EXPERIMENT 5
TO INVESTIGATE THE TEMPERATURE DEPENDENCE OF RADIATION FROM A HOT FILAMENT

Structure

5.1 INTRODUCTION

We all know that a material body necessarily emits radiations of different wavelengths at all temperatures above absolute zero. In this process, energy is carried by electromagnetic waves from the hot object to the surroundings: the hotter the object, the greater is the energy radiated. Our best known source of radiation is the Sun. At night, the earth cools by radiating energy. Radiative transfer is the dominant mode of transfer of thermal energy in interstellar space as well as our galaxy. In our immediate surroundings, energy is transmitted from the cooking stoves, the fire-places, an ordinary incandescent lamp etc. Our body radiates and loses ample energy through the skin.

As such, the term radiation embraces the entire range of wavelengths - from γ rays to microwaves, radiowaves and beyond. Our eye is sensitive only to a small portion of wavelengths extending from about 4000Å to 8000Å, which is termed the visible region. The infra-red (λ > 8000Å) wavelengths, though invisible to the eye, carry rather large amounts of energy and produce in us the sensation of warmth. When we use hot water bottles or heating pads, or resort to hydrotherapeutic treatment like sedative bath or steam inhalations, infra-red waves are the carriers of thermal energy. Now you may like to know: What laws govern the emission and absorption of thermal radiations? In your school physics curriculum you have learnt these laws. You got another opportunity to learn their physical basis in the PHE-06 course on Thermodynamics and Statistical Mechanics. Though we have repeated the essential physics arguments in Sec. 5.2, we would like you to refresh your knowledge for better comprehension before you proceed.

In this experiment, we propose to study power radiated by an electric bulb since we expect it not to be substantially different from that due to a black body. The thermodynamic property that we wish to investigate here is temperature variation of the resistance of an electric bulb. You had performed a similar experiment in the course PHE-03(L), entitled Physics Laboratory-I. Therefore you are advised to go through that experiment again to recapitulate the niceties of physics principles in operation.

Objectives

After performing this experiment, you will be able to

- use a metre bridge in Wheatstone's network
- measure the variation of resistance with temperature
- estimate the temperature of the hot filament, and
- determine the temperature dependence of the power radiated by a body.

5.2 BASIC PRINCIPLES REVISITED

The credit for giving a quantitative explanation of energy radiated and absorbed by a body goes to Kirchhoff.

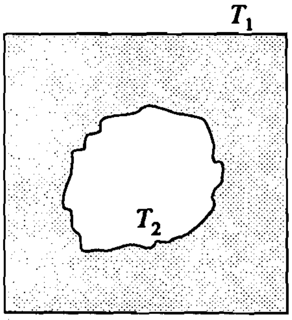

Fig. 5.1: An insulated object at temperature T_2 is surrounded by walls at temperature T_1. Both surfaces absorb and emit energy.

Every substance emits electromagnetic radiation. The frequency and intensity of the emitted radiation depends on the nature and temperature of the substance. For example, we can see a portion of the energy emitted by a glowing ember which is at a high enough temperature. In the case of a warm stove, which is at a comparatively lower temperature, we can feel the radiation coming from it. All objects emit as well as absorb radiation. And the ability of a body to radiate is closely related to its ability to absorb radiation. To understand this point better, refer to Fig. 1 which shows an object at temperature T_2 surrounded by walls at temperature T_1 ($> T_2$). Experience tells that these temperatures eventually approach the same value and the system is said to have attained thermal equilibrium at some intermediate temperature T. Then the surface of the enclosed object must emit and absorb energy at the same rate, and so must the surrounding wall surface to maintain thermal equilibrium. That is, at temperature T, each surface must absorb and emit energy at the same rate. Thus, a good absorbing surface is also a good emitting surface. And a poor absorbing surface is a poor emitting surface. This correspondence suggests that the rate of energy emission of a given wavelength is equal to the rate of absorption of the same wavelength. Its manifestations in everyday life are many. When a piece of china with a dark pattern on a white background is examined immediately after being heated to red hot in a dark room, the pattern appears brighter than the background, i.e., the dark pattern is a good emitter as well as a good absorber. Thus, an ideal emitting surface would also be an ideal absorbing surface. An ideal absorbing surface would absorb all radiation incident upon it, regardless of frequency and none would be reflected. Since no incident radiation is reflected from the ideal emitter-absorber, it is called a **black body. The sun is the most striking example of a black body in nature**. In the laboratory, a black body can be approximated by a hollow cavity with a small hole leading to its interior. Any radiation incident on the hole enters the cavity and is trapped. How? It undergoes reflection back and forth until it is absorbed.

A black body is idealisation only. In reality, no material has a surface with emissivity equal to one.

You must have experienced that when an iron bar is heated, its colour changes progressively from dull red to bright orange-red, and eventually to whitish, i.e., the apparent colour of the body depends on its temperature. The reason is that a body radiates more when it is hot than when it is cold. Thus, the rate at which energy is emitted (absorbed) depends directly on temperature. It also depends on the wavelength of the emitted energy. The dependence of energy emitted per second per unit area of a black surface on the wavelength of the emitted radiation is shown in Fig.5.2 for several temperatures. From Fig.5.2 you will notice that each curve has a peak at a wavelength λ_{max} at which the energy emitted per unit area per unit time is maximum. As T increases, λ_{max} shifts to shorter wavelengths. In fact, it is found experimentally that $\lambda_{max} T$ = constant. This is known as **Wien's displacement law.** The sun emits electromagnetic radiation whose energy distribution corresponds approximately to radiation from a body with a temperature of 6000 K. Surprisingly, light from a filament lamp has a distribution corresponding to the wire at a temperature of about 2000K.

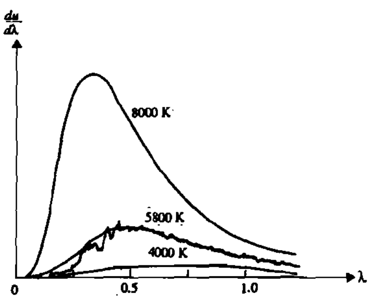

Fig. 5.2: The energy emitted per second per unit area of surface at wavelength λ. Curves are shown for several surface temperatures.

What about the total energy emitted by a black body at a given temperature? This will be the area under the curves shown in Fig.5.2 at a given temperature. Experiments show that the total energy radiated by a body at absolute temperature T is proportional to its size, its ability to radiate and its temperature. For a black body, the energy radiated per unit time from an area A is $\sigma A T^4$. This is **Stefan-Boltzmann** law. The constant of proportionality is called the Stefan-Boltzmann constant and has the value 5.67×10^{-8} W m^{-2} K^{-4}. The rate at which a body absorbs energy from the surroundings at temperature T_S is $\sigma A T_S^4$. Hence, if the temperature of the black body is greater than that of the surroundings (T_S) the net rate of energy loss is given by

$$\frac{dQ}{dt} = \sigma A\,(T^4 - T_S^4)$$

To give you a feel for the numbers, let us calculate the energy radiated per second by a tungsten filament of surface area 0.3 cm^2. If the temperature of the filament is 3000K, then

$$\frac{dQ}{dt} = (0.3\times10^{-4}\,\text{m}^2)(3\times10^3\text{K})^4\times(5.67\times10^{-8}\text{W m}^{-2}\text{K}^{-4})$$
$$= 137.8\text{W}$$

You may also find it interesting to know the rate at which a person ($A = 1.9\,m^2$) radiates energy while sitting in a room maintained at a temperature of 22°C. The temperature of skin is about 28°C (lower than the internal body temperature of 37 °C). If we assume emissivity of skin to be unity, the rate at which energy is radiated out per second is given by

$$Q = \sigma A\,(T^4 - T_S^4)$$

$$= (5.67\times10^{-8}\,W\,m^{-2}\,K^{-4})\times(1.9\,m^2)\,[(301\,K)^4-(295\,K)^4]$$

$$= (10.773\,W\,K^{-4})\,[6.3519\,K^4]$$

$$= 68.4\,W$$

We will now make use of this background information to study radiation of energy from a hot filament. Although you have done a similar experiment in your first Physics Laboratory course [PHE-03(L)], here we would like to show as to how you can investigate the same phenomenon in different ways. The underlying idea is as follows : We know that a filament carrying current I dissipates power (= I^2R where R is its resistance). If we know the temperature dependence of R, we can determine how the power radiated from the filament varies with temperature! Don't you think this is an interesting way to study radiative energy transfer?

Let us now briefly discuss the principle underlying this experiment.

To Investigate the Temperature Dependence of Radiation from a Hot Filament

Energy loss by radiation can be minimised if the radiating surface is made a good reflector of electro-magnetic radiation. It is for this reason that a thermos flask consists of a double walled glass vessel whose walls are coated with silver. When a hot liquid is put inside, the energy radiated out is reflected back by the silver coating. The outer silver coating prevents radiation from coming in.

5.3 THEORY OF THE EXPERIMENT

You have studied in Sec.5.2 that the energy radiated per second by a black body is proportional to the fourth power of its temperature (taken in kelvin). Even in the case of other bodies, the radiation is expected to depend on some power of temperature. To study the variation of power (energy per unit time) radiated with temperature by an incandescent electric bulb filament, we connect it in a Wheatstone bridge, as shown in Fig.5.3. Here S is a standard resistance, x and y signify two segments of the metre bridge and R_T denotes the resistance of the filament in the lamp at its operating temperature. These resistances are connected in the arms BC, AD and AB, respectively. A galvanometre G is connected between B and D and shows deflection on both sides of the zero mark, which is in the centre of the scale. When the bridge is balanced, no current flows through the galvanometer. It signifies that B and D are at the same potential.

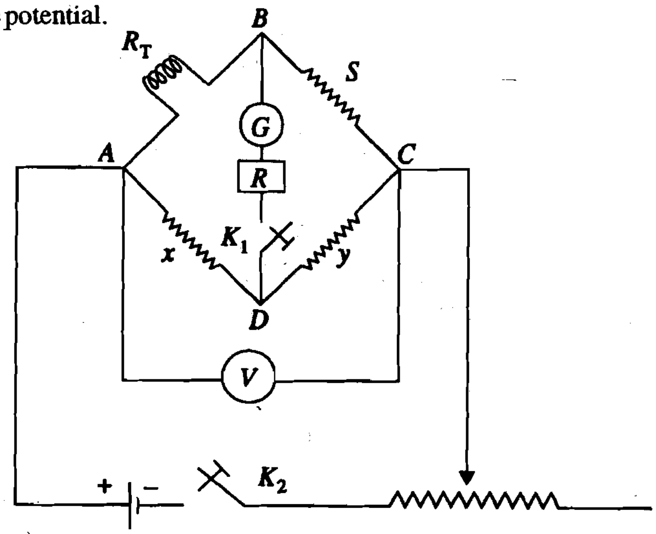

Fig.5.3: Wheatstone's bridge

For a balanced bridge, the following condition holds good :

$$\frac{R_T}{S} = \frac{x}{y} \qquad (5.1)$$

It shows that the unknown resistance R_T can be determined once we know the other three resistances. What would you do to ensure maximum sensitivity of the bridge ? All four resistances should be of the same order. We can rewrite Eq.(5.1) as

$$\frac{R_T+S}{S} = \frac{x+y}{y} \tag{5.2}$$

Suppose that the potential difference between points A and C, i.e., across R_T and S together, is V. You can read it easily from the voltmeter shown in Fig.5.3. The power dissipated in the filament is given by the expression

$$P = I^2 R_T$$

When the bridge is balanced (the galvanometer shows no deflection), the current in the circuit is given by

$$I = \frac{V}{R_T+S}$$

so that the expression for power dissipated in the filament takes the form

$$P = \frac{V^2}{(R_T+S)^2} R_T$$

Using Eqs. (5.1) and (5.2), we can rewrite it as

$$P = \frac{V^2 y^2 R_T}{(x+y)^2 S^2} = \frac{V^2 x y}{S(x+y)^2} \tag{5.3}$$

Since the current in the circuit can be altered by means of the rheostat, it is possible to obtain null condition for different currents. In each case we shall obtain a new set of x and y. Therefore, we can obtain a set of values of R_T and P, corresponding to different currents (or temperatures) using Eqs. (5.1) and (5.3), respectively. Thus, by allowing varying currents to flow through the filament, you alter its temperature, and hence its resistance and the power dissipated through it. Now, if you draw a graph between P and R_T and extrapolate it to $P = 0$, you will obtain the resistance (R_0) of the filament at zero current.

You may recall a similar exercise from your first level physics laboratory course. For completeness we have repeated the details.

From a graph which relates R_T/R_0 with T (and should be available in your Study Centre physics laboratory), you can read the temperature corresponding to each value of R_T, without actually having to measure it in the laboratory. From these values of P and T, it is possible to determine the temperature dependence of the power radiated. Let us assume that P is proportional to T^n. That is,

$$P = \alpha T^n$$

where α is the constant of proportionality.

On taking natural logarithm of both sides, we get

$$\ln P = \ln \alpha + n \ln T \tag{5.4}$$

If you draw a graph by taking $\ln T$ along the x-axis and $\ln P$ along the y-axis, you will obtain a straight line whose slope gives n. Theoretically, n should come out to be four, but you should not be surprised if it has a value other than this.

In case the R_T/R_0 versus T graph is not available in physics laboratory of your study centre, it is still possible to determine n using the following alternative procedure.

Since R_T is proportional to T, we can write

$$P = VI = \alpha (R_T)^n$$

or

$$VI = \alpha \left(\frac{V}{I}\right)^n$$

so that

$$I^{n+1} = \alpha V^{n-1} \quad (5.5)$$

Taking natural logarithm of both sides, we get

$$(n+1) \ln I = \ln \alpha + (n-1) \ln V$$

or

$$\ln I = \frac{\ln \alpha}{n+1} + \frac{n-1}{n+1} \ln V \quad (5.6)$$

Do you recognise the form of this equation? It is the equation of a straight line ($y = c + mx$)

with $m = \frac{n-1}{n+1}$. By inverting this result, we find that

$$n = \frac{m+1}{1-m} \quad (5.7)$$

Thus, the slope of the ln I versus ln V curve would yield n.

We are sure that now you have understood the basic principle of this experiment. However, if you have any doubt, go through this section once again carefully.

Before doing the experiment, you should know the apparatus and the method of setting it.

Apparatus

Metre bridge, galvanometer, voltmeters of 0-3V and 0-12V range, 12V battery or low tension power supply, rheostat, two resistance boxes, an incandescent lamp, two one-way tapping keys, jockey and connecting wires.

5.4 SETTING THE APPARATUS

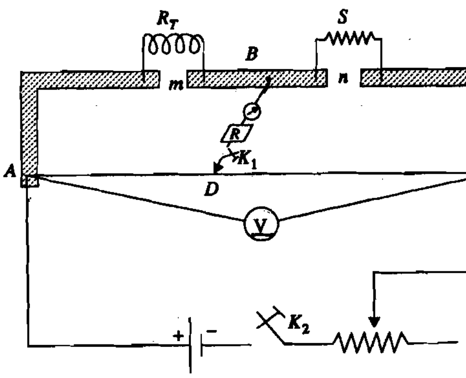

Fig. 5.4: Circuit diagram for studying variation of resistance of a tungsten filament with current

1. Place the metre bridge on the table and keep it so that the gaps in the copper strip are away from you.

2. Refer to Fig.5.4 and identify various terminals. It has two gaps in the copper strip where we introduce the bulb and the known resistance.

3. Connect the galvanometer G between the terminal B and the sliding tapping key (or the jockey) at D through a high resistance R and a tapping key (K_1). You must clean the ends of the connecting wires with sandpaper.

4. Connect the incandescent bulb and the resistance box in gaps *m* and *n*.

5. Connect a battery, a one way tapping key and a rheostat between the terminals *A* and *C*. Also insert a voltmeter between these points to measure the potential difference. Initially insert a dc voltmeter of range 0 – 3V. (Subsequently it should be replaced by one of higher range (0 – 12V).

   The points *A*, *B*, *C* and *D* here correspond exactly to those of the Wheatstone's bridge shown in Fig.5.3.

6. Adjust the rheostat (or the output control of the power supply) so that the voltmeter reads one division.

7. Take out the plug key of the high resistance box. Gently tap the jockey on both ends of the metre bridge wire to ensure that the galvanometer shows deflection on both sides of the zero mark. You should not slide the jockey along the wire. Can you locate the balance point roughly by contacting the jockey somewhere around the centre of the bridge wire? If so, you can be sure that circuit connections are correct and you get ready to take observations. If you do not get deflection on both sides, you should check your connections again and repeat steps 2-6. You should succeed. If you do not, go to your counsellor for help.

5.5 MEASUREMENT OF RESISTANCE

This experiment essentially consists of measurement of resistance as a function of temperature due to applied potential difference. Follow the steps given below.

We know that resistance offered by a wire of cross - sectional area *A*, length *l* and resistance per unit length ρ is given by

$$R = \frac{\rho l}{A}$$

Since l_1 and l_2 are measured for the same wire, ρ and *A* do not change. Therefore, length of the wire will be a measure of resistance offered:

$$x = k\,l_1$$

$$y = k\,l_2$$

where *k* is constant of proportionality.

In Eqs. (5.1) and (5.3) *x* and *y* appear in ratios and the constant *k* cancels out.

1. Insert the plug key of the high resistance. Locate the balance point by moving the sliding key over the bridge wire and tapping it gently at different points. At the balance point, the galvanometer needle should not move at all.

2. Note the position of the balance point with the help of the metre scale mounted along the bridge wire and record your readings for *V*, l_1 and l_2 in the Observation Table 5.1. The lengths l_1 and l_2 are measures for *x* and *y*. Calculate R_T and *P* using Eqs. (5.1) and (5.3) and record the values in the Observation Table 5.1.

Observation Table 5.1 : Measurement of Resistance

Value of known resistance *S* = ... Ω

S. No.	*V* (volts)	*x* (Ω)	*y* (Ω)	R_T (Ω)	*P* (W)	R_T/T_0	*T*(K)	ln*P*	ln*T*
1.									
2.									
3.									
.									
.									
.									

3. Increase the potential difference across the bridge by moving the slider of the rheostat. Take at least five readings in steps of 0.2V and record the corresponding positions of the null point. Complete the Observation Table 5.1 for all these readings.

4. Now connect the voltmeter of higher range and change the potential difference in steps of 0.5 or 1V. It is sufficient to take a total of 15 readings. However, you should limit upto about 5V.

5. Calculate R_T and P in each case using Eqs. (5.1) and (5.3). Draw a graph between V, taken along x-axis, and R_T, taken along y-axis. Extrapolate the graph to meet the y-axis. The intercept gives R_0, the limiting value of resistance for zero current through the bulb.

6. For each value of R_T/R_0, determine the temperature of the filament using the R_T/R_0 versus T graph given to you in the laboratory.

7. Draw a graph between $\ln T$ and $\ln P$. For this graph, it is desirable to use only those readings which correspond to higher potential difference. Calculate the slope of the straight line. This defines the order of dependence of power radiated on temperature.

Comment on your findings in the space given below :

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