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

Recording and evaluating with CASSY

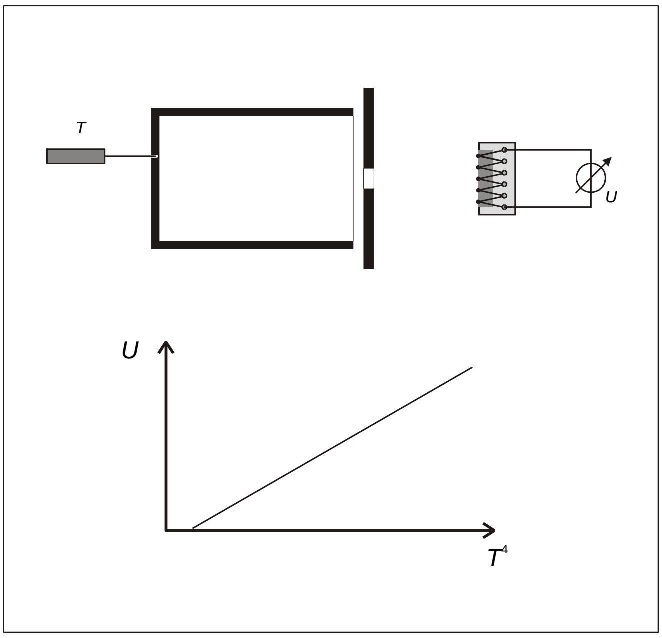
Objects of the experiment

- Conducting relative measurements of the radiant intensity of an electric oven with the black body accessory in the temperature range from 300 to 750 K using a *Moll’s* thermopile.
- Displaying 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 is defined as

$$M = \sigma \cdot T^4 \qquad \text{(I)}$$

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

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 Thus, we do not measure the total radiated radiant exitance M, but rather the radiant exitance M’ withdrawn from the black body by radiation. The radiant exitance absorbed from the environment is

$$M_o = \sigma \cdot T_0^4 \qquad \text{(II)}$$

Therefore it follows that

$$M' = \sigma \cdot (T^4 - T_O^4) \qquad \text{(III)}$$

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 connected to CASSY is used to measure the temperature at the brass cylinder.

The thermal radiation is measured using a Moll’s thermopile to which is connected to CASSY via the µV-box. 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'.

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Apparatus

1 Electric oven for 230 V 555 81
1 Black body accessory 389 43
1 Safety connection box with ground 502 061
1 Support for electric oven 555 84

1 Sensor-CASSY .... 524 010 USB
1 CASSY Lab.. 524 200
1 NiCr-Ni Adapter S 524 0673
1 NiCr-Ni Temperature sensor 1.5 mm 529 676
1 µV-box 524 040
1 Moll's thermopile 557 36

1 Small optical bench, shortrod...................... 460 43
1 Stand base, V-shape, 28 cm....................... 300 01
4 Leybold multiclamp 301 01
1 Universal clamp, 0-80 mm 666 555
1 Pair cables 100 cm, red/blue 50146

additionally required: 1 PC with Windows 98 or higher

Additionally recommended:
1 Immersion pump 12 V................................. 388 181
1 Low-voltage power supply 521 230
1 Silicone tubing, 7 mm Ø............................. 667 194
1 Laboratory bucket, 10 l 604 291

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.

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.

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-coloured clothing),
radiators,
sunlight
and other light sources.

Fig. 1 shows the experiment setup.

- Slide the burnished cylinder of the black body accessory into the electric oven.
- 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.
- 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.

When using water cooling:

- Fill sufficient water into the vessel and hang the submersible pump into the water.
- Connect the output of the submersible pump so that the inflow is at the bottom hose nipple and the outflow is at the top hose nipple of the screen and guide the outlet water drain into the water vessel.
- Connect the submersible pump to the low-voltage power supply.

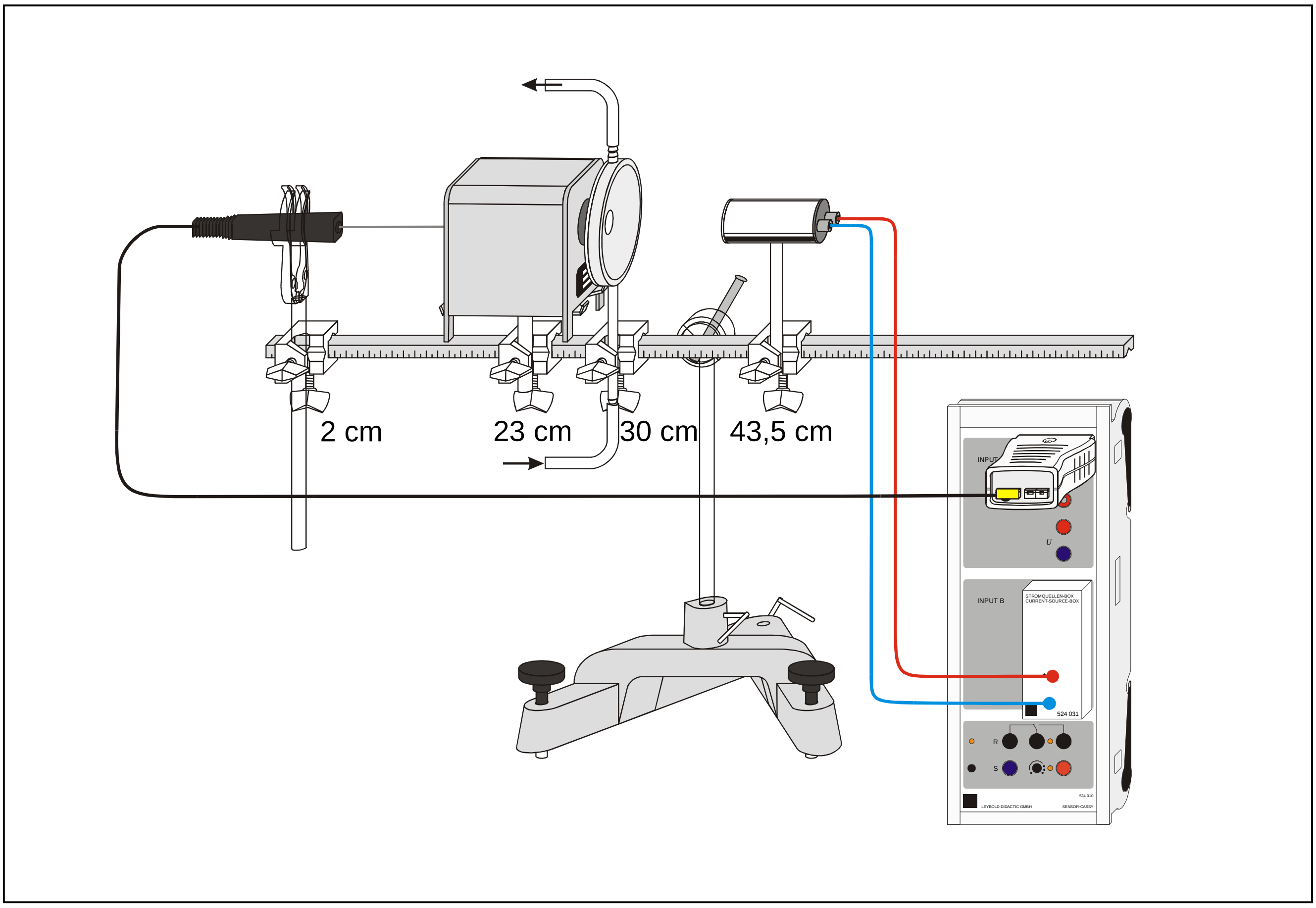
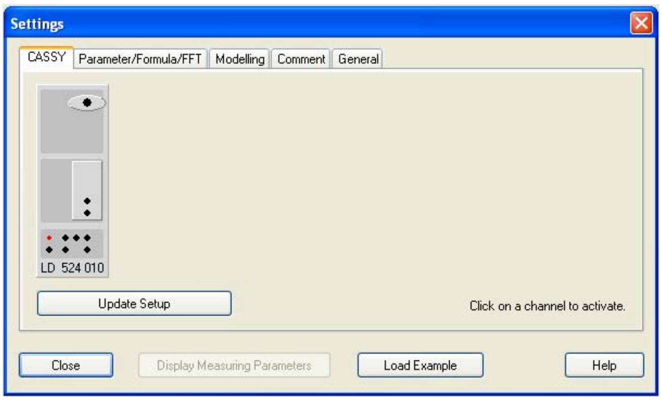


Fig. 1: Experimental setup schematically.

CASSY

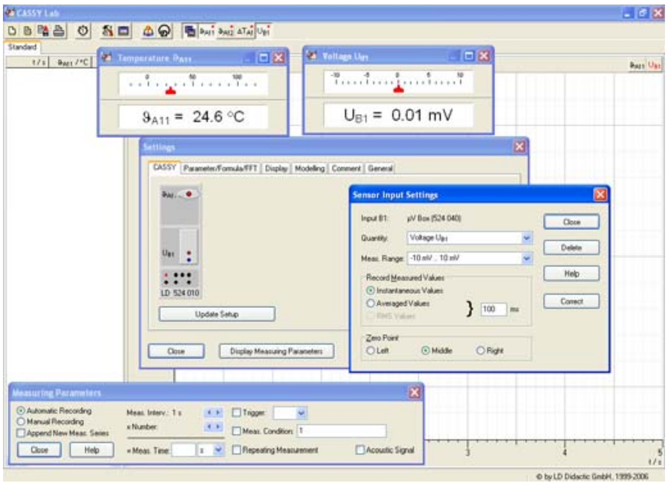
- Connect the Ni-Cr-Ni-Temperature Sensor via the Ni-Cr-Ni Adapter S to the “Input A” of the Sensor CASSY.
- Connect the thermopile via the µV-box to the “Input B” of the Sensor CASSY. Ensure that the black socket of the thermopile is connected to the ground socket of the µV-box.
- If not yet installed install the software CASSY Lab and open the software.
- Open the window “Settings” using the tool box button  or function key F5 from the top button bar:

- Sensor CASSY with the connected Sensors, i.e. the Ni-Cr-Ni-Temperature Sensor at “Input A” and the µV-box to the Input B should be displayed at the tab “CASSY” if Sensor CASSY is connected via the USB port to the computer.

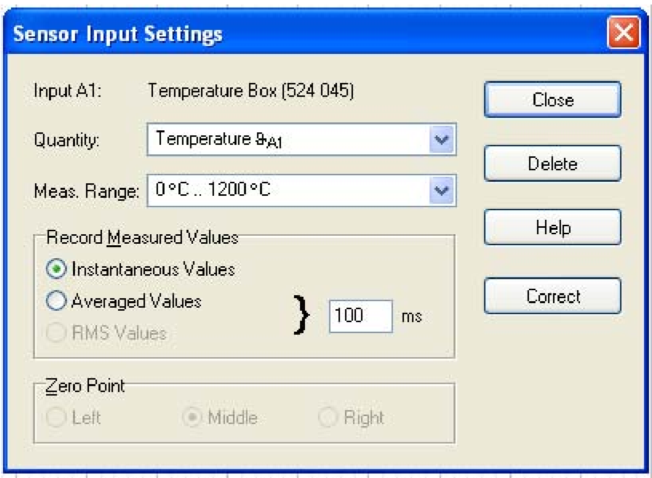


- Activate connected sensors by clicking at the Ni-Cr-Ni-Temperature Sensor and the µV-box.

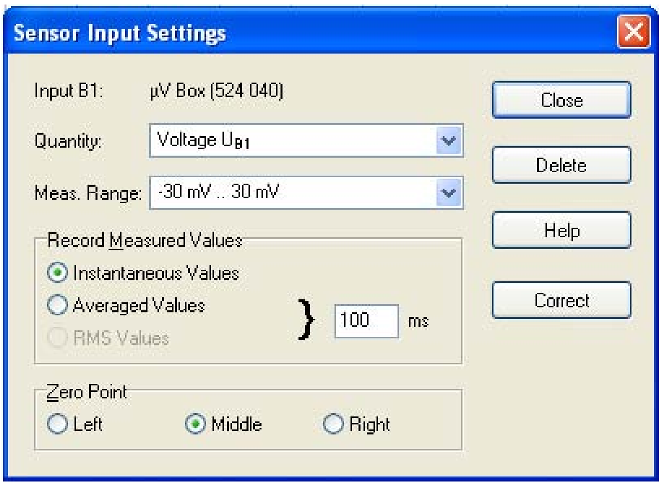
Note: Further details about connecting sensors to Sensor CASSY can be found in the manual “CASSY Lab Quick Start”.



- In the window “Measuring Parameters” set the measuring interval to 1 min.
- Click with the right mouse button on the window “Temperature” or the corresponding button in the top menu bar to select the temperature range “0 °C … 1200 °C”.



- Click with the right mouse button on the window “Voltage” or the corresponding button in the top menu bar to select the voltage range “-30 mV … 30 mV”.



- Close all windows.

Carrying out the experiment

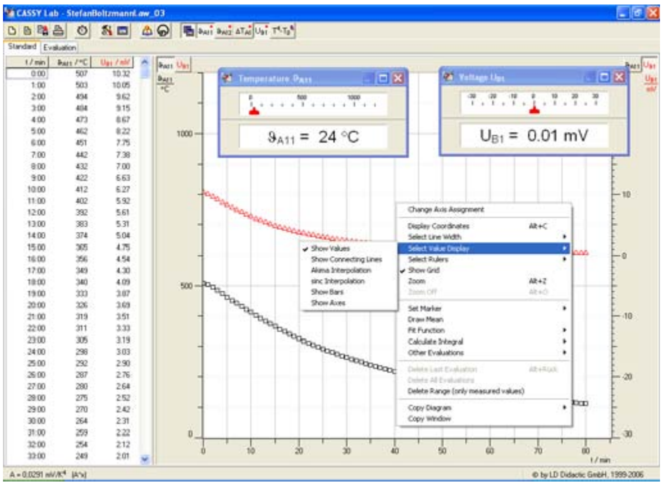
Note: The electric oven interferes with the temperature measurements when in heating mode.
Therefore, carry out the experiment only for decreasing temperatures, i.e. when plug of the electric oven is disconnected.

- Switch on the electric oven (connect the plug) and heat it to a temperature between 400 °C and 500 °C.
- Switch of the electric oven (pull the plug) and wait until the temperature starts to drop.
- Start the measurement by the button or function key F9 to start recording the voltage of the thermopile and the temperature as function of time.
- Stop data recording when the temperature reaches about 100 °C.

Note: The button works as a toggle switch. The data acquisition can be stopped by pressing or F9.

- Stop data recording when the temperature reaches about 100 °C.

Note: The measurement can be saved by pressing the button or using the function key F2.



Note: Click into the graphic display to access the display settings and the data evaluation tools. Select the option “Show Values” i.e. deactivate “Show Connecting Lines”.

Measuring example

Fig. 2 shows the temperature and the voltage of the thermopile as function of time while cooling of the electric oven.

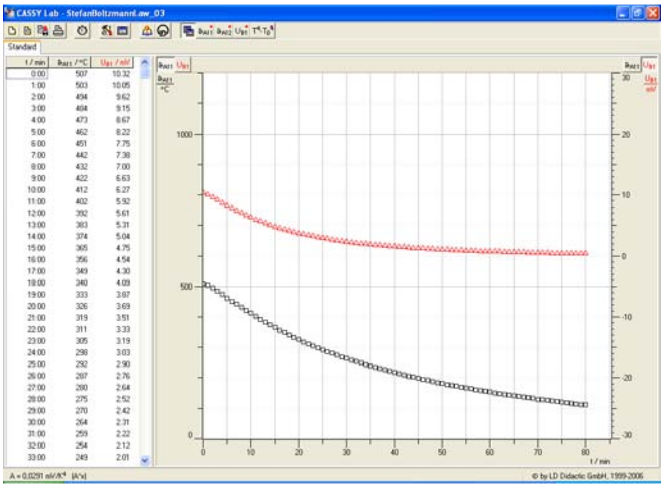


Fig. 2: Voltage of the thermopile and temperature as function of time.

Evaluation and results

- If the window “Settings” is not open press the button or function key F5 and select the tab “Parameter/Formula/FFT” (Fig. 3).
- Click on the button “New Quantity” to define $T^4 – T_0^4$
- Select “Formula” and enter (compare equation (III)):

((&JA11+273,15)^4-(273,15+22)^4)*10^-9

Notes:

In this formula a room temperature value of 22 °C (295 K) is assumed. You will need to mach this numerical value to the actual experiment conditions.

The temperature ϑ_{A11} is displayed as “&JA11”. How to enter Greek letters can be found in the appendix of the manual “CASSY Lab Quick Start”.

- Enter “T^4-T_0^4” to define the symbol.
- Enter “K^4” for the unit.
- Enter the values for the range, i.e. “0” to “500” and choose 1 decimal space.

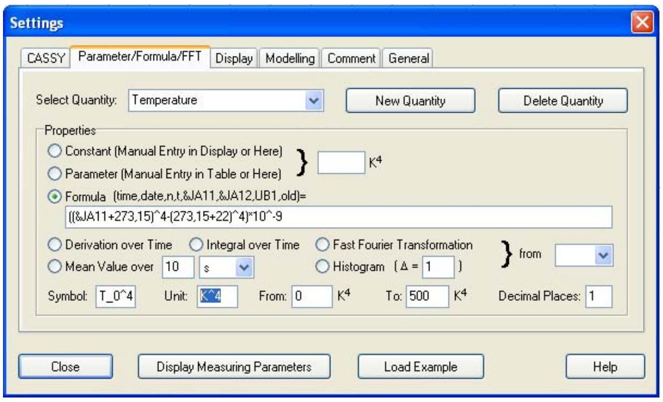


Fig. 3: Defining the formula $T^4 – T_0^4$ by using the new quantity tool (function key F5).

To plot the voltage “UB1” as function of $T^4 – T_0^4$ you may proceed as follows:

- Press the button or function key F5 and select the tab “Display” (Fig. 4).
- Click on the button “New Display”
- Enter a name, e.g. “Evaluation”
- Select “$T^4 – T_0^4$” for the X-axis and “UB1” for the Y-axis
- Close the window “Settings” and select the tab “Evaluation (Fig. 5).

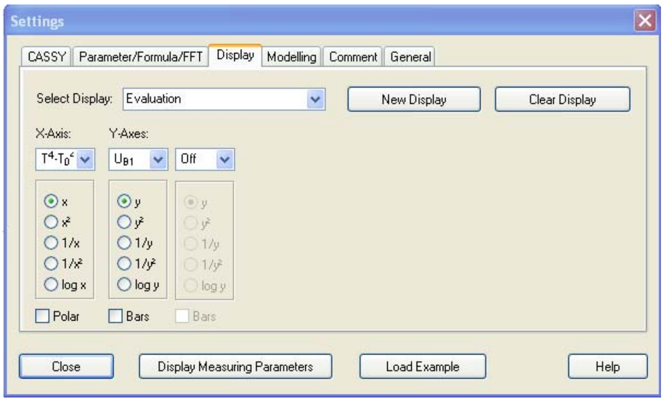


Fig. 4: Defining a new display "evaluation" to plot the efficiency voltage “UB1” as function of “$T^4 – T_0^4$” by using the new display tool (function key F5).

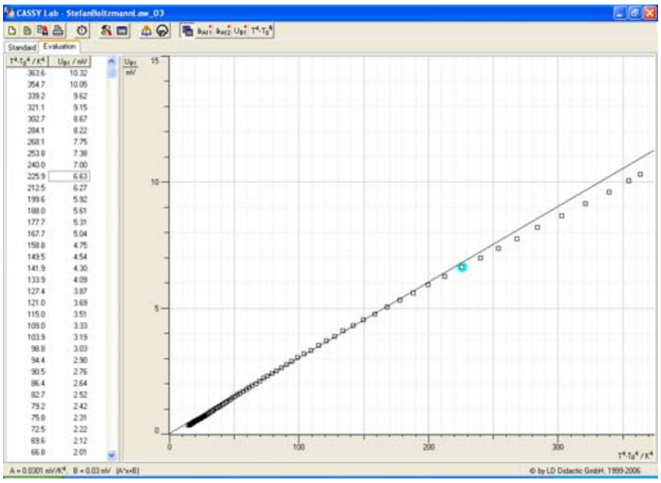


Fig. 5: Voltage “UB1” of the thermopile as function of $T^4 – T_0^4$.

- Click with the right mouse button into the graph to select
- Click with the right mouse button into the graph to access the “Fit Function” tool. Chose “Fit Function” and select “Best-fit to Straight Line”.
- Select the data to be fitted, e.g. between 100 $K^4$and 200 K^4 (selected data become blue) to confirm equation (III).

The experimental data deviate from the fit of a straight line which is the result of the following effects:

The measurement of 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.