Magnetic Phase Transitions
(Electricity and Magnetism)

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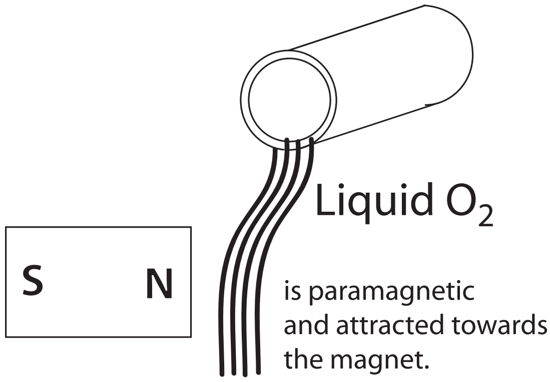
The magnetic phenomenon has been known since time antiquity. The ancient Greeks knew about the magnetic force of both magnetite and rubbed amber. Magnetite, a magnetic oxide of iron mentioned in Greek texts as early as 800 B.C.E., was mined in the province of Magnesia in Thessaly. Thales of Miletus is considered to have been the first man to study magnetic forces. According to Lucretius, a Roman philosopher in the first century BC, the term magnet was derived from the province of Magnesia.

Starting from these early discoveries in magnetism, through the Chinese invention of the magnetic compass to the pioneering work of scientists such as Oersted, Ampere, Faraday, Maxwell and Néel, we have indeed come a long way in our understanding of magnetism. Today, a complete understanding of magnetism requires a deep appreciation of the branch of physics, we call quantum physics. However, as a first approximation, we can also interpret magnetism in its full bloom, with the help of classical physics. Nature has given us materials with diverse magnetic properties. Ranging from the strongly magnetic iron and cobalt to the weakly magnetic (or in everyday language, the "non-magnetic") rubber and water, there exists a remarkable variety of magnetic materials. The kings of these materials are the *ferromagnets* and *ferrimagnets* that are used in inductors, transformers, motors and generators, antennas, audio and video tapes, loudspeakers and microphones and the exotic giant magnetoresistance (GMR) devices. We could say that in electrical engineering, magnetic materials and devices [1] are as pervasive as oxygen! Without transformers with ferrite cores, for example, it would be almost impossible to have the vast electric grid and supply systems that have transformed the fate of the post-industrial man.

There are other weaker forms of magnetism as well, such as *paramagnetism* that pulls in the material towards a strong magnetic field. Paramagnetism plays a vital role in many important chemical processes such as catalysis. Furthermore, every material exhibits some form of *diamagnetism*, pushing the material away from the strong magnetic field. For example, superconductors are perfect diamagnets; they will repel strong permanent magnets to the extent that they will hover in mid-air when placed on top of a magnet. This principle of *magnetic levitation* is at the heart of the super-fast train, the MAGLEV.

The present experiment on "magnetic phase tarnsitions" is quite different in character from our other experiments. The experiment is mostly dialogue-oriented in which the demonstrator will initiate a reasoned and informed discussion about the apparatus and its various features.



You will learn about new equipment and electric components, probe the safety features that have gone into the design of this setup and of course, will perform the experiment under the watchful supervision of the demonstrator. Remember to note down the answers to all the violet-coloured questions in your notebook.

You must follow all safety procedures and warnings. The experiment involves very large electric currents that can seriously risk your safety, well-being and life.

KEYWORDS

Ferromagnetism · Paramagnetism · Curie Point · Electrical Energy · Specific Heat Capacity · Stefan-Boltzmann Law · Variable Transformer · Digital Multimeter · Clamp meter · Electrical Safety

APPROXIMATE PERFORMANCE TIME 2 hours.

1 Conceptual Objectives

In this experiment, we will,

1. learn how to handle electricity, especially large currents, safely;
2. understand the role of thermal and electric insulators and conductors;
3. familiarize ourselves with common electrical test equipment such as the voltmeter, ammeter, multimeter, clamp meter and circuit components such as the circuit breaker and variable transformer (variac);
4. learn to interpret important thermal and electrical properties of materials;
5. appreciate the instantaneous nature of phase transitions; and finally,
6. appreciate the inter-relationship between electricity, magnetism and thermodynamics.

2 Experimental Objectives

The experiment determines the Curie point of a ferromagnetic material as its temperature is raised with the help of resistive heating. Besides the monitoring of the phase transition, we will also learn about the use of electrical measurement equipment and safety practices that must be observed when designing, operating or testing electric equipment.

3 Theoretical Introduction

3.1 Resistance and Ohm's Law

Ohm's law is an empirical observation deduced from experiments performed by Georg Simon Ohm in 1827. The modern form of Ohm's law is,

$$V = IR, \tag{1}$$

where V is the applied potential in volts (V), I is the current in amperes (A) and R is the resistance in ohms (Ω). Remember that Ohm's law has limited validity and applies only to the so-called *ohmic* resistors.

Resistance is due to the interaction of moving charged carriers (electrons) and the fixed atoms or ions in a conductor. Due to the applied potential difference, moving charge carriers drift from higher to lower potential and in the process, collide with the atoms of the material. This results in increased vibrations of the atoms. The increased kinetic energy raises the temperature of the conductor because temperature is proportional to the kinetic energy. This is the origin of the heating effect of current, called *Joule*'s or *resistive* heating.

3.2 Power Dissipated

The electric power P fed into any circuit component is given by,

$$P = VI. \tag{2}$$

If the component is a resistor, this power is dissipated as heated. Using Ohm's expression (1), we obtain,

$$P = I^2 R. \tag{3}$$

We know that power is

$$P = \frac{\text{energy}\,(E)}{\text{time}\,(t)}, \tag{4}$$

and substituting P with (2) we obtain,

$$E = VIt. \tag{5}$$

Q 1. Suppose we have two heating elements with identical lengths, but one has a higher resistance than than the other. Both are connected to identical voltage sources. Which of the elements will be heated more, the higher or the lower resistance element?

Q 2. Suppose we have two heating elements made from the same material, nichrome, commonly used in domestic heaters? One is twice the length of the other but the area is also doubled, so the two elements have the same resistance. They are connected to identical supplies for the same amount of time. Which wire would acquire the higher temperature?

3.3 Magnetism in Materials

To a very good first approximation, the origin of magnetism in materials lies in the motion of electrons. The magnetic material can be thought of as being composed of *elementary magnets* also called *magnetic dipoles*. These are similar to tiny magnets with a north and south pole. An atom contains electrons in motion. These electrons constitute a current and hence, produce a magnetic field. One such atom can be thought of as an elementary magnet. Now the material as a whole, will be made up of many elementary magnets. The arrangement and orientation of these elementary magnets determine the overall magnetic properties.

3.3.1 Paramagnetic materials

In paramagnetic materials, the elementary magnets are all randomly oriented. Suppose, we draw a tiny vector corresponding to the orientation of the dipole. Now take the vector sum of these dipoles. What do we get? The resultant is zero, showing that in the absence of an external field, the paramagnetic material is unmagnetized. However, this observation does not mean that there are no elementary magnets. The elementary dipoles still exist; it just happens that they completely cancel the effect of one another.

Once we apply an external field with intensity H, the dipoles rotate and *tend* to orient in the direction of the field. This overall alignment results in a net *magnetization* M of the sample. The alignment, however, is by no means perfect. Being perfect only at absolute zero temperature, at any higher temperature, the thermal agitation will kick them out of perfect alignment. The situation is clearly depicted in Figure 1. The light purple arrow shows the direction of the magnetization vector, that is defined as,

$$\overrightarrow{M} = \frac{\sum_k \overrightarrow{\mu}_k}{V}, \tag{6}$$

where μ_k is the *dipole moment* of the elementary magnet and V is the total volume of the sample [1, 2].

3.3.2 Ferromagnetic materials

On a microscopic level, approximately *millionth* of a meter, metals look like drought struck soil of the summer sun. These 'cracked segments' are called *grains* and the cracks are called *grain boundaries* (see page 54 of [2]). As the name suggests, grain boundaries separate one grain from another.

Ferromagnetic materials are quite distinct in their character from paramagnetic materials. Ferromagnets have regions called *magnetic domains*. Elementary magnets within each domain

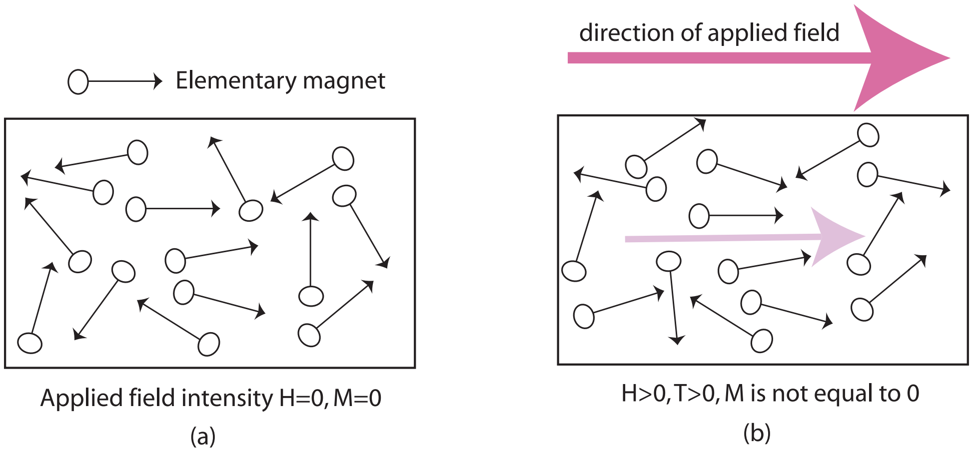


Figure 1: The alignment of the elementary magnets in a paramagnetic sample. (a) Shows the situation when the applied field is zero. (b) As the applied field intensity H is increased, the magnets preferentially tip in the direction of the applied field, resulting in a net magnetization of the sample.

are aligned with respect to one another, even though the domains can be aligned in all possible directions.

Now, one grain can comprise more than one domains. Figure 2(a) is a simplified representation of a polycrystalline material. The grain boundaries are shown as black lines whereas the *domain walls* are drawn as red lines. Within each domain, the net magnetization is represented by the purple coloured arrows. The individual domains are randomly oriented (Figure 2(c)). For the same reason, even a strongly magnetic material such as iron can be unmagnetizaed in the absence of a field.

As the applied field intensity H is increased, the domains that are favourably aligned, *i.e.*, tilted towards the applied field, grow in size and the unfavourably oriented domains shrink (Figure 2(d,e)). As the applied field is ramped up, the growing domain engulfs the smaller domains with the result that there is one domain per grain (Figure 2(f)). Finally, with a sufficiently strong field, the magnetization of the grain (=magnetization of the domain) rotates so as to align itself with the applied field.

3.3.3 Curie temperature

Ferromagnets have a much higher magnetization than paramagnets. In addition, the phenomenon of ferromagnetism comes about due to a totally different mechanism. In ferromagnetic materials, the elementary magnets act in a cooperative fashion, forcing neighbouring magnets to align within themselves. Soon all elementary magnets within a domain are unitedly pointing in one direction. This configuration lowers the energy, called the *exchange energy*.

The exchange energy, however, acts in conflict with the thermal energy that tends to misalign the elementary magnets. As the temperature is increased, the thermal energy starts dominating over the exchange energy and the magnetization drops. However, the material is still ferromagnetic as the domain structure is preserved. Above a critical temperature, the *Curie*

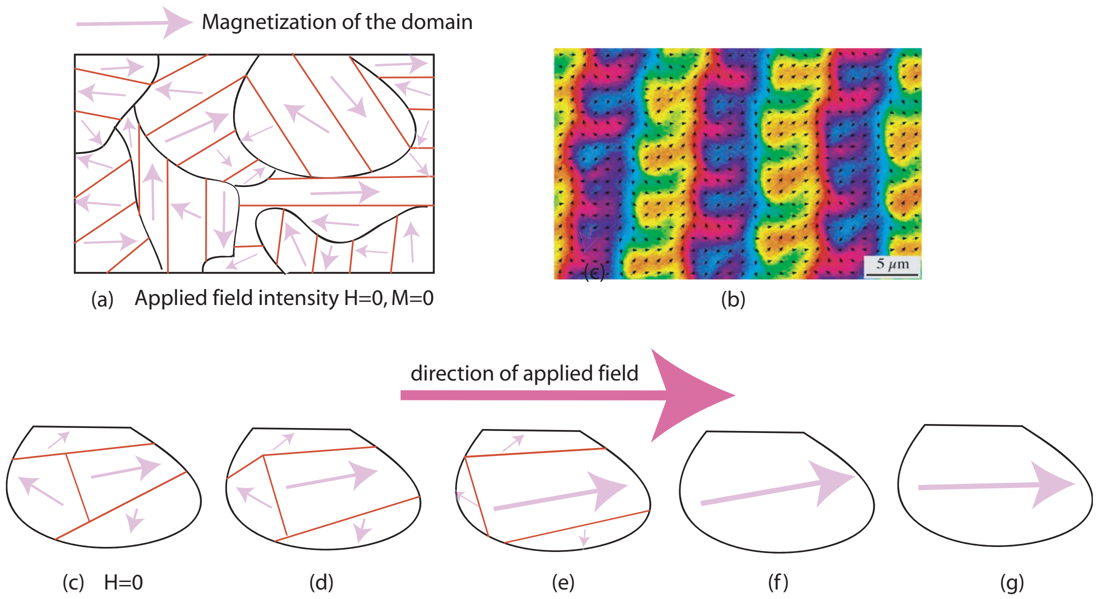


Figure 2: The magnetic moments, domains and grains in a ferromagnetic material. (a) The grains and domains in a polycrystalline material. One grain comprises several domains and the magnetization within a domain is indicated by a purple arrow. (b) Domain microstructure of an amorphous ribbon (figure extracted from [3]). (c-g) Illustrations for a single grain. (c) The magnetization is zero in the absence of the applied field intensity H. (d-f) As the applied field increases, domains grow and shrink, to the extent that there is only one domain per grain, and (g) finally, the magnetization rotates in the direction of the applied field.

temperature T_c, the ferromagnet suddenly turns into a paramagnet. The T_c's of the most common ferromagnets are presented in Table 1.

Element	T_c (°C)
Fe	770
Ni	358
Co	1127
Gd	16

Table 1: Curie temperatures for common ferromagnetic elements [1].

4 Apparatus and Experimental Preparation

There are several examples of undergraduate experiments [4, 5, 6] used to determine the T_c for various materials. The present experiment is an adaptation of the approach followed in [6].

A schematic sketch of the apparatus is shown in Figure 5 and photographs of some of the components are presented in Figure 4. Given below is a short description of the equipment used. You are required to note down answers to the following questions, before you start the experiment in the lab. Carefully observe the experimental setup and remember, **"do not**

switch on the mains power supply".

Your experiment starts here!

1. **Variac** The variac (*Electrodynamic Works, Karachi*) is a variable transformer. The ac mains supply from WAPDA (or the local generator) is connected across the primary coil and the variable output is taken from the sliding contact on the output side. The voltage is step down in the ratio of

$$\frac{V_{out}}{V_{in}} = \frac{N_{out}}{N_{in}} = \frac{I_{in}}{I_{out}}, \tag{7}$$

where N_{in} and N_{out} are the total number of turns in the primary coil and the turns between the output tap and ground (Figure 3).

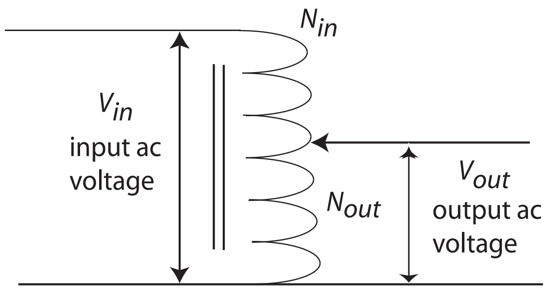


Figure 3: Simplified internal construction of a variac.

★ **Q** 3. The input of the variac is connected to the 220 V mains. The output is connected to a load resistor that draws a current of 5 A. If the ratio $N_{in}/N_{out} = 2/1$, what is (a) the output voltage and (b) the input current drawn from the mains?

★ **Q** 4. How is the variac different from an ordinary transformer?

2. **Digital multimeter** A digital multimeter (*GW-Instek GDM-451*) measures the output voltage from the variac.

3. **Clamp meter** Currents are measured with the help of a clamp meter (*Kyoritsu*). The jaws of the clamp meter surround the wire through which the current is to be determined.

★ **Q** 5. How does a clamp meter work? Discuss with the demonstrator.

★ **Q** 6. Will the clamp meter work for direct current (dc)?

★ **Q** 7. For alternating current (ac), the direction of the current is constantly changing, but the clamp meter shows one positive current reading. Resolve this apparent anomaly.

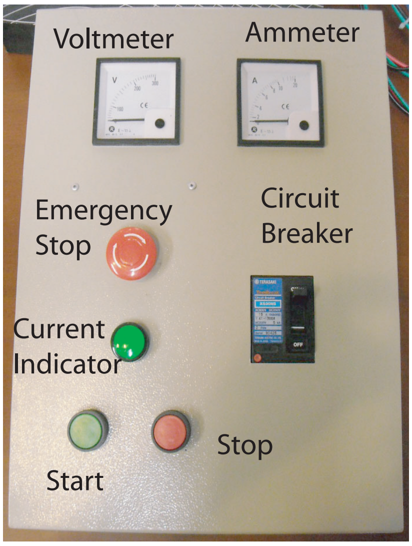
4. **Control box** The control box has been designed and assembled in-house and serves as the main electric distribution box for the experiment.

The panel is fitted with an analog voltmeter and ammeter that measure, respectively, the ac mains voltage and the current through the heating element (to be discussed later). However, we will use the clamp meter for the most accurate current readings. The box is also fitted with a red emergency stop button. **Press this button in case of**

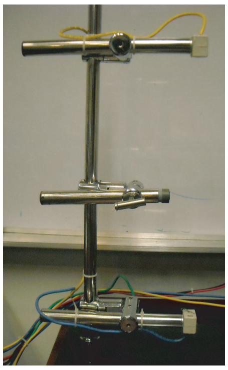
(a)

(b)

(c)



(d)



(e)

Figure 4: Photographs of selected components: (a) variac, (b) digital multimeter, (c) clamp meter, (d) electric panel box (control box), (e) pole for ferromagnetic heating element.

leakage of current or fear of electric shock. The button can be reset by turning it clockwise and releasing.

The control box is also fitted with a circuit breaker (*Terasaki*) rated at 15 A. As soon as the current goes beyond the rated value, the circuit breaker trips and opens the circuit; the current drops to zero.

For electric protection of the circuit components, a magnetic contactor (*NHD Industrial Co., Taiwan, SC-16*) has also been used. Ask your demonstrator if you want to know more about the working of the contactor.

The exposed metal parts of the apparatus, including the mounting screws of the control box, have all been earthed. This prevents electric shocks if by accident or damage, a live wire comes in contact with the metal body.

★ **Q** 8. What is the difference between a circuit breaker and a fuse?

★ **Q** 9. Why are ammeters connected in series?

Internal wiring of the control box.

★ **Q 10.** What is the function of the earth wire? Draw a simple diagram to describe your reasoning. If in doubt, ask the demonstrator.

★ **Q 11.** What is the role of the magnetic contactor in the circuit?

5. **Ferromagnetic heating element** In our experiment, current passes through a ferromagnetic heating element. The element we have chosen is a commercially available material called *Kanthal-D* (*Kanthal* and *Hyndman Industrial Products*). We will use a heating element approximately 100 cm in length and wound into a spiral shape. Important dimensions of Kanthal-D wire required in this experiment are listed in Table 2.

Quantity	**Value**
Mass	2.35 ± 0.01 g
Diameter	0.723 ± 0.02 mm
Length	100 ± 0.1 cm

Table 2: Dimensions of Kanthal-D wire [7].

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Some properties of Kanthal-D alloy are also presented in Table 3.

★ **Q 12.** Define specific heat capacity and derive its units.

★ **Q 13.** Define resistivity and derive its units.

★ **Q 14.** Does the specific heat capacity change with temperature?

6. **Pole for Kanthal and magnet assembly.** The pole for the Kanthal and magnet assembly was fabricated locally (*Noor Trading and Consultancy, Rawalpindi*) and modified in-house. The Kanthal wire is hooked up between porcelain insulators fixed to the top and bottom arms (see Figure 4(e)). The middle arm has an array of ferrite disk magnets (*Hall Road*) epoxied onto an alumina silicate base. The whole pole assembly is made of mild steel.

Property	Value
Composition	83.2%Fe 22%Cr 4.8%Al
Specific heat capacity c	460 K kg^{-1} K^{-1}
Resistivity ρ at 20°C	1.39 Ωmm^{-2} m^{-1}.
Emissivity ε	0.7
Density	7.25 g cm^{-3}
Melting point	1500°C

Table 3: Important properties of Kanthal-D alloy [7].

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Suspension insulators used
with electric towers

★ **Q** 15. Why have we used porcelain for mounting the heating element on the pole?

★ **Q** 16. Why have we used metal to construct this pole?

★ **Q** 17. Why cannot we attach the magnets directly to the metallic post? Why do we need to insert the alumina silicate ceramic in between?

★ **Q** 18. In the experiment we will use a tester to detect current leakage. The tester is made to touch a conductor. If the conductor is live, a small bulb inside the tester will glow. How does a tester work?

5 Experimental Method

5.1 Inspection

The mains supply is still switched off. Follow all rules and safety procedures. In this section we will test the safety features of the circuit.

The electric current in this experiment can kill! Follow all rules.

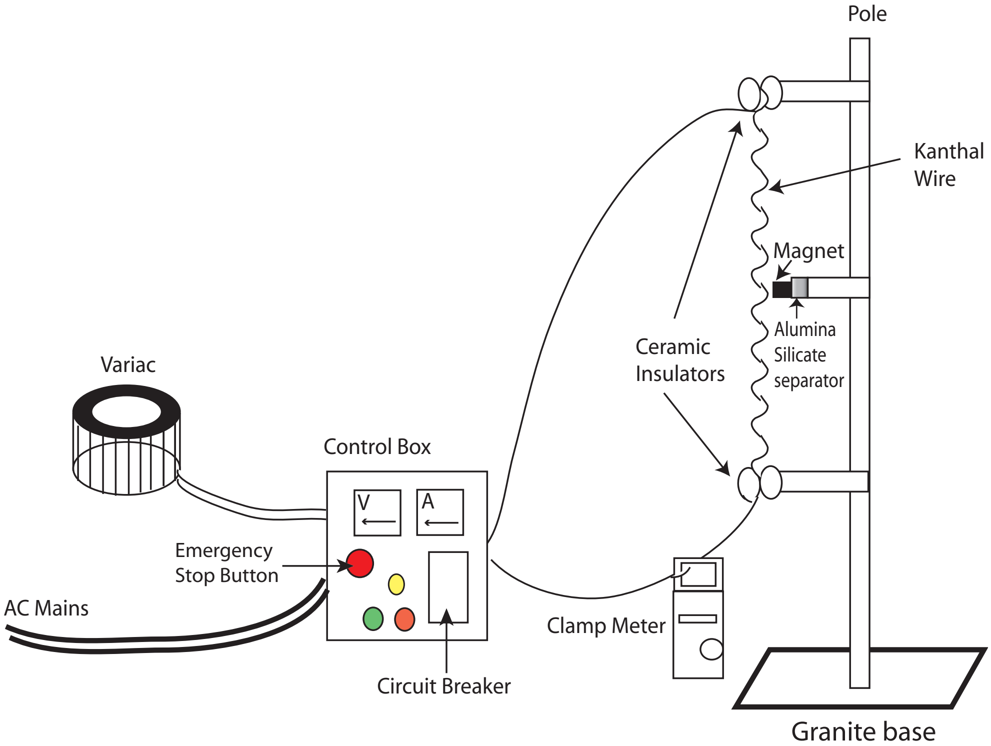

Figure 5: Schematic diagram of the experimental setup.

★ **Q** 19. Visualize and sketch a possible circuit diagram for the experiment?

★ **Q** 20. Check the zero error for the analog voltmeter and ammeter on the control box. Use the adjusting screw at the base of the pointer to correct.

★ **Q** 21. Attach a three-pin shoe to the control box.

★ **Q** 22. What are the different colour codes for wires in live, neutral, earth? Suggest why do we have two additional colours.

Ask the demonstrator to check the electrical connections. Do not attempt to switch on the mains supply in the absence of the demonstrator.

★ **Q** 23. Set the regulator on the variac to its minimum output voltage, zero. The demonstrator will switch on the mains supply. Press the green START button on the control box.

★ **Q** 24. Check that there is no current leakage using a tester in **all** three components (variac, control box and pole). Put the tester on bare metal surface to check for leakage.

★ **Q** 25. Slowly increase the output voltage (voltage from the output of the variac) to 15 V (measured on the digital multimeter). Check for current leakage again.

★ **Q** 26. What is the reading on the clamp meter?

★ **Q** 27. Test the emergency stop button. Does the clamp meter reading go to zero? If it doesn't, immediately inform the demonstrator.

★ **Q** 28. Set the regulator on the variac to its minimum output voltage, zero, again and

press the green START button.

★ **Q** 29. Test the circuit breaker, using the test button.

★ **Q** 30. Hook the clamp meter to the WAPDA mains and measure the current. For this experiment you need to attach the clamp meter to any one of the output voltage wire of the variac.

5.2 Measurement of Curie temperature

★ **Q** 31. Press the green START button, set the output voltage regulator on the variac to 24 V and press STOP.

★ **Q** 32. You are required to measure the current (using the clamp meter) and the time Kanthal wire takes to reach the Curie temperature. You will be provided with a stopwatch. Press the green START button. When the heating element snaps away from the magnet, immediately press the red STOP button to switch off the circuit.

★ **Q** 33. Repeat the experiment twice or thrice at one voltage setting. Allow the heating element to sufficiently cool between two successive measurements.

If the wire does not reach the Curie point within one minute, STOP the experiment and inform the demonstrator.

★ **Q** 34. Repeat the experiment five times, **always** keeping the voltage in the range 23-30 V.

★ **Q** 35. Switch off the mains supply.

5.3 Calculations

The electrical energy supplied in a certain interval of time is defined in Equation (5). In the present experiment, this energy is used up in two processes:

1. absorbed by the heating element, raising its temperature from the ambient room temperature T_0 to the Curie temperature T_c; and
2. radiated away by the heating element.

The energy absorbed E_a may be expressed as

$$E_a = mc(T_c - T_0) \tag{8}$$

where m is the mass of the wire and c the specific heat capacity given in Table 2 and 3, respectively.

The energy radiated (E_r) form the wire is,

$$E_r = \varepsilon\sigma S(T_c^4 - T_0^4)\, t \tag{9}$$

where T_c is the Curie temperature ε is the emissivity, σ is the Stefan-Boltzman constant ($\sigma = 5.675 \times 10^{-8} W/m^2K^4$) and S is the surface area of the heating element.

★ **Q** 36. Using Equations (5),(8) and (9) and the principle of energy conservation, write down the energy balance equation.

★ **Q** 37. Express your final equation in terms of the data obtained in the previous section. This step requires some careful thinking. You will obtain an equation with the unknown variable T_c.

★ **Q** 38. Run Matlab on the PC and solve the energy balance equation using the command,

>>**solve('equation')**.

where *equation* is inserted within single quotes and represents the Matlab format for the energy balance equation.

★ **Q** 39. What are the four different numbers that you see? Which one will you choose?

★ **Q** 40. Convert you answer to degrees Celsius. What is the T_c for the Kanthal-D alloy?

★ **Q** 41. What are the major sources of error in your calculation of T_c?

6 Experience Questions

1. While using a tester, does the current really pass through us?

2. Why do our muscles jerk when we get an electric shock?

3. Can high magnetic fields effect our nervous system?

7 Idea Experiments

1. What is the Hall effect? Use a Hall effect sensor to measure the magnetic field due to permanent magnets of various shapes and strengths [8].

2. Ferromagnetic materials display the phenomenon of hysteresis. Build a teaching apparatus that demonstrates hysteresis [9].

3. Drive an electric bulb at various frequencies. Plot the voltage-current relationship and see whether the resistive element in the bulb satisfies Ohm's law. Furthermore, demonstrate hysteresis in the behaviour of the resistive element [10].

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