Thermodynamics

Transport of Heat

PHYSICS EXPERIMENT

Heat Conduction

MEASURE CONDUCTION OF HEAT IN METAL BARS

- Measure how temperature changes with time along metal bars which are heated at one end but remain cool at the other in both dynamic and steady states.
- Measure the flow of heat in the steady state.
- Determine the heat conductivity of the material from which the bar is made.

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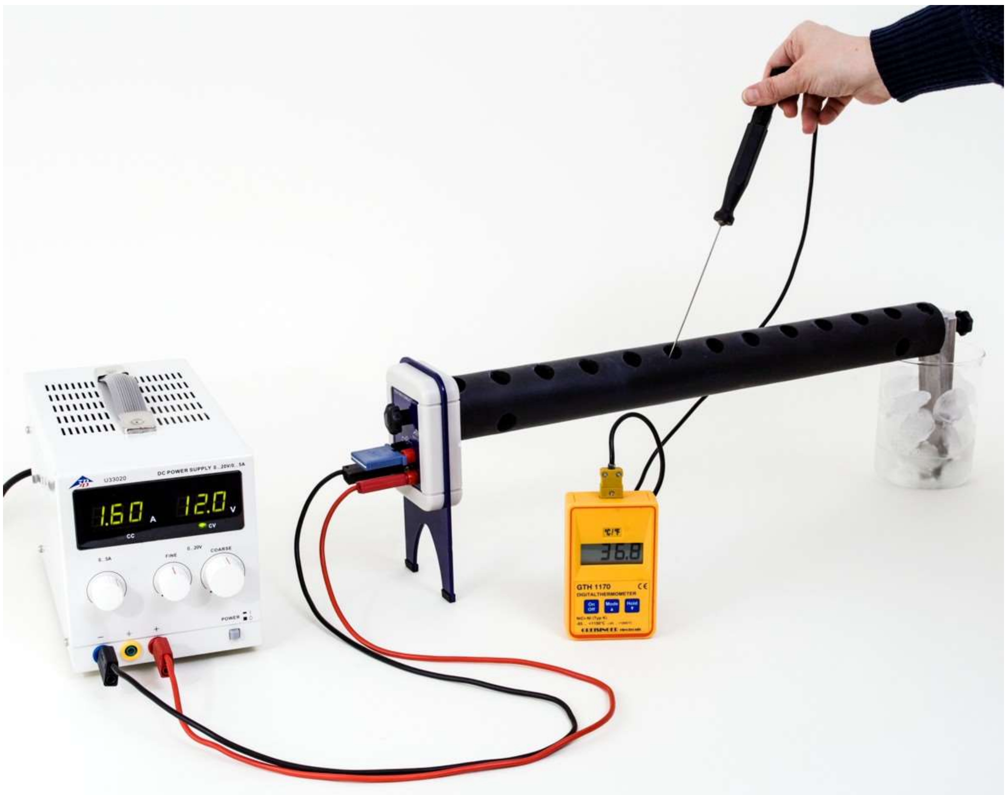

Fig. 1: Measurement set-up

GENERAL PRINCIPLES

Heat can be transported from a hotter area to a colder one by conduction, radiation or convection. Conduction of heat involves heat being transferred from a hotter part of an object to a colder area by means of the interaction between neighbouring atoms or molecules, although the atoms themselves remain in place. For instance, when a metal bar is heated, the atoms at the hotter end vibrate more vigorously than those at the cooler end, i.e. they vibrate with more energy. Energy is transferred due to collisions between neighbouring atoms, passing the energy from one atom to another and thereby conducting it along the bar. Metals are particularly good conductors of heat since collisions also occur between atoms and free electrons.

In a bar with a cross-sectional area of *A*, when the ends are maintained at different temperatures, after a while a temperature gradient emerges along the bar, whereby the temperature decreases uniformly along the length towards the cold end. In a time period d*t* a quantity of heat d*Q* flows through the cross-section of the bar and there arises a constant flow of heat P_Q:

$$(1)\quad P_Q = \frac{dQ}{dt} = -\lambda \cdot A \cdot \frac{dT}{dx}$$

P_Q: Flow of heat (measured in watts)
A: Cross-sectional area of bar
λ: Heat conductivity of material from which the bar is made
T: Temperature
x: Coordinate of length along the bar

Before the constant temperature gradient arises, the temperature distribution at a specific time *t* is given by T(*x*,*t*), which gradually becomes closer to the steady state. The following differential equation then applies

$$(2)\quad \lambda \cdot \frac{\partial^2 T}{\partial x^2}(x,t) - c \cdot \rho \cdot \frac{\partial T}{\partial t}(x,t) = 0\ ,$$

c: Specific heat capacity
ρ: Density of material from which bar is made

In the steady state the situation is in agreement with equation (1)

$$(3)\quad \frac{\partial T}{\partial t}(x,t) = 0 \text{ and } \lambda \cdot \frac{\partial T}{\partial x}(x,t) = const. = \frac{P_Q}{A}\ .$$

In this experiment the bar is heated at one end by electrical means. An electronically regulated source of heat provides the bar with an amount of heat which can be determined by measuring the heater voltage *U* and current ***I***:

$$(4)\quad P_{el} = U \cdot I$$

Electronic regulation of the current ensures that this end of the bar rapidly reaches a temperature of about 90°C and this temperature is then maintained constant.

The other end of the bar is kept at the temperature of melting ice or simply water at room temperature via its cooling baffles. This allows the heating to be determined by calorimetry.

An insulating sleeve minimises the loss of heat from the bar to its surroundings and ensures the temperature profile is more linear in the steady state. Using an electronic thermometer that determines temperature within a second, temperatures are measured at pre-defined measurement points along the bar. Both a copper bar and an aluminium bar are provided.

LIST OF EQUIPMENT

1	Heat Conduction Equipment Set	1017329
1	Heat Conducting Rod, Aluminium	1017331
1	Heat Conducting Rod, Copper	1017330
1	DC Power Supply 20 V, 5 A @230 V	1003312
or		
1	DC Power Supply 20 V, 5 A @115 V	1003311
1	Digital Quick Response Pocket Thermometer	1023780
1	K-Type NiCr-Ni Immersion Sensor, -65–550°C	1002804
1	Safety Experimental Leads, 75 cm, blue, red (2 pcs)	1017718
1	Beaker 500 ml low form	1025691
Additionally recommended:		
2	Digital Multimeters P1035	1002781
	Ice water	

SET-UP AND PROCEDURE

Note:
The experiment is described using the aluminium heat conducting bar as an example.

- Clean the ends of the conducting bar where it will make contact and smear a very thin coating of thermal conducting paste on them.
- Attach the heater module to the bar by means of securing screws, aligning the bar in such a way that the holes in it for measuring the temperature are facing upwards.
- Slide the insulating sleeve over the conducting bar, lining up the gaps in the foam over the temperature measurement holes.
- Loosely screw on the pair of baffles at the end of the bar, line them up inside the cooling vessel (glass beaker) and then screw them on tight.
- Fill the beaker with ice water, topping it up if necessary during the course of the experiment.
- To provide the power, connect the plug-in DC power supply to the power terminals, making sure that the polarity is correct: red = positive pole. The second pair of sockets should be shorted together with a jumper.
- To measure the current flowing through the heater, connect an ammeter between the two upper sockets instead of the jumper.
- To determine the electrical power consumed as accurately as possible (the product of the heater voltage and heater current), the voltage should be measured directly across the heater module via the lower pair of sockets and not read from the power supply.
- The temperature should be measured with an electronic thermometer (quick-response pocket thermometer with thermocouple) at measurement points 1 to 13 along the conducting bar at time intervals as equal as possible (Table 1). Smear a small amount of conducting paste at the measurement points in advance for this purpose.
- Carry out several sets of measurements, e.g. starting at 150 s till a steadz state has been reached (Table 1).

SAMPLE MEASUREMENT

Heater voltage *U*: 12 V

Heater current *I*: 1.6 A

Table 1: Measurement points *N*, distance between measurement points *x* and temperatures *T* at measurement points for five different sets of measurements at time intervals of 150 seconds and 50 seconds

N	*x* / cm	*T* / °C				
		t = 0 s	*t* = 150 s	*t* = 300 s	*t* = 350 s	*t* = 400 s
1	1	88.7	88.8	90.0	90.0	90.6
2	5	74.0	78.3	81.0	82.0	84.5
3	9	63.6	68.9	72.0	75.0	78.4
4	13	55.3	61.1	64.1	68.0	72.0
5	17	48.8	54.6	57.8	62.0	66.6
6	21	43.9	49.1	52.2	55.9	61.3
7	25	39.6	44.0	46.8	51.0	56.1
8	29	36.2	39.9	42.3	46.5	50.9
9	33	33.5	36.6	38.9	41.9	46.3
10	37	31.5	34.4	36.0	38.0	41.7
11	41	29.6	32.1	33.6	35.2	37.4
12	45	28.8	30.3	31.8	32.0	32.9
13	49	27.6	28.8	29.8	28.3	29.1

EVALUATION

- Plot the sets of measurements in Table 1 in a graph of *T* against *N* (Fig. 2).

Over a period of time, the measurement points settle down to a linear gradient along the bar, which corresponds to a settled, steady state.

- Convert the temperatures for time *t* = 400 s in Table 1 to Kelvin as follows:

$$\text{(5)}\quad \mathrm{K} = {}^\circ\mathrm{C} + 273.15 = \frac{\left({}^\circ\mathrm{F} + 459.67\right)}{1.8}$$

  Plot the temperatures against the distances *x* along the bar and fit a straight line to the measurement points (Fig. 3).

The following results for gradient *k*:

$$\text{(6)}\quad k = -1.28\,\frac{\mathrm{K}}{\mathrm{cm}}.$$

Gradient *k* corresponds to the temperature gradients in equation(1):

$$\text{(7)}\quad k = \frac{\mathrm{d}T}{\mathrm{d}x} = -\frac{P_\mathrm{Q}}{\lambda\cdot A}.$$

Initially make the simplified assumption that the power associated with the flow of heat P_Q is identical to the electrical power P_el consumed and work out the thermal conductivity λ. The following can be deduced from equation (7):

$$\text{(8)}\quad \begin{aligned}\lambda &= -\frac{P_\mathrm{Q}}{k\cdot A} \approx -\frac{P_\mathrm{el}}{k\cdot A} = -\frac{12\ \mathrm{V}\cdot 1.6\ \mathrm{A}}{-1.28\,\frac{\mathrm{K}}{\mathrm{cm}}\cdot 490\cdot\mathrm{mm}^2}\\ &= 306\,\frac{\mathrm{W}}{\mathrm{m}\cdot\mathrm{K}}\end{aligned}.$$

The value determined by measurement differs by about 30% from that quoted in literature, λ = 236 W/(m·K).

In fact the flow of heat P_Q is really equal to the electrical power provided P_el with power losses P_l subtracted:

$$\text{(9)}\quad P_\mathrm{Q} = P_\mathrm{el} - P_\mathrm{l}$$

Therefore:

$$\text{10)}\quad \lambda = -\frac{P_\mathrm{el} - P_\mathrm{l}}{k\cdot A} \Leftrightarrow P_\mathrm{l} = P_\mathrm{el} + k\cdot\lambda\cdot A.$$

Thus if the value quoted in literature is λ = 236 W/(m·K), then it follows that the power losses are as seen below:

$$\text{(11)}\quad \begin{aligned}P_\mathrm{l} &= 12\ \mathrm{V}\cdot 1.6\ \mathrm{A} - 1.28\,\frac{\mathrm{K}}{\mathrm{cm}}\cdot 236\,\frac{\mathrm{W}}{\mathrm{m}\cdot\mathrm{K}}\cdot 490\,\mathrm{mm}^2\\ &= 4.4\ \mathrm{W}\end{aligned}.$$

Note: Measurement of flow of heat in steady state: If instead of using ice water in the beaker, water at room temperature is used and the vessel suitably insulated, then the flow of heat P_Q can be determined calometrically from the heat d*Q* transferred over to the time interval d*t*:

$$\text{(12)}\quad P_\mathrm{Q} = \frac{\mathrm{d}Q}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left\{c_\mathrm{H2O}\cdot m_\mathrm{H2O}\cdot\mathrm{d}T\right\} = c_\mathrm{H2O}\cdot m_\mathrm{H2O}\cdot\frac{\mathrm{d}T}{\mathrm{d}t}$$

c_H2O: Specific heat capacity of water
m_H2O: Mass of water
d*T*/d*t*: Increase in water temperature over time d*t*

The increase in water temperature over a given period can be measured directly. The thermal conductivity λ taking into account losses in power then follows directly from equation (7) with the gradient *k* from equation (6).

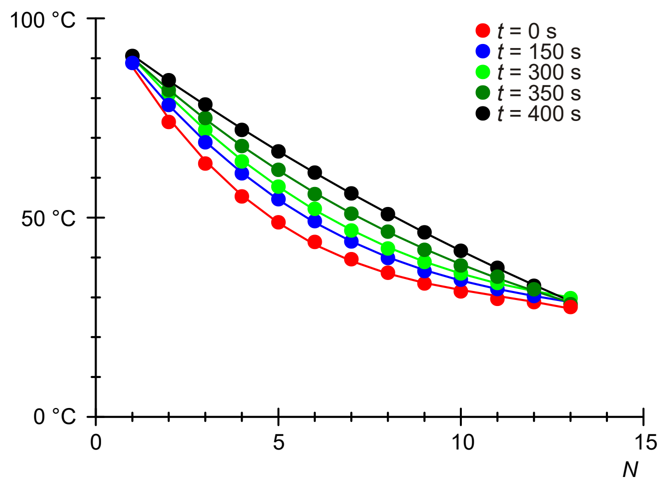

Fig. 2: Temperatures along the aluminium rod in five sets of measurements made at time intervals of 150 s

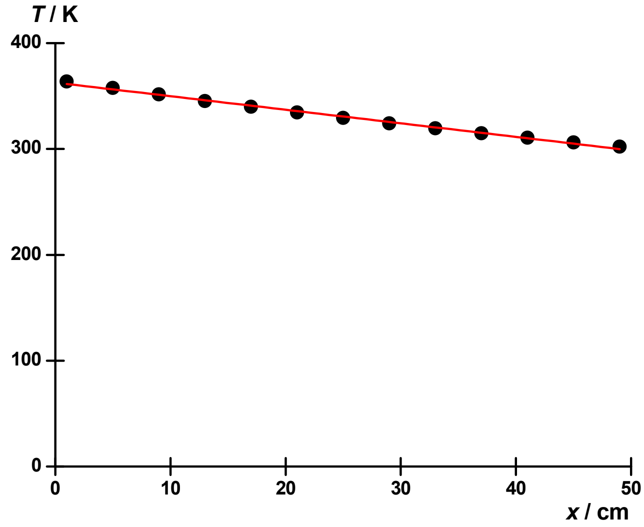

Fig. 3: Temperature *T* in as a function of distance *x* to measurement points in steady state