Electricity

DC and AC circuits

Electrical work and power

LD Physics Leaflets

P3.6.6.1

Determining the heating power of an ohmic load in an AC circuit as a function of the applied voltage

Experiment objectives

- Measure the temperature change in water caused by an immersion heater
- Determine the power generated by the heater as a function of the applied voltage

Principles

There is a relationship between the electrical power P_{el} consumed by a resistor R and the DC voltage U applied across it. The relationship is given by the following equation:

$$P_{el} = U_= \cdot I_= = \frac{U_=^2}{R} \quad (1)$$

A similar relationship applies for an alternating voltage. If P_{el} is the power determined over a given period and the DC voltage $U_=$ and current $I_=$ are replaced by root mean square values:

$$U_{eff} = \frac{U_0}{\sqrt{2}} \text{ and } I_{eff} = \frac{I_0}{\sqrt{2}}$$

U_0: Amplitude of alternating voltage
I_0: Amplitude of alternating current

The relationship is then as follows:

$$P_{el} = U_{eff} \cdot I_{eff} = \frac{U_{eff}^2}{R} \quad (2)$$

The electrical power associated with a resistor R, which obeys Ohm's law, is converted into heat. Joule's law states that the heat generated per unit time in a circuit is proportional to the power in the circuit:

$$P_{el} = \frac{\Delta E_{th}}{\Delta t} \quad (3)$$

In this experiment, the heating power P_{el} generated by an immersion heater will be determined. The heat generated by the heating filament is transferred to the surrounding water, the calorimeter in which it is contained and into the surrounding environment. The change in the thermal energy E_{th} is proportional to the change in temperature:

$$\Delta E_{th} \sim (\vartheta_2 - \vartheta_1) \quad (4)$$

ϑ_1: Start temperature
ϑ_2: End temperature

By substituting equation (4) into equation (3), it can be seen that the change in water temperature $\Delta\vartheta = \vartheta_2 - \vartheta_1$ is proportional to the electrical power P_{el} consumed by the heater:

$$P_{el} \sim \frac{\Delta\vartheta}{\Delta t} \quad (5)$$

In the experiment, the rise in water temperature per unit time will be determined with various different voltages applied. This should verify the following relationship:

$$\frac{\Delta\vartheta}{\Delta t} \sim P_{el} \sim U_{eff}^2 \quad (6)$$

Set-up

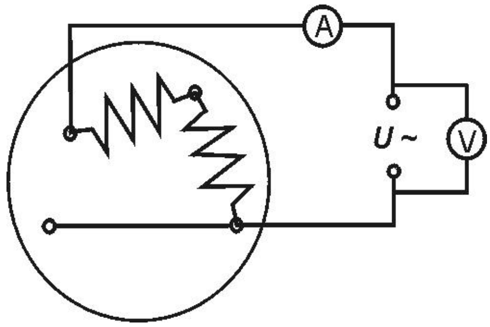

Fig. 1: Circuit diagram

Equipment

1 Lid and heater 590 50
1 Aluminium calorimeter 384 52

1 Variable extra-low voltage transformer S........... 521 35

1 LDanalog 20 multimeter 531 120
1 LDanalog 30 multimeter 531 130

1 Hand-held stop-watch I, 30 s/0.1 s 313 07
1 Thermometer, -10...+110°C............................... 382 34
1 Plastic beaker, 1000 ml 590 06

4 Experiment leads, 25 cm, black......................... 501 23
2 Experiment leads, 50 cm, black......................... 501 28

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A sketch of the experiment set-up is shown in Fig. 1. The following steps are required to set up the experiment:

- Fill the aluminium calorimeter with 200 ml of water.
- Insert the stirrer through the opening in the middle of the lid with the heater and put the lid on top of the calorimeter.
- Insert the thermometer into the large opening in the lid.
- Connect the heating filament of the immersion in series to the adjustable AC voltage output of the variable low-voltage transformer (see Abb. 2). Use the LDanalog 30 multimeter as an ammeter.
- Connect the LDanalog 20 to the AC voltage output in order to measure the voltage.

Procedure and example measurement

- Turn on the variable transformer.
- Set up an AC voltage U = 2.0 V.
- Read off the current I from the ammeter and make a note of it.
- Read off the initial temperature ϑ_1 and start the hand-held stop-watch at the same time in order to measure the duration of the heating.
- Keep moving the stirrer up and down while the water is being heated in order to ensure that it is heated evenly.
- Wait for the temperature to rise by about 0.2°C, then stop the watch. Make note of the time reading Δt and the final temperature ϑ_2.
- Increase the AC voltage in steps and repeat the experiment each time. You can use different changes in temperature for each step to ensure that the measurement always covers a few minutes.

Example measurement

U / V	I / A	ϑ_1 / °C	ϑ_2 / °C	Δt / s
2.0	0.26	23.4	23.6	630
4.0	0.44	23.6	24.2	480
6.0	0.68	24.4	25.0	330
8.0	0.94	23.2	23.8	180
10.0	1.20	24.6	25.4	150
12.0	1.42	25.4	26.6	150

Conclusions

In order to verify equation (6), calculate the values of U^2, $\Delta\vartheta$ and $\frac{\Delta\vartheta}{\Delta t}$ from the measurement results and plot $\frac{\Delta\vartheta}{\Delta t}$ against U^2 on a graph.

Example measurement:

U^2 / V^2	$\Delta\vartheta$ / K	$\frac{\Delta\vartheta}{\Delta t}$ / $\frac{K}{s}$
4.0	0.2	$3.2 \cdot 10^{-4}$
16	0.4	$8.3 \cdot 10^{-4}$
36	0.6	$1.8 \cdot 10^{-3}$
64	0.6	$3.3 \cdot 10^{-3}$
100	0.8	$5.3 \cdot 10^{-3}$
144	1.2	$8.0 \cdot 10^{-3}$

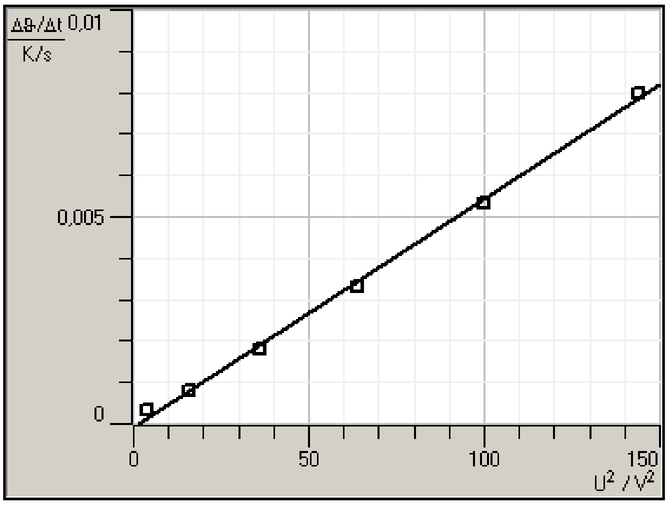

Fig. 2: Plot of $\Delta\vartheta / \Delta t$ against U^2

A straight line through the results is a close match to the measurements. This provides verification of the relationship $\frac{\Delta\vartheta}{\Delta t} \sim U_{\text{eff}}^2$, confirming that $P_{el} \sim U_{\text{eff}}^2$.

Note

In this experiment it is not possible to make a quantitative comparison between the electrical power P_{el} and the thermal energy E_{th}. That some of the heat is transferred to the calorimeter vessel and some to the surrounding environment cannot be neglected, but it is not possible to quantify the magnitude of this heat transfer. It is possible to make such a quantitative comparison using the equivalent of heat apparatus (384 20) and the Dewar vessel (386 48) (see LD Physics Leaflet P2.3.4.1).

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