to the measured values for heating, and the triangles represent the values for cooling

Fig. 3 shows the output voltage U of the thermopile as a function of the difference between the absolute oven temperature T and the absolute room temperature T_0 , each raised to the fourth power. This relationship is a close approximation of a straight line, as predicted by the *Stefan-Boltzmann* law. When we examine this curve closely, we can recognize a slight deviation from our best-fit straight line, which is the result of the following effects: the measurement with the thermopile is affected by convection and radiant losses to the environment, especially when the glass window is removed. Also, we cannot completely rule out increasing heat build-up in the comparison points of the thermopile as the oven temperature increases.