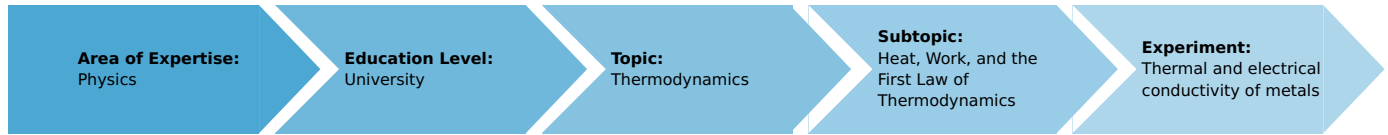


Thermal and electrical conductivity of metals

(Item No.: P2350200)

Curricular Relevance



Difficulty



Intermediate

Preparation Time



1 Hour

Execution Time



1 Hour

Recommended Group Size



2 Students

Additional Requirements:

Experiment Variations:

Keywords:

Electrical conductivity, Wiedmann-Franz law, Lorenz number, Diffusion, Temperature gradient, Heat transport, Specific heat, Four-point measurement

Overview

Short description

Principle

The thermal conductivity of copper and aluminium is determined in a constant temperature gradient from the calorimetrically measured heat flow. The electrical conductivity of copper and aluminium is determined, and the Wiedmann-Franz law is tested.



Fig. 1: Set-up

Safety instructions



Caution:

Keep the immersion heater always sufficiently immersed into the water, and keep refilling evaporated water during the experiment - the heater will be destroyed by overheating, if the water level is too low.

Equipment

Position No.	Material	Order No.	Quantity
1	Temperature meter digital, 4-2	13617-93	1
2	Temperature probe, immersion type, Pt100	11759-01	1
3	Surface temperature probe PT100	11759-02	2
4	Magnetic stirrer without heating, 3 ltr., 230 V	35761-99	1
5	Magnetic stirring bar 30 mm, cylindrical	46299-02	1
6	Calorimeter vessel, 500 ml	04401-10	1
7	Calor.vessel w.heat conduct.conn.	04518-10	1
8	Immers.heater,300W,220-250VDC/AC	05947-93	1
9	Heat conductivity rod, Cu	04518-11	1
10	Heat conductivity rod, Al	04518-12	1
11	Heat conductive paste,50 g	03747-00	1
12	Bench clamp expert	02011-00	1
13	Tripod base PHYWE	02002-55	1
14	Support rod, stainless steel, 1000 mm	02034-00	1
15	Support rod, stainless steel, 750 mm	02033-00	1
16	Right angle clamp expert	02054-00	6
17	Universal clamp	37715-00	4
18	Supporting block 105x105x57 mm	02073-00	1
19	Gauze bag	04408-00	1
20	Stopwatch, digital, 1/100 s	03071-01	1
21	Beaker, 400 ml, low-form	46055-00	1
22	Portable Balance, OHAUS CL2000J	49201-00	1
23	PHYWE multitap transformer DC: 2/4/6/8/10/12 V, 5 A / AC: 2/4/6/8/10/12/14 V, 5 A	13533-93	1
24	PHYWE Universal measuring amplifier	13626-93	1
25	Rheostat, 10 Ohm , 5.7A	06110-02	1
26	Digital multimeter 2005	07129-00	2
27	Connecting cord, 32 A, 500 mm, red	07361-01	3
28	Connecting cord, 32 A, 500 mm, blue	07361-04	4
29	Connecting cord, 32 A, 1000 mm, red	07363-01	1

Tasks

1. Determine the heat capacity of the calorimeter in a mixture experiment as a preliminary test. Measure the calefaction of water at a temperature of 0 °C in a calorimeter due to the action of the ambient temperature as a function of time.
2. To begin with, establish a constant temperature gradient in a metal rod with the use of two heat reservoirs (boiling water and ice water) After removing the pieces of ice, measure the calefaction of the cold water as a function of time and determine the thermal conductivity of the metal rod.
3. Determine the electrical conductivity of copper and aluminium by recording a current-voltage characteristic line to confirm the Wiedemann-Franz law.

Set-up and procedure

1. Measurement of the heat capacity of the lower calorimeter

- Weigh the calorimeter at room temperature.
- Measure and record the room temperature and the temperature of the preheated water provided.
- After filling the calorimeter with hot water, determine the mixing temperature in the calorimeter.
- Reweigh the calorimeter to determine the mass of the water that it contains.
- Calculate the heat capacity of the calorimeter.
- Determine the influence of the heat of the surroundings on the calefaction of the water (0 °C without pieces of ice) by measuring the temperature change in a 30-minute period.

2. Determination of the thermal conductivity

- Perform the experimental set-up according to Fig. 1.
- Weigh the empty, lower calorimeter.
- Insert the insulated end of the metal rod into the upper calorimeter vessel. To improve the heat transfer, cover the end of the metal rod with heat-conduction paste.
- Attach the metal rod to the support stand in such a manner that the lower calorimeter can be withdrawn from beneath it.
- The height of the lower calorimeter can be changed with the aid of the supporting block. When doing so, care must be taken to ensure that the non-insulated end of the rod remains completely immersed in the cold water during the experiment.
- The surface temperature probe must be positioned as close to the rod as possible.
- The outermost indentations on the rod (separation: 31.5 cm) are used to measure the temperature difference in the rod. To improve the heat transfer between the rod and the surface probe, use heat-conduction paste.
- Using an immersion heater, bring the water in the upper calorimeter to a boil, and keep it at this temperature.



Caution: Keep the immersion heater always sufficiently immersed into the water, and keep refilling evaporated water during the experiment - the heater will be destroyed by overheating, if the water level is too low.

- Ensure that the upper calorimeter is well filled to avoid a drop in temperature due to contingent refilling with water.
- Keep the water in the lower calorimeter at 0°C with the help of ice (in a gauze pouch).
- The measurement can be begun when a constant temperature gradient has become established between the upper and lower surface probes, i.e. when no changes occur during the differential measurement.
- At the onset of measurement, remove the ice from the lower calorimeter.
- Measure and record the change in the differential temperature and the temperature of the water in the lower calorimeter for a period of 5 minutes.
- Weigh the water-filled calorimeter and determine the mass of the water. Settings of the temperature measuring device 4-2:

In the first display on the measuring device, the temperature of the lower calorimeter is displayed.

In the second display, the differential measurement between the upper and the lower surface probe is shown.

- The thermal conductivity of different metals can be determined from the measuring results.

3. Measurement of the electrical conductivity.

- Perform the experimental set-up according to the circuit diagram in Fig. 2 (set-up in accordance with a 4-conductor measuring method).

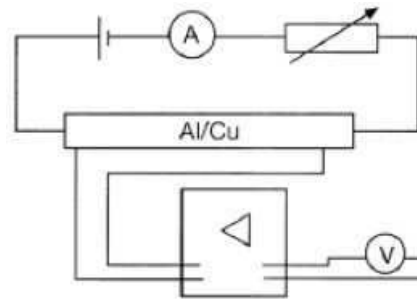


Fig. 2: Circuit diagram.

- Set the voltage on the variable transformer to 6 V.
- The amplifier must be calibrated to 0 in a voltage-free state to avoid a collapse of the output voltage.
- Select the amplifier settings as follows:
Input: Low Drift
Amplification: 10^4
Time Constant: 0
- Set the rheostat to its maximum value and slowly decrease the value during the experiment.
- Read and note the values for current and voltage
- The resistance, and thus the electrical conductivity, can be determined from the measured values.

Theory and evaluation

If a temperature difference exists between different locations of a body, heat conduction occurs. In this experiment there is a one-dimensional temperature gradient along a rod. The quantity of heat dQ transported with time dt is a function of the cross-sectional area A and the temperature gradient dT/dx perpendicular to the surface.

$$\frac{dQ}{dt} = -\lambda A \cdot \left(\frac{\partial T}{\partial x} \right) \quad (1)$$

The temperature distribution in a body is generally a function of location and time and is in accordance with the Boltzmann transport equation

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho \cdot c} \cdot \left(\frac{\partial^2 T}{\partial x^2} \right) \quad (2)$$

Where ρ is the density and c is the specific heat capacity of the substance.

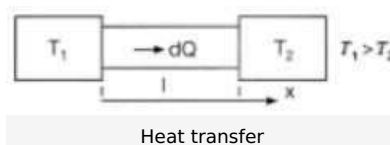
After a time, a steady state

$$\frac{\partial T}{\partial t} = 0 \quad (3)$$

is achieved if the two ends of the metal rod having a length l are maintained at constant temperatures T_1 and T_2 , respectively, by two heat reservoirs.

Substituting equation (3) in equation (2), the following equation is obtained:

$$T(x) = \frac{T_2 - T_1}{l} \cdot x + T_1 \quad (4)$$



Heat transfer

1. The heat capacity of the calorimeter is obtained from results of the mixing experiment and the following formula:

$$C = c_W \cdot m_W \cdot \left(\frac{\vartheta_W - \vartheta_M}{\vartheta_M - \vartheta_R} \right) \quad (5)$$

c_W = Specific heat capacity of water

m_W = Mass of the water
 ϑ_W = Temperature of the hot water
 ϑ_M = Mixing temperature
 ϑ_R = Room temperature

The measurement supplies a value of approximately 78 J/K \pm 25%. The large variations in the results are a result of the manner in which the experiment is performed and of the experimental set-up.

The addition of heat from the surroundings is calculated from the temperature increase ΔT of the cold water in the calorimeter.

$$\Delta Q = (c_W \cdot m_W + C) \cdot \Delta T \quad (6)$$

where $\Delta T = T - T_0$,
 with T_0 = Temperature at time $t = 0$.

2. The heat energy supplied to the lower calorimeter can be calculated using Equation (6). The values and the change in the temperature difference on the metal rod are plotted as a function of time.

In the diagram illustrating the temperature difference, one can see that the temperature essentially remains constant. Consequently, equation 3 can be considered as having been satisfied. In order to calculate the heat energy transported by the metal rod according to Equation 1, the ambient heat fraction must be subtracted.

$$\frac{dQ_{\text{rod}}}{dt} = \frac{dQ_{\text{tot}}}{dt} - \frac{dQ_{\text{surr}}}{dt} \quad (7)$$

dQ/dt for the ambient heat can be calculated from the slope of the graph in Fig. 3. dQ/dt for the entire set-up can be calculated from the slope of the graph of Q over t in Figs. 4 and 5. With the values for the length of the rod ($\Delta x = 31.5$ cm), the area ($A = 4.91 \cdot 10^{-4} \text{ m}^2$) and the averaged temperature on the metal rod, the heat conduction number can be calculated using Equation (1). The following result as the average values:

$\lambda_{\text{Al}} = 254 \text{ W/Km}$
 $\lambda_{\text{Cu}} = 447 \text{ W/Km}$

The literature values are:

$\lambda_{\text{Al}} = 220 \text{ W/Km}$
 $\lambda_{\text{Cu}} = 384 \text{ W/Km}$

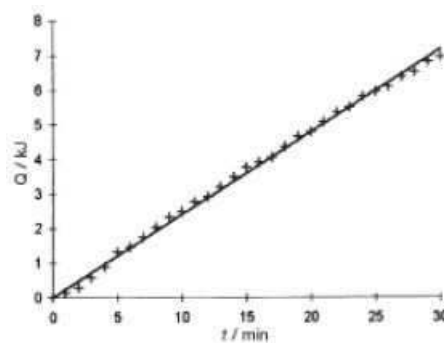


Fig. 3: Heat of surroundings over time.

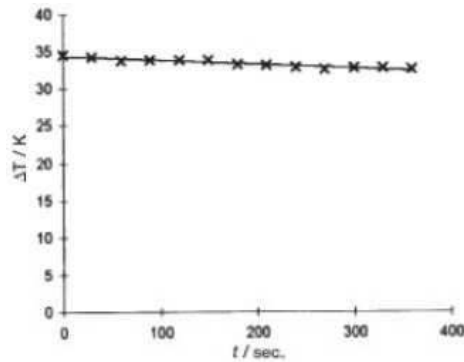


Fig. 4a: ΔT as function of time for aluminium.

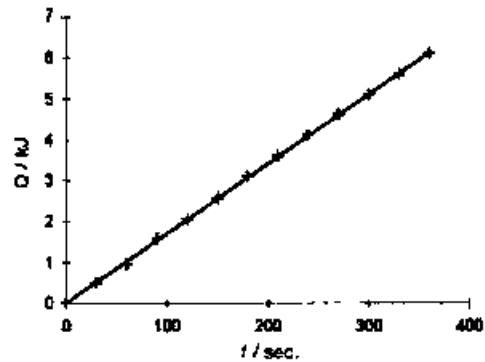


Fig. 4b: Q as function of time for aluminium.

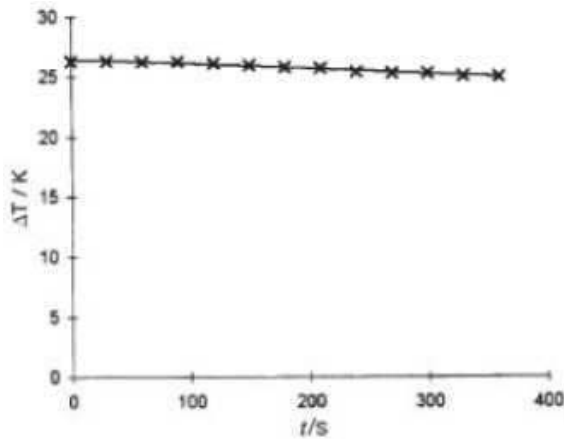


Fig. 5a: ΔT as function of time for copper.

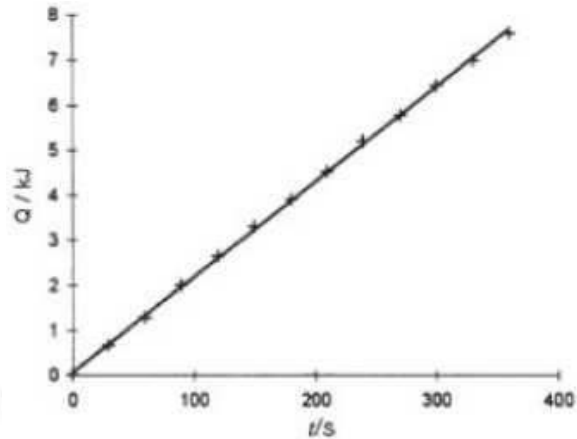


Fig. 5b: Q as function of time for copper.

3. At room temperature the conduction electrons in metal have a much greater mean free path than the phonons. For this reason heat conduction in metal is primarily due to the electrons. The resulting correlation between the thermal conductivity λ and the electrical conductivity σ is established by the Wiedemann-Franz law:

$$\frac{\lambda}{\sigma} = LT \tag{8}$$

The Lorenz number L , which can be experimentally determined using Equation (8), is established by the theory of electron vapour (for temperatures above the Debye temperature) to be:

$$L = \frac{\pi^2}{3} \cdot \left(\frac{k^2}{e^2} \right) = 2.4 \cdot 10^{-8} \frac{\text{W}\Omega}{\text{K}^2} \tag{9}$$

k = Universal gas constant = $1.38 \cdot 10^{-23} \text{ J/K}$
 e = Elementary unit charge = $1.602 \cdot 10^{-19} \text{ AS}$

The electrical conductivity is determined by the resistance R of the rod and its geometric dimensions ($l = 0.315 \text{ m}$, $A = 4.91 \cdot 10^{-4} \text{ m}^2$).

$$\sigma = \frac{l}{A \cdot R} \tag{10}$$

From Equation (8) the following values result for $T = 300 \text{ K}$ and the λ from the second part of the experiment.

	$R/10^{-6} \Omega$	$\sigma/10^7 (\Omega\text{m})^{-1}$	$L/10^{-8} \text{ W}\Omega \text{ K}^{-2}$
Al	19.6	3.27	2.5
Cu	12.04	5.33	2.35

The Debye temperatures of copper and aluminium are 335 K and 419 K, respectively. Below the Debye temperature the ratio of the conductivity is smaller than given by Equation (8).

