# DEVELOPMENT OF APPROPRIATE INSTRUMENTATION AND CONTROL SYSTEMS FOR PALM KERNEL NUTS DRIER


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**PHY/96/8893**


A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF

*MASTER'S OF TECHNOLOGY (M. TECH.)*

IN

*ELECTRONIC MEASUREMENT AND INSTRUMENTATION*


DEPARTMENT OF PHYSICS
FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE
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AUGUST, 2002

# CERTIFICATION

I hereby certify that this project was carried out by **Mr. Ajagunna, Adebowale Olufunso** in the Department of Physics, School of Science, Federal University of Technology, Akure under my supervision.

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# DEDICATION

*To the all sufficient GOD,*

*the Creator of heaven and earth.*

# ACKNOWLEDGEMENT

I acknowledge the matchless grace of the Lord Jesus Christ throughout the period of this work.

My profound appreciation goes to my supervisor, Dr M. T. Babalola for his understanding, love, care, concern and support in the course of this work. May the Lord remember you for good.

My gratitude also goes to the Acting Head of Department of Physics, Dr. (Mrs) I. A. Fuwape, Dr. M.O. Ajewole, Dr. Babatunde Rabiu, Dr. S. O. Ajayi, Dr. M. O. Osiele and a host of other Lecturers in the Physics Department for their assistance. I do appreciate also the support given me by the Laboratory Staff of the same Department, most especially the personal assistance of Mr. Olasoji.

Indeed, I treasure very highly the understanding, patience, and unequalled love of my amiable spouse and precious daughter during this period of study.

To my dear parents, Mr & Mrs A. A. Ajagunna, I say a big thank you for making it a point of duty to always be there for me. I also wish to thank my Sisters and Brothers for their understanding and encouragement. And to all who in one-way or the other have contributed to the success of this work.

Thank you all.

## ABSTRACT

A cabinet drier with dimensions 0.82m x 0.45m x 0.52m, having four trays and capable of drying 4kg of palm kernel per hour was constructed. Using electrical heating, hot air is produced and allowed to flow through the product in order to remove the moisture. The drier is heavily lagged to conserve heat. Type k thermocouple was constructed and used to monitor the temperature. The electronic instrumentation section of the drier has a digital display unit that allows the temperature of the drying chamber to be read. A control circuit for regulating and presetting the temperature of the drier was also developed. This permits the temperature of the drying chamber to be fixed between ambient temperature and 100°C. This drier was found to work satisfactorily, achieving complete drying of the nuts within the temperature range of 80°C to 100°C under 60minutes of its operation without discoloration of the kernels or the resultant extracted oil. It is also suitable for drying several agricultural products under varying temperature condition.

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## NOMENCLATURES

| Symbol | Meaning |
|---|---|
| $X'$ | Moisture content |
| $X'_C$ | Critical moisture content |
| $X'_E$ | Equilibrium moisture content |
| $X'_T$ | Total moisture content |
| $P$ | Pressure of fluid |
| $P_O$ | Saturated vapour pressure of water (fluid) |
| $P_g$ | Saturated pressure of water vapour in the air |
| $\rho$ | Fluid density |
| $\rho_b$ | Bulk density of food |
| $g$ | Acceleration due to gravity |
| $V$ | Velocity of fluid |
| $Z$ | Height above the reference point of fluid |
| $R_e$ | Reynold number |
| $N_u$ | Nusselt number |
| $P_r$ | Prandtl number |
| $G_r$ | Grasshof number |
| $D$ | Diameter of pipe |
| $\mu$ | Fluid viscosity |
| $a_w$ | Water activity |
| $Q$ | Rate of heat transfer |

| | |
|---|---|
| $q$ | Heat flux |
| $M$ | Drying rate |
| $h$ | Convective heat transfer coefficient |
| $h_c$ | Surface heat transfer coefficient for convective heating |
| $U$ | Overall heat transfer coefficient |
| $K_m$ | Mass transfer coefficient |
| $A$ | Area available for heat transfer |
| $\theta_u$ | Air stream temperature |
| $\theta_s$ | Surface temperature |
| $\theta_{source}$ | Average wet-bulb temperature of drying air or Temperature of heat source |
| $\theta_a$ | Average dry-bulb temperature of drying air |
| $\theta$ | Bulk fluid temperature |
| $h_{fg}$ | Latent heat of vapourization |
| $H_s$ | Relative humidity at the surface of the food |
| $H_a$ | Relative humidity of air |
| $G$ | Mass flow rate of air |
| $k$ | Thermal conductivity |
| $a$ | Thermal diffusivity |
| $C_p$ | Specific heat at constant pressure |
| $\beta$ | Coefficient of thermal expansion |
| $\Delta\theta$ | Temperature difference |
| $L$ | Length of pipe |
| $E_b$ | Blackbody emissive power |

| | |
|---|---|
| $T$ | Absolute temperature |
| $\sigma$ | Stefan-Boltzmann constant |
| $\epsilon$ | Emissivity of a body |
| $Q_{inc}$ | Radiation flux incident on a body |
| $Q_{abs}$ | Radiation flux absorbed by a body |
| $\alpha$ | Absorptivity |

## CHAPTER ONE

## INTRODUCTION

There has never been enough food available to feed the whole human family properly. According to Robbele, et al. (1989), even in Great Britain, where nowadays, food is very plentiful, there was recorded famine one year in every ten. Mechanized farming, the liberal use of fertilizers, irrigation and pest control, together with the application of food technology in preserving food between harvests have, in recent years, removed food shortages in the industrialized countries. The shortages remain however in the non-industrialized countries, such as Nigeria.

The present-day food industry has its origins in pre-history when the first food processing took place to preserve foods against famine, or to improve their nutritional quality. For example, grains were sun-dried to extend their shelf life and meat was roasted to improve its flavour. Mechanical processing equipment was developed to reduce the time and labour involved in manual methods. Food processing equipment now allows increasingly sophisticated control of processing conditions to achieve the two aims of reduced processing costs and reduced damages (particularly heat damage) to the sensory and nutritional qualities of foods. Energy saving is also an important feature of most food processing equipment (Fellows, 1990).

According to Robbele, et al (1989), collectively, oil crops and their products are the second most valuable commodity in world trade. Production and trade in these commodities have expanded rapidly in response to a growing world population and rising living standard. This ever increasing demand for oil has necessitated our work in this area.

Some oil crops such as groundnuts are used directly as food, but most crops are processed by pressing and/or extracting to obtain fat or oil and cake. Palm kernel nuts are also an important oil source, with a composition similar to coconut oil (Robbele, 1989). Palm kernels oil (PKO) is a vegetable oil that is derived from the seed which is protected by the endocarp of palm kernel. Nigerians have developed and acquired taste for imported vegetable oil, which in recent times has come primarily from Malaysia and other countries around her. Palm trees grow abundantly in the Southern part of Nigeria. From its fruits, we can obtain palm oil and palm kernel oil (PKO). PKO is a good replacement for imported edible vegetable oil. Therefore, in order to conserve our foreign exchange earnings, it is imperative that efforts should be geared towards improving the Nigerian crude palm kernel oil.

Oils and fats are vital components of the human diet because they are important sources of energy and act as carrier of fat-soluble vitamins. The required fat intake for good health varies with the individual depending on the climate and the work performed. Demand for oil cake arises from its high nutritional value as a result of its high content of good quality protein.

There is a growing awareness of the importance of oils and fats in human nutrition. Robbele, et al. (1989) pointed out that the oil palm produces the largest quantity of oil per unit area of all oil-bearing plants with production in 1989 amounting to 5 to 7 tonnes of oil per hectare. They also emphasized that palm oil became the world's second most important vegetable oil after soybean in 1980 and its production has increased in a spectacular manner, more than doubling during the decade from 1970 to 1980.

The chief significance of the oil seeds and their products is to satisfy the vital demand for oils and fats and for high protein animal feed. About 80% of the fats and oils produced is used for edible purposes and the rest is processed in the technical sector (Richtter and Knaut 1984). Table 1.1 shows some of the uses of palm oil. The list of uses is certainly not exhaustive but it gives some idea of the great variety of possible uses and indeed importance of vegetable oils in the world economy.

**Table 1.1: Examples of the Use of Vegetable Oils**

| Edible Oil Uses | Technical oil uses |
|---|---|
| Cooking oils | Chemicals, candles |
| Fats for the bakery, confectionery industry and mayonnaise manufacturers | Cosmetics |
| | Linoleum |
| Margarine | Lubrication |
| Oils for the fish and canning industry | Paints and resins, coatings |
| Salad oils | Pharmaceutical product |
| Shortenings | Plastic coatings |
| Vanaspati | Soaps |
| | Technical products |

Products of palm kernel nuts such as palm kernel oil (PKO) and soap are in great demand by many consumers. Thousands of people in the southern part of Nigeria are engaged in the business because of its economic importance locally. For example, the locally processed black PKO is used for the following; (a) medically as an antidote against poison to reduce or nullify the effect of poison,(b) as body and haircream,(c) for producing the local black soap. The list is not exhaustive. However, the major setback it has as a cooking ingredient is due to its bad taste, awful odour and black colour which emanates from the contamination of the oil by soot during the drying process. The application of too much heat burns the nuts and turns them black. However, it is realized by the elite class that PKO can be used as edible oil if the nuts are properly dried and the oil is extracted by pressing. Insufficiently dried kernel nuts have shown a much higher rate of increase in free fatty acid (FFA), which lowers the quality of the product (Timms, 1985).

During the dry season, sun drying is found to be efficient and clean. But sun drying is extremely difficult especially during rainy season. This problem was initially brought into focus by a local user of the product who had carried out the drying process using the local methods listed in table 1.2, all of which have failed to yield the desired result because o

some attendant problems.

**Table 1.2: Some Sources of Heating of PK Nuts Locally and attendant Problems**

| Source of Heating | Attendant Problem |
|---|---|
| (a) Fire wood | Nuts acquired a lot of smoke and soot |
| (b) Diesel engine | Nuts acquire a lot of smoke and soot |
| (c) Electricity | Inefficient harnessing of the heat because the heat from the source did not get to the nuts |

Objectives of this project are to:

(i) Remove any moisture content in the stored palm kernel nuts before using it for any product manufacture and

(ii) Remove any moisture content that may also accompany the dried nuts within the drier as a result of vapour condensation.

(iii) Construct a machine of high efficiency, which will conserve energy during drying process and give us a cleaner PKO than hitherto produced by local manufacturers.

(iv) Design and construct the electronic instrumentation and control systems for regulating and presetting the temperature of the machine

The problems discussed above will be examined critically and solved in a rather more scientific fashion. The source of heating is electrical. The method of drying will be by using heated atmospheric air, which is controlled to transfer the necessary heat of evaporation to the palm kernel nuts.

CHAPTER TWO

# 2.0 LITERATURE REVIEW

## 2.1 OIL PALM (ELAEIS GUINENSIS)

The oil palm (*Elaeis Guinensis*) is a perennial plant indigenous to tropical West Africa. It is found naturally in semi-wild groove or under cultivation throughout most of the tropics between latitude $15^0$N and $15^0$S. It requires hot humid conditions. It is a unique crop in that it is one of the world's main sources of edible and soap making oil, and yields more oil per year than any other oil-bearing plant in Nigeria.

The two most important products of the palm tree are the palm oil and the palm kernel, both of which are obtained from the fruits. The fruits are harvested when they are ripe enough and still fresh. Over-ripening increases the percentage of FFA, which decreases the quality of palm oil.

Two types of oil are obtained from the oil palm, palm oil (from the pericarp) and the palm kernel oil from the endocarp that is, the hard nut inside the fruit of palm tree. Palm oil and the kernel oil became important in the latter part of the 19th century as industrial oils mostly secured from West Africa. It is interesting that although both oils are derived from the same fruit, their characteristics are different and the processing of palm oil can affect the quality of the palm kernel seed.

The quality of the palm fruit is judged mainly by its oil, shell and dirt contents, while that of the PKO is judged mainly by its FFA. Palm kernels constitute about 45-48% (by weight) of the palm fruit. On a wet basis, the kernels contain about 47-50% by weight of oil whose properties and characteristics are quite different from palm oil.

### 2.1.1 PRODUCTION OF PALM KERNELS

In the kernel recovery process, the nuts contained in the cake discharged by the press are separated from the fiber in a depericarper. They are then dried and cracked in centrifugal crackers to release the kernels. The kernels can be separated from the shell by using a combination of winnowing and hydrocyclones.

During the nut-cracking process some of the kernels are broken. The rate of FFA increases much faster in broken kernels. Breakage of kernels should therefore be kept as low as possible given other processing considerations. Steam sterilization of the wet kernels for several minutes prior to drying was reported to reduce the rate of increase of FFA in the kernels during storage.

Teoh and Muh (1985) recommended that kernels must be dried to moisture content of about 7% before packing.. Drying of kernels is normally carried out using hot air and provided the temperature of the air does not exceed 80°C, no discoloration of the kernels occurs (Jorgensen, 1985). Figure 2.1 shows the flow diagram of the drying processes.

### 2.1.2 FACTORS AFFECTING THE QUALITY OF PALM KERNEL

Strict quality control right from fruit processing to kernel extraction is necessary to ensure production of good quality oil and other by-products. The primary aim of the processes is to maximize oil recovery from the kernels. As the quality of the final product is dictated primarily by the quality of the raw material, the kernel processor usually is very concerned about the nature and quality of the kernel he receives from the suppliers.

The parameters analyzed invariably are dirt and shell content, oil content, and the colour of kernels. There is the need to check for the ratio of whole nuts to broken nuts which results from kernel cracking because excess of broken nuts result in a rise in FFA of

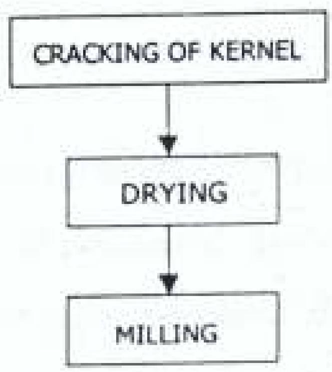



Fig. 2.1: Flow diagram of the drying process

the extracted oil. The moisture content and the mode of storage which can cause the moldiness of the nuts are also very important factors that must be reckoned with. All these parameters can affect the yield and quality of the products.

Out of these factors, our work will be directed towards the design and construction of a drier to remove the moisture content since the problem of drying the nuts is still there and methods of drying locally have so far proved inefficient.

## 2.2 FLUID FLOW

Many types of fluid are transported during processing. Gases obey the same laws as liquids and for the purposes of calculations; gases are treated as compressible fluids. The study of fluids is therefore of great importance in food processing. It is divided into fluid statics and fluid dynamics.

One property of a static fluid is the pressure that it exerts on the containing vessel. The pressure is related to the density of the fluid and the depth of fluid in the vessel. Fluids at the base of a vessel are at a higher pressure than those at the surface, owing to the weight of fluid. It is important in the design of holding tanks and processing vessels to ensure that the vessel is constructed using materials of adequate strength.

When a fluid flows through a processing equipment, there are friction losses and changes in the potential energy, kinetic energy and pressure energy. Energy is also added by pumps or by heating the fluid.

To calculate the energy balance when a liquid flows through a pipe-work, Bernoulli's equation is made use of. This equation holds for non-compressible fluids only.

$$\frac{P_1}{\rho_1} + \frac{V^2_1}{2} + Z_1 g = \frac{P_2}{\rho_2} + \frac{V^2_2}{2} + Z_2 g \qquad (2.1)$$

where P is the pressure, $\rho$ is the fluid density, g is the acceleration due to gravity, V is the velocity of the fluid and Z is the height above the reference point. The subscripts 1 and 2 indicate the first and second positions in the pipe-work respectively.

In any system in which a fluid flows, there exists a surface film of fluid next to the surface over which the fluid flows (figure 2.3). The thickness of the boundary film is influenced by a number of factors including, the fluid velocity, viscosity, density and temperature. Fluids, which have a low flow rate or high viscosity may be thought of as a series of layers which move over one another without mixing. This produces movement of the fluid in a single stream, which is termed laminar flow. In a pipe, the velocity of the fluid is highest at the centre and zero at the wall. Above a certain flow rate, which is determined by the nature of fluid and the pipe, the layers of liquid mix together and turbulent flow is established (figure 2.4).

Fluid flow is characterized by a dimensionless parameter termed the Reynolds number $R_e$, which is given by the formula.

$$R_e = \frac{DV\rho}{\mu} \qquad (2.2)$$

where D is the diameter of the pipe, V is the average velocity, $\rho$ is the fluid density and $\mu$ is the fluid viscosity.

A Reynolds number of less than 2100 describes laminar flow and Reynolds number of more than 4000 describes turbulent flow. For Reynolds numbers between 2100 and 4000, transitional flow is present, which can be either laminar or turbulent at different times. These different flow characteristics have important implication for heat transfer and mixing operations. Turbulent flow produces thinner boundary layers, which in turn permits higher rates of heat transfer. In turbulent flow, particles of fluid move in all directions and solids

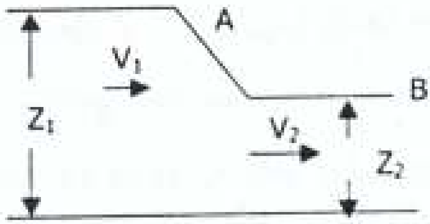



Fig. 2.2: Fluid Flow through a Pipe.

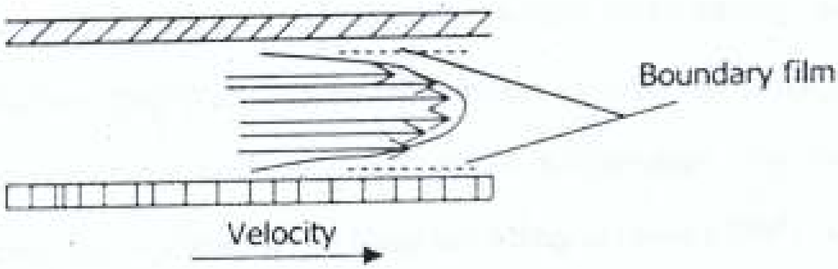



Fig. 2.3: Showing boundary or surface film

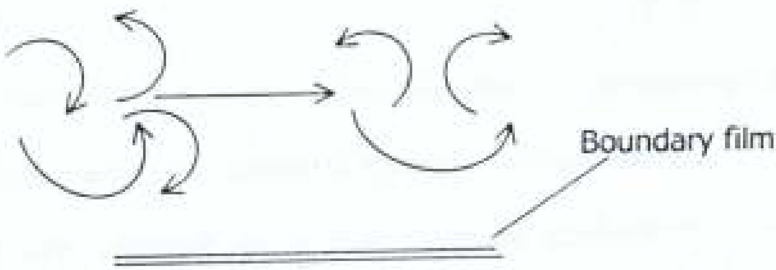



Fig. 2.4: Turbulent flow.

are retained in suspension more readily. This reduces the formulation of deposits on heat exchangers and prevents solids from settling out in pipe work. Streamline flow produces a larger range of residence times for individual particles flowing in a tube. This is important when calculating the residence time required for heat treatment of liquid foods, as it is necessary to ensure that all parts of the food receive the required amount of heat. Turbulent flow causes higher friction losses than streamline flow and therefore requires higher energy input from pumps.

## 2.3 WATER ACTIVITY

Deterioration of foods by micro-organisms can take place rapidly, whereas enzymatic and chemical reactions take place more slowly during storage. In either case, water is the single most important factor controlling the rate of deterioration. The moisture content of foods can be expressed on a wet-weight basis according to Lewis (1987) as;

$$X' = \frac{\text{mass of water} \times 100}{\text{mass of sample}} \quad (2.3)$$

Alternatively, it is expressed on a dry - weight basis as

$$X' = \frac{\text{mass of water}}{\text{mass of solids}} \quad (2.4)$$

The dry - weight basis is more commonly used for processing calculations whereas the wet-weight basis is frequently quoted in food composition tables.

Some foods are unstable at a low moisture content (for example peanut oil deteriorates if the moisture content exceeds 0.6%) whereas other foods are stable at relatively high moisture contents (for example potato starch is stable at 20% moisture). It is the availability of water for microbial, enzymatic or chemical activity that determines the shelf life of a food, and this is measured by the water activity ($a_w$) of a food. Some foods have to be packaged to prevent moisture loss, while some must be packaged to prevent moisture uptake. Examples of unit operations that reduce the availability of water in foods include those that physically remove water, which is *dehydration*.

Water in food exerts a vapour pressure. The size of the vapour pressure depends on the amount of water present, the temperature and the concentration of dissolved solutes in the water. Water activity, $a_w$, is defined as the ratio of the vapour pressure of water in food to the saturated vapour pressure of water at the same temperature:

$$a_w = \frac{P}{P_0} \qquad (2.5)$$

where P is vapour pressure of the food and $P_0$ is the vapour pressure of pure water at the same temperature, $a_w$ is related to the moisture content by the Brunauer – Emmett – Teller (BET) equation (Fellows,1990)

$$\frac{a_w}{X'(1-a_w)} = \frac{1}{X'_1 C} + \frac{(C-1)\,a_w}{X'_1\,C} \qquad (2.6)$$

where X' is the moisture at percentage dry weight, $X'_1$ is the moisture (dry weight basis) of a monomolecular layer and C is a constant.

The movement of water vapour from food to the surrounding air depends upon the moisture content and composition of the food and the temperature and humidity of the air. At a constant temperature, the moisture content of the food changes and comes into equilibrium with the water vapour in the surrounding air. The food neither gains nor loses weight on storage under those conditions. This is called the *equilibrium moisture content* of the food and the relative humidity of the storage atmosphere is known as the *equilibrium relative humidity*. When the values of relative humidity versus equilibrium moisture content

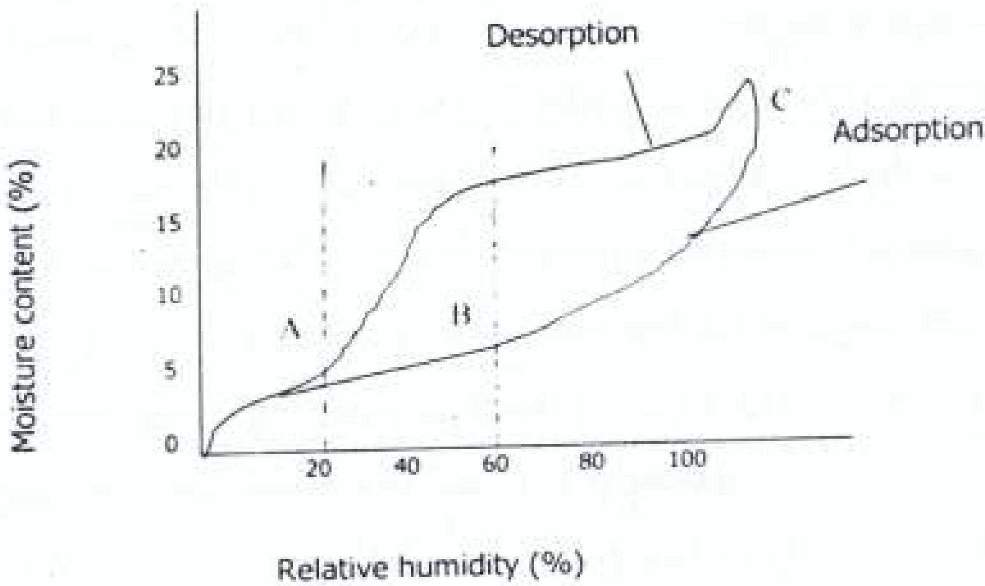



Fig 2.5: Water sorption isotherm

are plotted, a curve known as *water sorption* isotherm is obtained such as shown in figure 2.5.Each food has a unique set of sorption isotherms at different temperatures. The shape of the sorption isotherm is caused by differences in the physical pressure, chemical composition and extent of water binding within the food, but all sorption isotherms have a characteristic shape similar to the one in figure 2.5. The first part of the curve, to point A represents monolayer water, which is very stable, unfreezable and not removed by drying. The second relatively straight part of curve (AB) represents water adsorbed in multilayer within the food and solutions of soluble components. The third portion, (above point B) is "free" water condensed within the food and held by only weak forces. It is easily removed by drying and easily frozen, as indicated by the steepness of the curve. Free water is available for microbial growth and enzymatic activities, and the food which has a moisture content above point B on the curve is likely susceptible to spoilage.

The sorption isotherm indicates the water activity ($a_w$) at which food is stable and allows prediction of the effect of changes in moisture content on $a_w$ and hence on storage stability. It is used to determine the rate and extent of drying, the optimum frozen storage temperatures and the moisture barrier properties required in packaging materials.

The rate of change of $a_w$ on a sorption isotherm differs according to whether moisture in removed from the food (desorption) or whether it is added to the dry food (absorption) as in figure 2.5 above. This is termed a *hysteresis loop*. The difference is large in some foods (for example rice) and is important in determining the protection required against moisture uptake.

Psychrometry is the study of the interrelationships of the temperature and humidity of air. These properties are most conveniently represented on a *psychrometric Chart*. The temperature of the air measured by a thermometer bulb is termed the dry bulb temperature. If the thermometer bulb is surrounded by a wet cloth, heat is removed by evaporation of the water from the cloth and the temperature falls. This lower temperature is called the wet-bulb temperature. The difference between the two temperatures is used to find the relative humidity (RH) of air on the psychometric chart. An increase in air temperature or reduction in the relative humidity causes water to evaporate more rapidly from the wet surface of a solid and therefore produces a greater fall in the temperatures of the solid.

Foods are characterized as hygroscopic and non-hygroscopic. *Hygroscopic foods* are foods in which the partial pressure of water vapour varies with the moisture content while *Non-Hygroscopic foods* have a constant water vapour pressure at different moisture contents (Karel, 1975).

## 2.4 THEORY OF DRYING

### 2.4.1 DEFINITION AND INTRODUCTION

Drying is a process wherein moisture is removed from a food product to enhance its storability, transportability, flavour or texture (Karel, 1975). During this operation, the water activity of a food is lowered by removal of nearly all the water normally present through vaporization or sublimation (in the case of freeze drying).

In effect, drying can be defined as the application of heat under controlled conditions to remove the majority of the water normally present in a food by evaporation. This definition excludes other unit operations which remove water from foods for example; mechanical separations, membrane concentration, evaporation and baking as these normally remove much less water than drying. The main purpose of dehydration is to extend the shelf life of the food by a reduction in water activity. This inhibits microbial growth and enzyme activity, but the product temperature is usually insufficient to cause inactivation. The reduction in weight and bulk of food reduces transport and storage costs and for some types of food, provides greater variety and convenience for the consumer. Drying may cause deterioration of the eating quality and the nutritive value of the food. The design and operation of dehydration equipment aims at minimizing these changes by selection of appropriate drying conditions for different types of food. Examples of commercially important dried foods are sugar, coffee, milk, potato, flour (including bakery mixes), beans, pulses, nuts, breakfast cereals, tea and spices (Fellows, 1990).

Dehydration as defined above does not include removal of water extraction with suitable solvents. Furthermore, production of foods of low water activity by incorporation of such osmotic agents as sugar or salts is not included in this definition (Fellows, 1990).

Dehydration can be carried out in various kinds of driers. Since dehydration is a combined heat and mass-transfer operation, the driers can be classified according to the methods by which these transfers are accomplished. The heat and mass transfer are affected by the total pressure at which the drier operates. Driers operating at atmospheric pressure can be batch or continuous and the heat transfer can be by convection, conduction, radiation or dielectric heating (Karel, 1975).

The most widely used dehydration methods involve the exposure of foods to heated air. In these driers the primary mode of heat transfer is by convection (Karel, 1975). The process of dehydration by examples chosen from air-drying methods will be illustrated.

### 2.4.2 BASIC CONCEPT

Consider the typical wet food product put in a slab having its surface exposed to an air stream with a specified velocity, temperature, pressure, and relative humidity. If the

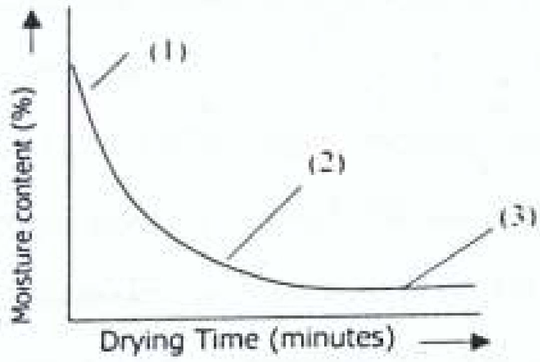



Fig. 2.6: A typical drying curve for a food product

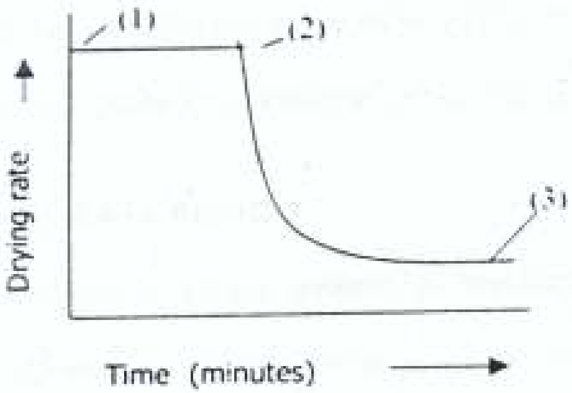



Fig. 2.7: Drying rates versus time for a typical food product.

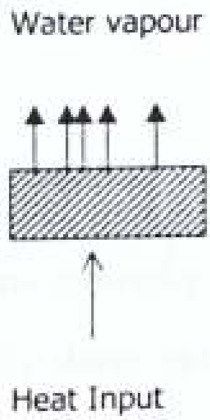



Fig. 2.8: A slab of material being dried via conduction heat transfer

weight of material is measured and plotted as a function of time, a curve similar to that shown in figure 2.6 would be obtained.

Between points (1) and (2), a nearly linear decrease relationship between moisture content and time exist. Between points (2) and (3) the curve asymptotically approaches an equilibrium moisture content dependent on the temperature and relative humidity of the air steam. The drying rate can be found by determining the slope of the curve in figure 2.6 at any point.

Figure 2.7 illustrates a typical drying rate curve. The portion of this curve from point (1) to (2) is called *constant – rate period* while the curve from (2) to (3) is called the *falling – rate period*. The moisture content at point 2 is called the *critical moisture content*.

### 2.4.3 CONSTANT DRYING RATE PERIOD

During this period moisture is always present on the surface of the material being dried and latent heat of vaporization causes water to evaporate. The water within this material is able to diffuse through to the surface at a rate faster than the rate at which it leaves the surface. For heat addition by forced convection of hot air, the drying rate is given according to Karel (1975) by

$$M = \frac{hA\,(\theta_{\alpha} - \theta_s)}{h_{fg}} \qquad (2.7)$$

where M is the drying rate, h is the convective heat transfer coefficient, A is the area available for heat transfer, $\theta_{\alpha}$ is the air stream temperature, $\theta_s$ is the surface temperature, $h_{fg}$ is the latent heat of vaporization evaluated at $\theta_s$.

The surface temperature $\theta_s$ can usually be approximated as the wet bulb temperature of the air stream because the air steam flowing over a wet- bulb thermometer lowers the temperature of the thermometer. In a similar manner, the surface temperature of a wet material subjected to forced convective heat transfer reaches the wet bulb temperature given sufficient time.

Conduction is another mechanism for transferring heat to the material being dried. As illustrated in figure 2.8, heat intake occurs on one side of a wet food product while water vapour leaves on the other. If all the heat transfer occurs by conduction, the surface temperature of the material being dried will approximately be equal to the boiling point temperature. If both conduction and convective heat transfer modes are present, the surface temperature will be somewhere between the wet bulb temperature and the boiling point temperature. During the constant rate time period the drying rate is given (Karel, 1975) as

$$M = K_m A (P_g - P_v) \qquad (2.8)$$

where M is the drying rate, $K_m$ is the mass transfer coefficient, $P_g$ is the saturation pressure of water corresponding to the surface temperature, $P_v$ is the partial pressure of the water vapour in the air.

The value of the mass transfer coefficient is dependent on the drier design. Equation (2.8) indicates that for a given drier design, the drying rate is proportional to the surface area and the water vapour partial pressure difference. Another equation for estimating evaporation rates due to conduction heat transfer can be found in Karel (1975) as,

$$M = \frac{UA (\theta_{source} - \theta_s)}{h_{fg}} \qquad (2.9)$$

where U is the overall heat transfer coefficient between heat source and the surface, $\theta_{source}$ is the Temperature of the heat source, $\theta_s$ is the surface temperature, and A is the area available for heat transfer. The three characteristics of air that are necessary for successful drying in this period are; (a) a moderately high dry – bulb temperature (b) a low RH (c) a high air velocity.

The boundary film of air surrounding the food acts as a barrier to the transfer of both heat and water vapour during drying. Primarily the air velocity determines the thickness of the film. If velocity is too low, water vapour leaves the surface of the food and increases the humidity of the surrounding air, thereby causing a reduction in the water vapour pressure gradient and the rate of drying (Fellows, 1990). Similarly, if the temperature of the drying air falls or the humidity rises, the rate of evaporation falls and drying slows down.

### 2.4.4 FALLING-RATE TIME PERIOD

This period begins when water within the material being dried can no longer diffuse to the surface at a rate fast enough to keep the entire surface saturated with moisture. The surface therefore dries out. This is usually the longest period of drying operation and in some foods (e.g. grain drying) where the initial moisture content is below the critical moisture content, the drying curve contains the falling rate period. At this point, the factors that control the rate of drying change and the properties of the material being dried begin to influence the drying rates (Fennemma, 1975). Initially the important factors that control the rate of drying are similar to those in the constant-rate period but gradually the rate of mass transfer becomes the predominant factor. This depends mostly on the temperature of the air and the thickness of the food. It is unaffected by both the relative humidity of the air and the velocity of the air (Fellows, 1990).

When the moisture content of the food falls below the critical moisture content, the influence of water mobility on drying rate increases and the rate of drying slowly decreases until it approaches zero at *the equilibrium moisture content* (that is, the food comes into equilibrium with the drying air). This is known as the falling rate period. Water mobility is determined primarily by diffusion and capillary flow.

During the falling rate period, the amount of water evaporating from the surface gradually decreases but as the same amount is being carried by the air, the surface temperature rises until it reaches the dry-bulb temperature of the drying air. Most heat damages to food therefore occurs in the falling –rate period.

Non-hygroscopic foods have a single falling-rate period, whereas hygroscopic foods have two periods. In the first period, the plane of evaporation moves inside the food and water diffuses through the dry solids to the drying air. It ends when the plane of evaporation reaches the centre of the food and the partial pressure of water falls below the saturated water vapour pressure. The second period occurs when the partial pressure of water is below the saturated vapour pressure, and drying is by desorption (Fellows, 1990).

In practice, foods may differ from these idealized drying curves owing to shrinkage, change in temperature and rate of moisture diffusion in different parts of the food, and changes in the temperature and humidity of the drying air.

### 2.4.5 CALCULATION OF DRYING RATE

The rate of drying depends on the properties of the drier (i.e. the dry bulb temperature, RH, velocity of the air, and the surface heat transfer coefficient), the properties of the food (i.e. the moisture content, surface to volume ratio, the surface temperature and the rate of moisture loss). The size of food pieces has an important effect on the drying rate in both the constant- and falling – rate period. In the constant rate period, smaller pieces have a larger surface area available for evaporation whereas in falling

- rate period, smaller pieces have a shorter distance for moisture to travel through the food. Other factors which influence the rate of drying include

(1) The fat content of the food; higher fat contents generally result in slower drying as water is trapped within the body.

(2) The method of preparation of the food; cut surfaces lose moisture more quickly than the skin of the seed, and

(3) The quantity of food placed into a drier. In a given drier, faster drying is achieved with smaller quantities of food.

According to Fellows (1990), the rate of heat transfer is given by

$$Q = h_c A\ (\theta_a - \theta_s) \qquad (2.10)$$

While the rate of mass transfer is found using

$$-M = K_m A\ (H_s - H_a) \qquad (2.11)$$

During the constant rate period equilibrium exists between the rate of heat transfer to the food and the rate of mass transfer in the form of moisture loss from the food. These rates are according to Fellows (1990) related by equation

$$-M = h_c A\ (\theta_a - \theta_s)/\ h_{fg} \qquad (2.12)$$

where Q is the rate of heat transfer, $h_c$ is the surface heat transfer coefficient for convective heating, A is the surface area available for drying, $\theta_a$ is the average dry-bulb temperature of drying air, $\theta_s$ is the average wet-bulb temperature of drying air, M is the change in mass with time (i.e drying rate), $K_m$ is the mass transfer coefficient, $H_s$ is the relative humidity at the surface of the food, $H_a$ is the relative humidity of air, $h_{fg}$ is the latent heat of evaporation at the wet-bulb temperature.

The surface heat transfer coefficient ($h_c$) is related to the mass flow rate of air using the following equations (Fellows, 1990);

For parallel air flow

$$h_c = 14.3G^{0.8} \quad (2.13)$$

For perpendicular air flow

$$h_c = 24.2\,G^{0.37} \quad (2.14)$$

where G is the mass flow rate of air

For a tray of food, in which water evaporates only from the upper surface, the drying time is found using

$$-M = h_c(\theta_a - \theta_s)/h_{fg}\rho_b x \quad (2.15)$$

where $\rho_b$ is the bulk density of food and x is the thickness of the bed of food. The drying time in the constant rate period is found, using

$$t = \rho_b h_{fg} x(X'_s - X'_c) / h_c(\theta_a - \theta_s) \quad (2.16)$$

where t is the drying time, $X'_s$ is the initial moisture content, $X'_c$ is the critical moisture content.

## 2.5 HEAT TRANSFER

Practically, all the operations that are carried out in the drier involve the production or absorption of energy in the form of heat. Heat transfer is an energy–transfer phenomenon. Increased heat energy increases the kinetic energy of the molecules. Heat is transferred when a fast moving molecule collides with a slow moving molecule to gain kinetic energy (Freeman, 1955).

Heat transfer is one of the most important unit operations in the food industry. Nearly every process requires either heat input or heat removal to alter the physical, chemical and storage characteristics of the product. An understanding of the physical principles enables one to predict the heating phenomenon and to determine the optimum operating conditions. In determining the optimum operating conditions, consideration must of course, be given not only to the rate of energy transfer but also to food quality. This has necessitated the work in this area.

### 2.5.1 NATURE OF HEAT FLOW

When two objects at different temperatures are brought into thermal contact, heat flows from the object at the higher temperature to that at the lower temperature. The net flow is always in the direction of the temperature decrease. The mechanisms by which the heat may flow are three: conduction, convection and radiation. In reality, temperature distribution in a medium is controlled by the combined effects of these three modes of heat transfer; therefore, it is not actually possible to isolate entirely one mode from interacting with the other modes. However, for simplicity, one can consider, each mode separately whenever heat transfer by the two other modes is negligible (Lund, 1975). With this approach, the following sections give a qualitative description of these three distinct modes of heat transfer.

### 2.5.2 CONDUCTION

This is the mode of heat transfer in which energy exchange takes place from the region of high temperature to that of low temperature by the kinetic motion or direct impact of molecules, as in the case of fluid at rest, and by the drift of electrons, as in the case of metals (ozisik, 1985). Conduction occurs when thermal energy is transferred from one molecule or atom to an adjacent molecule or atom without gross change in the relative positions of the molecules. Molecular movement is limited to oscillation about a fixed position, allowing any given molecule to make contact with only its immediate neighbours (Freeman, 1955).

In a solid which is a good electrical conductor, a large number of free electrons move about the lattice; hence materials that are good electric conductors are generally good heat conductors. A few of them are copper, brass, silver and many other metals or liquid metals.

The empirical law of heat conduction is based on the experimental observations of Biot but is generally named after the French mathematical physicist Joseph Fourier (Freeman, 1955) who used it in his analytic theory of heat. The Fourier law of heat transfer by conduction states that the rate of heat transfer through a uniform material in a given direction is directly proportional to the area normal to the direction of heat flow and to the temperature gradient through the material in that direction and inversely proportional to the thickness of the material. Stated mathematically according to Ozisik (1985), Fourier's law is

$$Q_x = \frac{dQ}{dt} = -kA\frac{d\theta}{dx} \qquad (2.17)$$

where $Q_x$ = the rate of heat flow in the positive x direction, through area A normal to the x direction, and

$$\frac{d\theta}{dx} = \lim_{\Delta x \to 0} \frac{\Delta\theta}{\Delta x} \qquad (2.18)$$

is the gradient of temperature in that direction.

Hence,

$$q_x = \frac{Q_x}{A} = -k\frac{d\theta}{dx} \qquad (2.19)$$

is the heat flux in the positive x direction. The proportionality constant k is called the thermal conductivity of the material. Its unit is watts per metre per Kelvin. It is the reciprocal of resistance to heat transfer called conductance of the material.

Note that $q_x$ represents the amount of heat flow per unit area, per unit time in the x direction. The minus sign is as a result of the following. If the temperature decreases in the positive x direction, $d\theta/dx$ is negative; $Q_x$ is a positive quantity. Therefore the heat flow is in the positive x direction.

If on the other hand, the temperature increases in the positive x direction, $d\theta/dx$ is positive, $Q_x$ becomes negative and the heat flow is in the negative x direction.

### 2.5.3 STEADY-STATE CONDUCTION

Under steady-state conditions there is a constant temperature difference between two surfaces through which heat flows. The amount of heat entering one surface of the material equals the amount of heat leaving at the opposite surface. The rate of heat transfer therefore is calculated using

$$Q = kA(\theta_1 - \theta_2)/ x \qquad (2.20)$$

The thermal conductivity of foods is influenced by a number of factors concerned with the nature of the food for example the cell structure, the amount of air trapped between the cells, and the moisture content, its temperature and pressure of the surroundings. A reduction in moisture content causes a substantial reduction in thermal conductivity. This has important implications in unit operations, which involve conduction of heat through food to remove water. In table 2.1, we compare the thermal conductivities of common foods and other materials.

**Table 2.1: Thermal Conductivity of Selected Foods and Other Materials**

| Foods and other Materials | Thermal Conductivity $Wm^{-1} k^{-1}$ | Temperature of Measurements (K) |
|---|---|---|
| Orange | 0.410 | 273 – 288 |
| Green beans | 0.800 | 260.9 |
| Egg | 0.960 | 265 |
| Ice | 2.250 | 273 |
| Water | 0.570 | 273 |
| Aluminum | 220.000 | 273 |
| Copper | 388.000 | 273 |
| Stainless steel | 21.000 | 293 |
| Other metals' | 45.000 – 400.000 | 273 |
| Brick | 0.690 | 293 |
| Concrete | 0.870 | 293 |
| Polystyrene foam | 0.036 | 273 |
| Polymethane foam | 0.026 | 273 |

### 2.5.4 UNSTEADY–STATE CONDUCTION

In the majority of food processing applications the temperature of the food and that of the heating or cooling medium are constantly changing, and unsteady state heat transfer occurs. Calculations of heat transfer under these conditions are extremely complicated but are simplified by making a number of assumptions and in some cases using prepared charts to give approximate solutions. The temperature at a given point within a food during processing depends on the time of heating and the position in the food. It therefore changes continuously. The factors that influence the temperature change are the temperature of the heating medium, the thermal conductivity of the food and the specific heat capacity of the food.

The basic equation for unsteady state heat transfer in a single direction x is

$$\frac{d\theta}{dt} = \frac{k d^2\theta}{\rho c\, dx^2} = a \frac{d^2\theta}{dx^2} \qquad (2.21)$$

where $a = k/\rho C$ = thermal diffusivity, $\frac{d\theta}{dt}$ is the change in temperature with time of food, k is the thermal conductivity of food, c is the specific heat capacity of food, and ρ is the density of the food.

### 2.5.5 CONVECTION

In heat transfer by convection the molecules are free to move about, resulting in mixing of warmer and cooler portions of the same material. Convection is thus restricted to the flow of heat in a fluid, either a gas or a liquid. When a fluid flows over a solid body or inside a channel and the temperatures are different, heat transfer takes place between the fluid and the solid body as a result of the motion of the fluid. This mechanism of heat *transfer is called convection.* If there is no fluid motion, the heat transfer is by *conduction.* If the fluid motion is artificially induced with a pump, a blower, a fan or wind that forces the flow over the surface, the heat transfer is said to be by *forced convection.* However, if the fluid motion is set up by buoyancy effects resulting from density difference caused by temperature difference in the fluid, the heat transfer is said to be by free (or natural) convection.

In engineering applications, to simplify the heat transfer calculations, a quantity called the *heat transfer coefficient* h is defined between a hot surface at $\theta_{source}$ and a cold fluid flowing over it at a bulk temperature $\theta_a$ as

$$q = h\,(\theta_{source} - \theta_a) \qquad (2.22)$$

where q is the heat flux (in watts per square metre) from the hot wall to the cold fluid and the temperatures are in degrees celsius (or kelvins), then the heat transfer coefficient has the dimension $W/m^2K$ and it is always a positive quantity. Alternatively, the heat transfer from the hot fluid to the cold wall is written as

$$q = h\,(\theta_{a} - \theta_{source}) \qquad (2.23)$$

where q represents the heat flux from the hot fluid to the cold wall. Historically, the form given by equation 2.22 was first used as a law of cooling for the removal of heat from a hot body into a cold fluid flowing over it. It is generally referred to as the Newton's law of cooling.

The determination of the heat transfer coefficient for convection problems is a very complicated matter because h varies with the type of flow (i.e laminar, turbulent or transitional), the geometry of the body, the physical properties of the fluid, the temperature difference, the position along the surface of the body and whether the mechanism is forced or free convection. When h varies with the position along the surface of the body, for convenience in engineering applications, its average value $h_m$ over the surface is considered instead of its local value h.

Therefore, the rate of convective heat transfer governed by Newton's law of cooling which states that the rate of heat transfer by convection is directly proportional to the heat transfer over the temperature difference between the hot and cold fluid. Mathematically, it can be expressed (Bayazitoglu and Ozisik, 1988) as

$$Q = hA\Delta T \qquad (2.24)$$

Q is the rate of heat transfer, $\Delta T$ is the Temperature difference, A is the heat transfer area, h is the proportionality constant which is heat transfer coefficient.

The surface heat transfer coefficient is a measure of the resistance to heat flow caused by the boundary film and is therefore equivalent to the term k/x in the conduction equation $Q = kA(\theta_1 - \theta_2) / x$ (2.25)

It is therefore higher in turbulent flow than in streamline flow. Table 2.2 shows the surface heat transfer coefficient values of some fluids.

**Table 2.2: Values of Surface Heat Transfer Coefficients (Fellows, 1990)**

| | $h_c$ ($Wm^{-2}K^{-1}$) | Typical Applications |
|---|---|---|
| Boiling liquids | 2400-6000 | Evaporation |
| Condensing saturated steam | 12000 | Canning, Evaporation |
| Condensing steam | | |
| with 3% air | 3500 | Canning |
| with 6% air | 1200 | Canning |
| Liquid flowing through | | |
| Pipes (a) At low viscosity | 1200-6000 | Pasteurization |
| (a) At high viscosity | 120-1200 | Evaporation |
| Moving air ($3ms^{-1}$) | 30 | Freezing, baking |
| Still air | 6 | Cold Stores. |

This data indicates that heat transfer through air is lower than through liquids and higher rates of heat transfer are obtained by moving air when air is used for heating or cooling. The surface heat transfer coefficient is related to the physical properties of the fluid (that is, its density, viscosity, and specific heat capacity), gravity, temperature difference and the dimension of the container under investigation. According to Fellows (1990), the formulae that relate these factors are expressed as dimensionless numbers as follows:

Nusselt number given as $N_u = h_c D/k$ (2.26)

Prandtl number given as $P_r = C_p\mu/k$ (2.27)

Grashof number given as $G_r = D^3\rho^2 g\beta\Delta\theta/\mu^2$ (2.28)

Where $h_c$ is the convection heat transfer coefficient at the solid-liquid interface, D is the characteristic dimension (i.e the diameter or the length), k is the thermal conductivity of the fluid, $C_p$ is the specific heat at constant pressure, ρ is the density, μ is the viscosity, g is the acceleration due to gravity, β is the coefficient of thermal expansion, and Δθ is the temperature difference.

For streamline flow through pipes, Nusselt number is given as

$$N_u = 1.62\,(R_e\,P_r\,D)^{0.33}/\,L \qquad (2.29)$$

where L is the length of pipe, when $R_e\ P_r\ D\ /\ L > 120$ and all physical properties are measured at the mean bulk temperature of the fluid. For turbulent flow through pipes,

$$N_u = 0.023\,(R_e)^{0.8}\,(P_r)^n \qquad (2.32)$$

where n is 0.4 for heating or n is 0.3 for cooling. The Grasshof number is used for natural convection when there is no turbulence in the fluid.

### 2.5.6 OVERALL HEAT-TRANSFER COEFFICIENT

It is reasonable to expect the heat flux to be proportional to a driving force. In heat flow, the driving force is taken as $\theta_h - \theta_c$, where $\theta_h$ is the average temperature of the hot fluid and $\theta_c$ is that of the cold fluid. The quantity $\theta_h - \theta_c = \Delta\theta$, the overall local temperature difference. Along a tube, Δθ can vary considerably from point to point and, since the heat flux is proportional to Δθ, the flux also varies with tube length. By focusing attention on a differential area dA through which a differential heat flow dq occurs under the driving force of a local value of Δθ, the local flux is then dq/dA and is related to the local value of Δθ by the equation

$$\frac{dq}{dA} = U\Delta\theta = U\,(\theta_\alpha - \theta_s) \qquad (2.31)$$

The quantity U is a proportionality factor and is called the Local Overall Heat-Transfer Coefficient (OHTC). Most cases of heat transfer involve heat transfer through a number of different materials. For example, heat transfer from a hot fluid through the wall of a vessel to a second fluid as shown in fig. 2.9.

Heat transfer is a dynamic process wherein heat is transferred from a hot body to a cold body. A temperature difference is therefore necessary and this temperature difference is called the "driving force" for heat transfer. In transferring heat energy from one body to another, resistance is encountered. This resistance to heat flow can occur within or at the surface of the material. Like all rate processes, the rate of heat transfer is inversely proportional to resistance and directly proportional to the driving force. Thus,

$$\text{Rate of transfer} = \frac{\text{Driving force}}{\text{Resistance}} \qquad (2.32)$$

For the diagram shown in fig. 2.9, in steady state, the rate of heat transfer across each physical boundary is constant. The heat-transfer coefficient characterizing transfer of heat from the hot fluid to the wall is

$$q = hA\Delta\theta = \frac{\Delta\theta}{1/h_a A}$$

a thermal conductivity characterizing heat transfer through the wall is

$$q = \frac{\Delta\theta}{x/kA}$$

and finally a heat transfer coefficient for transfer of heat from the wall to the cold fluid is given by

$$q = \frac{\Delta\theta}{1/h_b A}$$

Hence, the overall temperature difference is found using

$$\Delta\theta = \theta_a - \theta_b = \frac{Q}{A}\left[\frac{1}{h_a} + \frac{x}{k} + \frac{1}{h_b}\right] \qquad (2.33)$$

Note that $\theta_a$ decreases as it moves toward the cold fluid through the wall, and $\theta_a$ is approximately $\theta_1$ while $\theta_4$ is approximately $\theta_b$ in figure 2.9.

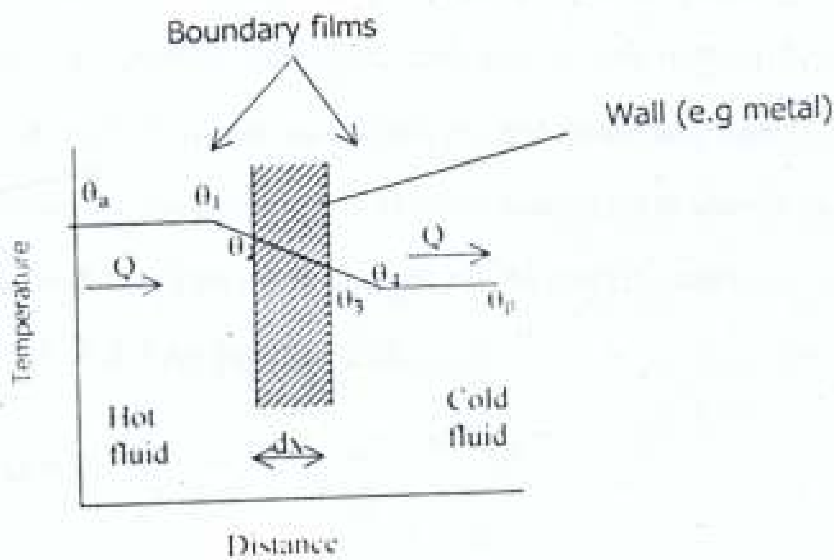



Figure 2.9: Indirect heat transfer as temperature changes from a hot fluid through a vessel wall to a cold fluid.

The unknown wall temperatures $\theta_2$ and $\theta_3$ are not required and all factors can be measured. The sum of the resistances to heat flow is termed the overall heat transfer coefficient (OHTC) U and the rate of heat transfer may then be expressed as

$$Q = UA\,(\theta_a - \theta_b) \qquad (2.34)$$

This indicates that the rate of heat transfer is the product of three factors; overall heat transfer coefficient, temperature difference, and area of the heating surface. The OHTC is an important term, which is used to indicate the effectiveness of heating or cooling in different types of processing equipment. And in every heating application, it is necessary to establish the magnitude of U so that the equipment can be properly sized.

To complete the definition of U, from equation 2.31,

$$\frac{dq}{dA} = U\Delta\theta = U(\theta_d - \theta_s),$$

it is necessary to specify the area. If A is taken as the outside tube area $A_o$, U becomes a coefficient based on that area and is written $U_o$. Likewise, if the inside area $A_i$ is considered, the coefficient is also based on that area and is denoted by $U_i$. Since $\Delta\theta$ and dq are independent of the choice of area, it follows that

$$\frac{U_o}{U_i} = \frac{dA_i}{dA_o} = \frac{D_i}{D_o} \qquad (2.35)$$

Where $D_i$ and $D_o$ are the inside and outside tube diameters respectively.

## 2.5.7 NATURAL CONVECTION

As an example of natural convection, consider a hot, vertical plate in contact with air in a room. The temperature of the air in contact with the plate is equal to that at the surface of the plate, and a temperature gradient exists from the plate out into the room. At the bottom of the plate, the temperature gradient is steep, as shown by the full line marked

"Z = 10mm" in fig. 2.10. At distances above the bottom of the plate, the gradient becomes less steep as shown by the full curve marked "Z = 240mm". At a height (Z) of about 600mm from the bottom of the plate, the temperature distance curves approach an asymptotic condition and do not change with further increase in height.

The density of the heated air immediately adjacent to the plate is less than that of the unheated air at a distance from the plate, and the buoyancy of the hot air causes an imbalance between the vertical layers of air of differing density. As a result of the unbalanced forces, a circulation is generated, by which hot air near the plate rises and cold air flows toward the plate from the room to replenish the rising air stream. A velocity gradient near the plate is formed. Since the velocities of the air in contact with the plate and that out in the room are both zero, the velocity is a maximum at a definite distance from the wall. The velocity reaches its maximum a few millimeters from the surface of the plate. The dashed curves in the figure 2.10 shows the velocity gradients for heights of 10mm and 240 mm above the bottom of the plate. For tall plates, an asymptotic condition is approached.

The temperature difference between the surface of the plate and the air in the room at a distance from the plate causes a transfer of heat by conduction into the current of gas next to the wall, and the stream carries the heat away by convection in a direction parallel to the plate.

### 2.5.8 FORCED CONVECTION

This takes place when a stirrer, pump or fan is used to agitate the fluid (air). This produce higher rates of heat transfer and rapid temperature redistribution. Consequently,

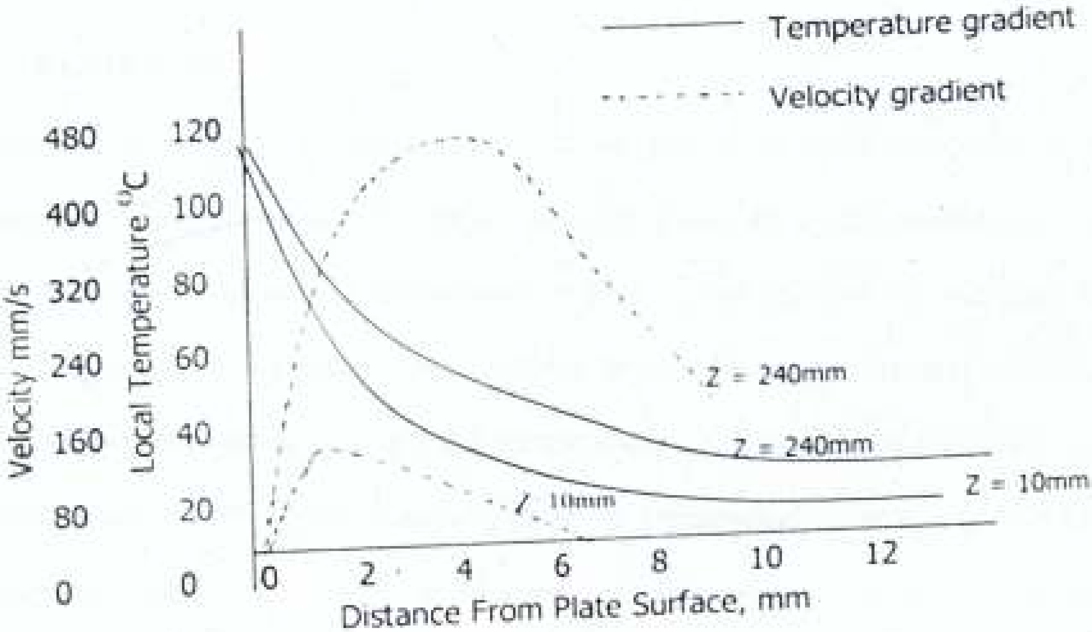



Fig. 2.10: Velocity and temperature gradients, natural convection from heated vertical plate (McCabe et al, 1985).

forced convection is more frequently used in food processing. The rate of heat transfer from a hot fluid to the surface of a food is found using

$$Q = h_c A(\theta_\alpha - \theta_s)$$

where $\theta_s$ is the surface temperature and $\theta_\alpha$ is the bulk fluid temperature.

### 2.5.9 RADIATION

Transfer of heat by radiation occurs by means of an electromagnetic radiation. Electromagnetic radiation passes unimpeded through space and is not converted to heat or any other form of energy until it collides with matter. Upon collision the radiation can be transmitted, absorbed, or reflected. Only absorbed energy can appear as heat.

All bodies emit energy due to their temperature. The energy thus emitted is called *thermal radiation*. The radiant energy emitted is transmitted in space in the form of electromagnetic waves according to Maxwell's classic electromagnetic wave theory. Alternatively it can be described in the form of discrete photons according to Planck's hypothesis. Both concepts have been utilized in the investigation of radiative heat transfer. The emission or absorption of radiation energy by a body is a bulk process; that is, the radiation originating from the interior of the body is emitted through the surface. Similarly, the radiation energy incident on the surface of a body penetrates into the depths of the body, where it is attenuated. If the emission and absorption of radiation take place within a very short distance from the surface, then the radiation process is called *surface radiation* and the body is said to be *opaque* to thermal radiation. Examples of opaque materials are metals, wood, stone and paper.

In contrast to this, a sheet of glass is said to be semi-transparent to the solar radiation incident upon it, because part of the solar radiation is absorbed, part reflected, and the remainder transmitted by the glass. Another example of semitransparent medium is a body of water but the solar radiation incident on it is gradually attenuated by water as the beam penetrates deeper in to the water. Radiation propagating in a medium is weakened as a result of absorption. It is only in a vacuum that radiation propagates without attenuation. Therefore, a vacuum is considered completely *transparent* to radiation. For all practical purposes, the atmospheric air contained in a room is considered transparent to thermal radiation because the attenuation of radiation by air is insignificant unless the air layer is several kilometres thick.

### 2.5.10 EMISSION OF RADIATION

The maximum radiation flux emitted per unit area by a body at temperature T is given by the Stefan – Boltzmann's law

$$E_b = \sigma T^4 \qquad (2.36)$$

where $E_b$ is the black body emissive power, T is the absolute temperature in Kelvin and $\sigma$ is the Stefan – Boltzmann constant.

Only an ideal radiator (also called *blackbody)* can emit the maximum radiation flux according to equation 2.36. The radiation flux q emitted by a real body at an absolute temperature T is always less than the blackbody emissive power and it is given by

$$q = \epsilon E_b = \epsilon \sigma T^4 \qquad (2.37)$$

where $\epsilon$ is the emissivity of the body, $\epsilon < 1$ for all real bodies and $\epsilon = 1$ for a blackbody.

### 2.5.11 ABSORPTION OF RADIATION.

If a radiation flux $q_{inc}$ is incident on a blackbody, it is completely absorbed by the blackbody. The absorbed energy $q_{abs}$ is given by $q_{abs} = q_{inc}$ (2.38)

But a real body absorbs only a fraction of the radiation that falls on it. The energy absorbed $q_{abs}$ is given by

$$q_{abs} = \alpha q_{inc} \qquad (2.39)$$

$\alpha$ is the absorptivity, which lies between zero and unity. The absorptivity $\alpha$ of a body is generally different from its emissivity $\epsilon$. However, in many practical applications, to simplify the analysis, $\alpha$ is assumed to be equal to $\epsilon$.

### 2.5.12 RADIATION EXCHANGE

When two bodies at different temperatures are near each other, heat is exchanged between them by radiation. If the intervening medium is filled with a substance such air which is transparent to radiation, the radiation emitted from one body travels through the intervening medium with no attenuation and reaches the other body and vice versa. Then the hot body experiences a net heat loss, and the cold body a net heat gain, as a result of the radiation heat exchange.

Fig. 2.11a shows a small, hot, opaque plate of surface area $A_1$, and emissivity $\epsilon_1$ maintained at an absolute temperature $T_1$ and exposed to a large surrounding area $A_2$ at an absolute temperature $T_2$ (if $A_1/A_2 \rightarrow 0$).

The space between them contains air, which is transparent to thermal radiation. The radiation energy emitted by the surface $A_1$ is given by $A_1 \epsilon_1 \sigma T_1^4$. The large surrounding area can be approximated as a blackbody in relation to the small surface $A_1$. Then, the radiation flux emitted by the surrounding area is $\sigma T_2^4$, which is also the radiation flux incident on the surface $A_1$. Hence, the radiation energy absorbed by the surface $A_1$ is given by $A_1 \alpha_1 \sigma T_2^4$. The net radiation loss at the surface $A_1$ is the difference between the

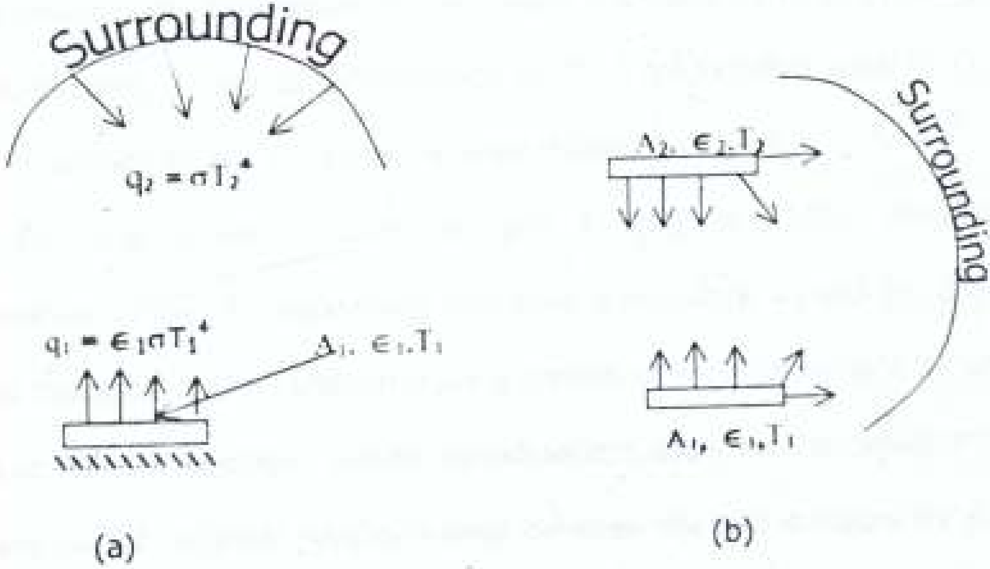



Fig. 2.11: Radiation exchange between different surfaces and surrounding (Ozisik, 1985)
(a) Radiation exchange between a surface $A_1$ and its surrounding
(b) Radiation exchange between surfaces $A_1$ and $A_2$

energy emitted and the energy absorbed;

$$Q_1 = A_1 \epsilon_1 \sigma T_1^4 - A_1 \alpha_1 \sigma T_2^4 \qquad (2.40)$$

For $\epsilon_1 = \alpha_1$, this result simplifies to

$$Q_1 = A_1 \epsilon_1 \sigma (T_1^4 - T_2^4) \qquad (2.41)$$

which provides the expression for calculating the radiation heat exchange between a small surface element $A_1$ and its surroundings at $T_2$. The positive value of $Q_1$ implies heat loss from the surface $A_1$ and the negative value implies heat gain.

For two infinite surfaces $A_1$ and $A_2$ (figure 2.11b), maintained at absolute temperature $T_1$ and $T_2$ respectively and have emissivities $\epsilon_1$ and $\epsilon_2$, the physical situation implies that part of the radiation leaving surface $A_1$ reaches surface $A_2$ while the remaining is lost to the surroundings. Similar considerations apply for the radiation leaving surface $A_2$. The analysis of radiation heat exchange between the two surfaces for such a case should include the effects of the orientation of the surfaces, the contribution of radiation from the surroundings, and the reflection of radiation at the surfaces. If we assume that the radiation flux from the surroundings is negligible compared to those from surfaces $A_1$ and $A_2$, then the net radiation heat transfer $Q_1$ at the surface $A_1$ can be expressed in the form

$$Q_1 = F_1 A_1 (T_1^4 - T_2^4) \qquad (2.42)$$

where $F_1$ is a factor that includes the effects of the orientation of the surfaces and their emissivities.

To simplify the heat transfer calculations, it may be possible, under very restrictive conditions, to define a radiation heat transfer coefficient $h_r$, analogous to the convection heat transfer coefficient as

$$q_1 = h_r (T_1 - T_2) \qquad (2.43)$$

The concept can be applied to the result given by Equation 2.41. We therefore have,

$$Q = A_1 \epsilon_1 \sigma (T_1^2 + T_2^2)(T_1 + T_2)(T_1 - T_2) \qquad (2.44)$$

If $/T_1 - T_2/ << T_1$, then $T_1 \cong T_2$,

Hence Equation 2.44 is linearised as

$$Q_1 \cong A_1 \epsilon_1 \sigma 4T_1^3 (T_1 - T_2) \qquad (2.45)$$

$$\text{Or } q_r = \frac{Q}{A_1} = (4T_1^3 \epsilon_1 \sigma)(T_1 - T_2) \qquad (2.46)$$

A comparison of equations 2.43 and 2.46 reveals that for specific case given by equation 2.41, a radiation heat transfer coefficient hr can be defined (Ozisik, 1985) as

$$h_r = 4T_1^3 \epsilon_1 \sigma \qquad (2.47)$$

## 2.5.13 COMBINED HEAT TRANSFER MECHANISM

In many practical situations heat transfer from a surface takes place simultaneously by convection due to the ambient air and by radiation to the surroundings. For a small plate of area A and emissivity $\epsilon_w$ of the wall surface that is maintained at $T_w$ and exchanges energy by convection with a fluid at $T\alpha$ with a heat transfer coefficient $h_c$ and by radiation with the surroundings at $T_s$. The heat loss per unit area of the plate, by the combined mechanism of convection and radiation, is given by McCabe et al (1985) as

$$q_T/A = q_c/A + q_r/A = q_w = h_c (T_w - T\alpha) = \epsilon\sigma(T_w^4 - T_s^4) \qquad (2.48)$$

If $/T_w - T_s/ << T_w$, the second term according to Ozisik (1985) can be linearized to obtain,

$$q_w = h_c (T_w - T\alpha) + h_r (T_w - T_s) \qquad (2.49)$$

where, $q_T/A$ is the total heat flux, $q_c/A$ is the heat flux by conduction-convection, $q_r/A$ is the heat flux by radiation, $h_c$ is the convective heat transfer coefficient $\epsilon_w$ is the emissivity of surface, $T_w$ is the temperature of surface, T is the temperature of surroundings.

However, $T_\alpha$ and $T_s$ are both temperatures of the surrounding.

i.e $T\alpha = T_s = T$

$$q_T / A = q_w = (h_c + h_r)(T_w - T) \quad (2.50)$$

where $h_r$ is the radiation heat – transfer coefficient defined by

$$h_r = q_r / A(T_w - T) \quad (2.51)$$

which depends strongly on the absolute magnitude of $T_w$ and to some extent on the temperature difference $T_w - T$. However, when the temperature difference is small, the value of $h_r$ can be approximated from a simple equation using only one temperature. Expansion of the fourth – power term in equation 2.48 gives

$$q_r/A = \sigma\epsilon_w (T_w^4 - T^4) = \sigma\epsilon_w (T_w^2 + T^2)(T_w + T)(T_w - T) \quad (2.52)$$

If $T_w - T$ is very small, T can be replaced by $T_w$ in all but one term of equation 2.52 to give

$$q_r/A \approx \sigma\epsilon_w (2T^2_w)(2T_w)(T_w - T) = \sigma\epsilon_w (4T^3_w)(T_w - T) \quad (2.53)$$

From the definition of $h_r$, eq. 2.51 becomes

$$h_r \approx 4\sigma\epsilon_w T^3_w \quad (2.54)$$

Equations 2.51 and 257 apply to a small area completely surrounded by a surface of much larger area, so that only the emissivity of the small area influences the heat flux (McCabe et al, 1985).

## 2.6 SOURCES OF HEAT AND METHODS OF APPLICATION TO FOODS

The cost of energy for food processing has become one of the major considerations in equipment design and ultimately the cost of the food and the profitability of the operation. Different energy sources have specific advantages and limitations in terms of cost, safety, risk of contamination of the food, flexibility of use, and capital and operating costs for the heat transfer equipment. Sources of energy use in food processing are electricity, gas (i.e natural and liquid petroleum gas), liquid fuel oil, and solid fuels (i.e anthracite, coal, wood and charcoal).

Direct and indirect methods may be used to heat foods but only indirect methods are used for cooling foods (Fellows, 1990).

### 2.6.1 DIRECT METHODS

The heat and products evolved from the burning fuel come directly into contact with the food. There is an obvious risk of contamination of the food by odours of incompletely burned fuel and for this reason, only gas and to a lesser extent liquid fuels are used. Electricity is not a fuel in the same sense as the other types described above.

**TABLE 2.3: Advantages and Limitations of different energy sources for food processing (Fellows, 1990)**

| | Electricity | Gas | Liquid fuel | Solid fuel |
|---|---|---|---|---|
| Energy per unit mass or volume | Not applicable | Low | High | Moderate to high |
| Cost per kilojoule of energy | High | Low | Low | Low |
| Heat transfer equipment cost | Low | Low | High | High |
| Efficiency of heat | High | Moderate to High | Moderate to low | Low |
| Flexibility of use | High | High | Low | Low |
| Rate of explosion hazard | Low | High | Low | Low |
| Risk of food contamination | Low | Low | High | High |
| Labour and handling cost | Low | Low | Low | High |
| Amount (%) used in Europe | 9.60 | 38.20 | 30.44 | 21.76 |

### 2.6.2 INDIRECT METHODS

Indirect heating methods employ a heat exchanger to separate the food from the products of combustion and consists of burning fuel beneath a metal plate and heating by radiated energy from the plate. The most common type used in food processing is steam generated by a heat exchanger located away from the processing area.

Indirect electrical heating uses resistance heaters or infrared heaters. Resistance heaters are nickel-chromium wires contained in solid plates, which are attached to the walls of vessels, in flexible jackets, which wrap around vessels, or in immersion heaters which are submerged in the food. These types of heater are used for localised or intermittent heating.

### 2.6.3 EFFECT OF HEAT ON MICRO-ORGANISMS, NUTRITIONAL AND SENSORY PROPERTIES OF FOODS (6)

The preservative effect of heat processing is due to the denaturation of proteins, which destroys enzyme activity and enzyme controlled metabolism in micro-organisms. The rate of destruction is a first-order reaction; when food is heated to a temperature that is high enough to destroy contaminating micro-organisms, the same percentage die in a given time interval regardless of the numbers present initially. This is known as the *logarithmic order of death* and is described by a *death rate curve*.

The destruction of many vitamins, aroma compounds and pigments by heat follows a similar first-order reaction to microbial destruction. Nutritional and sensory properties are better retained by the use of higher temperatures and shorter times during heat processing.

## 2.7 TYPES OF DRIER

Various kinds of driers can be designed to carry out dehydration of foods. Since dehydration is a combined heat and mass transfer operation, the driers can be classified according to the methods by which these transfers are accomplished. Most commercial driers are insulated to reduce heat losses, and they re-circulate hot air to save energy. Many designs have energy–saving devices, which recover heat from the exhaust air or automatically control the air humidity. Computer controlled driers are increasingly becoming sophisticated and also result in savings of energy.

### 2.7.1 ATMOSPHERIC BATCH DRIERS

Batch driers are used when different types of materials are to be dried and where the operations are small or seasonal. Examples of batch driers are

#### 2.7.1.1 Kiln drier

This consists of a two-storey building with a slotted floor separating the drying rooms in the upper storey from the rooms on the lower floor. The lower floor rooms contain burners heating air which, along with the combustion gases, supply heat to a layer of fruit (up to 20cm deep) resting on the slotted floor. These driers have been used traditionally for drying apple rings or slices in the USA, and hops or malt in Europe. There is limited control over drying conditions and drying times are relatively long. High labour costs are incurred by the need to turn the product regularly, and by manual loading and unloading. However, the driers have a large capacity and are easily constructed and maintained at low cost.

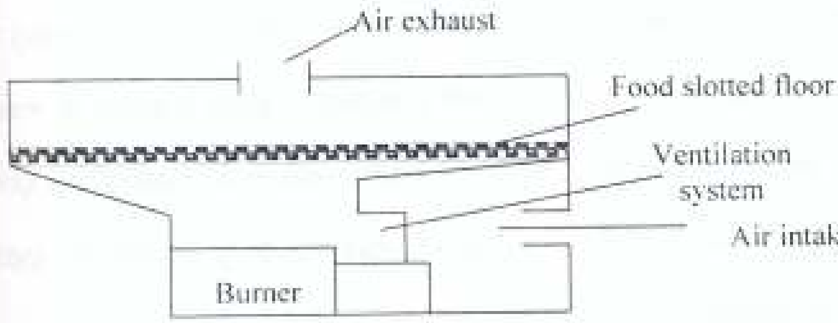



Fig 2.12: Schematic representation of a kiln drier.



#### 2.7.1.2. Cabinet or tray drier

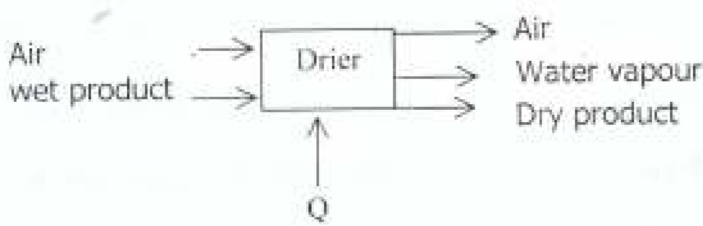



Fig. 2.13: A control volume for a tray, tunnel or belt drier

This use a hot circulating air stream to provide the energy needed for drying. It consists of an insulated cabinet fitted with shallow mesh or perforated trays which contains a thin (about 2 – 6cm deep) layer of food. Air is heated by direct combustion with fuels or by steam or electric coils. Dampers are installed and regulated to control the amount of air entering and exiting the drier thereby controlling the humidity within the drier. Hot air is therefore circulated through the cabinet at 0.5 - 5ms$^{-1}$ per square metre tray area. A system of ducts and blower is used to direct air over and/or through each tray to promote uniform air distribution. Additional heaters may be placed above or alongside the trays to increase the rate of drying. Tray driers are used for small-scale production (1 to 20 tonnes per day) or for pilot plant scale operation. They require low capital and maintenance costs but have relatively poor control and produce more variable product quality.

The energy required for operation of tray driers like tunnel and belt driers can be estimated if the properties of all the mass flow entering and leaving the drier are known. An energy balance for this system gives,

Heat transfer needed = Heat received by product + Heat carried by dry air + Heat due to absolute humidity of air + Heat of vaporization of the moisture content of the product + Heat loss to the walls and by air leaks to surrounding.

$$Q = M_{po}C_{po}(\theta_{po} - \theta_{pi}) + m_{ai}C_a(\theta_{ao} - \theta_{ai}) + H_{pai}(h_{ve} - h_{vi})) + m_{evap}(h_{ve} - h_l) + Q_{loss} \quad (2.55)$$

where

$Q$ = heat transfer needed,

$M_{po}$ = product mass flow rate leaving the system

$C_{po}$ = product specific heat at product exit,

$\theta_{po}$ = product temperature at the exit

$\theta_{pi}$ = product temperature at the entrance,

$M_{ai}$ = dry air mass flow rate entering the drier,

$C_{pa}$ = constant pressure specific heat for dry air

$\theta_{ao}$ = temperature of air at the exit,

$\theta_{ai}$ = temperature of air at the entrance

$H_{ai}$ = absolute humidity of air entering the drier

$h_{ve}$ = enthalpy of the water vapour at the air exit,

$h_{vi}$ = enthalpy of the water vapour at the air entrance,

$M_{evap}$ = evaporation rate within the drier,

$h_{li}$ = enthalpy of liquid $H_20$ at the product entrance

$Q_{loss}$ = heat loss through the walls and by air leaks

For a given drier production rate, the mass flow rates $m_{pp}$ and $m_{evap}$ in the equation above are fixed. However, the air mass flow rate ($M_{ai}$) can vary, depending on the temperature and relative humidity within the drier. The last term ($Q_{loss}$) accounts for heat losses from the drier by conduction through the walls and air leaks. These losses can be significant and should be included for an accurate analysis. Typically, these heat losses amount to 20% of the total heat input but can vary significantly depending on such factors as how well the driers are insulated and the air leakage.

An important consideration in the operation of tray drier system that recirculate air is to determine the fraction of the air stream to be exhausted. Increasing the amount of air exhausted generally increases energy costs, but it reduces the humidity within the drier, and hence increases the rate of evaporation. Thus, there is a trade-off between production rate and energy costs. Predicting the influence of humidity on production rates is difficult and accurate data can often only be obtained by measurement.

**Table 2.4: Expected effects of several process parameters on drying rates of food pieces dried in layers (Basis: Unit surface area of tray) (Karel, 1975).**

| Parameter | Effect with increasing value of each parameter | | |
|---|---|---|---|
| | Drying rate in constant rate period ($w'_c$) | Duration of Constant rate period ($t_c$) | Drying rate in falling rate period ($w'_{II}$) |
| Air velocity (G) | Increases | Decreases | Small effect |
| Air temperature (T) | Increases | Decreases | Increases |
| Air humidity (H) | Decreases | Decreases | Decreases |
| Piece size | In flow over trays, minimal effect; in crossflow, decreases | Decreases | Increases |
| Bed depth* | Inflow over trays, minimal effect; Incrossflow, increases | Depends on degree of packing in the layers | Depends on degree of packing in the layer |
| Material properties | No effect | Unaffected | High effect |

*Note that the basis is unit area of tray and not unit weight of food. The effects are quite different for the two bases.

It is however difficult to quantitatively analyse the course of drying in batch driers. However, it is possible to predict the effects of various operational parameters on rate of drying and these are summarized in table 2.4.

In this work however, the batch design of processing equipment shall be used by constructing a tray drier to dry the kernel nuts. Some of the advantages of tray driers as processing equipment are;

1. Greater flexibility in being able to change product types or production rates
2. Lower capital cost for equipment.
3. Simpler operation and control to produce desired product
4. Fragile crystals can be handled gently
5. Reliable, safe and economical (that is, operating maintenance costs not excessive)

6. Pollution is highly reduced and controllable

7. Energy consumption is minimized.

The choice of tray drier is justified by the above advantages and this contributes to the reason why the most widely used dehydration methods involve exposure of foods to heated air. In this drier, the primary mode of heat transfer is by convection.

### 2.7.2 CONTINUOUS HOT-AIR DRIERS

In many food-dehydration operations, drying is conducted continuously in tunnel driers, or belt driers.

**2.7.2.1** <u>**Tunnel drier**</u> – Here, layers of food are dried on trays, which are stacked or loaded onto trucks or carts programmed to move semi-continuously through an insulated tunnel. Different designs use one of the types of air flow described in table 2.5. The air stream in a tunnel drier could be arranged to flow in the same direction (parallel or co-current flow), opposite direction (counter-current flow) or at right angles (cross flow with respect to the direction in which the carts move through the tunnel. Flow arrangement are chosen depending on the properties of the product. Counter-current flow provides the highest temperatures at the point where the moisture content is lowest and therefore counter-balances the increasing resistance to drying. This arrangement increases the danger of "scorching" the product (i.e damage due to non-enzymatic browning), this reaction has a maximum rate at intermediate moisture contents. Co-current flow allows the use of high entering air temperatures and therefore results in rapid initial drying, which is often desirable but in a few cases is deleterious to the texture of products.

Typically, a 20m tunnel contains 12-15 trucks with a total capacity of 5000kg of food. This ability to dry large quantities of food in a relatively short time (5 – 16 h) made tunnel drying widely used, especially in the USA. However, the method has now been largely superceeded by conveyor drying and fluidised–bed drying as a result of their higher energy efficiency, reduced labour costs and better product quality.

2.7.2.2 **Belt drier** Conveyor driers are up to 20m long and 3m wide. Food is dried on a mesh belt in beds 5 – 15cm deep. A continuous moving system of belts moves the product through the drier. The belts are perforated to allow the hot air to flow through them in a cross flow manner. Belts driers with parallel and counter airflow to the product flow are also utilized.

This type of drier improves uniformity of drying and saves floor space. Foods are dried to 10-15% moisture content and then transferred to bin drier for finishing. This

**Table 2.5: Advantages and limitations of parallel flow, counter-current flow, centre-exhaust and cross-flow drying (Fellows, 1990).**

| Flow Type | Advantages | Limitation |
| --- | --- | --- |
| Parallel<br>Food ——►<br>Airflow ——► | Rapid initial drying. Little shrinkage of food low bulk density, less heat damage to food. No risk of spoilage | Low moisture content difficult to achieve as cool moist air passes over dry food. |
| Counter-current<br>Food ——►<br>Airflow ◄—— | More economical use of energy. Low final moisture content as hot air passes over dry food | Food shrinkage and possible heat damage. Risk of spoilage from warm moist air meeting wet food. |
| Centre exhaust<br>Food ——►<br>Airflow —► ▲ ◄— | Combined benefits of parallel and counter-current driers but less than cross-flow driers | More complex and expensive than single – direction air flow. |
| Cross flow type<br>Food ——►<br>Airflow ▼▲ | Flexible control of drying conditions by separately controlled heating zones, giving uniform drying and high drying rates | More complex and expensive to buy, operate and maintain |

equipment has good control over drying conditions and high production rates. It is used for large scale drying of food (e.g fruits and vegetables). It has independently controlled drying zones and is automatically loaded and unloaded, which reduces labour costs. As a result, it has largely replaced the tunnel drier.

**2.7.2.3** **Rotary drier** A slightly inclined rotating metal cylinder is fitted internally with flights to cause the food to cascade through a stream of hot air as it moves through the drier. Airflow may be parallel or counter-current. The agitation of the food and the large area of food exposed to the air produce high drying rates and a uniformly dried product. The method is especially suitable for foods that tend to mat or stick together in belt or tray driers. However, the damage caused by impact and abrasion in the drier restrict this method to relatively few foods (e.g sugar, crystals, and cocoa beans). This drier is another important type of continuous drier, suitable for large-scale production of "flow-able" products.

## 2.7.3 ATMOSPHERIC CONDUCTIVE DRIERS

### 2.7.3.1 Drum drier (roller drier)

Conduction heat transfer is used to provide energy for vaporization of water. Steam condenses inside the drum to provide heat source. As the drum rotates, a thin layer of product is applied to the drum through dipping, splashing, spraying, use of spreading devices or feeding rollers. The speed of rotation of the drum is adjusted so that the desired moisture content is obtained when the dried product is scrapped off the drum by a knife. The room in which a drum drier is placed must have adequate ventilation to remove the water vapour produced. Drum driers consist of hollow drums constructed of carefully machined iron or stainless steel.

The drier may consist of single or double (twin) drums. The single drum is widely used as it has greater flexibility, a larger proportion of the drum area available for drying, easier access for maintenance and no risk of damage caused by metal objects falling between the drums. The drier has a high drying rates and high energy efficiency. It is suitable for slurries in which the particles are too large for spray drying. However, the present applications of drum drying in the food industry are limited.

**2.7.3.2** **<u>Heated Surface driers</u>** Driers in which heat is supplied to the food by conduction have two main advantages over hot air drying. First, it is not necessary to heat large volume of air before drying commences, and the thermal efficiency is therefore high. Secondly, drying may be carried out in the absence of oxygen to protect components of foods that are easily oxidized.

Typically, heat consumption is 2000 – 3000kJ per kg of water evaporated compared with 4000 – 10,000kJ per kg of water evaporated for hot air driers. However, foods have low thermal conductivity which become lower as the food dries. There should therefore be a thin layer of food to conduct heat rapidly without causing heat damage. Foods may shrink during drying or lift off the hot surface. It may therefore introduce an additional barrier to heat transfer. Careful control is necessary to minimise shrinkage and to determine the thickness of the feed layer.

### 2.7.4 SPRAY DRIER

Spray drying is the most important technique for dehydrating liquid food products (Karel, 1975) as in the drying of milk products, coffee, and eggs. A fine dispersion of pre-concentrated food is first atomized. Atomization determines the size distribution of droplets. It is the most important feature of a spray drier and can be achieved by means of high-pressure nozzles in which a fluid acquires a high-velocity tangential motion while being forced through the nozzle orifice. The fluid swirls out in a cone-shaped sheet, which breaks up into droplets 10-200μm in diameter. The atomized food is sprayed into a current of heated air at 150 – 300$^0$C in a large drying chamber (Fellows, 1990).

In principle, a liquid or a paste is atomized into a chamber, where it is put in contact with a stream of hot air and rapidly dried. The dry particles become suspended in the air stream and flow into separation equipment where they are removed from the air, collected, and packaged or subjected to further treatment such as instantizing.

Spray driers vary in size from small pilot scale models for low volume high value products, to large commercial models capable of producing 80,000kg of dried milk per day (Ashworth, 1981). The main advantages are rapid drying, large-scale continuous production, low labour cost and simple operation and maintenance. Major limitations are high capital costs and the requirement for a relatively high feed moisture content to ensure that the food can be pumped to the atomizer. This results in higher energy costs (to remove moisture) and higher volatile losses. Conveyor belt driers and fluidized bed driers are beginning to replace spray driers as they are more compact and energy efficient (Brenndorfer et al, 1985).

### 2.7.5 FLUIDIZED BED DRIERS

Metal trays with mesh or perforated bases contain a bed of particulate food up to 15cm deep. Hot air is blown through the bed, causing the food to become suspended and vigorously agitated (fluidized). As the hot air flows over the bed, the pressure drop across the bed balances the weights of the bed and at greater velocities the bed expands and particles become suspended in air. The hot air thus acts as both the drying and fluidizing medium, and maximum surface area of food is made available for drying (Fellows, 1990).

As the velocities increase further, the bed is disturbed and assumes the appearance of a "boiling fluid". At still higher air velocities, individual particles are carried away (conveyed) by the air. Driers may be batch or continuous in operation. They are compact and have good control over drying conditions, relatively high thermal eficiencies and high drying rates. The major limitation of fluidized drying is the limited range of particle sizes which can be effectively fluidized without excessive mechanical damage.

### 2.7.6 PNEUMATIC DRIERS

In these driers particles of food are carried along by a stream of air as they are simultaneously exchanging mass and heat with the air. In principle, the drying is similarly to spray drying, except it is applied to solid particles. It has the advantage of high drying velocities, similar to those of spray and fluidized bed drying, and is limited primarily by the type and size of particle that can be conveyed effectively without damage by an air stream. The capital costs are relatively low and thermal efficiencies are high. The driers have close control over drying conditions. They are often used after spay drying to produce foods which have a lower moisture content than normal.

### 2.7.7 FOAM MAT DRIER

Liquid foods (e.g fruit juices) are formed into stable foam by the addition of a stabilizer (Fellows, 1990) and aeration with nitrogen or air. The foam spread on a perforated belt to a depth of 2 - 3mm and dried rapidly in two stages by parallel and then counter-current air flows. Foam drying is approximately three times faster than drying a similar thickness of liquid. The rapid drying and low product temperatures result in a high-quality product. However, large surface area is required for high production rates, and capital costs are therefore high. Practical application of this method are still limited.

### 2.7.8 SUN AND SOLAR DRYING

Sun drying is the most widely practiced agricultural processing operation in the world (Fellows, 1990). More than 250,000,000 tonnes of fruits and grains are dried by solar energy per annum. In some countries, foods are simply laid out on roofs or other flat surfaces and turned regularly until dry. More sophisticated methods, for example solar drying collects solar energy to heat air, which in turn is used for drying. Solar driers are classified into

(a) Direct natural circulation driers - These combine the collector and the drying chamber.

(b) Direct driers with separate collector

(c) Indirect forced - convection driers - These have the drying chamber separated from the collector.

Both solar and sun drying are simple inexpensive technologies, in terms of both capital input and operating costs. Energy inputs and skilled labour are not required. The major disadvantages are relatively poor control over drying conditions, and over drying rates than those found in artificial driers. This results in products which have lower quality and greater variability. In addition, drying is dependent to the weather, the time of the day and requires a larger labour force than other methods. They cannot be used during very cold weather or incessant rainfall.

### 2.7.9 BIN DRIERS (Deep-bed driers)

Bin driers are hot-air driers with cylindrical or rectangular container fitted with a mesh base. Hot air moves up through a bed of food at relatively low speeds (e.g 0.5m/s per square metre of an area). These driers have a high capacity and low capital and maintenance costs. They are mainly used for "finishing" (to 3 – 6% moisture content) after drying in other types of equipment. Bin driers improve the operating capacity of the initial driers by taking the food when it is in the falling-rate period, when moisture removal is most time consuming. The deep bed of food permits variation in moisture content to be equalized and acts as a store to smooth out fluctuations in the product between drying stages and packaging. However the driers may be several metres high, and it is therefore important that foods are sufficiently strong to withstand compression at the base and to retain an open structure to permit the passage of hot air through the bed.

**TABLE 2.6: A classification of some atmospheric driers (Karel, 1975)**

| | Driers | |
|---|---|---|
| Mode of heat transfer | Batch operation | Continuous operation |
| Convection | Kiln drier<br>Cabinet drier | Tunnel drier<br>Conveyor or belt drier<br>Spray drier<br>Fluidized-bed drier |
| Conduction | Heated-shelf drier<br>Agitated pan drier | Drum drier |
| Radiation | Infrared heated-shelf drier | Infrared heated belt drier |
| Internal generation of heat | Microwave oven | Dielectric continuous oven<br>Microwave tunnel |
| Mixed | Shelf drier | Rotary drier |

## 2.8 ELECTRONIC MATERIAL

To design and construct the instrumentation and control for the palm kernel drier, which is a key aspect of the drier electronic components such as resistors, diodes, transistors, logic gates, analogue to digital and digital to analogue converters are used. A summary of the characteristics of the materials is explained as follows.

## 2.9 RESISTOR

A resistor is a conductor, which has some amount of electrical resistance to the flow of electric current through it. Resistors are used to limit the amount of current flowing in a circuit. The opposition to the flow of current is called resistance and it is measured in ohms (Ω). There are two types of resistor; fixed resistor and variable resistor. Examples of fixed resistors are include: Carbon composition, carbon film, metal oxide, metal glaze and wire wound. Exampies of variable resistors are the resistance box, rheostat and the potentiometer. The latter consists of a track of some kind of resistive material to which a movable wiper makes contact. The following resistive materials are used in potentiometers:

(a) Carbon - either molded carbon composition giving a solid track, or a coating of carbon plus an insulating filler onto a substrate.

(b) Wire-wound – Nichrome or other resistance wire wound onto a suitable insulating former.

(c) Cermet – A thick film of resistance coating on a ceramic substrate.

A resistor may be intended only as a resistance that requires to be preset and therefore adjusted only a few times during its operational life, or as a control that is required to be continually varied over the whole of its track. The latter must be robust,

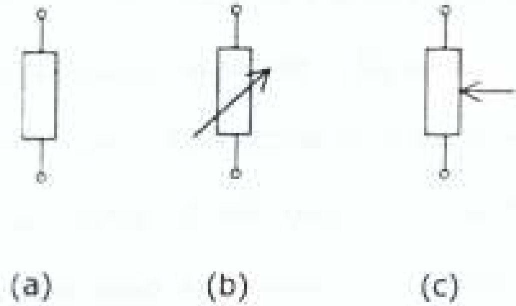



Figure 2.14: Conventional circuit symbol for Resistors
(a) fixed resistor (b) variable resistor (c) potential divider resistor

## 2.10 CAPACITOR

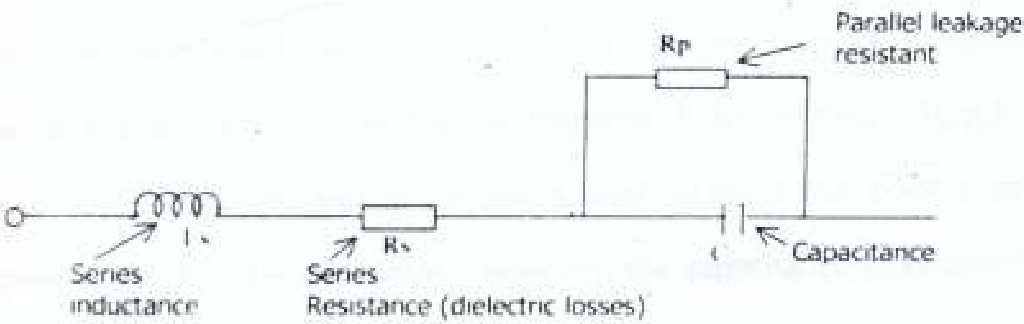



Figure 2.15: Equivalent circuit for a capacitor.

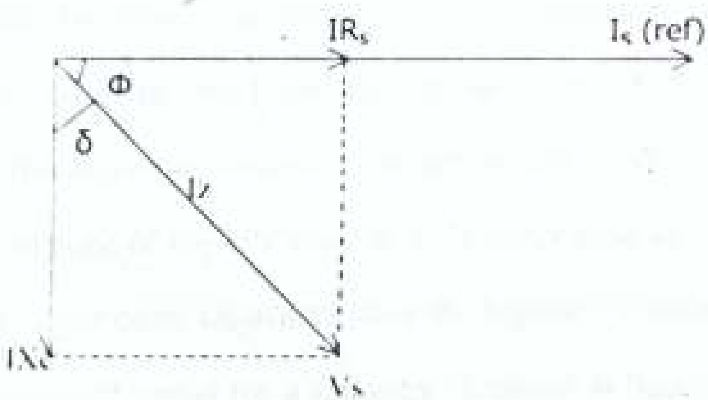



Figure 2.16: Phasor diagram showing the effect of the series resistance losses,

where δ is the loss angle, Φ is the phase angle, Tan δ is the $Rs/X_c$ (dissipation factor),

Cos Φ = Rs/Z.

stable, and capable of many thousands of rotations before failing. The symbol used to show a resistor in a circuit diagram is shown in figure 2.14.A capacitor is an electronic device that stores an electrical charge. Connecting its leads directly across a power supply can charge it almost instantly. Some of the uses of capacitors are signal filtering, power supply filtering, coupling and spike and noise suppression. A capacitor is made of two parallel conducting plates separated by an insulating *dielectric*. The capacitance C of a capacitor is the measure of how much charge it can store. For a parallel plate capacitor, C is given by

$$C = \varepsilon_o \varepsilon_r A / d \qquad (2.56)$$

where $\varepsilon_o$ is the absolute permittivity, $\varepsilon_r$ is the dielectric constant or relative permittivity, A is area of one of the plates and d is the thickness of the dielectric. To achieve a reasonable value of capacitance the area of the plates must be large, the dielecric constant high, and the thickness of the dielectric small. However, the capacitance-to-volume ratio is important since the space available for a capacitor on a circuit board is usually limited. In order to achieve a large capacitance to volume ratio, long strips of thin conducting foils separated by a thin dielectric are rolled together to make the capacitor. Another constraint is that the thin insulating dielectric must be able to withstand a reasonable d.c voltage without breakdown. Therefore the dielectric strength is also important. And often, the CV product is used as a measure of the efficiency of a capacitor type as it gives the total charge Q that can be stored. Electrolytic capacitors have the highest CV value available

The equivalent circuit for a capacitor is shown in figure 2.15. The figure shows that a capacitor consists of a series inductance, a series resistance, and a capacitance with parallel leakage resistance. Neglecting the leakage resistance for the moment, the rest forms a series resonant circuit. Below resonance, the impedance is capacitive; at resonance, it is resistive and above resonance it becomes inductive. It is therefore important to keep the inductance low in order to increase the working frequency range of a capacitor. Electrolytic capacitors may have resonant frequencies well below 100kHz, and this is the reason why they cannot be used to remove short-duration switching spikes from power supply lines.

Referring to the equivalent circuit (fig 2.15), for frequencies below resonance we neglect the effect of the series inductance. The loss angle δ is a measure of the size of the series resistance compared to the capacitive reactance while the dissipation factor is a measure of how "lossy" a capacitor is and is quoted at a particular frequency ($50H_z$ for electrolytic capacitors and 1kHz for other types). The phasor diagram is as shown in figure 2.16.

For a capacitor, δ must be small. Hence, the dissipation factor (d.f) = $Rs/X_c$ = tan δ. Its value ranges from as low as 2 $\times 10^{-4}$ for polystyrene capacitors (at $1kH_z$) and above 0.3, for large value aluminum electrolytic type at $50H_z$. Alternatively, some manufacturers may quote the power factor which is given as power factor Rs/z = Cos Φ = Sin δ. (For small angles δ < $5^0$), Sin δ = tan δ.

The leakage resistance, Rs, for most non-electrolytic types of capacitor is very high, typically greater than $10^{10}\Omega$. For electrolytic capacitors, the actual leakage current is usually quoted, which for a large size type may be several milliamps. Leakage resistance and leakage current are dependent on both temperature and applied voltage. The resistance decreases as voltage and temperature are increased.

### 2.10.1 CAPACITOR TIME CONSTANT

Capacitor time constant (RC product) is formed by the actual capacitor and its parallel leakage resistance. If a capacitor is charged and then disconnected from the supply, the charge leaks away through the parallel leakage resistance, and the time for the voltage to fall by 63% is equal to one time constant. RC products for polystyrene capacitors are said to be among the highest recorded values, approaching several days, while at the other extreme the RC value for aluminum electrolytic may be as low as a few seconds. The RC product is used extensively as an indication of capacitor deterioration during life test. Capacitor circuit symbols are as shown in fig 2.17.

## 2.11 TRANSFORMER

Fig. 2.18 shows the general arrangement of a transformer. An iron core C consists of laminated sheets, insulated from one another by thin layers of paper or varnish or by spraying the laminations with a mixture of flour, chalk and water, which, when dried, adheres to the metal. The purpose of laminating the core is to reduce the loss due to eddy currents induced by the alternating magnetic flux. For frequencies in excess of 100kHz, high resistivity ferrite cores are used rather than laminated core used for low frequency application.

Coils P and S are wound on the limbs (the vertical portions of the core). The yokes are the top and bottom. Coil P is connected to an a.c supply and is termed the primary; Coil S is connected to the load and is termed the secondary. An alternating voltage applied to P circulates an alternating current through P and this current produces an alternating flux in the core, the path of this flux being represented by the dotted line D. If the whole of the flux produced by P passes through S, the e.m.f. induced in each turn is the same for P and S. Hence, if $N_1$ and $N_2$ be the number of turns on P and S respectively,

$$\frac{\text{e.m.f. induced in S}}{\text{e.m.f. applied to P}} = \frac{N_2 \times \text{e.m.f. per turn}}{N_1 \times \text{e.m.f. per turn}} = \frac{N_2}{N_1} \qquad (2.57)$$

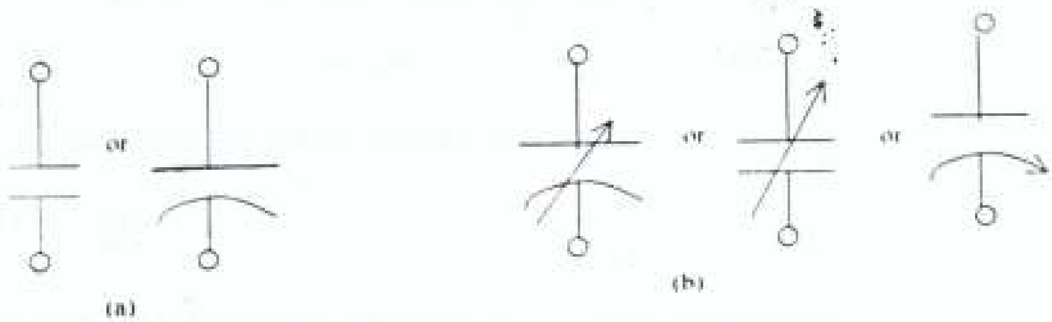



Figure 2.17: Conventional circuit symbols for (a) fixed and (b) variable capacitors.

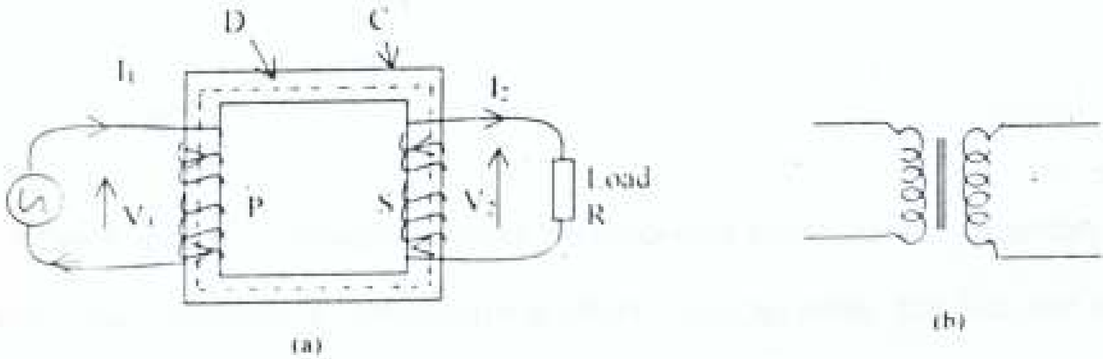



Figure 2.18: A transformer and its Circuit symbol

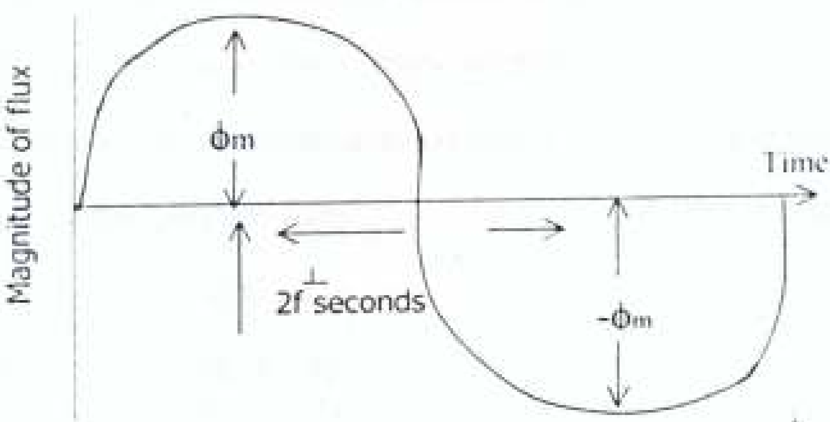



Figure 2.19: Waveform of flux variation

When the secondary is on open circuit, its terminal voltage is the same as the induced e.m.f. The primary current is then very small, so that the applied voltage $V_1$ is practical equal and opposite to the e.m.f. induced in P. Hence,

$$\frac{V_2}{V_1} = \frac{N_2}{N_1} \qquad (2.58)$$

Since the full-load efficiency of a transformer is nearly 100 percent,

$I_1V_1$ x primary power factor = $I_2V_2$ x secondary power factor.

But the primary and secondary power factors at full load are nearly equal

$$\therefore I_1V_1 = I_2v_2$$

or
$$\frac{I_1}{I_2} = \frac{V_2}{V_1} \qquad (2.59)$$

When a load R is connected across the secondary terminals, the secondary current , by Lenz's Law, produces a demagnetizing effect. Consequently, the flux and the e.m.f. induced in the primary are reduced lightly. But this small change may increase the difference between the applied voltage and the e.m.f. induced in the primary from, say 0.05 percent to, say, 1 percent, in which case the new primary current would be 20 times the no-load current. The demagnetizing ampere-turns of the secondary are thus nearly neutralized by the increase in the primary ampere-turns; and since the primary ampere-turns on no load are very small compared with the full-load ampere turns,

∴ Full load primary ampere-turns = Full load secondary ampere-turns

i.e $I_1 N_1 = I_2N_2$,

so that
$$\frac{I_1}{I_2} = \frac{N_2}{N_1} = \frac{V_2}{V_1} \qquad (2.60)$$

### 2.11.1 PRACTICAL TRANSFORMERS

For large transformer ratios, it is a common practice to make the low-voltage high-current winding of heavy gauge wire in order to reduce $I^2R$ losses in the winding. The other winding is a large number of turns of fine wire since only a small current is present. An equivalent circuit of a practical transformer is illustrated in figure 2.20.

The inductances in the primary and secondary circuits are caused by leakage magnetic flux which does not link both windings, so that the opposing fluxes do not quite cancel. The resistances are included to account for the resistance of the wire in the windings. The inductance $L_m$ accounts for the small magnetizing current corresponding to the no-load primary current. The capacitors on the primary and secondary sides result from the layer-to-layer capacitances between windings.

According to this equivalent circuit, a transformer is ineffective at low frequency where the reactance of $L_m$ becomes so small that current is shunted from the primary winding of the ideal transformer. High frequency performance is impaired by the leakage flux inductances and winding capacitances. In spite of these limitations, transformers can be designed for effective performance over useful frequency intervals.

Transformers serve two important functions in electronic circuitry: they change the ac line voltage to a useful (usually lower) value that can be used by the circuit, "isolate" the electronic device from actual connection to the power line, because the windings of a transformer are electrically insulated from each other. Moreover, they are used for coupling and also as matching devices.

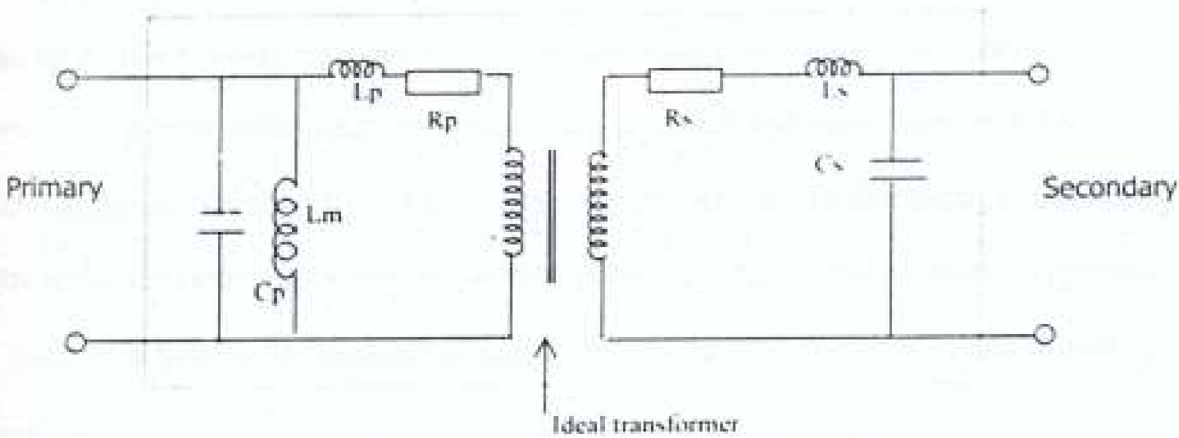



Fig. 2.20: Equivalent circuit of a practical transformer.

## 2.12 JUNCTION DIODE

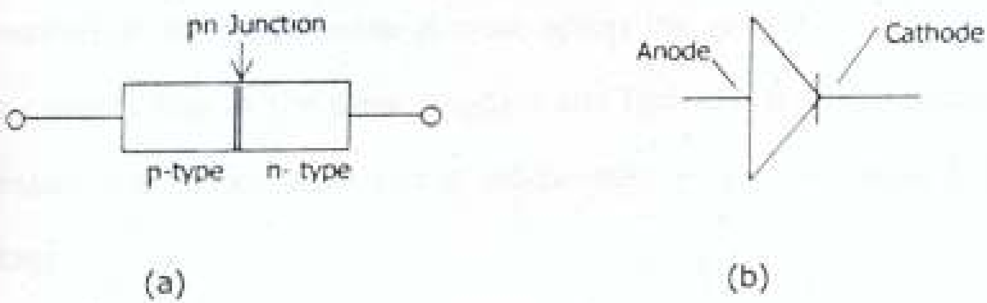



Fig. 2.21: P-n junction diode and its symbol

This consists of a p-type material and an n-type material melted together in a single crystal. A p-n junction separates the materials. The majority carriers in the p-material, are holes while the majority carriers in the n-material are electrons. Due to density gradient, holes in the p-type diffuse across the junction to n-type and recombine with the electrons which diffuse across the junction from the n-type material. An electrical potential gradient builds up which opposes further movement of charges across the junction. This region of the junction is said to be depleted of mobile charges and is therefore called depletion region.

If a p - n junction is connected as in Figure 2.23a, the holes in the p-type are attracted to the negative plate of the battery and the electrons in the n – type material to the positive plate. The result is movement of both charges away from the junction. Thus, at a steady state the majority carriers are prevented from crossing the junction. However, a small current flows because a small number of hole-electron pairs are generated throughout the crystal as a result of thermal agitation. The holes so formed in the n-type material wander over to the junction and constitute a current. Similarly, the electrons generated at the p-type material move across the junction and constitute a current. The two currents flow in the same direction and form the reverse saturation current $I_o$ which increases with temperature and is independent of the magnitude of the applied reverse voltage.

In the forward bias shown in fig. 2.23b, the height of the potential barrier at the junction is lowered by the applied voltage V. Holes are injected from the p-type into the n-type where they constitute injected minority carriers. Similarly electrons are injected from the n-type into the p-type. The two currents are in the same direction. Their sum constitutes the total current I across the junction.

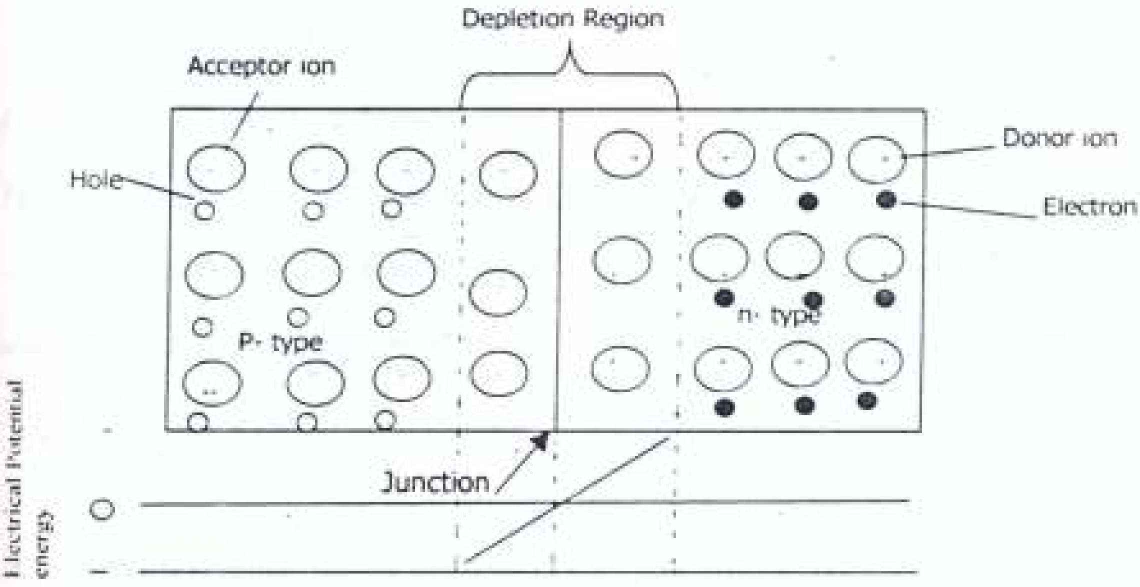



Fig. 2.22: P n junction and potential energy variation across the junction

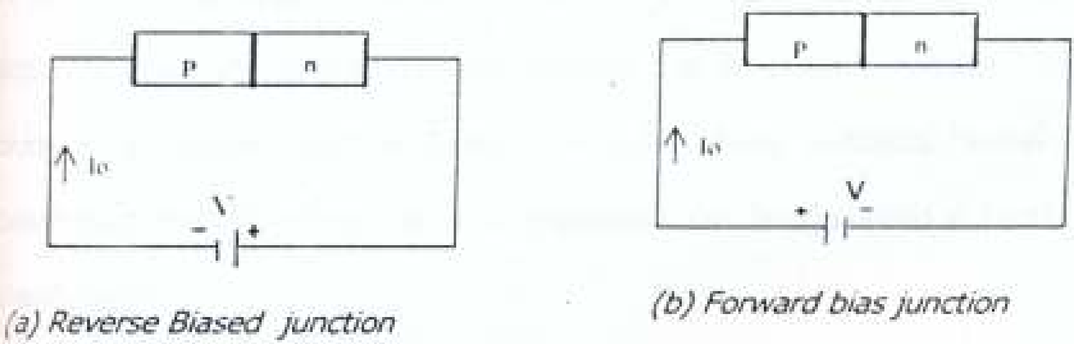



Fig. 2.23: P n Junction Biasing

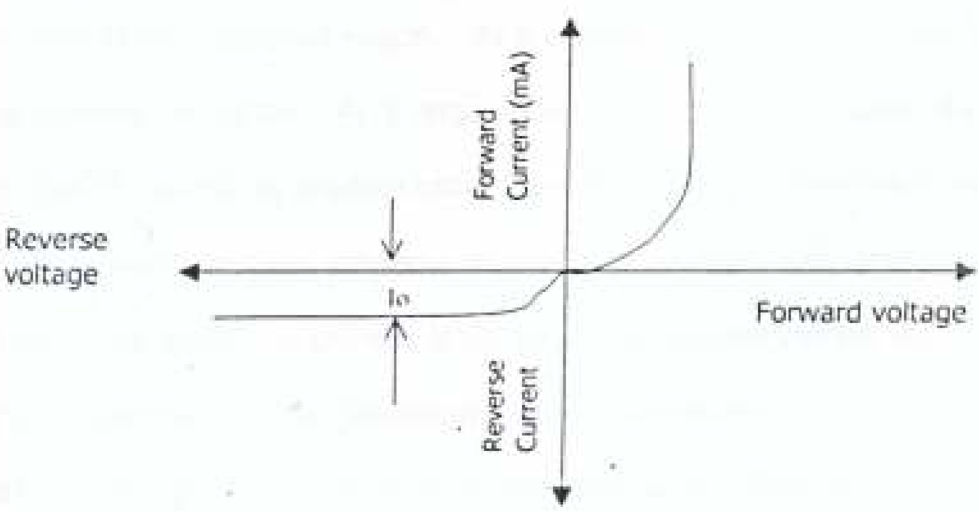



Fig. 2.24: Volt – Ampere Characteristic of Junction diode

$$I = I_o (e^{V/\eta V_T} - 1) \quad (2.61)$$

At room temperature $V_T \approx 26mV$

The constant $\eta$ is 2 for silicon and 1 for germanium

The volt-ampere characteristic of a diode is of the form shown fig 2.24. The forward current ranges from milliamperes to amperes. The reverse current is several microamperes for germanium and several nanoamperes for silicon.

## 2.13 ZENER DIODE

Ideally, a pn junction diode conducts in the forward direction and does not conduct in the reverse direction. The zener diode is designed specifically to conduct in the reverse direction when the reverse voltage exceeds the *breakdown voltage*. Therefore a zener diode is a voltage sensitive switch. A zener diode conducts heavily at a fixed pre-determined reverse voltage. Reserve breakdown can be explained in terms of the following phenomena:

(a) AVALANCHE BREAKDOWN: A zener diode is heavily doped hence its depletion region is very thin. When the diode is reverse biased the minority carriers are accelerated by the electric field in the depletion region. As the reverse voltage increases, the velocity of the minority carriers increases. At a large value of the reverse voltage the minority carriers acquire enough velocity to produce other free electrons by collisions with atoms.

These electrons are similarly accelerated by the field and in turn cause other ionizations. This avalanche process leads to a large reverse current and the junction is said to suffer breakdown. The breakdown is not destructive, however, unless the power dissipation increases the temperature to the point where local melting destroys the diode.

The voltage across the junction remains quite constant over a wide current range in the breakdown region.

(b) ZENER BREAKDOWN: In the presence of a strong electric field at the junction, a sufficiently strong force can be exerted on a bound electron by the field to tear it out of its covalent bond. The new hole-electron pair which is created increases the reverse current. This method of breakdown does not involve collision of carriers with crystal ions like in the avalanche multiplication. Zener breakdown occurs only in zener diodes that have breakdown voltage below 5V. Zener diodes with breakdown voltage greater than 5V operate predominantly by avalanche breakdown. Zeners are commercially available with breakdown voltages between 2.5V - 72V. A typical V-I characteristic of a zener diode and its symbol is shown in figure 2.25. $V_z$ is the breakdown voltage and $I_Z$ is the zener current.

## 2.14 LIGHT EMITTING DIODE (LED)

Some p-n junctions emit visible light when forward biased. This occurs because when the injected minority carriers recombine at the junction, energy is liberated. The energy is the excess energy which the electrons give off as they fall from the conduction band to the valence band in order to recombine. For a LED, the energy is in the visible region. LEDs are made of gallium arsenide or gallium phosphide. Possible colours include red, green, and yellow. Visible LEDs find wide application as inexpensive, low-power consumption indicators.

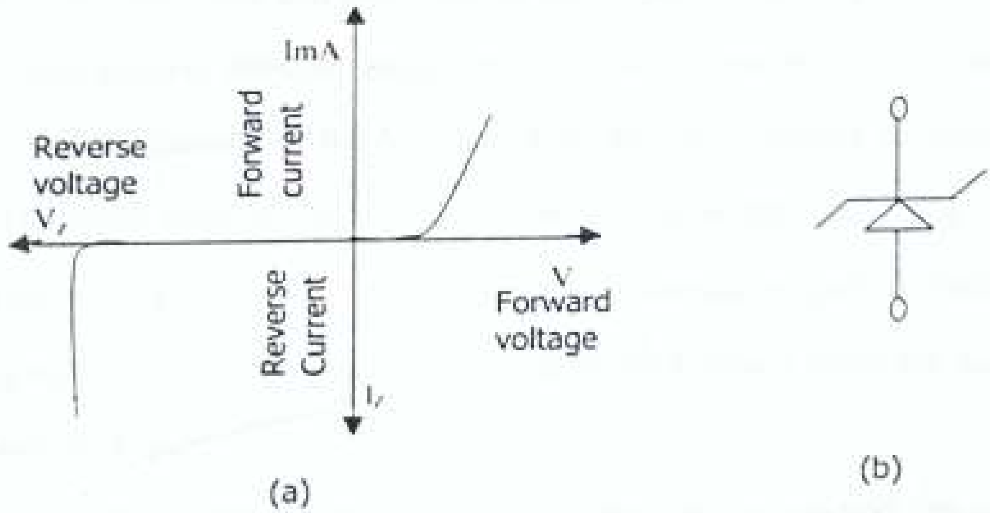



Fig. 2.25: Volt - Ampere characteristic and symbol of zener diode

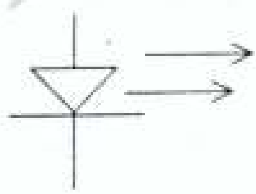


Fig. 2.26: Symbol for a LED

## 2.15 BIPOLAR JUNCTION TRANSISTOR (BJT)

A transistor is a three terminal active device. There are two types of this transistor:- npn and pnp. The two forms and their symbols are shown in fig. 2.27. The operations of the two are conceptually identical except for the interchange of minority and majority carrier types and the polarity of the bias potentials so that it suffices to discuss the pnp transistor. The three terminals of a transistor are named emitter, base and collector. A junction transistor consists of two parallel p-n junctions juxtaposed back to back in a single crystal. In operation, the emitter–base junction is forward biased while the collector-base junction is reversed biased.

Holes injected into the n-type base region at the emitter junction diffuse across to the collector junction where they are collected by the electric field at the junction. Variations in the emitter-base voltage change the injected current correspondingly and this signal is observed at the collector junction. The forward biased emitter represents a small resistance and the reverse-biased collector a large resistance.

For common base connection, a useful figure of merit for a transistor is the current gain $\alpha$, which is the ratio of the change in collector (or output) current to the change in emitter (or input) current for constant collector voltage. For most devices, $\alpha$ is very nearly unity. In many applications, the transistor is used in the common emitter configuration in which the input signal is applied at the base of the transistor and the output signal is taken at the collector. For this configuration the relevant current gain is $\beta$.

$$\beta = \frac{\text{Change in collector current}}{\text{Change in base current}} \qquad (2.62)$$

Typical values of $\beta$ range from 20 to 1000.

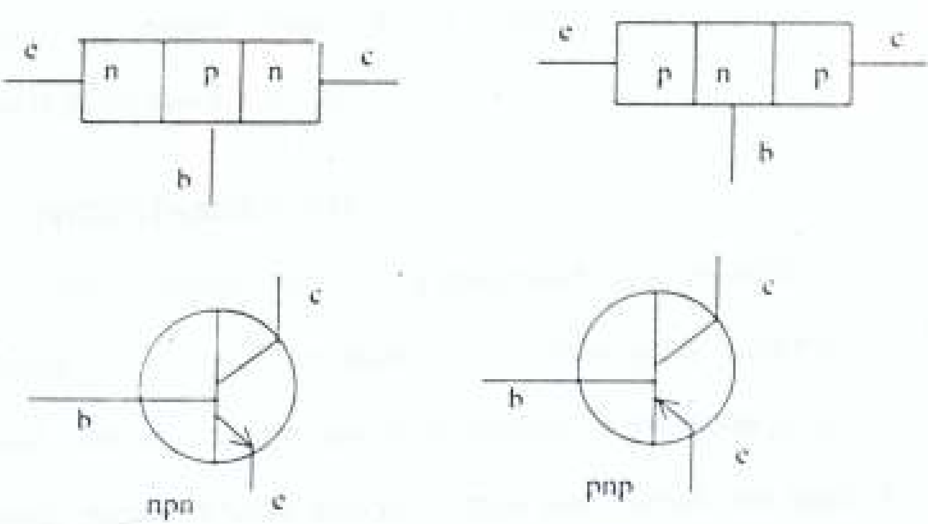



Fig. 2.27: Transistors and their symbols

## 2.15.1 COLLECTOR CHARACTERISTICS

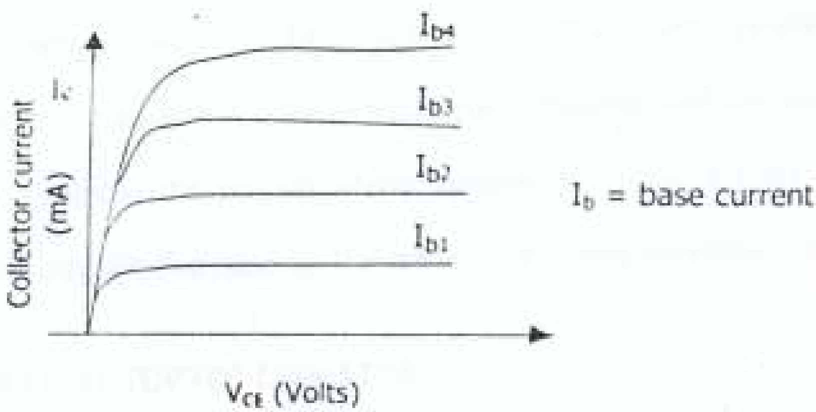



Fig. 2.28: Sketches of collector characteristics for common emitter configuration.

A convenient way to represent the I-V characteristics of a transistor is the collector characteristics. A typical shape of the collector characteristics for common emitter configuration is as shown in fig 2.28.

## 2.16 PHOTOTRANSISTOR

In principle, a phototransistor is a photodiode plus an amplifier on the same chip as shown in figure 2.29a. A photodiode is a junction diode sensitive to light which when reverse biased, minority carriers flow in the circuit. If the diode junction is now illuminated, the light energy produces more electron – hole pairs, which are swept across the junction. An increased current flows through the diode.

A phototransistor is light-sensitive and the base is usually left disconnected. When light falls on the emitter side, more electron-hole pairs are produced in the base. This is amplified by transistor action, and a larger current is obtained. The phototransistor output current is typically 100 times larger than the photodiode current. The higher gain is accompanied by non-linearity, a consequence of the variation of $\beta$ with $I_e$. Also, the response time is less. Thus the phototransistor is not as good as the photodiode where linearity and speed are essential. The phototransistor works well for interrupted light beam applications, for example the burglar alarm syetem.. Relatively high output currents, as well as high sensitivity are provided by the darlington connection shown in fig 2.29d.

## 2.17 OPTICAL (OPTO) ISOLATOR

An optical isolator or coupler consists of a LED and a photodiode mounted in the same package (Fig. 2.30). The photodiode is mounted to capture the maximum amount of light from the LED; that is, the two diodes are optically coupled but electrically isolated. These

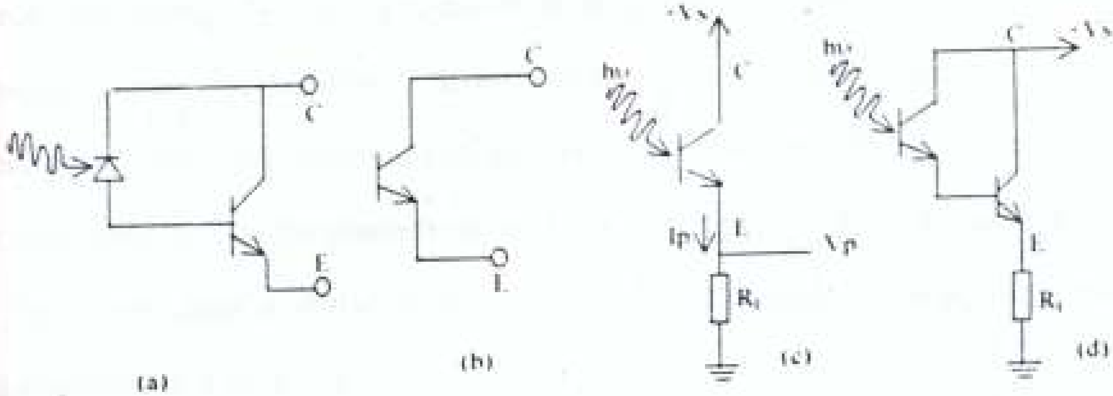


Figure 2.29: Phototransistors
(a) equivalent circuit (b) symbol
(c) simple resistor load (d) Darlington type

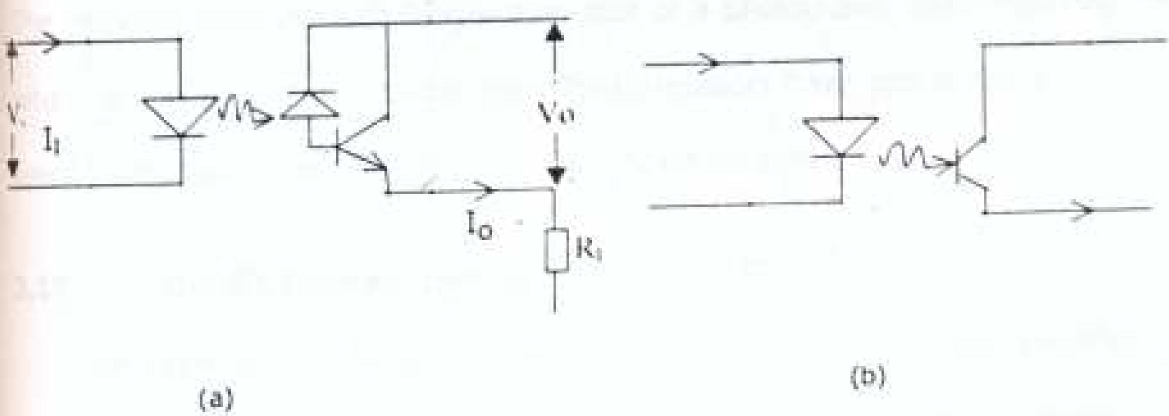


Figure 2.30: Optical Isolator (a) Equivalent circuit (b) Symbol

devices are useful in isolating grounds in large systems and where high voltage isolation between circuits is required. Some isolators have a built-in transistor which can be operated in either the common collector mode or the common emitter mode. Because of the slightly nonlinear LED characteristics, the current gain $\beta = I_o/I_i$ varies with the current $I_i$. The current gain is in the range of 0.1 to 10. The frequency response is beyond 1MHz, and insulation of 1 to 3kV are typical.

## 2.18 PHOTO-RESISTOR (LDR)

These are made of photosensitive material, such as cadmium sulfide. This cadmium sulfide light dependent resistor is normally provided with a clear end window. The resistance decreases as the intensity of the light falling on the device increases. The resistance of a cell may change from over 10MΩ in the dark to under 10Ω in bright light. The response time is much longer than that of a photodiode, often requiring over 10ms to return to the dark conductance level. Photo-resistors have poorer sensitivity, stability, and speed than photodiode. They are used mostly where cost is a factor.

## 2.19 OPERATIONAL AMPLIFIERS (OP-AMPS)

An op-amp is a high–gain, integrated circuit, direct-coupled amplifier. It contains several components as diodes, transistors, capacitors, and resistors, all in one single chip of a semiconductor. The Op-amp is usually used in the field of analogue operations. And with suitable feedback, it can be designed to perform many mathematical operations such as addition, differentiation, multiplication, and integration to mention a few. They perform the operations with high degree of accuracy and reliability. The ideal op-amp is shown in figure 2.31.

The terminals labelled + and − are the input terminals. The terminals labelled $+V_{cc}$ and $-V_{cc}$ are the power supply lines, which provide the voltages required to drive the components in the IC. It should be noted that the amplifier output $V_o$ is given with respect to the power supply common or ground connection. The output voltage $V_o$ of an ideal differential input op-amp is proportional to the difference in voltage of two signal sources (V+and V-) as indicated by

$$V_o = A_o (V_2 - V_1) \tag{2.63}$$

where Ao is the open-loop gain and its typical value is $10^5$

An ideal op-amp has the following characteristics:

(i) Its input impedance in infinite. Therefore no current enters through the inputs. This ensures that any signal could be supplied to it without the IC loading the signal source.

(ii) Its output impedance is zero. This ensures that no loss of signal through the device is recorded.

(iii) The open loop voltage gain $A_o$ is infinite.

(iv) The bandwidth is infinite.

(v) There is perfect balance i.e $V_o$ = o when $V_1 = V_2$ (CMRR).

(vi) The characteristics do not drift with temperature.

## 2.19.1 OP-AMP SPECIFICATION

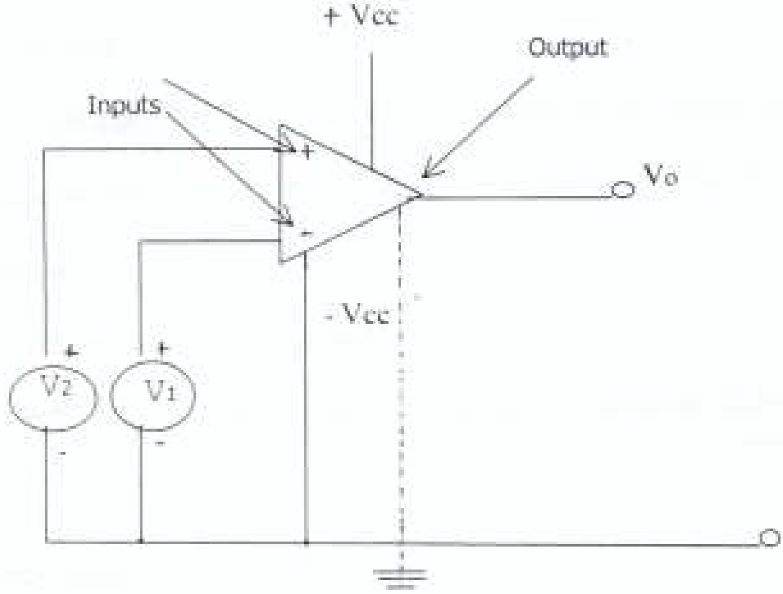



Fig. 2.31: Ideal OP-AMP.

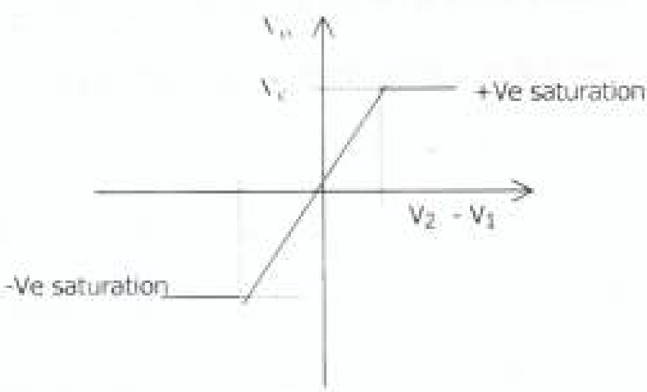



Fig. 2.32: The Network ideal characteristic behaviour of Op – Amp.

Few electronic devices approach their ideal behaviour. For the op-amp, several non-ideal characteristics must be recognized.

a. OUTPUT SATURATION

An excessive input voltage drives the output to positive or negative saturation, a limiting voltage which is somewhat less in magnitude than the power-supply voltage. The op-amp saturates at ± \Vcc - 2V\.

Thus, the three region of operations possible are

(i) Linear Region, where the output voltage is directly proportional to the voltage i.e $V_o = A_o(V_2 - V_1)$

(ii) Positive saturation region, $V_o = V_{cc} - 2V$

(iii) Negative saturation region, $V_o = -V_{cc} + 2V$

b. INPUT OFFSET VOLTAGE

It is impossible to have perfect matching of transistors and resistors, therefore some circuit imbalance is inevitable. This usually results in a small voltage at the output even when the input to the amplifier is zero. Ideally, the output should be zero when the input is zero. The input offset voltage is the small voltage that must be applied to the input terminals to force the quiescent output voltage to zero.

c. COMMON MODE REJECTION RATIO (C.M.R.R)

This is a measure of the ability of an op-amp to reject signals simultaneously applied to both inputs. The c.m.r.r is the ratio of the differential voltage gain to the common mode gain expressed in decibels.

d. BANDWIDTH: This is frequency range over which an op-amp will function. It is the frequency at which the gain falls to unity.

INPUT BIAS CURRENT

A small bias current flows into both inputs of an op-amp. For an op-amp with BJT input, the bias current is with the base current of the input transistor and is in the range of 10nA. For op amps with FET inputs, the bias current is much smaller, often below 0.1 pA.

INPUT OFFSET CURRENT

This is the difference between the currents flowing into the two input terminals when the quiescent output voltage is zero.

INPUT (COMMON – MODE) VOLTAGE RANGE.

Op-amps work properly only if input voltages are within a specified range, termed the common- mode operating range. If the maximum allowable input voltage is exceeded, the device will be destroyed. Newer model ICs have permissible input voltage range roughly equal to the output saturation range.

SLEW RATE

Many op- amps cannot deliver the full- voltage output at high frequencies. This limitation is specified by the slew rate, defined as the maximum output voltage change per unit time. If a square wave is applied to the input, the change in the output voltage is not instantaneous. The output initially rises linearly at the slew rate (typically 1V/μs).

## 2.19.2 SOME BASIC APPLICATIONS OF OP-AMPS

(a) NON-INVERTING AMPLIFIER

A non-inverting amplifier is shown in fig. 2.33. Its purpose is to amplify an input voltage $V_i$ by a factor A to give an output voltage $V_o$. A fraction β of the output voltage is fed back to the inverting input of the op-amp. The net signal between the inputs of the op-amp is;

$$V_2 - V_1 = V_i - \beta V_o \qquad (2.64)$$

This is an example of negative feedback. The output voltage $V_o$ is given by

$$V_o = A_o(V_2 - V_1) = A_o(V_i - \beta V_o) \qquad (2.65)$$

Rearranging,

$$\frac{V_o}{V_i} = \frac{A_o}{1 + \beta A_o} \qquad (2.66)$$

For a properly designed amplifier, β is chosen so that $\beta A_o$ is much larger than 1. This usually presents no difficulty because $A_o$ is typically high (between $10^4$ and $10^6$). Assuming therefore that $\beta A_o >> 1$, we ignore 1 in the denominator.

$$\frac{V_o}{V_i} = \frac{1}{\beta} \qquad (2.67)$$

$$\beta = \frac{R_1}{R_1 + R_2} \qquad (2.68)$$

Therefore the overall voltage gain

$$A = \frac{1}{\beta} = \frac{R_1 + R_2}{R_1} \qquad (2.69)$$

It can be noted that the voltage gain A is independent of $A_o$.. At low frequencies equation 2.64 is quite accurate in practice. Where accurate gain is desired, close- tolerance resistors (1 percent) are used, and closed – loop gain A is limited to 100 or less. The best range of $R_2$ is 2kΩ to 100kΩ . We note however that as the gain of the op-amp drops at higher frequencies, there is a frequency above which equation 2.69 is not valid. An advantage of the non-inverting amplifier is its high input impedance. The minimum gain is unity when $R_1 = \infty$ and $R_2 = 0$.

Fig 2.33 below is designed for operation down to zero frequency. When the input is a signal source of low output resistance (e.g. a thermocouple) the resistor Rx is needed. This latter requirement arises from the fact that the amplifier must draw its input bias current from the signal source and must therefore see a d.c path to earth. Resistor Rx is in circuit simply to ensure that both inputs see the same resistance to earth.

For minimum offset, Rx must have the value;

$$\frac{R_1 R_2}{R_1 + R_2} \qquad (2.70)$$

It may be thought at first that Rx, being in series with the signal, will cause significant attenuation. Fortunately, this is not the case because the non-inverting amplifier has an input impedance of at least 50 MΩ. Small Rx is about 10kΩ, signal loss across Rx negligible. If the signal source has an output resistance comparable with Rx, its value must be subtracted from Rx.

(b) INVERTING AMPLIFIER

An inverting amplifier is shown below in figure 2.34. The input and output signals are 180° out of phase. The signal at the non-inverting input $V_2 = 0$. Since $A_o$ is large, the signal between the op amp input is negligible. The inverting input is a virtual ground.

$$\frac{V_i - V_1}{R_1} = \frac{V_1 - V_0}{R_2} \qquad (2.71)$$

Since $V_1 \approx 0$,

The closed loop gain $A = \frac{V_0}{V_i} = \frac{-R_2}{R_1}$ (2.72)

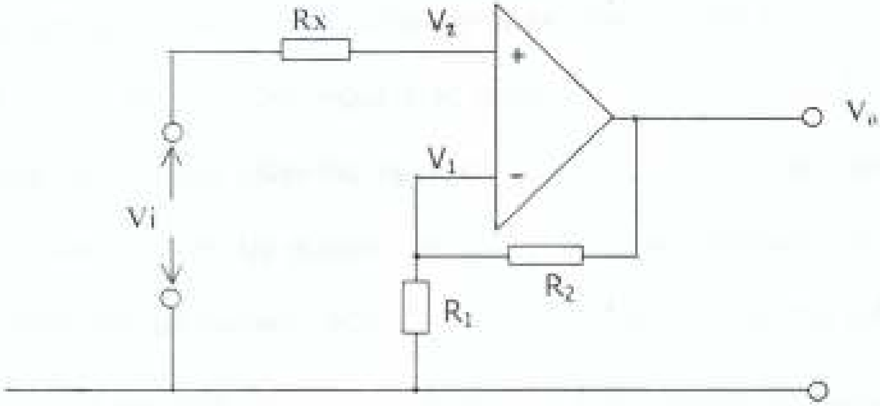



Figure 2.33: Non-inverting amplifier

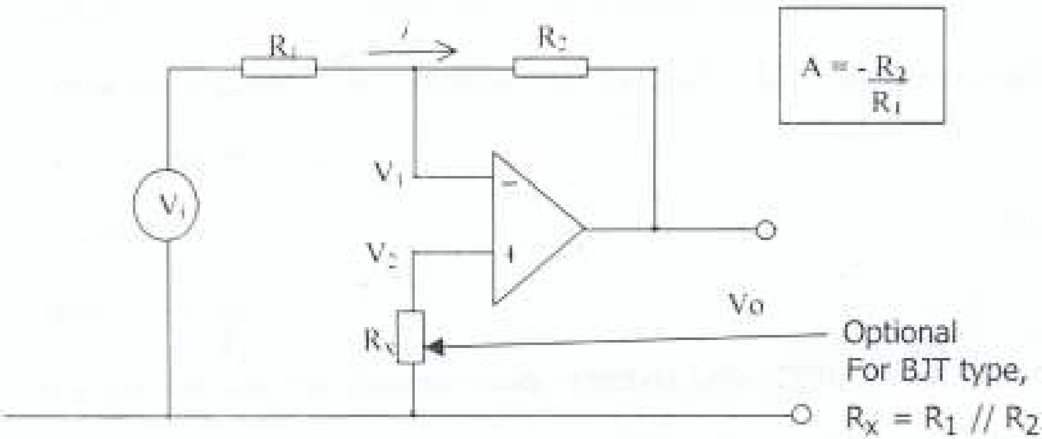



Fig. 2.34: Inverting Amplifier

(c) DIFFERENTIAL AMPLIFIER

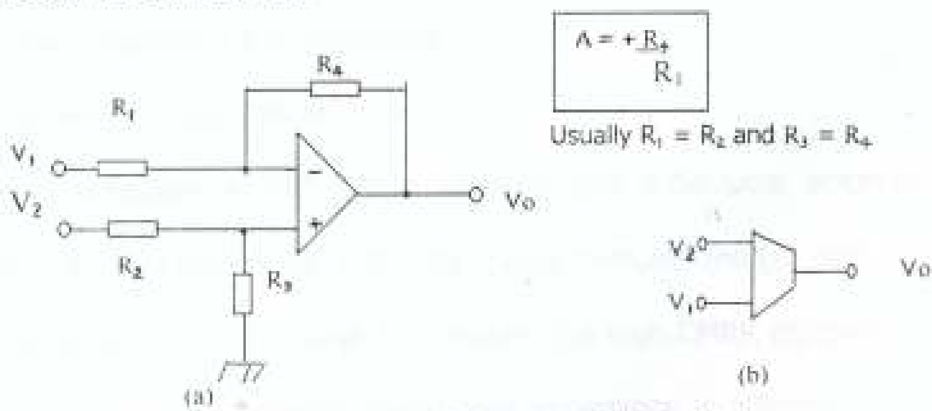



Figure 2.35: Differential Amplifier (a) Circuit (b) Symbol

A disadvantage of the inverting amplifier is its relatively low input impedance, which is equal to $R_1$ because the inverting input is at ground potential. The input impedance, however, is ordinarily much larger than the op-amp output impedance and therefore rarely presents a problem when driven by another op-amp. The input resistance $R_1$ must not be too high (over 100k) for an op-amp with BJT inputs or the effect of the bias current may become significant. If the bias current is a problem, a bias current compensation resistor ($R_X = R_1$) may be added from the non-inverting input to ground. Closed loop gain A of value 0.1 to 100 is practical. The gain is independent of the supply voltage.

The differential amplifier employs negative feedback to stabilize the gain A. Putting

$R_1 = R_2$ and $R_3 = R_4$

$$V_o = A\,(V_2 - V_1) \qquad (2.73)$$

where $A = \dfrac{R_4}{R_1}$

For many applications, the common-mode rejection ratio (CMRR) must be made as large as possible. In order to change the gain of the amplifier $R_1$ and $R_2$ may be made variable over a narrow range. If the input impedance of this circuit is too low for the desired application, unity gain amplifiers are added preceding each input. An improved version of the differential–input amplifier is the instrument amplifier.

(c) INSTRUMENTATION AMPLIFIER

An instrumentation Amplifier is a variable gain differential amplifier consisting of three op-amps, as indicated in fig 2.36. Its special features are (a) high input impedance, especially if op-amps $A_1$ and $A_2$ have FET inputs (b) high CMRR (c) precision high gain, if the resistors R is precision resistor. High input impedance is achieved using the non-inverting amplifier configuration on the inputs. Precision high gain is achieved by two stages

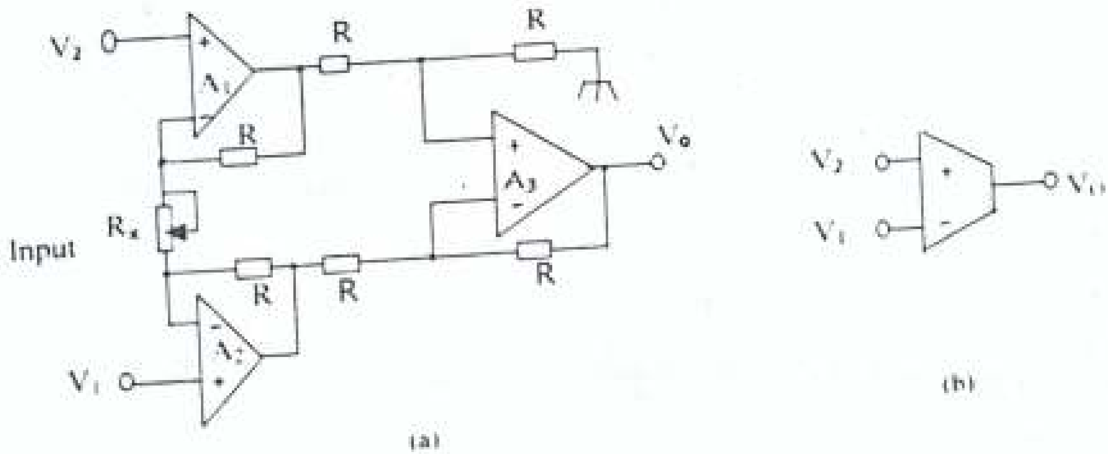



Figure 2.36: Instrumentation amplifier (a) Circuit (b) Symbol.

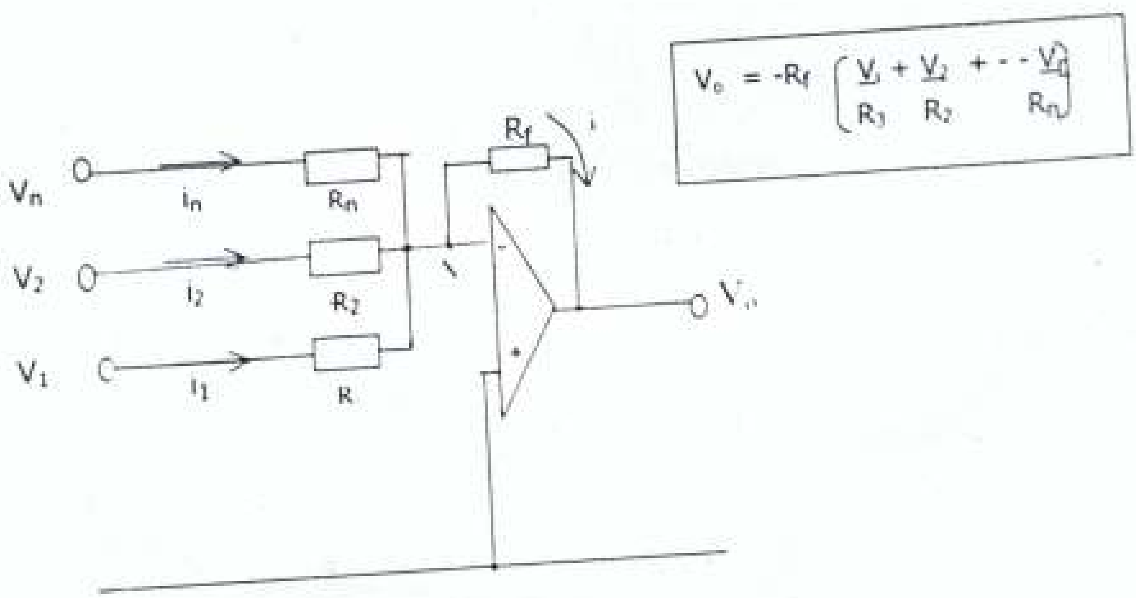



Figure 2.37: Inverting summing Amplifier

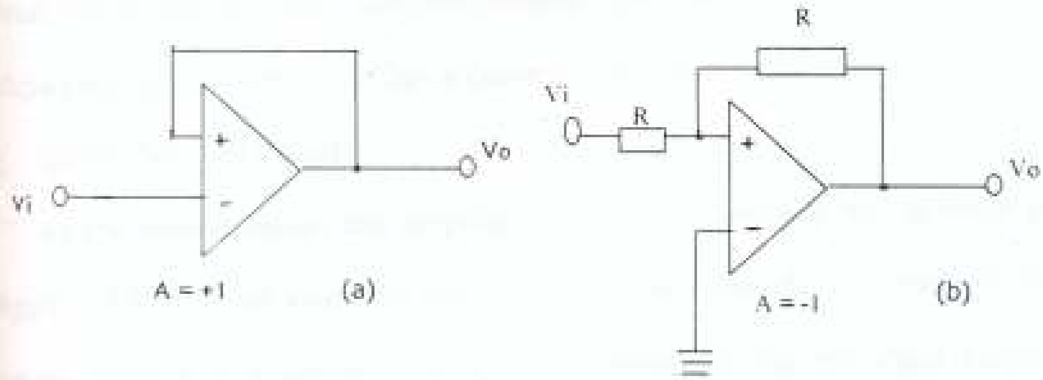



Figure 2.38: Unity- gain amplifier (a) Non-inverting (b) Inverting

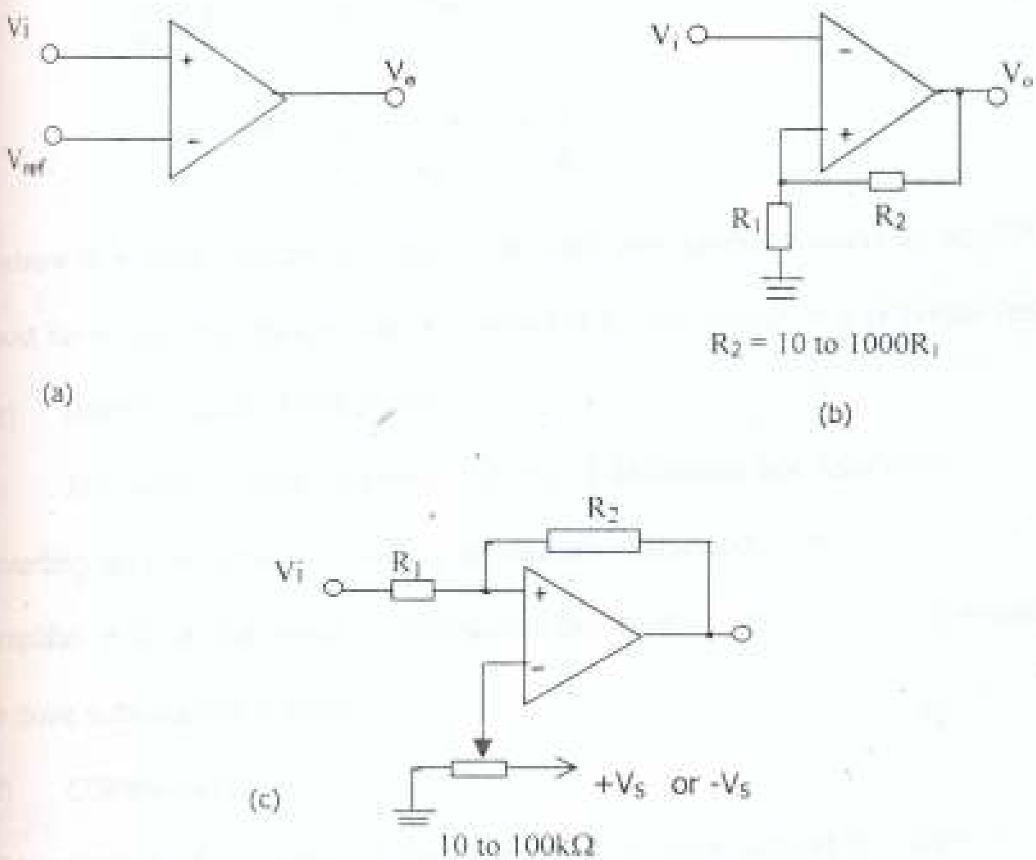



Figure 2.39: Op-amp comparators (a) Simple comparator with variable threshold voltage (b) Inverting comparator with hysteresis (c) Non-inverting comparator with hysteresis and a variable threshold.

of feedback amplifier. High common –mode rejection is achieved by the dual non-inverting configuration circuit, which utilizes a common feedback resistor $R_v$.

(d) SUMMING AMPLIFIER

As the name implies the amplifier is used for summing two or more signals as shown in figure 2.37. It is an inverting amplifier with many inputs. Because of the feedback, the summing point **x** is a virtual ground. As a consequence, the input currents $i_1$, $i_2$, $i_3$ are independent of one another, while the output current i is the sum of the input currents.

That is $$i_1 + i_2 + \cdots + I_n = i \quad (2.74)$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \ldots + \frac{V_n}{R_n} = -\frac{V_o}{R_b} \quad (2.75)$$

$$V_o = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \ldots + \frac{V_n}{R_n}\right) \quad (2.76)$$

where n = total number of inputs. As with the standard inverting amplifier, signal sources must have low impedance, such as provided by the output of a previous feedback amplifier.

(e) UNITY – GAIN AMPLIFIER.

The unity – gain amplifiers of fig. 2.38 above are specialized versions of the non-inverting and inverting amplifiers previously discussed. The main use of the non-inverting amplifier is as a high input – impedance buffer which has an output impedance low enough to drive subsequent stages.

(f) COMPARATOR.

The response of an op-amp comparator is positive saturation when the input differential voltage ($V_2 - V_1$) is greater than 1mV. When the input differential voltage is negative and of magnitude greater than 1mV, the output swings to negative saturation.

Three versions of the comparator are shown in fig 2.39. In fig 2.39(a) a reference V is applied to one input. Because of the high open - loop gain of the op-amp, an input voltage above $V_{ref}$ causes the output to swing from negative to positive saturation. Reducing V, below $V_{ref}$ can reverse the output polarity. Positive feedback is utilized in fig 2.39b, to speed the transition and to provide hysteresis. With hysteresis the input voltage required to produce positive saturation is slightly higher than that required to produce a negative saturation. False transition due to noisy signals is eliminated by hysteresis.

## 2.20 LOGIC ELEMENTS

The logic elements in digital instruments are the basic building blocks of the circuits that control data flow and processing of standard signals. Each logic element is a network of electronic components. Logic elements include the following gates AND, OR, NOT, NAND, NOR, EX- OR, COMPARATOR and FLIP-FLOP. The various logic elements are treated below. The symbols for the gates are shown in fig 2.40.

**TABLE 2.7: Truth Table of different types of gate**

| Inputs | | Outputs | | | | | |
|---|---|---|---|---|---|---|---|
| A | B | AND gate | OR gate | NAND gate | NOR gate | EX-OR gate | EX-NOR gate |
| 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 |
| 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 |
| 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 |
| 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 |

| Input A | NOT gate X |
|---|---|
| 0 | 1 |
| 1 | 0 |

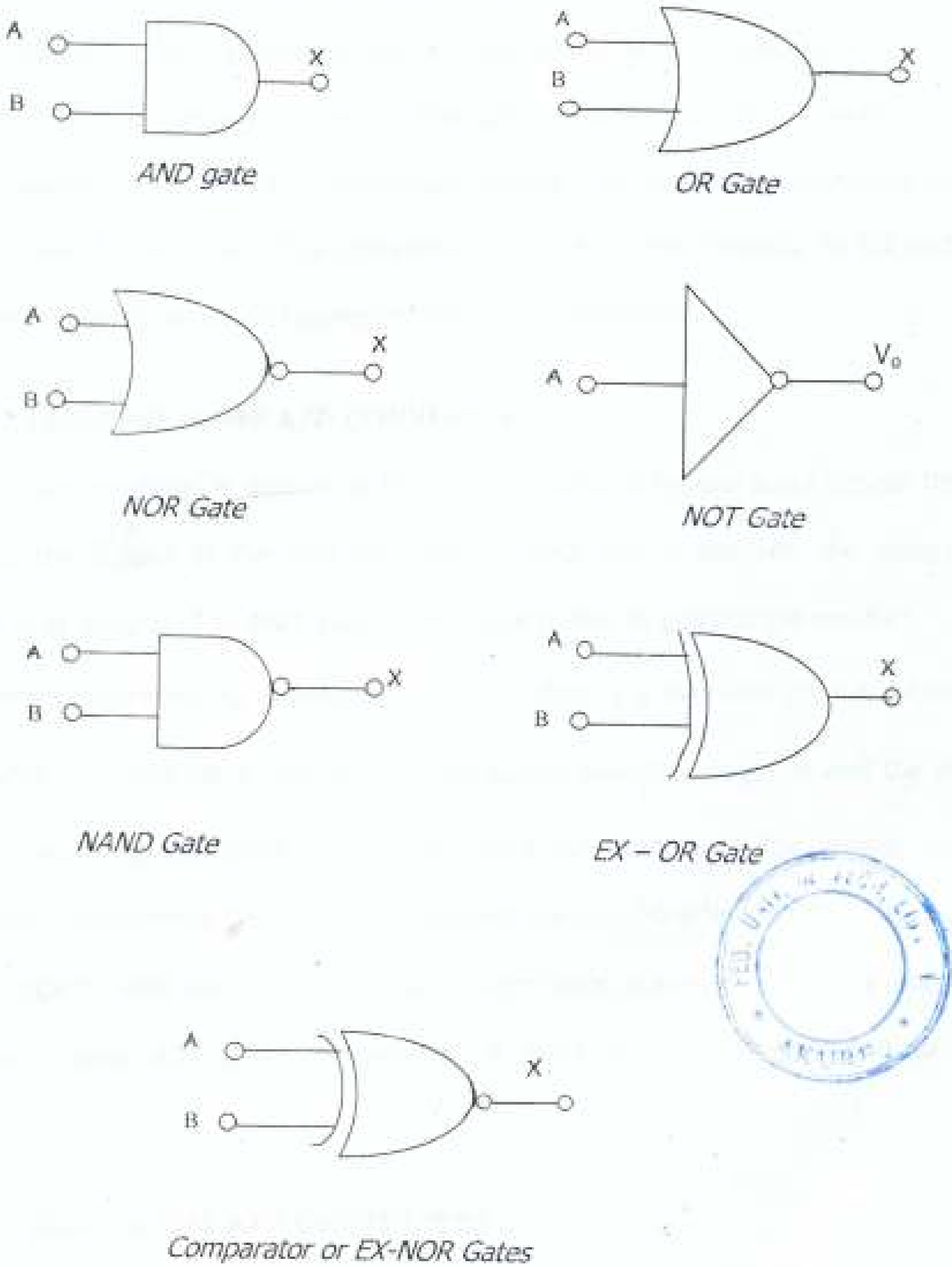



Fig 2.40: Symbols of different Gates

## 2.21 ANALOG TO DIGITAL CONVERTER (ADC)

A/D converters are required to convert analog signals into corresponding, equivalent digital codes, after a certain time delay. The A/D conversion process is more complicated and time consuming than the D/A conversion. Different types of A/D converters have been developed some of which use a D/A Converter as a part of their circuitry. In the section that follows some simple types of A/D converter are briefly discussed.

### 2.21.1 STAIRCASE RAMP A/D CONVERTER

The block diagram is shown in fig 2.41. Initially, a trigger input resets the digital counter. $V_a$, the output of the D/A converter is zero. For $V_i$ positive, the output of the comparator is at logic 1. The AND gate allows clock pulses to pass to the counter.

As time progresses, $V_a$ increases in steps producing a staircase output waveform. At the point where $V_a$ exceeds $V_i$, the comparator output switches negative and the pulses to the counter cease. At this point, the digital output corresponds to the analog input. The clock frequency determines the rate of conversion but has no effect on the accuracy. The time grows rapidly with the number of bits, a significant drawback for many applications. This staircase ramp A/D converter provides a good method for digitizing to a high resolution.

### 2.21.2 DUAL-SLOPE A/D CONVERTERS

Figure 2.42a shows a block diagram of a dual-slope A/D converter. The op amp $A_1$ acts as an integrator. A conversion cycle starts with the integrator output at 0V, the counter resets to zero, and the input switch is connected to the unknown input voltage $V_{in}$. Assuming $V_{in}$ is positive, the integrator output ramps in a negative direction. As soon as the integrator pushes the negative input of the comparator a few micro-volts negative, the output of the comparator goes high and enables the AND gate. This lets the clock signal into the counter. In this phase $V_o = - V_{in}\ t / RC$.

The integrator output is allowed to ramp negative for a fixed number of counts. This is shown as $t_1$ in fig. 2.42b. After the fixed number of counts, the control circuitry resets the counter to zero and switches the integrator input to a negative reference voltage $V_{ref}$ which causes the integrator output to ramp positive as shown by the section labeled $t_2$. When the integrator output goes a few micro-volts above 0V again, the comparator output goes low. This disables the AND gate and shuts off the clock signal to the counter. The control circuit then latches the accumulated count, resets the counters to zero, and switches the integrator input back to the unknown input voltage to start another conversion cycle. The number of counts stored on the latches is proportional to the input voltage.

Since the same R and C are used for the signal integrate ramp and the reference integrate ramp, variations in R or C with temperature has no effect on the accuracy of the output reading. This is the major advantage of a dual-ramp converter over a single ramp type. Since $t_1$ and $V_{ref}$ are constants, this equation shows that $t_2$ is directly proportional to $V_{in}$. It is noted that the value of RC of the integrator is selected so that the op-amp does not go into saturation when the maximum input voltage is applied to the integrator input.

The advantages of a dual slope converter are high resolution, low cost, and immunity to temperature changes. The major disadvantage of dual-slope converter is its slow speed. Examples of A/D converter based on dual slope integration are ICL7107, ICL7137 ICL7136.

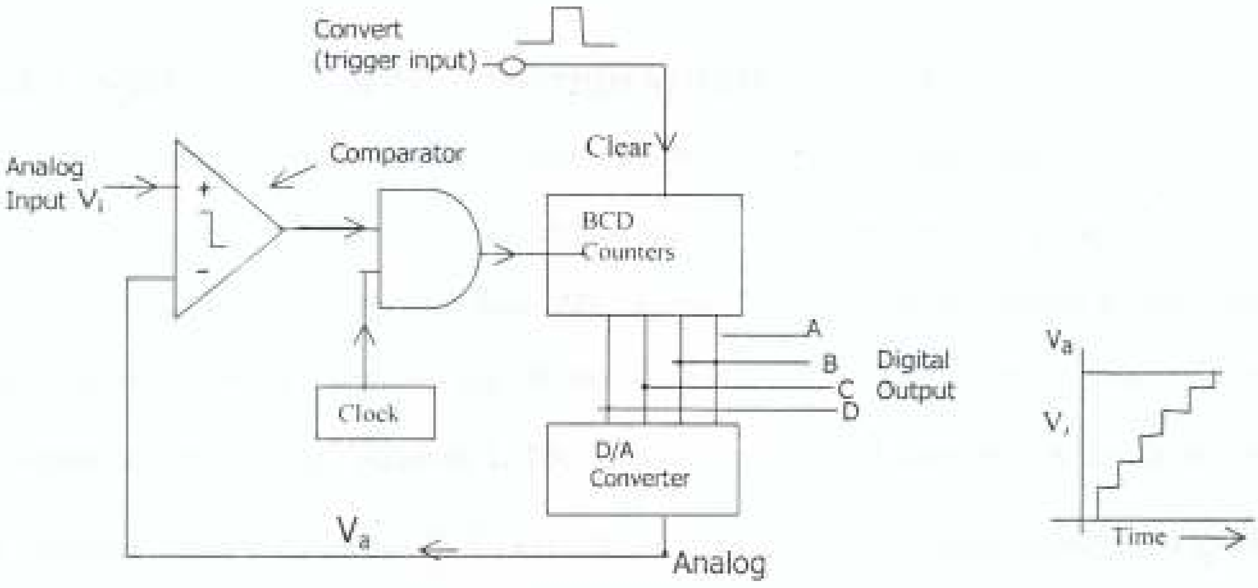



Fig 2.41: Block diagram of a counter– type A/D converter.

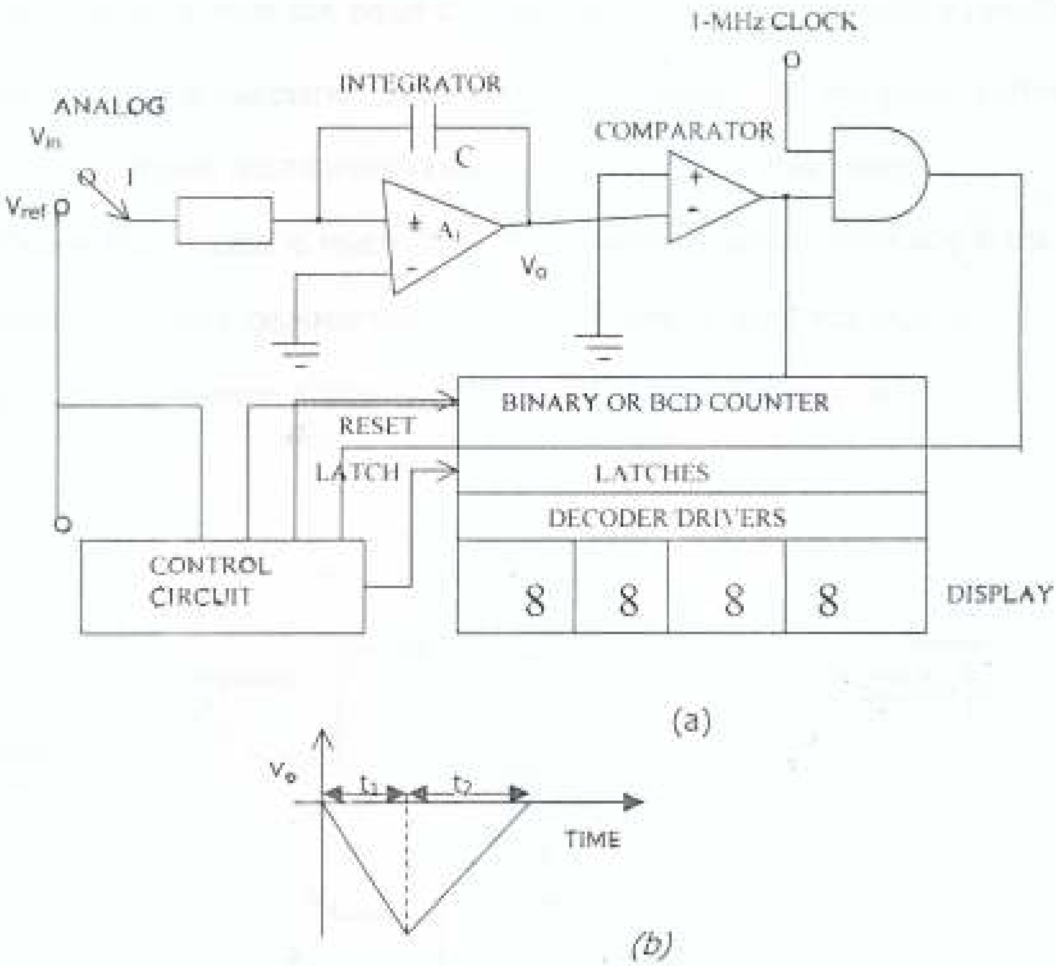



Figure 2.42: (a) Dual-slope A/D converter, (b) integral output waveform for two different input voltage.

### 2.21.3 SUCCESSIVE – APPROXIMATION A/D CONVERTERS

This is one of the fastest and most commonly used A/D converters. It comprises a voltage comparator, logic programmer, digital register and D/A converter as shown in figure 2.43. It is similar to the counter type ADC except that the bits are tested in succession starting from the most significant bit. At the beginning of the conversion process, the most significant bit (MSB) is put equal to 1. The output $V_a$ of the D/A converter is compared with the analogue input voltage $V_{in}$. If $V_{in}$ exceeds $V_a$, the comparator output is high and the bit is retained. If not, the bit reverts to 0.

The next bit is then put equal to 1 and the comparison between $V_a$ and $V_{in}$ is made. Other bits are tried in succession. After the LSB has been tried, the digital output of ADC is read. This is the digital word corresponding to the analogue input voltage.

Clearly the process is much faster than counting pulses, especially if the number of bits is large. The main disadvantage is that the control logic required is rather involved. Fortunately, this converter is now available in IC form. For example, AD0804 is an 8-bit converter.

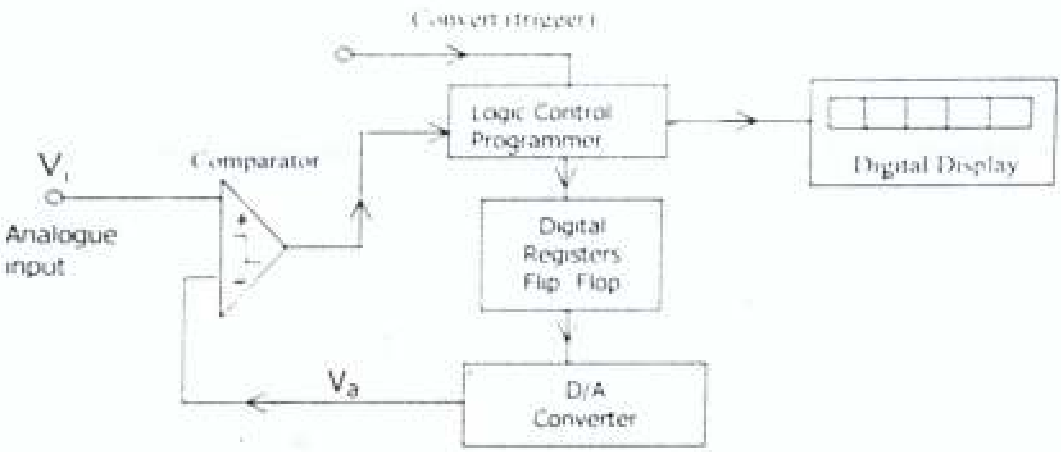



Fig 2.43: Block diagram of Successive – approximation A/D Converter.

### 2.21.4 FLASH CONVERTERS

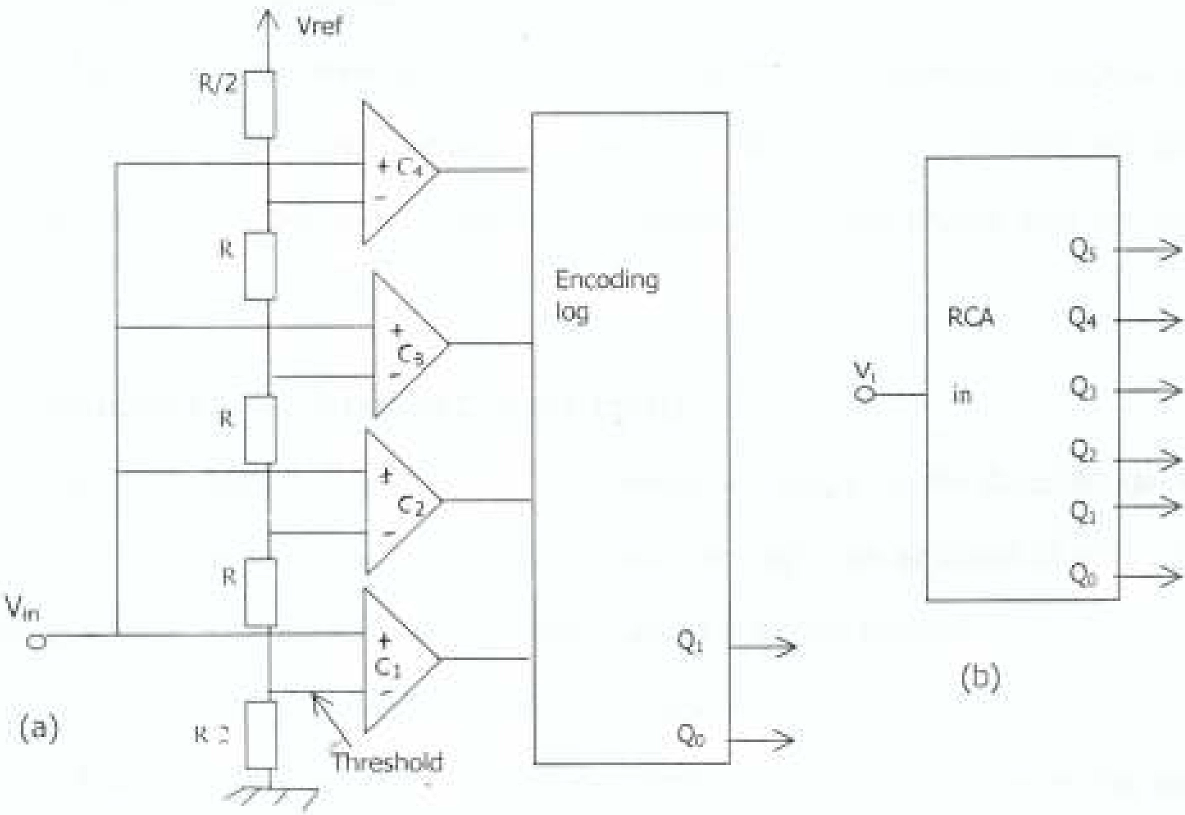



Fig. 2.44: Flash converters (a) Simple 2-bit converter (b) 6-bit converter

A flash converter (fig 2.44) utilizes a series of comparators with the threshold inputs spaced at regularly increasing voltages. All comparators with threshold voltages below the analogue input $V_{in}$ are turned on. An encoder converts the comparator outputs to a Binary code. The number of comparator increases with the number of bits. A standard 6-bit converter requires 63 comparators.

A flash converter does not utilize clock signals for the conversion process. The converter has only one step. Conversion speed is of the order of 100-MHz. No other converter approaches this speed. However the resolution is more limited than the other types of A/D converters.

## 2.22 SILICON CONTROLLED RECTIFIER (SCR)

This is a three terminal device. The terminals are known as the Gate, Anode and Cathode. Often the device (also known as thyristor) is used in an ac circuit to control the power delivered to the load such as an electric motor or a heating element.

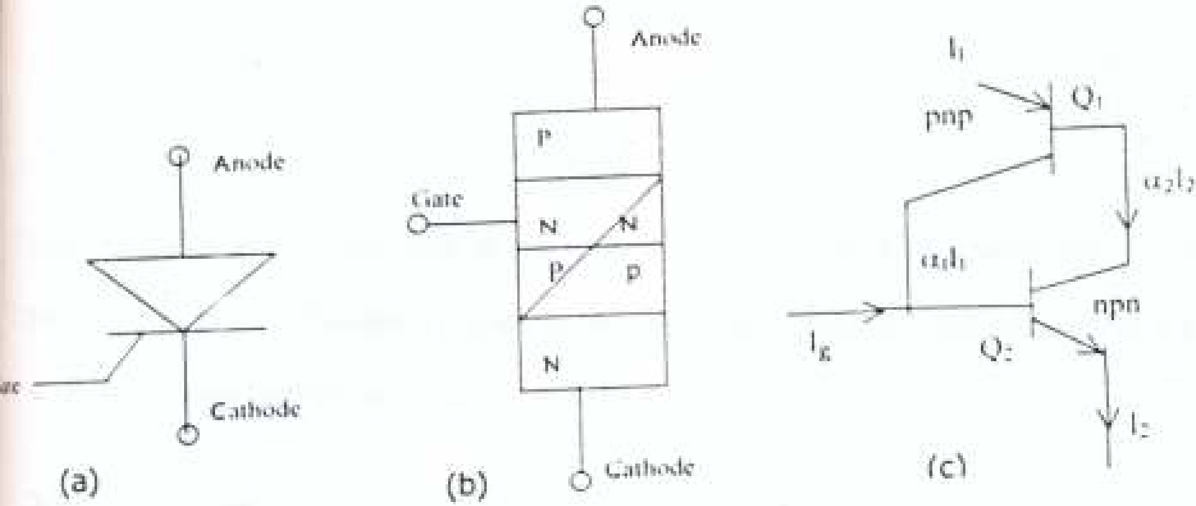
STRUCTURE: It consists of four layers of semiconductor in a pnpn sandwich. A positive potential applied to the p type terminal puts the centre pn junction under reverse bias while the two other junctions are forward-biased. The device may be looked upon as the back – to back combination of two transistors $Q_1$ and $Q_2$ (fig 2.45c). Let $I_1$ be emitter current in $Q_1$. Its collector current $Ic_1 = \alpha I_1$. Similarly, if $I_2$ is the emitter current of $Q_2$. Its collector current, $Ic_2 = \alpha_2 I_2$.Using kirchhoff's current rule at the collector junction,

$$I_2 = \alpha_1 I_1 + \alpha_2 I_2 + I_g \qquad (2.77)$$

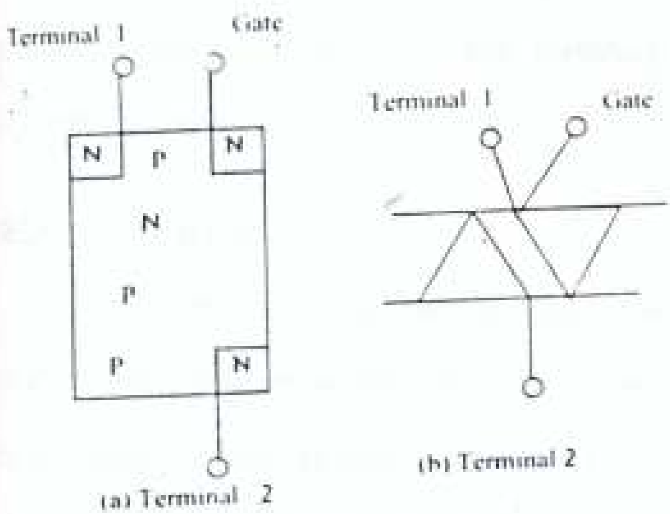
where $I_g$ = gate current

The overall current input to the device is given as

$$I_2 = I_g + I_1 \qquad (2.78)$$




2.45: Silicon controlled Rectifier (a) Symbol (b) Four layer construction
(c) Its interpretation in terms of a pnp transistor coupled to an npn transistor



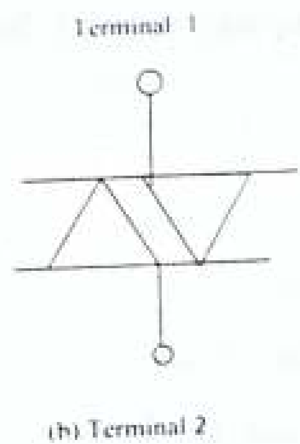




Fig. 2.46: The Triac, a gate controlled rectifier
(a) Construction (b) Symbol

Fig. 2.47: The DIAC symbol

From eqn 2.72 and 2.73

$$\therefore I_2 = \frac{(1 - \alpha_1) I_g}{1 - (\alpha_1 + \alpha_2)} \qquad (2.79)$$

From equation 2.79, if the sum of the current gains $\alpha_1 + \alpha_2$ is near unity, the current $I_2$ can be very large even though the gate current is small. Thyristors can be used in d.c circuits such as in lamp flashers and high- speed trip circuit.

## 2.23 TRIAC

The triac is similar in operation to two thyristors connected in reverse parallel but with a common gate connection (fig 2.46). This means that the device can pass or block current in both directions. Also it can be triggered to conduction in either direction by applying either a positive or a negative gate signal. Triacs are mostly used in full- wave a.c control circuits in preference to two thyristors because a simpler heat sink and a more economical trigger circuit can be used.

## 2.24 DIAC

Diac is basically a two-terminal parallel-inverse combination of semiconductor layers that permits triggering in either direction as shown in fig. 2.47 above. The diac like a triac is bi-directional switch between the main terminals, but it does not have a gate. The characteristics of the device clearly demonstrate that there is a breakover voltage in either direction. This possibility of an 'on' condition in either direction can be used to its fullest advantage in ac applications to deliver full power when switched. Note that neither terminal is referred to as the cathode but as terminal 1 and terminal 2.

## 2.25 THE 555 TIMER AS AN ASTABLE MULTI-VIBRATOR

The 555 timer IC is a device which can be used to form monostable, bistable and astable multivibrators. Its internal structure is shown in fig 2.48a. By means of the three resistors R, the trigger and threshold terminals are set at 1/3 $V_{cc}$ and 2/3 $V_{cc}$ respectively. This device can be used to produce an output signal without any input signal. Hence the name free-running. It is a closed loop regenerative feedback circuit. Figure 2. 48c shows the 555 timer used as an astable multi-vibrator.

The output is a train of positive pulses with the width and frequency determined by external timing components – $R_A$, $R_B$ and C. Pins 2 and 6 are connected together which allows the capacitor to charge and discharge between the threshold and trigger levels. At switch-on, C charges via $R_A$ and $R_B$ towards $V_{cc}$. When the voltage across C reaches 2/3 $V_{cc}$, the output changes state and C is discharged via $R_B$ towards OV. When the voltage across C falls to 1/3 $V_{CC}$, the circuit again changes state, the internal discharge transistor turns off, and C charges Via $R_A$ and $R_B$ towards $V_{cc}$. Thus a continuous train of pulses appears at the output.

To get an almost symmetrical output waveform, $R_B$ is made very large with respect to $R_A$, say 50 times and in that case the frequency f, will be primarily determined by $R_B$ and C.

Figure 2.45 (d) is a typical waveform

$$f = \frac{1.49}{(R_A + 2R_B)C}$$

$$\text{The duty cycle} = \frac{\text{Time output high}}{\text{Period}} = \frac{(R_A + R_B)}{(R_A + 2R_B)} \quad (2.50)$$

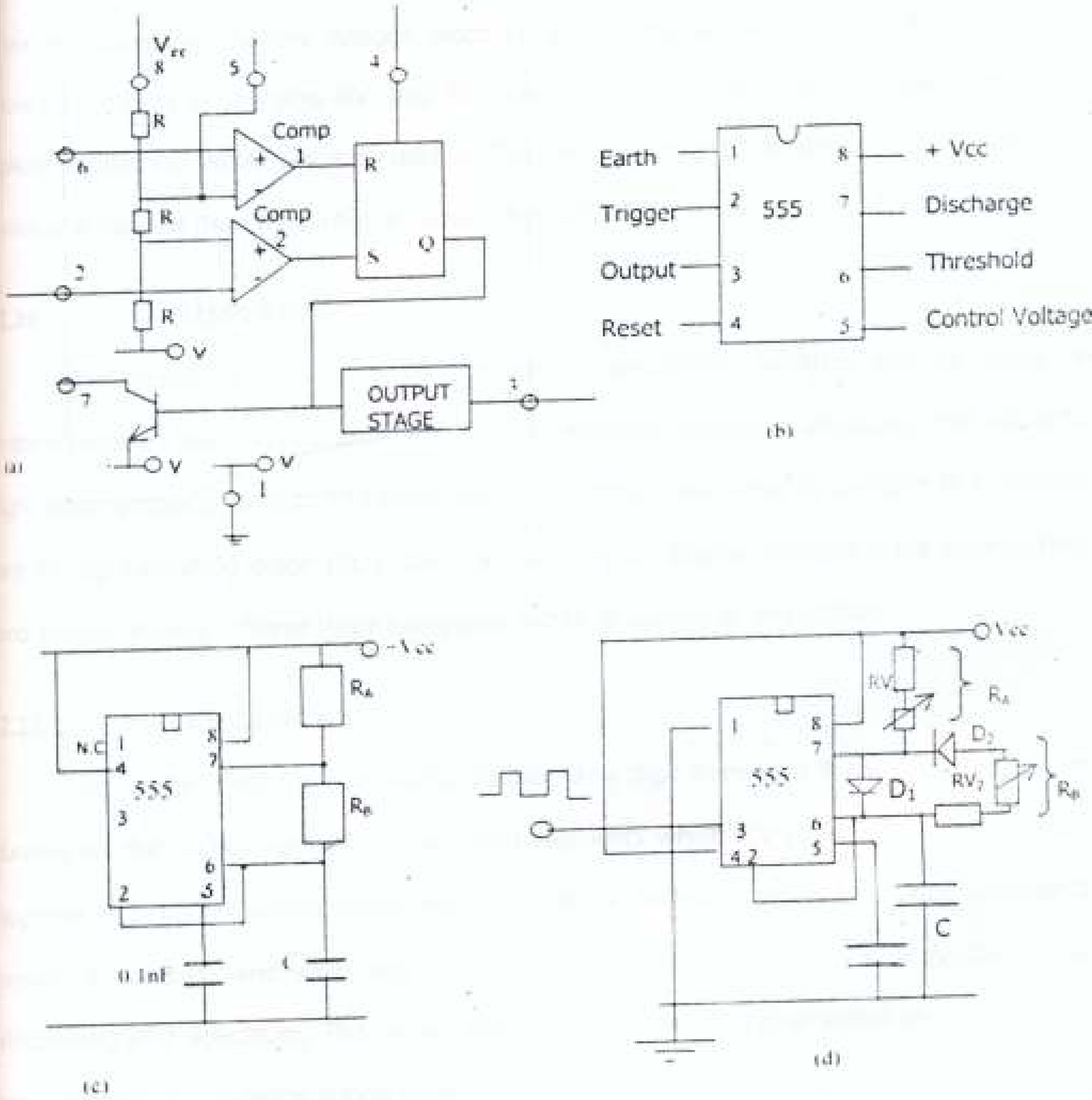



Fig 2.48: The 555 timer (a) Internal structure (b) Pin arrangement
(c) 555 timer as astable multivibrator (d) Modified astable multivibrator

To achieve some control over duty cycle, a circuit such as shown in fig 2.48d is used. Here the capacitor charges through diode $D_1$ and discharges through $D_2$. $R_A$ and $R_B$ are varied by means of the pots $RV_1$ and $RV_2$. Using pin 4, the reset, as a control, can create gated oscillators. While pin 4 is held at OV, the oscillation is inhibited, but if a positive voltage is applied then the circuit is allowed to oscillate.

## 2.26 DISPLAYS

The increasing use of digital displays in calculators, watches and all forms of instrumentation has contributed to the current extensive interest in structures that will emit light when properly biased. The three types in common use today to perform this function are the light-emitting diode (LED) and the liquid-crystal display (LCD) and the high current and voltage display. These three categories will be discussed in this section.

### 2.26.1 LED DISPLAY

This is the most common digital display. Any digit from 0 to 9 can be displayed by turning on the proper combination of seven segments which are shown in fig 2.49a. Each segment is a light emitting diode made of Gallium Arsenide. When the diode is forward biased, it conducts and emits red, yellow or green light, all in the visible region of the electromagnetic spectrum. The seven segments can be connected either in the common cathode form and common anode form.

In the common anode form (shown in fig 2.49b) the anodes are joined together. A segment is activated if the cathode of the corresponding cathode is grounded. In the common cathode form (fig 2.49c) the cathodes are connected to the positive supply and the anode of the LED is grounded in order for a segment to be activated.

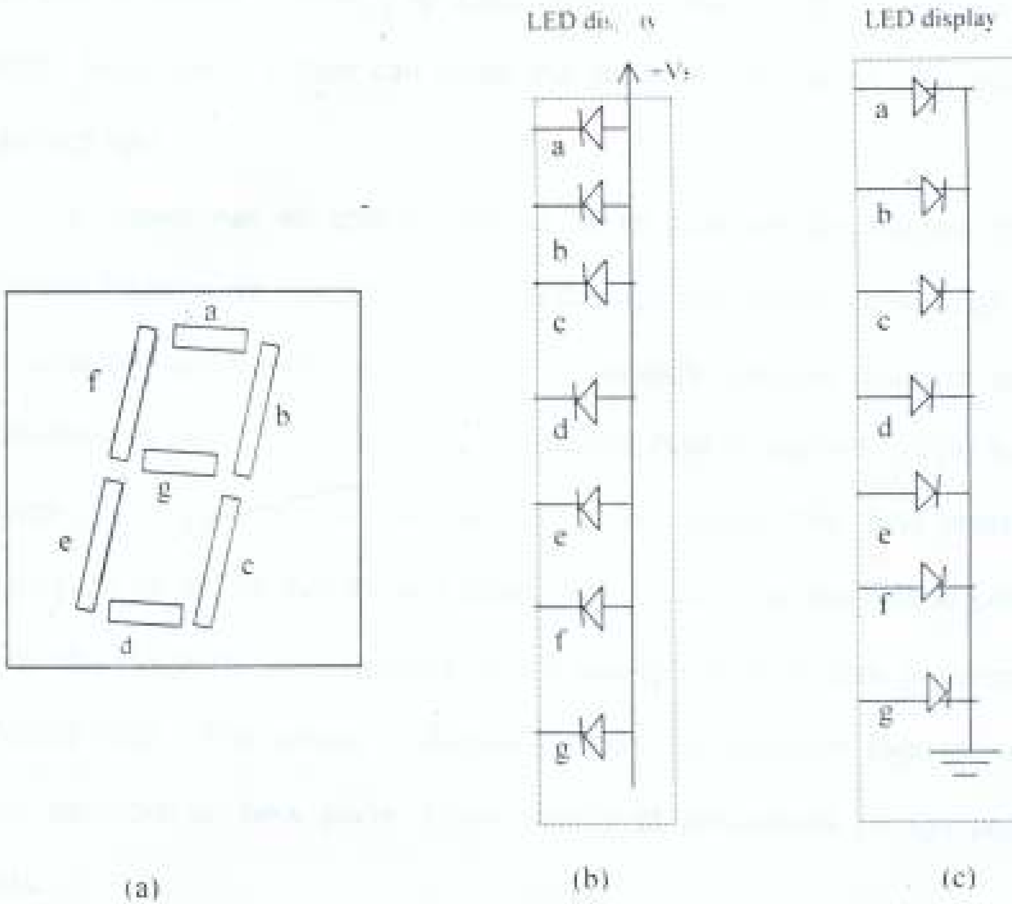



Figure 2.49: LED Display (a) Seven – segment array for numerals
(b) Common anode. (c) Common cathode

## 2.26.2 LIQUID CRYSTAL DISPLAYS (LCDs)

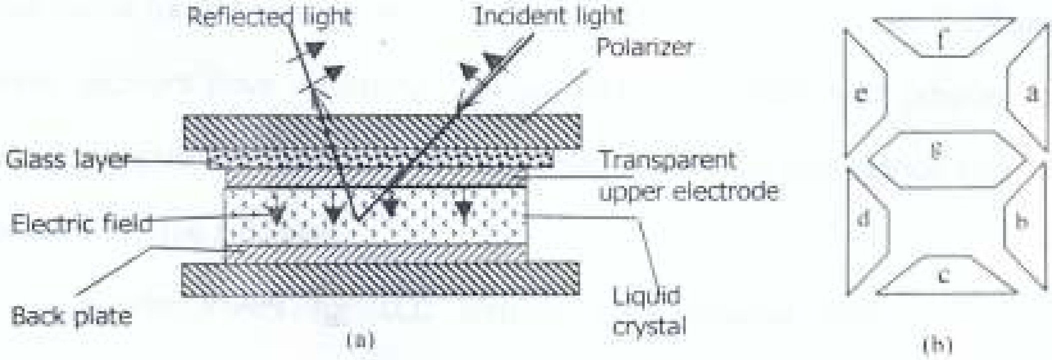



Figure 2.50: Liquid crystal displays (LCD) principle (Reflection type);
(a) Expanded cross- sectional view. (b) Top- view of seven- segment display.

Liquid crystals consist of a high concentration of asymmetric molecules in a transparent organic solvent (Fig 2.50). These molecules can be oriented by an external electric field, which in turn can rotate the plane of polarization of a transmitted beam of polarized light.

A display has an optical polarizer which polarizes the incident light beam. If the polarized beam is not rotated as it passes through this crystal region, then it passes through the polarizer again (reflection type) or a similarly oriented polarizer on the other side (transmission type) with little loss. An electric field is applied to the liquid crystal by a voltage (3 to 20v) across the transparent electrodes. The field rotates the plane of polarization by $90^{0}$ so that the exit polarizer does not allow the light to pass. Thus the area below the electrode (one segment of the display) appears dark in contrast to the white reflected area. The voltage is applied between an individual segment and the common lower electrode or back plane. Either polarity of the applied voltage produces the same effect.

An LCD will respond to and may be tested with a dc or a single polarity voltage. However, the life of the display is short unless an ac square wave driver with no dc component is used. This is accomplished by applying a square wave to the back plane. The input signal for the segment is applied through the X- OR gate. An X-OR gate provides the proper segment drive (reversing the truth table) for a data input provided by the standard decoder output. The square wave (30 to 300Hz) must be symmetrical otherwise the display voltage will have a dc bias.

Decoder/drivers for LCD displays have internal XOR gates. Normally, a decoder/driver is required for each digit, although the back plane is common. Most LCD displays cannot be multiplexed.

### 2.26.3 HIGH CURRENT AND VOLTAGE DISPLAYS

Gas discharge, neon, or incandescent lamp seven-segment displays are similar to the LED displays except for; (1) the current and voltage requirements on the drivers and (2) the lamp segments are electrically un-polarized so that either the common – anode or common-cathode drive circuits will work with any display.

Neon or gas – discharge displays are bright, large, and low- cost but require a high – voltage drive (about 100 V at 1mA). Most IC drivers are inadequate, and a high- voltage driver transistor for each segment is a common solution (see fig 2.51a)

Incandescent displays (Fig. 2.51b) have roughly the same advantages and disadvantages as the gas – discharge displays except that the special power- supply requirement is a relatively high – current, at a lower voltage. Here also, individual segment drivers are usually required. Sometimes a resistor Rw is added to keep the filament warm, thus reducing the warm-up shock. These displays require a fair amount of power but can be made as large as desired so that the display can be read at a distance.

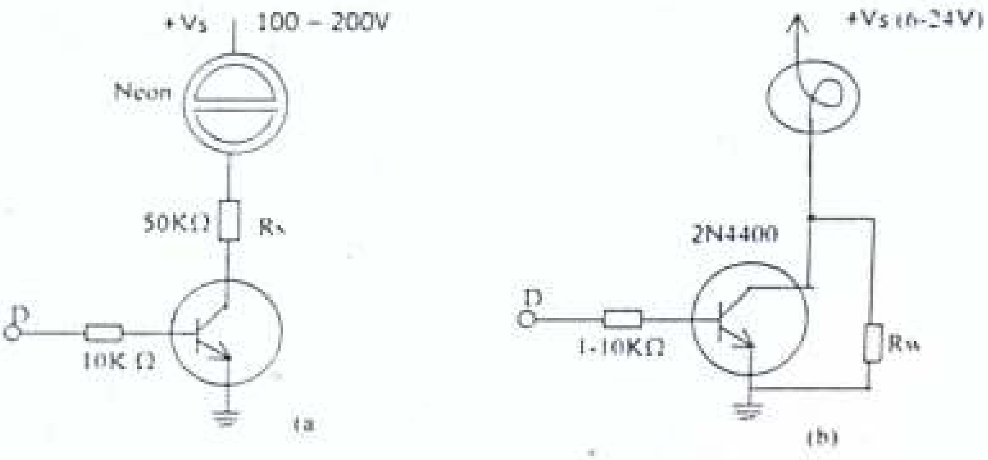
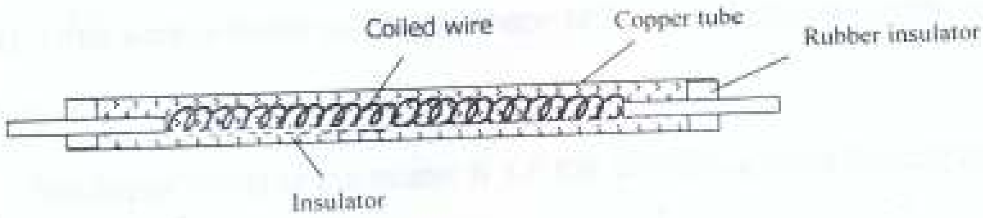
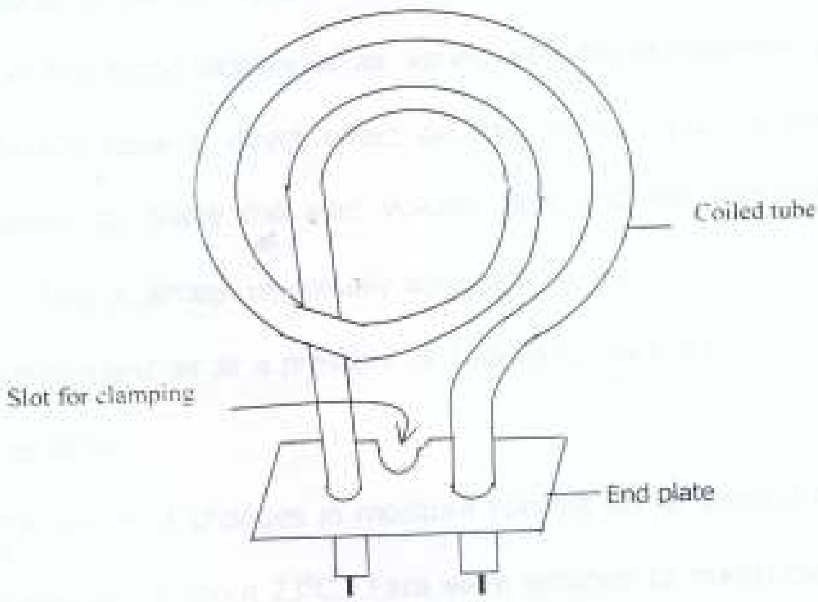



Figure 2.51: Seven- segment drive circuit for (a) Gas (b) Incandescent lamp.

## 2.27 HEATER




(a)




(b)

Figure 2.52: The Heater (a) The internal construction (b) The shape of finished product

A heater of the type used for this project, is made of a resistive element coiled into a helical form and contained inside a copper tube insulated from tube wall by a suitable electrical insulator. The ends of the coil are soldered to good conductor studs, which are also insulated from the copper tube by means of a high temperature resistive rubber material (see fig. 3.17a). The tube is finally coiled into shape of figure (3.17b) completed with an end plate for positioning.

The power rating of the heater is 1.8 KW at $240V_{rms}$ while the current rating is 8.3A and its resistance is 32Ω.

## 2.28 FAN

A fan is a device which propels air continuously against the pressure loss of a closed circuit system, in which the ambient atmosphere may be a component (Obsorne,1979). The variation in the mean density of air varies with the atmospheric pressure and temperature, both of which have a direct effect on the power input to the fan. It is customary for manufacturers to quote the inlet volume flow and fan pressure for some "standard air" condition. This is almost universally agreed to be air having a density of 1.2 $kg/m^3$, which is that of atmospheric air at a pressure of 100kPa (1 bar), a temperature of $16^0C$, and a relative humidity of 65%.

The effect of changes in moisture content on air density can generally be ignored at temperatures below about $23^0C$. Fans were selected to match the system through which the air must pass in order to work at the highest efficiency. It is more convenient to connect fans in series.

# CHAPTER THREE

## 3.0 RESEARCH METHODOLOGY

The palm kernel nuts drier to be designed and constructed has two major parts. The first one is the housing unit or the body of the drier while the second is the control system. Here, these two shall be discussed.

## 3.1 DRIER BODY FABRICATION

The constructed drier is a metal box measuring 82cm in length, 45cm in breadth and 52cm in height. 2cm square pipes were used for the framework of the drier. Unto the framework, sheets of iron, 1mm thick, were welded. The main body was double walled with sawdust in between the walls as the lagging material. Lagging is important in order to avoid heat losses by conduction. The drier has three compartments, namely, the control section, the fan/heater section and the drying chamber. The three sections have lengths 20cm, 12cm, and 50cm respectively. The control compartment is thermally insulated from the fan/heater compartment by a lagged wall. This is to protect the electronic component in the control section from any form of overheating. The fan/heater section is separated from the drying chamber by a thin sheet perforated with holes. The fan blows hot air from the heater through the perforations into the drying chamber.

Stainless steel is not corrosive; it doesn't react with any material or rust. This property makes it the most adequate material to use in the construction of the trays inside the drying chamber. However, stainless steel was not locally available at the time of fabrication hence the trays were made of ordinary mild steel sheet. The dimension of each tray is 50cm by 36cm and 2.5cm deep.

The body of the drier was painted green, the interior, silver but the trays were unpainted because some quantity of kernel oil at the point of drying normally gets transferred from the interior of kernels to kernel the surface. This surface oil may react with the paint to contaminate the extracted oil.

## 3.2 DESIGN AND CONSTRUCTION OF CONTROL CIRCUITS AND SYSTEM

The knowledge of the values of the physical and thermal properties of any product is a pre-requisite for the design of equipment for processing of the product [Mujumda, 1986]. According to Jorgensen [1985], palm kernel nuts are best dried with hot air flowing over them at a temperature of 80°C. The drier is therefore designed to accommodate a preset temperature variable between 27°C (ambient temperature) and 100°C.

This design will provide a scientific approach to drying under controlled temperature, and a neat drying environment that will allow heated air to blow over the product to be dried. The design of the temperature sensor device (a thermocouple) and other circuit used in this work will be described in this section.

### 3.2.1 THE LOCALLY MADE THERMOCOUPLE

A thermocouple consists of two dissimilar metals joined together at one end but open at the other end. Heat at the short-circuited junction produces a small dc voltage across the open end, which is usually connected to a dc meter. The junctions must be at different temperatures for an emf to develop between the junctions.

The ends of a pair of copper and constantan wires were cleaned, twisted together and soldered. The thermocouple is as shown in figure 3.1. In this project, two thermocouples were constructed each wire being 1m long.

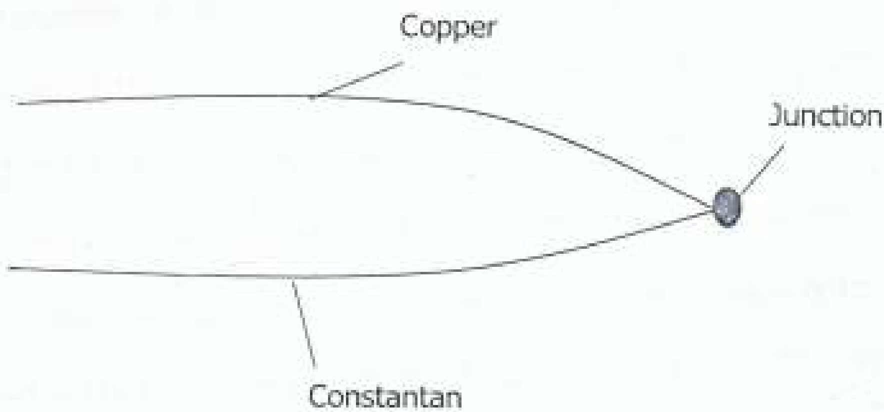



Fig. 3.1: A constructed thermocouple

### 3.2.2 EXPERIMENT TO DETERMINE THE CHARACTERISTICS OF THE THERMOCOUPLE

The set up is shown in fig 3.3. The LM 324 was used as a differential amplifier with a voltage gain of 100. The amplifier was connected to the output of the thermocouple to examine the response of the device to changes in temperature between 0° C and 100° C. The cold junction of the thermocouple was put in an ice bath at 0°C while its hot junction was subjected to the varying temperature of the heated water.

The readings of output voltage Vo versus temperature are shown in the second row of table 3.1. The readings were used to plot a graph of $V_o$ versus temperature $\theta$. The graph is shown in fig.3.2. From the graph, the gradient is 4.11mV/°C and the thermocouple constant is 41.1μV/°C.

The aim of the cold junction compensator is to obtain an equivalent circuit that would generate a voltage equivalent to the value of the cold junction emf at 0°C. The experimental set-up is shown figure 3.4. The resistors $R_3$, $R_4$, $R_5$, and $RV_1$ were chosen so that under steady conditions, the zener diode draws a current of 12mA thus ensuring that the voltage across it is constant. The water was heated to 100°C, $RV_1$ was adjusted until the output voltage at 100°C as read on a digital multimeter was 406mV. The water was allowed to cool down towards the room temperature; the readings obtained are shown in Table 3.2.

Using the second row data, the gradient is 4.04mV/°C. For the cold junction corrector, the thermocouple has a constant of 40.4μV/°C. Since the thermocouple amplifier has a gain of 100 at 100°C, the output voltage is 404mV. $V_o$ (observed) is the actual reading of the meter while $V'_o$ is the calculated output voltage obtained using the formula;

$V'_o$ = thermocouple constant x amplifier gain x temperature

$$= 40.4\mu V/^{\circ}C \times 100 \times \theta^{\circ} \quad (3.1)$$

According to R S Catalogue [1993], the K-class thermocouple has a constant of 40.6μV/°C. Hence, the thermocouple constructed belongs to this class with its constant equal to 40.4μV/°C.

It is observed from the table that $V_0$ and $V'_0$ agree and so the cold junction corrector is reliable. The output of the thermocouple amplifier is in analogue form. In order to read the temperature on a digital display, we must of necessity convert the analogue output to a digital word. This leads us to discuss the conversion process using ADC 0804.

**Table 3.1: Readings from the thermocouple shown in fig 3.3**

| Temp.($^0$C) | 10 | 20 | 28 | 30 | 35 | 39 | 44 | 55 | 68 | 73 | 77 | 82 | 88 | 98 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_0$ (mV) | .03 | .07 | .11 | .12 | .14 | .16 | .18 | .22 | .28 | .30 | .32 | .34 | .35 | .36 | .40 |

**Table 3.2: Readings from the thermocouple with the cold junction corrector**

| Temp $^0$C | 100 | 95 | 90 | 85 | 80 | 75 | 70 | 65 | 60 | 55 | 50 | 45 | 40 | 35 | 30 | 25 | 20 | 15 | 10 | 5 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_0$ observed output voltage (mV) | 406 | 386 | 366 | 342 | 326 | 305 | 283 | 264 | 242 | 224 | 204 | 183 | 164 | 145 | 128 | 100 | 82 | 64 | 46 | 28 | 10 |
| $V'_0$ calculated output voltage (mV) | 404 | 383 | 364 | 343 | 323 | 303 | 282 | 263 | 242 | 222 | 202 | 182 | 162 | 141 | 121 | 101 | 81 | 61 | 40 | 20 | 0 |

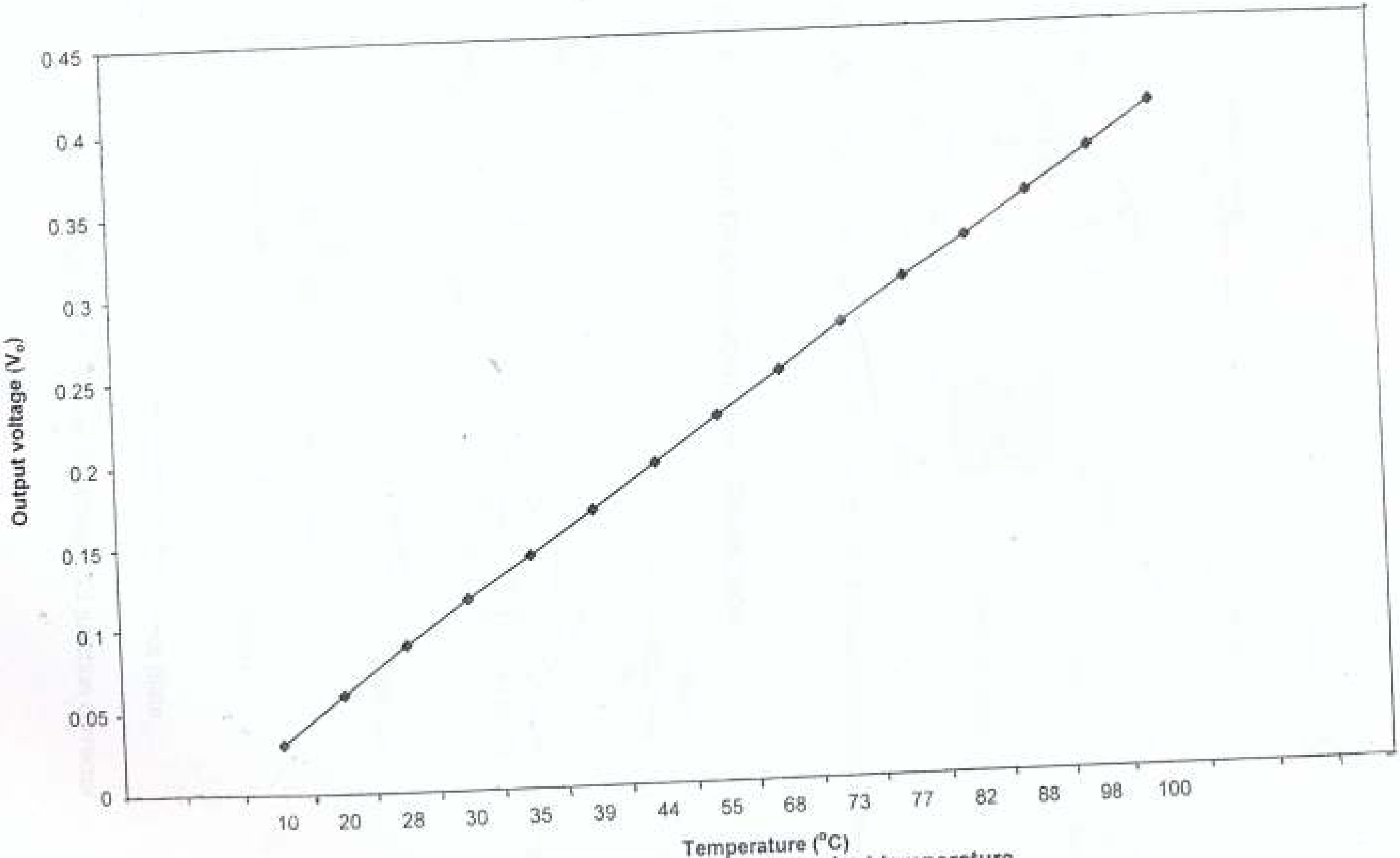



Fig 3.2 **Graph of output voltage against temperature**

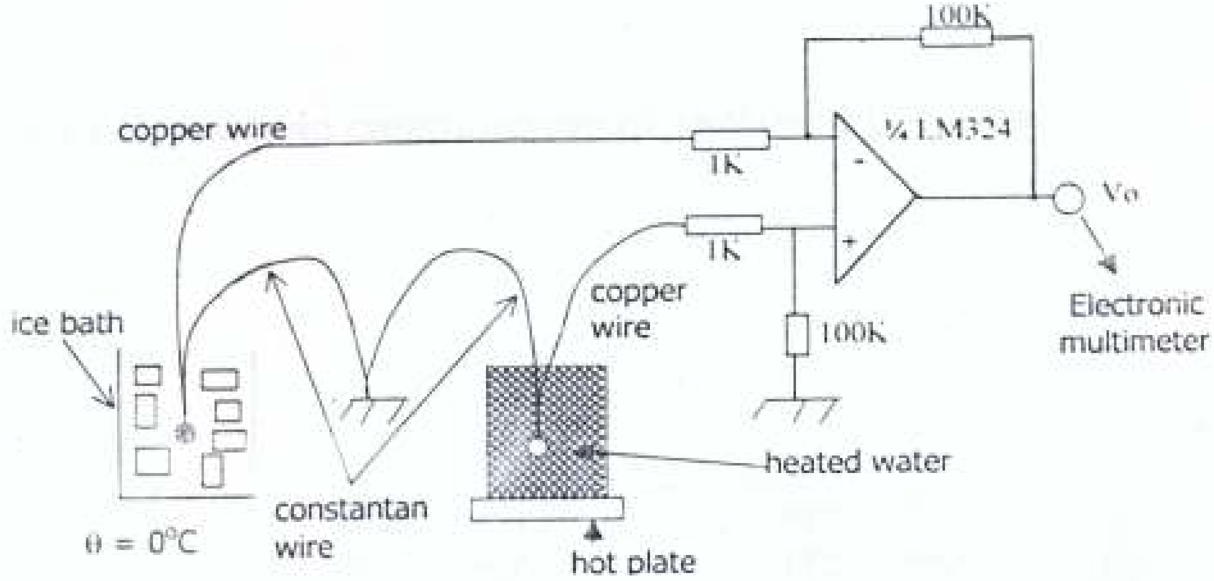



Fig 3.3: Circuit to observed temperature response of copper/constantan thermocouple

### 3.2.3 DESIGN OF COLD JUNCTION CORRECTOR

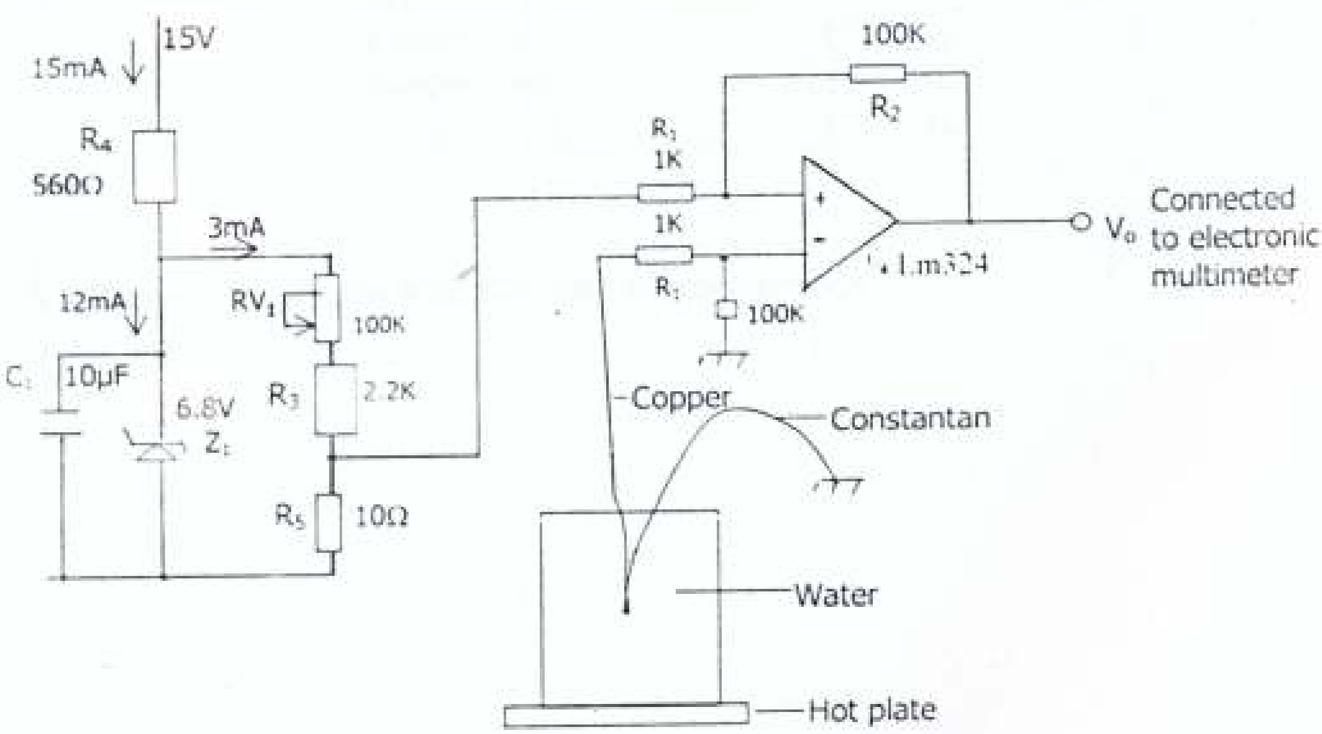



Figure 3.4: Circuit to obtain cold junction corrector

### 3.2.4 DESIGN AND CONSTRUCTION OF ANALOGUE TO DIGITAL CONVERTER

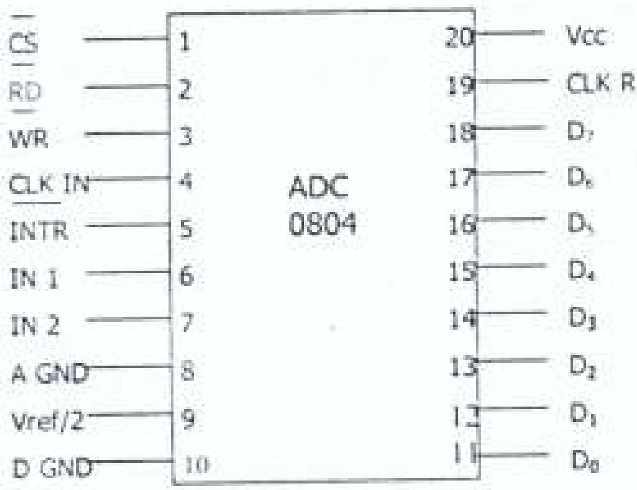



Figure 3.5a: Typical 8 bit ADC 0804 pin configuration

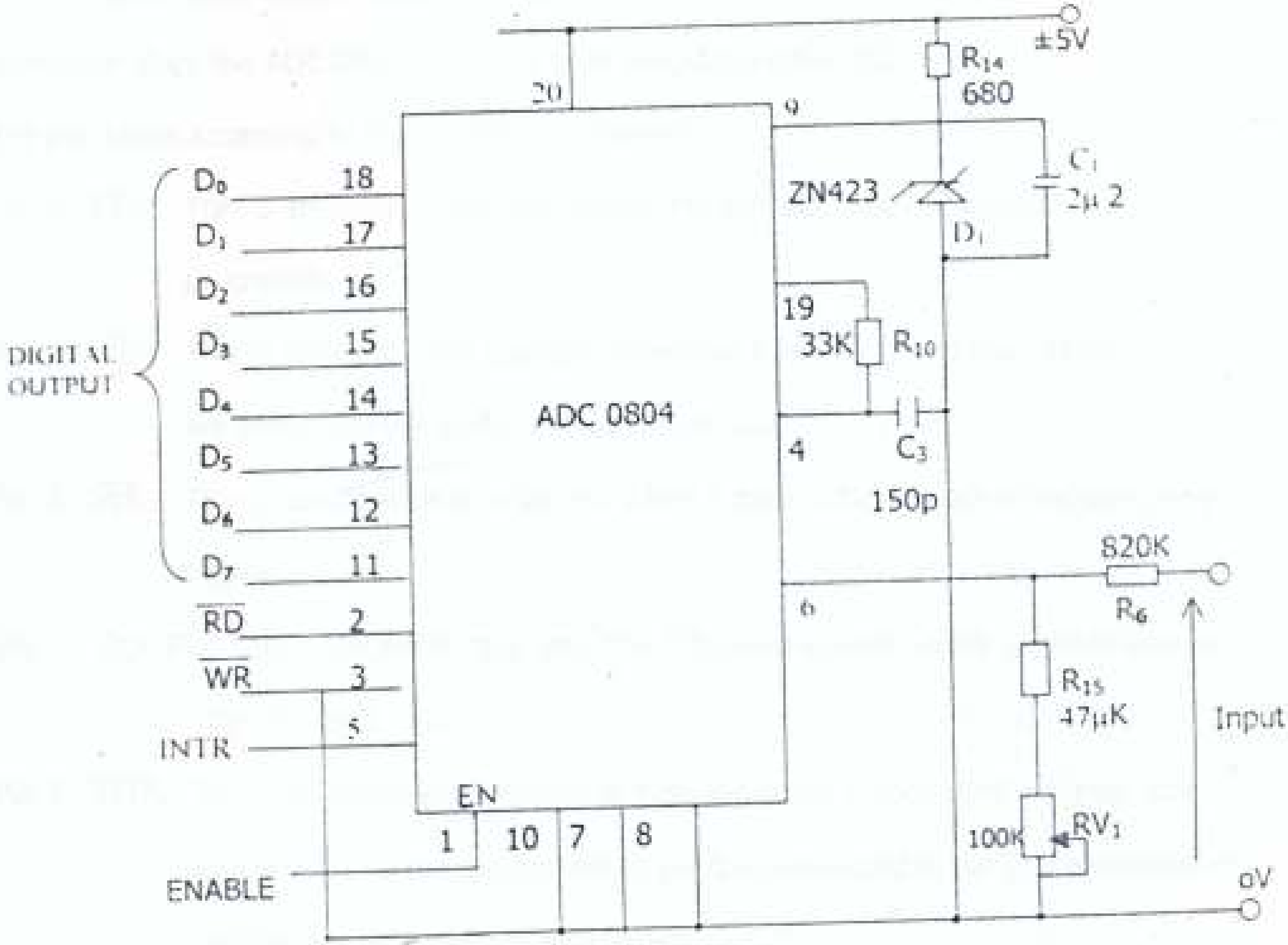



Figure 3.5b: Typical 8 bit ADC 0804 circuit diagram

Figure 3.5a shows the pin configuration for a typical successive approximation A/D converter chip, the ADC 0804. The IC is used in a stand-alone ADC circuit. The run down of the pin labels according to Puri (1997) is as follows:

Pin 1: $\overline{CS}$:- This is an active –LOW chip select. For the ADC 0804 to operate, the pin must be grounded.

Pin 2: $\overline{RD}$:- This is an active LOW read pin. When pin 2 is LOW, the three – state outputs are active and the digital output can be read.

Pin 3: $\overline{WR}$:- This is an active LOW write pin. When it goes LOW, the AD conversion process begins.

Pin 4: CLK IN:- This is the clock input pin. The TTL-Level square –wave signal is applied to this terminal.

Pin 5: $\overline{INTR}$:- This is an active low interrupt or halt. When pin 5 goes LOW it signals that conversion process is complete. If pin 5 is connected to pin 3, the conversion process will immediately begin again.

Pin 6 & 7:- These are the two differential input for analogue signals used for voltage offset adjustment. It has two grounds, the first ground is A GND at pin 8 and the second ground is D GND at pin 10.

Pin 8: A GND:- This means analogue ground i.e. the ground for analogue signals.

Pin 9: $V_{ref}/2$:- This pin controls the voltage to which the input analogue voltage is referenced. If left unconnected, $V_{ref}=V_{cc}/2$. By applying a reduced voltage to pin 9, the range of the input signal can be varied from 0 to 3V.

Pin 10: D GND:- This means digital ground. In practice pins 8 and 10 are connected to the common ground.

Pins 11-18: $D_0$ – $D_7$:- These are the three – state digital output. If pin 1 or pin 2 is high, then the digital outputs at Pins 11 to 18 float. When pins 1 and 2 are low, the digital output appears on pins 11 to 18.

Pin 19: CLK R:- This is the output from the internal clock. An external resistor and capacitor connected between pin 19 and the ground determine its frequency. The frequency is given by f=1 / 1.1RC.

Pin 20: Vcc:- This is the supply voltage typically 5V.

The circuit diagram of the ADC is shown in fig. 3.5b. According to Michael (1995), the following useful informations were obtained.

(i) A reference voltage of 1.26V is provided by a precision band – gap device $D_1$

(ii) The frequency of the ADC 0804's internal clock is determined by $R_{10}$ and $C_3$

(iii) Scaling of the input voltage is provided by the simple potential divider arrangement comprising of $RV_1$, $R_{15}$ and $R_6$.

(iv) The input resistance is 1MΩ and $RV_1$ is to be adjusted so that a full-scale output results from an input of 25.5V. In that condition, the converter operates in steps of 100mV.

From the information above, the following were carried out.

(i) Design of equivalent reference voltage as provided by ZN423. The ZN423 regulator was not available as at the time of design. From R S catalogue (1982), the reference voltage is 1.26V. To obtain such a steady voltage the circuit of figure 3.6 was used.

The currents flowing at various points in the circuit were fixed at the values shown. The values of the components were calculated as $R_8$ = 220Ω, 1/4W; $R_9$ = 470Ω, 1/4W and $RV_4$ = 1k, 1/2W.

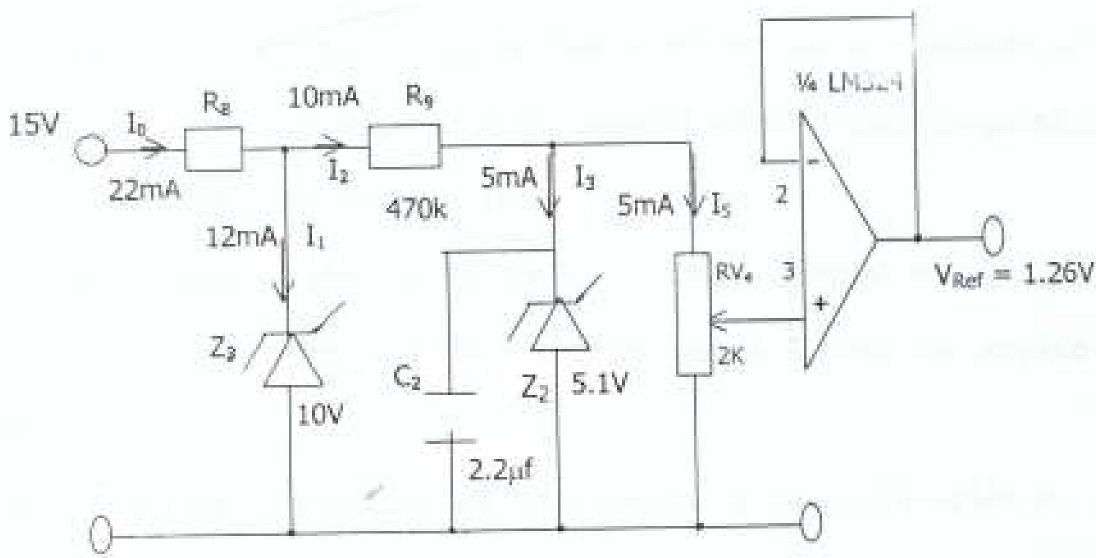



Fig. 3.6: Circuit to provide 1.26V reference voltage

The reference diodes $Z_3$ and $Z_2$ give reference voltages of 10V and 5.1V respectively. The purpose of the two is to stabilize the voltage across $Z_2$. Even if the input changes, the output will still be stabilized. The variable resistor $RV_4$ sets the final output at 1.26V. The booster affords a precision voltage of 1.26V with an output impedance close to zero. The capacitor $C_1$ stabilizes the voltage across the $Z_2$ in case of any voltage surge; thus ensuring that the final output remains at 1.26V.

(B) <u>Design of the amplifier for the input of the A/D converter:</u> The ADC 0804 converter IC is an 8-bit converter. Its output has 256 steps full-scale reading. There are 255 steps above 0V. In this work voltage per step is fixed at 100mV and the maximum temperature of the drier is 100°C. At this temperature, the amplifier output voltage is expected to be

100 steps x 100mV/step = 10V.

From the thermocouple constant of 40.4μV/°C, the thermo emf at 100°C = 4.04mV. If voltage input to the amplifier is 4.04mV and the output is 10V, the amplifier gain = 10V/4.04mV = 2475.

For this high gain, a cascaded two stage amplifier is required in which the output of stage A is 200mV at 100°C and that of stage B is 10V.

<u>Design of stage A:</u> This is the same as the thermocouple amplifier described in section 3.3.

<u>Design of stage B:</u> Stage B is a non inverting amplifier whose input signal is 404mV and output is 10V. Therefore, the gain = $(R_3+R_{16}) / R_3$. Putting $R_3$ =2.2 kΩ and $R_{16}$ = 51kΩ. $R_{16}$ was replaced with a series combination of a fixed resistor of 47kΩ and a 6.8KΩ pot, which was adjusted to give the required gain.

The complete amplifier including the cold junction corrector is shown in figure 3.7. The circuit of figure 3.7 is connected to the magnitude comparator. The 8-bits magnitude comparator has two 7486 EX-OR gates, two 7404 which are inverters and one 7430 which is an eight input NAND gate. Their connections are shown in figure 3.8. The magnitude comparator compares the signal from ADC and the Binary counters. When the two inputs of the magnitude comparator are equal. The output (EN) of the magnitude comparator will go low. This will disable the counters as well as enables the latches to read the output of the decade counter or to transfer the signal from the output of the decade counter to its (latch) output.

After the counter stops counting, it would not be able to count again unless reset. Therefore the circuit must be reset in order to be ready for a new process of counting and the reset pulse generator (figure 3.10) does that. Reset pulse generator resets while the gated clock pulse generator (figure 3.11) drives the counter. The design of the two pulse generators are discussed in section 3.6

### 3.2.5 COUNTERS, LATCHES AND DISPLAY

In figure 3.9, we have two 7493 ICs which are binary counters, two 7490 which are decade counters, four 7475 which are latches (memory to preserve data, when enabled it opens and reads data and transfers it to the output; when disabled it latches or locks up the data), and two 7447 ICs which are decoder/drivers to decode the BCD digits and drive it to the display unit. These were used along with the Seven Segment Display. Their connection network is as shown in figure 3.9. The circuit arrangement from the magnitude comparator to the decoder/driver can be substituted with 7107 IC. This IC was not available as at the time of construction. The circuits in figures 3.8 and 3.9 were therefore designed as replacement.

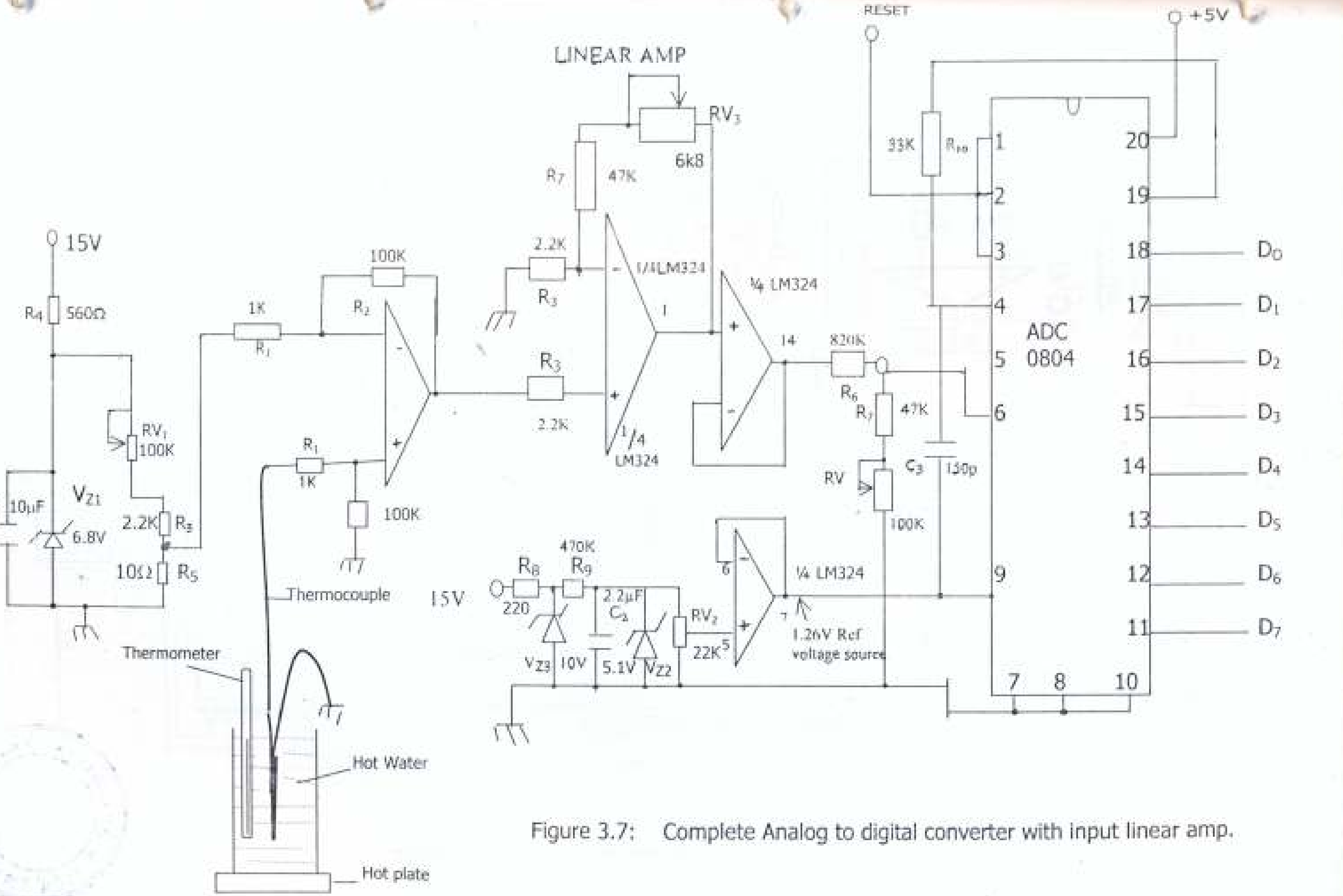



Figure 3.7: Complete Analog to digital converter with input linear amp.

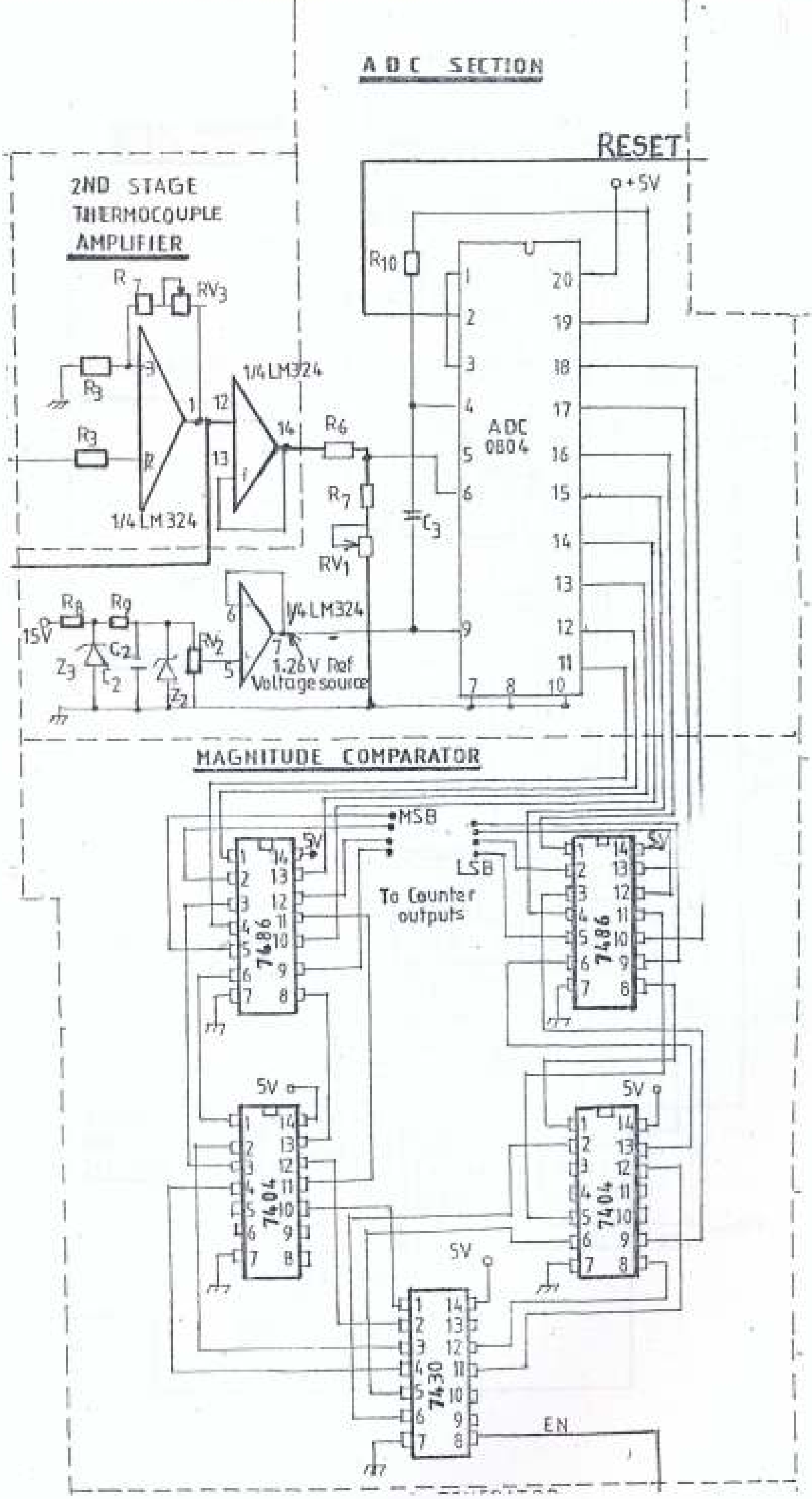



*Fig. 3.8: Connection of ADC to magnitude comparator.*

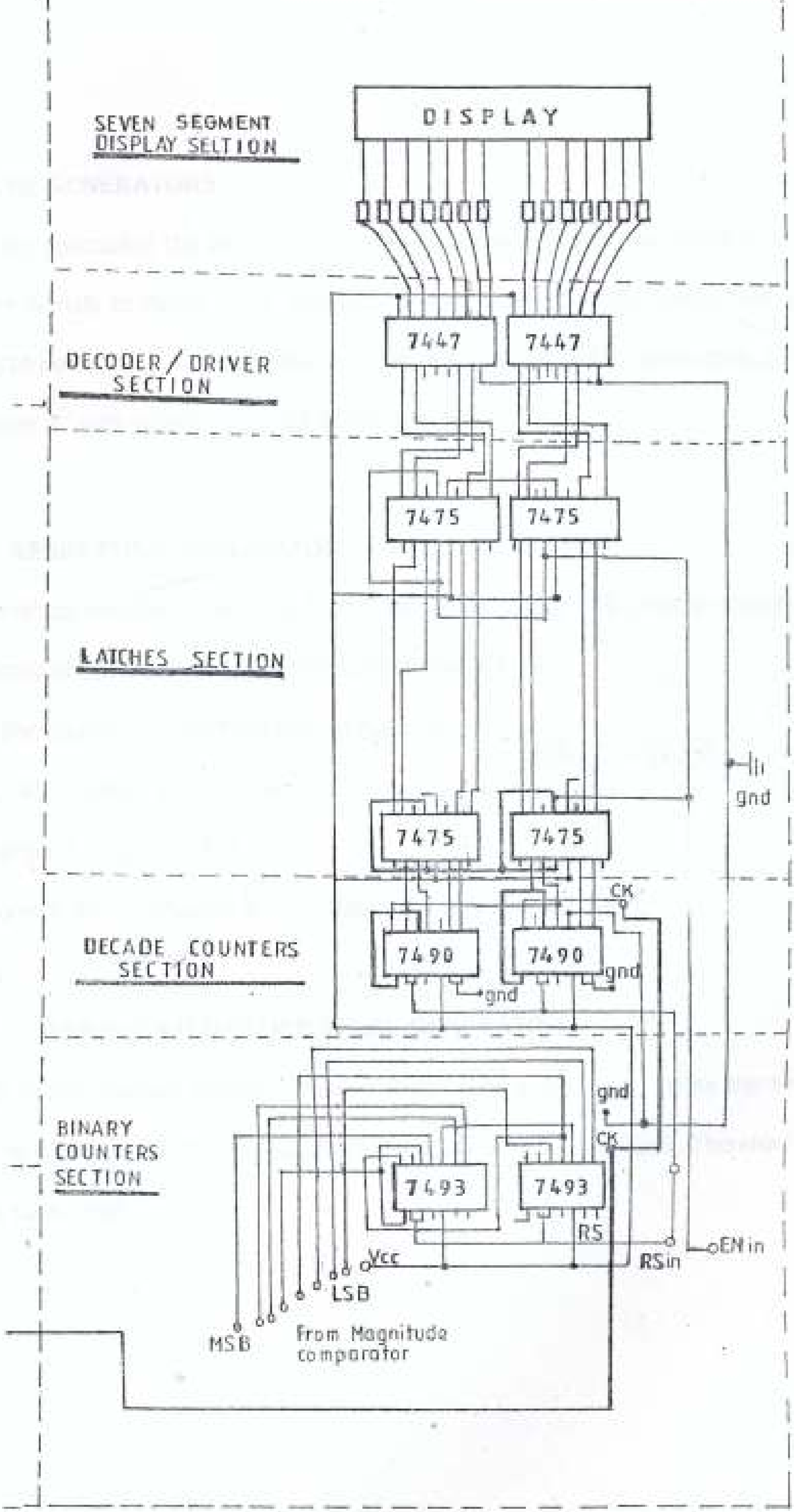



*Fig 3.9: The Counters, Latches and Display Circuit*

### 3.2.6 PULSE GENERATORS

Having concluded the design of the circuit that will amplify the thermocouple output and convert signals to digital form, attention is now focused on the circuit that will control the temperature of the heating chamber. For this reason, pulse generators are required. The 555 timer IC was extensively used in the design.

#### 3.2.6.1 RESET PULSE GENERATOR

The circuit diagram is as in fig 3.10. The circuit uses a 555 timer in an astable mode. The frequency of oscillation is 1Hz it is assumed that $R_1 << R_{11}$.

Therefore the equation of the frequency is given as

$$f = \frac{1}{0.693(R_1 + 2R_{11})C_4} \qquad (3.2)$$

If f = 1Hz, $R_{11} = 68k\Omega$ and $R_1 = 1k\Omega$

Using equation 3.6, $C_4 = 10.5\mu F$.

The component values selected is $C_4 = 10\mu F$, 16V and $C_5 = 0.01\mu F$.

#### 3.2.6.2 10KHz GATED CLOCK PULSE GENERATOR

The circuit diagram (figure 3.11) is the same as in fig 3.10. Here the frequency of oscillation is 10KHz. Let $R_{11} = 68k\Omega$, from equation 3.6, $C_6 = 1.05nF$. Therefore the value selected is $C_6 = 1.0nF$.

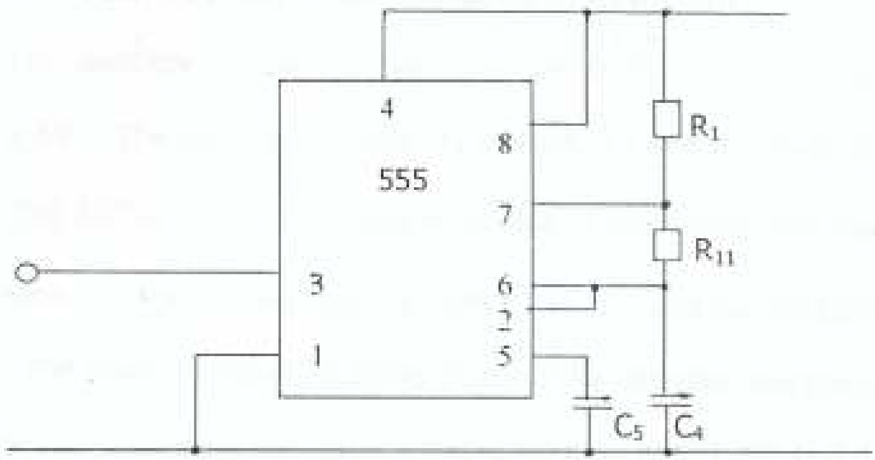
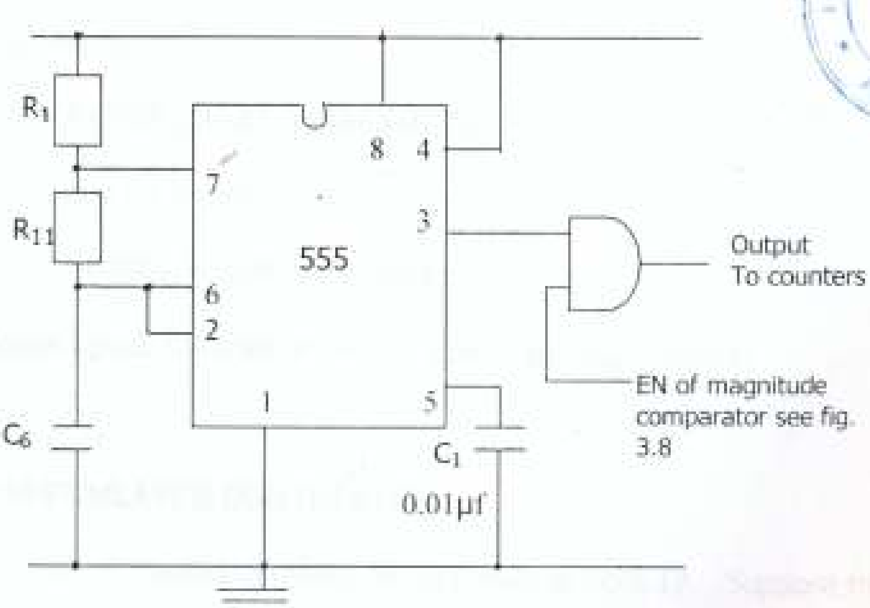



Fig. 3.10: 1Hz Reset Pulse generator




; 3.11: Gated clock pulse generator

### 3.2.6.3 VOLTAGE DEPENDENT PULSE GENERATOR

This oscillator is shown in the upper part of fig 3.12. The supply voltage to the 555 Timer is 5V. The capacitor $C_7$ charges through $R_{12}$ and the diode $D_1$ with a target voltage of $V_{var}$ (fig 3.13a). $V_{var}$ is the output voltage of the comparator that compares the output of the secc' 'tage thermocouple amplifier (fig 3.7) and the temperature preset circuit (fig 3.14). The charging time $t_1 = 0.693\ R_{12}C_7$. The capacitor discharges through $R_{13}$ and $D_2$, the target voltage being 0V. The discharging time $t_2 = 0.693\ R_{13}C_7$. For a large value of $V_{var}$, say 10V, $C_7$ takes less time to charge from $1/3V_{cc}$ to $2/3V_{cc}$ than to discharges from 2/3Vcc to $1/3V_{cc}$. Thus, $t_1 < t_2$.

Let $t_2 = 10\ t_1$

Hence the periodic time $T = t_1 + t_2 = 11\ t_1$

But $t_1 = 0.693\ R_{12}C_7$

Therefore, $T = 0.693R_{12}C_7 \times 11 = 7.623\ R_{12}C_7$

Let T = 1/10 s, and $C_7 = 1\mu F$,

$R_{12} = 13.12\ K\Omega$ and $R_{13} = 10R_{12} = 131K\Omega$

The component values selected are $R_{12} = 12K\Omega$, and $R_{13} = 120K\Omega$

### 3.2.7 FIRST HEATER CONTROLLER

The circuit of the heater controller is shown in fig 3.12. Suppose the power circuit is switched ON. At this instant, the differential voltage $V_{var}$ is maximum and higher than $V_{cc}$. The pulse generator has a waveform shown in Fig. 3.12. At time $t_1$ Pin 3 of the 555 timer is driven high. The transistor $Q_1$ is driven to saturation, transistor $Q_2$ is OFF. There is no current through the photodiodes $D_3$ and $D_4$. The heater is therefore OFF during this short

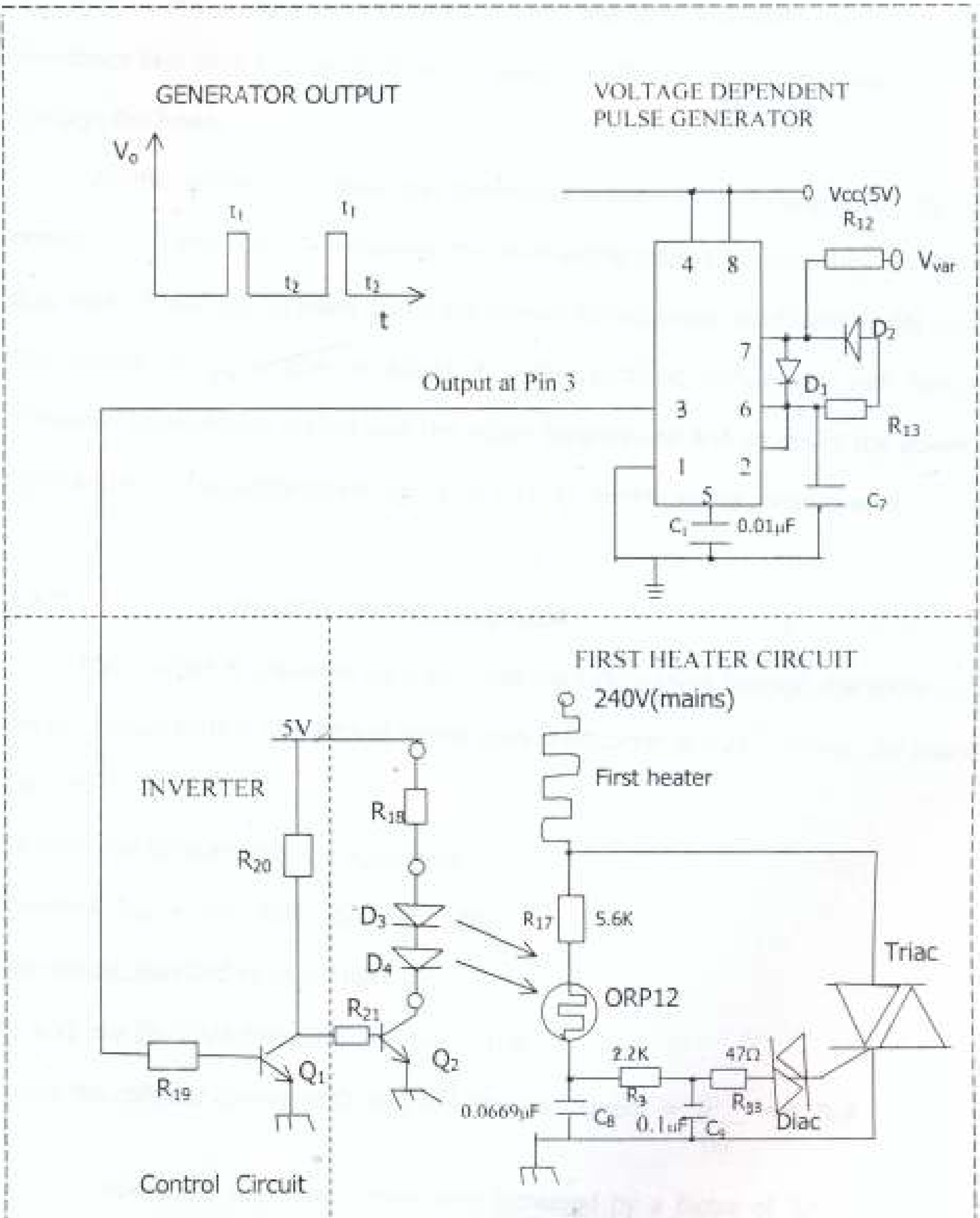



Figure 3.12: The Power Circuit

interval. In the interval $t_2$, Pin 3 of the timer is driven low. $Q_1$ cuts off and $Q_2$ saturates. The leds $D_3$ and $D_4$ turn on and they illuminate the light dependent resistor ORP12. The resistance falls from megaohms to a few kilo-ohms. At this instance the triac drives current through the heater.

As the temperature rises, the differential voltage (Var) falls and so, the charging period of the capacitor $C_7$ increases, the discharging time decreases thus, increasing the duty cycle. Therefore, in every cycle, the interval during which the heater is ON decreases. The control circuit is able to adjust its pulse width in accordance with temperature difference between the pre-set and the actual temperature and so drives the power circuit accordingly. It should be noted that in fig 3.12, $Q_1$ merely serves as an inverter.

### 3.2.7.1 DESIGN OF THE INVERTER

The inverter is shown in fig 3.12. Let the safe current through the photodiodes be 15mA. When biased, the voltage across each photodiode is 1.2V. Hence, for two diodes it is 2.4V.

Assume that for transistor $Q_2$, $V_{CEsat}$ = 0V.

Therefore, $R_{18}$ = (5 - 2.4)/ 15mA = 173Ω.

The nearest standard value is 180Ω.

$Q_1$ & $Q_2$ are 2N2222A transistor with $h_{FE}$ = 100

Taking the collector current of $Q_2$ as 15mA, its base current $= \frac{I_C}{h_{FE}}$ = 150μA.

For good operation, the base current was increased by a factor of 3.5. Therefore $I_b$ = 525μA, $R_{19}$ = (5 - 0.6)/ 525μA = 8.4kΩ, the nearest preferred value is 8.2kΩ. $R_{20}$ = 5V/15mA ≅ 330Ω and $R_{21}$ as 3.9kΩ.

### 3.2.7.2 DESIGN OF THE FIRST HEATER CIRCUIT

For the photoresistor, its resistance in darkness is 1MΩ (min) and its resistance when subjected to the radiation from the light emitting diode is 4.5kΩ.

For Diac BR100, $V_{BO} = (32 \pm 4)$ V

Averagely, $V_{BO} = 32$V.

When the diac breaks down, it conducts and its current fires the triac.

Let 240 Vrms from mains be equivalent to $90^0$, then 32 Vrms will be equivalent to $= 12^{\circ}$

From the basic ac theory, the phase angle for an RC network is $\tan \theta = \omega RC$.

If the mains frequency = 50Hz, $\tan 12^{\circ} = 2 \times \pi \times 50 \times R \times C$

But $R = (R_{17} + R_{eff}$ of ORP 12)

According to Loveday (1982), $R_{eff} = 4.5k\Omega$

If $R_{17} = 5.6k\Omega$, then $R = 10.1k\Omega$

and $\tan 12^{\circ} = 2 \times \pi \times 50 \times 10.1k \times C_3$

This gives $C_8 = 0.0669\ \mu F$.

Two capacitors $C_{8A}$ and $C_{8B}$ replace $C_8$.

$\therefore\ C_{8A} = C_{8B} = 0.1\ \mu F$

Therefore, the equivalent capacitance = 0.05 μF

The actual firing angle, θ is given by $\tan \theta = 2 \times \pi \times 50 \times 10.1k \times 0.05\ \mu F = 9.0^0$

The proportional temperature controller allows only one heater (rated 240V, 8.3A) to be used in the system as in fig 3.12. This does not provide the required heating because the triac rating is only 15A. If two of such heaters are used the current rating of the triac will be exceeded. For this reason, a second heater circuit was designed to drive another heater.

### 3.2.8 SECOND HEATER CIRCUIT

Consider figure 3.13a where $V_{ON}$ is the output voltage of the thermocouple amplifier. $V_{set}$ is the preset voltage corresponding to the desired temperature. If $V_{ON} > V_{set}$, then $V_{O1}$ is OV. $D_1$ and $Q_1$ are off, $Q_1$ emitter voltage is O V, $IC_2$ is in positive saturation and $V_{02}$= $V_{cc}$. Hence, $Q_2$ is saturated, $Q_3$ is OFF, the diode, the photo transistor $Q_4$ is off and the Thyristor $SRC_1$ is also off.

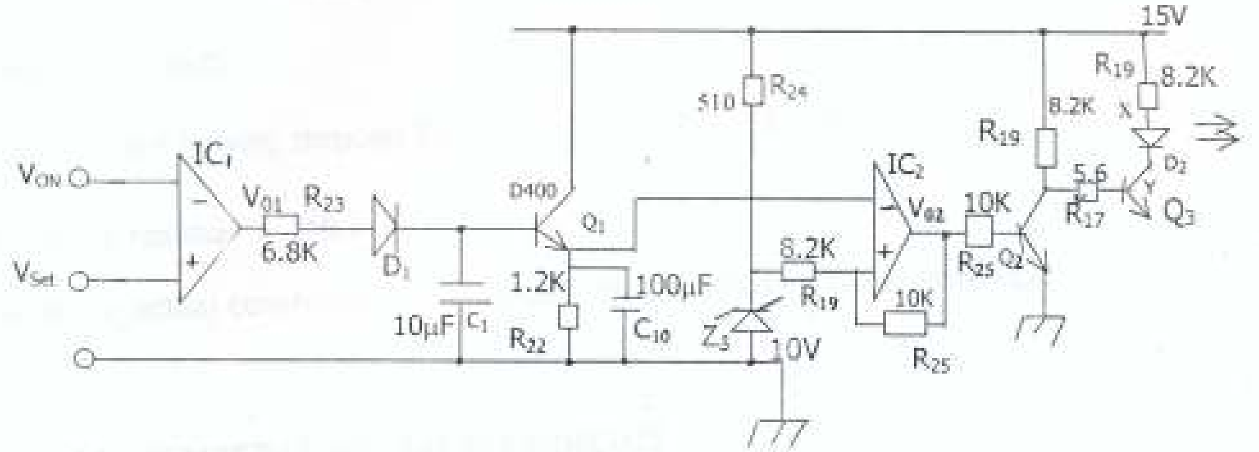
If $V_{ON} < V_{set}$, the process reverses. The phototransistor $Q_4$ is ON, hence it fires the thyristor $SCR_1$. When the thyristor conducts, sufficient ac current will be passed to the a.c. relay coil and the latter will change state and supply current to the heater.

Since a thermocouple is very sensitive, it responds rapidly to any slight change in temperature, diode $D_1$, traps the previous voltage and prevents oscillation. The time constant ($R_{22}C_{10}$) together with the hysteresis of comparator-2 ($IC_2$) further dampens the circuit to prevent erratic triggering due to transients.

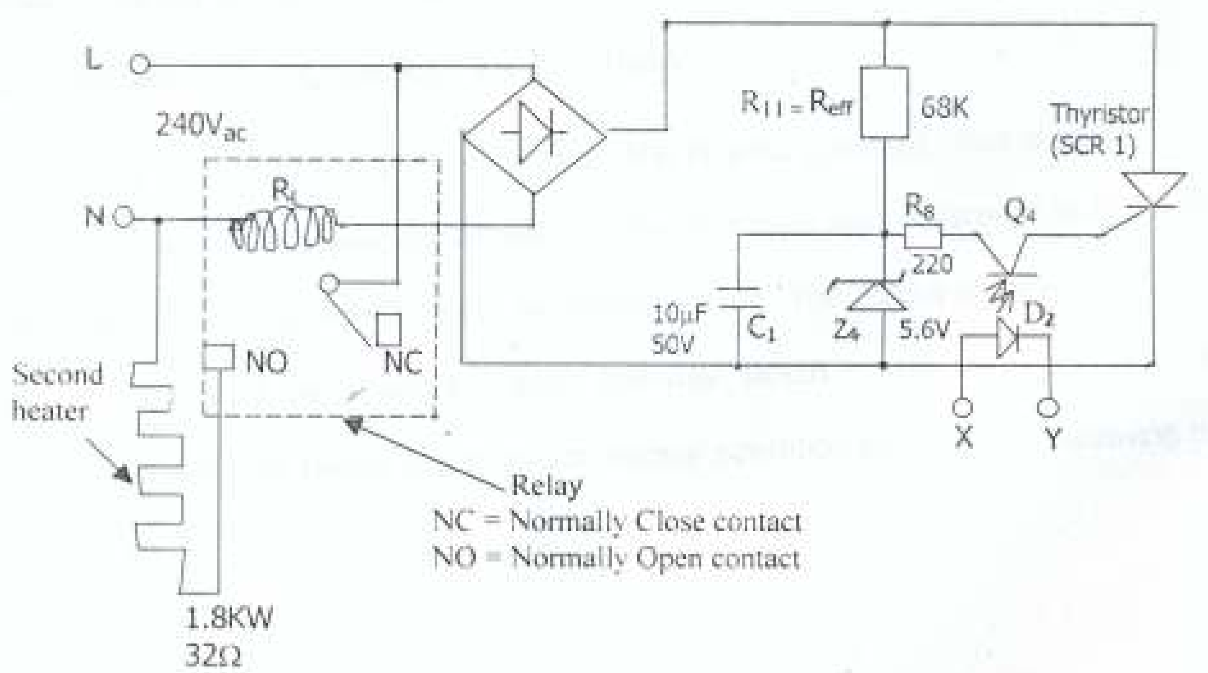
According to Douglas (1989) $V_{Hysteresis} = R_{19} \times \frac{(V_{cc} - 1)}{R_{19} + R_{25}} = 6.3V$

The resistors $R_{17}$, $R_{19}$, $R_{22}$, $R_{23}$, $R_{24}$, $R_{25}$ and capacitors $C_1$ and $C_{10}$ were chosen by assuming a current 1μA through $Q_1$, 10mA through $Z_3$, 1mA through $Q_2$ and 1mA through $Q_3$.

For the power circuit, the thyristor is a sensitive gate type with gate current of 0.2mA (min). Allowing a current of 3.0mA to flow through the zener, $Z_4$, the effective resistance




*(a) Controller*




*(b) Power Circuit*

Figure 3.13: Second heater circuit

$R_{eff}$ = (240 - 5.6)/3mA = 78kΩ = $R_{11}$

We take $R_{eff}$ = 68kΩ

The true current flowing through $Z_4$= (240 - 5.6)/68k = 3.4mA.

Power of the resistor = $I^2R$ = 0.8W.

However, in actual construction, four 270KΩ resistors in parallel replaced $R_{eff}$.

### 3.2.9 TEMPERATURE PRESET CIRCUIT

It is necessary to design the circuit to preset the temperature of the drying chamber of the drier to a fixed degree, 50°C say. This section gives the detail of the design.

$Vz_5$ = 13 V and $RV_4$ = 2K, 10 turn pot. Let $I_2$ = 10mA

Hence, $R_{15}$ = (15 - 13)/ 10mA = 2/10mA = 200Ω. The nearest standard value is 180Ω.

$IC_3$ is connected as a voltage follower. It acts as a high load resistance to the zener circuit and a low source resistance to the succeeding circuit. The output is connected to the input (Vin) of fig. 3.13 by a single - pole, two-way switch. And after, the chamber temperature is preset, the switch is returned to normal operation position, thus allowing the heater to turn on.

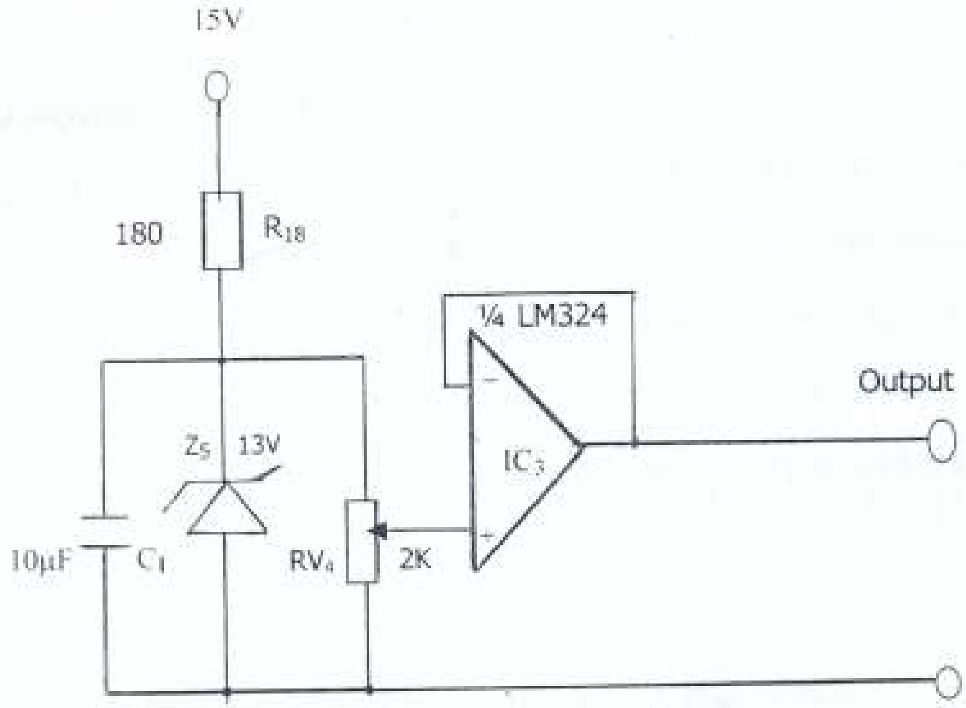



Fig. 3.14: Temperature preset circuit

### 3.2.10 POWER SUPPLIES

The various stages of these equipments require the following dc voltages (a) $\pm$5V for the operational amplifiers (b) +15V for the comparators. Now each of this supply is obtained from a single 240 V, 50Hz ac source.

### 3.2.10.1 5V-POWER SUPPLY, $I_o$ = 0.5A (Max)

A $240V_{rms}$, 50Hz ac source is applied to the primary of the transformer $TR_1$. The voltage at the secondary winding of the transformer is 15V. The bridge rectifier BR1 converts the voltage to dc. $R_{28}$ serves as the load resistor to the rectifier. $C_{11}$ is the filter capacitor. By means of $R_{27}$ and $Z_7$, the Vcc for the op amp is made 15V. The two zeners regulate the Vcc to a fixed voltage. The values of the components in figure 3.15 are chosen as follows $V_{Z7}$ = 8.2V and $V_{Z6}$ = 3.3V.

The properties of the transistors $Q_1$, $Q_2$ and $Q_3$ are as follow:

(A) For $Q_1$ :BFY 50; Icmax = 1A, $P_o$ = 800mW , $V_{CEO}$ = 35V, $V_{CBO}$ = 80V, $h_{fe}$ = 30min

(B) For $Q_2$: 2N3055; Ic max = 15A, $P_o$ (max) = 115W at 25 $^oC$, $V_{CEO}$ = 60V, $V_{CBO}$ = 100V, $h_{fe}$ = 20 – 70.

(C) For $Q_3$ : 2N222A; Ic max = 800mA, Power output $P_o$ = 500mW at 25 $^oC$, $V_{CEO}$ = 40V $V_{CBO}$ = 75V, $h_{fe}$ = 100 – 300, Take $I_3$ = 10mA and $I_2$ = 20 mA

$I_1 = I_2 + I_3$ = 30mA

$$\therefore R_{26} = \frac{8.2V - 3.3V}{10mA} = 490\Omega$$

Power rating $P_o$ = $(10mA)^2 \times 490\Omega$ = 49mW

The nearest standard value is 470Ω, 0.25W

The output of the transformer $= 15V_{rms}$, when the input voltage is $240V_{rms}$

$V_{dc} = (15 \times \sqrt{2}) - 2V_D = 21V - 1.4V = 19.6V$

$R_{27} = (19.6V - 8.2V)/30mA = 380\Omega$

$P_o = 30\ mA \times 30\ mA \times 380\ \Omega = 342mW$, hence $R_{27} = 390\ \Omega$, 1/2W.

The other components are as follows:

$R_{28} = 2.7k\Omega$, 0.5W; $R_{29} = 150\Omega$, 0.125W; $C_{11} = 4.700$ pF, 35V, and

$C_1 = 10\ \mu F$, 25V; $C_{12} = 47\ \mu F$, 25V. For $I_o\ (max) = 0.5A$

$Q_3$ is ON when the forward biased voltage is about 0.6V. Suppose the transistor is fully on at 0.6V, then $V_{R30} = 0.6V$, $R_{30} = 0.6V/0.5A = 1.2\Omega$. Since the load current flows through $R_{30}$, its power rating is $0.5^2 \times 1.2 = 0.3W$, $R_{30} = 1.2\ \Omega$, 0.5W.

The base resistor $R_{18} = 180\Omega$

In case of overload, such that output current is greater than 0.5A, $Q_3$ turns ON and diverts the base current of $Q_1$. The output voltage will drop to protect the series transistor $Q_2$. When the supply is not loaded, we allow a steady current of 2mA through $R_{35}$ and $RV_5$.

$R_{35} = 3.3V / 2mA = 1.5k\Omega$

$RV_5 = 1.7V / 2mA = 850\Omega$

$RV_5$ is a $2.2k\Omega$ pot, which was adjusted to make the output voltage just 5.0V. $Q_2$ is mounted on a suitable heat sink.

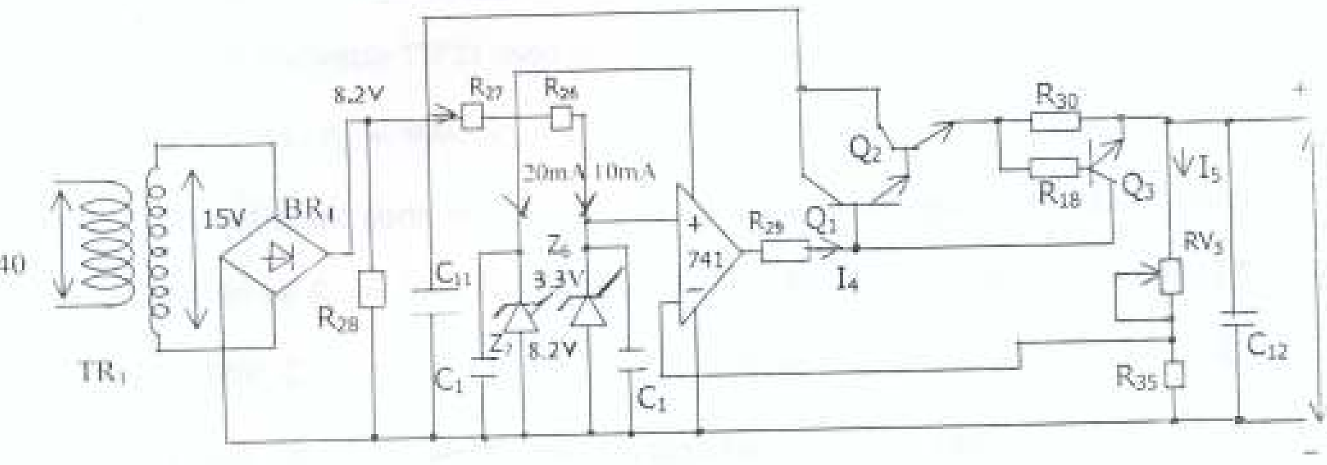



Fig 3.15: 5V, 0.5A stabilized and overload protected d.c power sunnly.

### 3.2.10.2 15V - POWER SUPPLY, $I_o$ = 0.5A

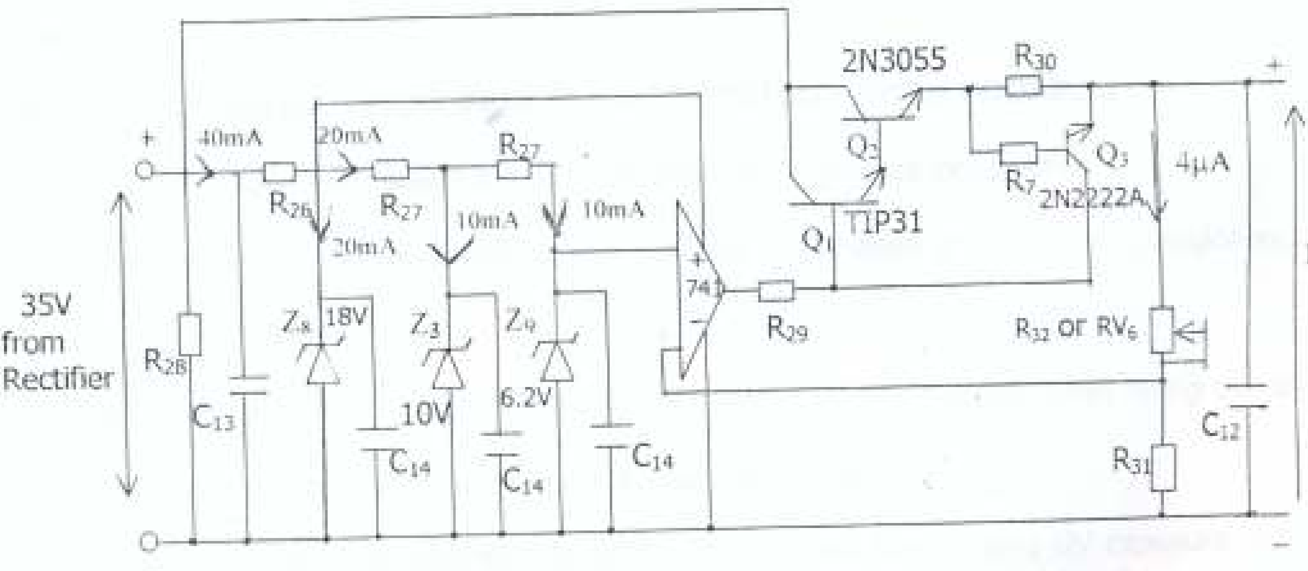



Fig. 3.16: 15V, 0.5A, stabilized and overload protected d.- power supply

Regulator Circuit.

The circuit shown in figure 3.16 is in every respect similar to figure 3.15. The component values in the circuit are therefore chosen as in section 3.10.1.

Properties of the transistor TIP31 used in this circuit are:

$I_c$ max = 3A, $P_o$ = 40w, $V_{CEO}$ = 60W, $V_{CBO}$ = 100, $h_{fe}$ = 10 – 50. The dc currents flowing in the different parts of the circuit are shown in the figure. The other components are computed to be $R_{27}$ = 390Ω, 0.5W; $R_{26}$= 470Ω, 1W; $R_{28}$ = 2.7kΩ; $C_{13}$ = 6800 μF, 50V; $C_{14}$ = 4.7μF, 50V; $C_{12}$ = 47 μF, 50V; $R_{29}$ = 150Ω; $R_{30}$ = 1.2Ω, 2.5W; $R_{31}$= 1.5 KΩ; $R_{32}$= 2.1 KΩ. A 4.7kΩ pot ($RV_6$) replaces $R_{32}$ and it is adjusted until Vo = 15V.

### 3.2.11 DESIGN OF THE PRINTED CIRCUIT USED

Printed circuits were produced using Photo - resist boards. These are copper-clad epoxy glass boards. The boards have positive photo-resist surfaces protected by a peel-off plastic film.

#### 3.2.11.1 PRODUCTION PROCESS OF PRINTED CIRCUIT BOARD (PCB)

The following steps were taken in the production of the printed circuit board.

(a) Each circuit was redrawn taking into account the shapes and sizes of components to use.

(b) The layout of the circuit (or art-work) was made on the drafting sheet using transfers, tracks, dual inline pads, transistor pads, round pads etc

(c) The artwork was "photocopied" on to the photo resist board using UV exposure unit for 2 minutes.

(d) The artwork pattern was developed using a sodium hydroxide solution as a developer. It was prepared by mixing 10g of sodium hydroxide powder with water to make up

500ml of solution in a beaker. The solution was poured into a plastic tray and the exposed board was placed in the solution. It was shaken continuously and examined from time to time until the pattern was completely developed. The board was removed and washed under running water.

(e) The board was then etched using Ferric chloride Hexahydrate solution. The etchant was prepared by mixing 200g of crystals with water making the solution to 500ml. The board was immersed in the etchant inside a plastic tray. Shaking was done continuously until the board was completely etched. In order to accelerate the etching process, the solution was pre-heated to 50°C before carrying out the process.

(f) The board was washed under running water and dried.

(g) The positions for component leads were drilled using 1mm drill bit.

(h) The developed pattern was scrapped using razor -blade to remove the insulation. The pattern was tinned with solder to protect the tracks.

(i) The components were sorted out, with their leads cleaned with fine emery paper.

Using the circuit diagrams, components were inserted into their respective locations. Masking tape was used to keep components in place and then the board over turned for soldering. Soldering was carried out and excess component leads trimmed. The wired board was tested to ensure that it was working properly.

### 3.2.12 INSTALLATION OF PARTS

The electronic components boards were mounted on metal racks having wooden bases. The racks were secured to the drier floor by means of screws. Electrical interconnections were achieved by the use of connectors. The motor of the fan was installed in the control section to prevent its being overheated, which would have occurred if it were located in the heater section. The spindle is projected into the fan/heater section. The blades rotate in this section and blow hot air around the heaters into the drying chamber.

The temperature sensor (thermocouple) was passed through a duct in the double wall and through a small hollow pipe, which has been welded to the roof of the drying chamber. The thermocouple junction projects out of the hollow cylinder into the drying chamber. Four equally spaced rails were welded to both sides of the vertical wall of the drying chamber. The racks were hung on the rails.

Another fan was installed on the back cover of the control section to cool the electronic components and the fan motor.

# CHAPTER FOUR

## 4.1 RAW MATERIAL SUPPLY AND PREPARATION

The palm kernel seeds used in this work were obtained from a village named "Board" after Oda town in Akure South Local Government within the South West zone of Nigeria. Akure is 7° 14' North of the Equator and 5° 08' East of the Greenwich Meridian. On receipt, the kernel was cleaned by removing the dirts and pebbles in it without washing because washing would introduce increased free fatty acid (FFA) which would affect the quality of the product. Care was taken to use newly cracked kernel and not old stock that has been partially dried. There was no need of *size reduction* because it already maintains approximately small and regular shape. Size reduction is the process of breaking the kernel nuts into smaller shape or size such that the nuts assume same size throughout and it aids drying process thereby reducing drying time.

## 4.2 TEST EQUIPMENT

The test equipment is a tray drier. The details of its construction were described in chapter 3. The drier has three compartments namely (i) drying chamber (ii) fan/heater section and (iii) Electronic instrumentation or control section.

The drying chamber can take four trays, each of length 50cm, breadth 36cm and depth 3cm. The trays were stacked about 10cm above each other within the vertical drying column. The chamber has a pipe, which carries the thermocouple wires from the electronic section to the drying chamber. The thermocouple senses the dry bulb temperature of the chamber. The roof of the chamber has a small opening of 2cm in diameter at the top of the drying section. This opening serves two purposes: it is one of the outlets for water vapour to escape from the drier and for the thermometer used to sense the wet-bulb temperature of the chamber. The chamber has a door with hinges, which allow easy loading and unloading of the kernels.

The second section houses the fan and the heater. Two 2kW heaters are installed next to the drying chamber. The fan was installed with its engine in the electronic section while the blade is in the fan/heater section directly blowing air around the heater into the drying chamber. An "air guard" was also installed over the fan to avoid air dispersal and focus the air into the drying chamber.

The third section is the electronic instrumentation compartment. This compartments houses the electronic components that regulate and control the temperature of the chamber and other electrical parts of the drier. A second fan is installed in this compartment to blow cool air over the electronic board and the coil of the first fan. The coil of the first fan is not in the fan/heater section to avoid its being overheated because the fan/heater compartment and the drying chamber are very hot. This dryer was designed to operate between 27°C and 99°C making it suitable to dry many food items such as maize and beans to mention a few.

## 4.3 EXPERIMENTAL APPROACH

This work reported here investigated the drying performance of the drier. Particle to particle and surface to particle heat transfer are key elements of the drying process. Drying of solids involves bringing heat to the particles to be dried. This can be done indirectly by a flowing hot gas or directly by means of heating surfaces. This investigation is limited to convective drying with influence of conduction (i.e. particle to particle heat transfer) and radiation from surrounding walls. The velocity of the air is constant at natural convection (not turbulent flow) and proportional to the power input to the fan and the fan pressure (that is, the rate at which it blows the air within the medium). The air temperature is measured by the thermocouple. If it is lower than the preset temperature, the heaters switch ON and the air temperature rises. When the air temperature reaches the preset temperature, the heaters switch OFF. The heaters switch ON again when the temperature falls to about 1°C below the preset temperature.

## 4.4 EXPERIMENTAL PROCEDURE

### 4.4.1 PRELIMINARY EXPERIMENTS (With drier only)

After installation, the completed work was test-run at some temperatures. The temperature readings on both digital display and a reference mercury-in-glass thermometer were recorded. The reading tracked each other. The maximum difference recorded was 0.5°C.

Four preliminary experiments were carried out to determine the characteristics of the drier.

**Experiment 1:** The drier was empty and the temperature of the chamber was preset at 100°C. Thereafter readings of the temperature were taken at regular intervals of 60 seconds. The readings taken two times are shown in columns 2 and 3 of table 4.1.

**Experiment 2:** Next the chamber was heated to 100°C and allowed to cool while the door was kept open. Readings of the temperature were recorded at intervals of 30 seconds. This is shown in column 4 of the table 4.1.

**Experiment 3:** The chamber was again heated to 100°C. It was allowed to cool while the door was kept closed. Readings of the temperature were recorded at intervals of 60 seconds. (See column 5 of table 4.1).

### 4.4.2 PALM KERNEL NUTS DRYING EXPERIMENTS

Before running the experiment the temperature of the chamber as read by the thermocouple was noted. A liquid - in - glass thermometer whose bulb was covered with a wick soaked in distilled water inside a beaker was placed inside the drying chamber to measure the wet-bulb temperature.

**First experiment:**

Each of the four trays was filled with a weighed sample of the nuts. 1kg of the nuts was spread in a thin layer of about two or three nuts depth inside each tray. In all, 4kg of the nut was used in each experiment. The trays were then inserted into the drying chamber. The chamber was maintained at a constant temperature of 40°C. At intervals of 15minutes the trays were emptied and weighed to determine the moisture loss. This experiment was repeated with the drier temperature preset to 60°C, 80°C, and 100°C respectively. The result is shown in table 4.2. The relative humidity of the drying chamber was deduced from the *Relative Humidity Tables* using the corresponding values of the wet- and dry-bulb temperatures (see table 4.3).

**Second experiment:**

For accuracy, the first experiment was repeated all over again but this time around the temperature of the drying chamber was preset to 60°C, 80°C and 100°C. For each preset temperature the readings were taken at interval of 20minutes (see table 4.4). The relative humidity table as shown in table 4.5 was deduced the same way as that of the first experiment.

The moisture content of each sample was determined using equation 2.4.

Re-writing equation 2.4,

$$X'_T = \frac{\text{mass of wet nuts - mass of dry nuts}}{\text{mass of dry nuts}} \qquad (4.1)$$

Note that the original mass of kernels = 1000g

The *mass of dry sample of kernels* was found by keeping sample (i.e. 1000g) in th oven for three hours at temperature 101°C. Re-weighing after three hours, the dry mass of the sample became 919. 70g. Therefore, using equation 4.1, at 40°C when the mass of "wet" kernel was 992.25;

$X'_T$ = = 0.0786 = $7.86 \times 10^{-2}$

This procedure was followed to obtain the values in row 7 of table 4.6.

The following precautions were taken during the experiment:

(i) The drier was turned ON for about 10minutes before drying commenced in order to enable the drying chamber walls reach thermal steady state. This highly reduced heat loss to the surrounding wall of the chamber during drying process.

(ii) The wet bulb temperature sensor was placed close to the dry-bulb sensor (thermocouple junction) in order for both to sense the same temperature per time and hence give accurate readings.

(iii) The laboratory used was well ventilated such that warm moist air discharged from the drier does not affect the original inlet conditions over the period of the experiment.

(iv) Drying was done under *constant drying condition* i.e., the temperature, humidity, velocity, wet material shape and direction of flow of the air across the drying surface are constant. It is noteworthy that only the conditions in the airstream are constant.

The moisture content and other factors in the solid (i.e., palm kernel nuts) do change however under constant drying condition (McCabe et al, 1985).

## 4.5 EXPERIMENTAL RESULTS AND DISCUSSION

### 4.5.1 Results and discussion for the preliminary experiments

The graphs of the various experiments are shown in figure 4.1. It can be observed from curves $1_a$ and $1_b$ that the temperature increases linearly with time until the preset temperature is approached. However, the graph of the first experiment is not as linear as that of the second experiment. The difference in the two graphs is due to the fact that some heat was lost to the inside wall of the drier during the first experiment in order to keep the system warm for the drying process. In the second experiment the inner wall of the drier had already been warmed up. The heat lost to the inner walls was lower. For this reason, whenever the drier was to be used, it was first turned ON for 10 minutes before the drying process actually commenced.

From curves 2 and 3, at about 100°C, the cooling rate when the door was opened was three times the cooling rate when the door of the chamber was closed. In both cases the cooling rate became slower and slower as the ambient temperature was approached.

This test running experiments showed that the drier, is highly reliable. Heat loss is minimized and time taken for the temperature to pick up is rapid. It takes maximum of 7 minutes for the drier temperature to rise from ambient to 100°C. And it is very easy to reduce the chamber temperature by keeping the door open after pre-setting to the required temperature. The maximum time the drier can take to cool to 40°C from 100°C is 10 minutes. However, when it is closed it takes as long as 34 minutes.

### 4.5.2 Results and discussion for the palm kernel nuts drying experiments

The results of the first set of kernels drying experiment at different temperature and time interval of 15minutes and 20minutes are as shown in tables 4.2 and 4.3 respectively. It is noted that the mass decreased as moisture evaporated from either the surface or the bulk of the nuts. Figures 4.2 and 4.3 show the drying curves for the dried nuts.

In all the drying experiments, the maximum drying time adopted was 60minutes. The curves in figures 4.2 and 4.3 show that kernels have two stages of drying which are; the falling rate and the constant rate periods. The constant-rate period of drying when heat is supplied by convection is amenable to analytical treatment because it is essentially independent of the solid material. The falling-rate period is not as amenable to treatment as the constant–rate period because the falling rate depends largely on the internal structure of the nuts.

Immediately after contact between the wet nuts and the drying medium, the solid temperature increases until it reaches a steady state. At steady state, the temperature of the surface of wet nuts is the wet-bulb temperature of the drying medium. At this point, the drying rate remains constant. It ends when a solid reaches the critical moisture content, $X'_C$. Beyond this point, the surface temperature rises, and the drying rate falls off rapidly. The falling–rate period sets in and it takes a far longer time than the constant rate period even though the moisture removed may be less.

The drying rate approaches zero at some equilibrium moisture content, $X'_E$, which is the lowest moisture content obtainable with the solid under the drying conditions used. However, from figure 4.4, observation shows that the critical moisture content and the equilibrium moisture content exhibit dependency on temperature as well as time.

For the drying chamber at 40°C, there was no falling rate period of drying observed but prolonged and undefined constant rate period. Hence, the drying process of kernel nuts was slow and would possibly take more than 120 minutes. Similarly, at 60°C and 80°C, the drying period was longer than 60minutes due to the steepness that can still be observed as the drying curves terminate at 60minutes. However, at 100°C, the drying period is within 60minutes. At this point the drying rate at the falling rate period is approximately constant. Figure 4.3 (from the result of the second experiment in table 4.4) also supports the above observations.

It is noteworthy that the drier will dry more effectively if after loading, the drying chamber door is permanently closed for 40 to 60minutes say, without unloading the nuts at intervals to weigh them. Under this condition it is found that the drier was capable of drying the nuts within 60minutes at 80°C. It is also found that at temperatures up to 100°C no discolouration of the kernel nuts or the extracted oil was noticed.

The computed relative humidity values are shown in table 4.3. From this table, the graph of relative humidity versus wet - bulb temperature (or dry bulb temperatures) can be plotted, as shown in figure 4.5. The observed curve reveals that relative humidity within the drier reduces with increase in temperature. The computed relative humidity for the second experiment (table 4.4) is shown in table 4.5. The curve behaves in a way similar to that of figure 4.5.

According to McCabe et al (1985), since the air entering a drier is seldom completely dry but contains some moisture and has a definite relative humidity, the portion of the water in the wet solid which cannot be removed because of the humidity of the inlet air is called the *equilibrium moisture*. The free moisture is the difference between the total-moisture content of the solid and the equilibrium moisture content. Thus, if $X_T$ is the moisture content and if $X'_E$ is the equilibrium moisture content, the free moisture X is

$$X = X_T - X'_E \tag{4.3}$$

This can therefore be calculated as

$$X = \frac{\text{(original mass of kernels – mass of the dry sample)}}{\text{mass of the dry sample}} - X'_E \tag{4.4}$$

Table 4.6 was obtained from table 4.2. This table shows that the drier can dry the kernel nuts leaving about 5% of the original moisture (retained in the nuts) within 60minutes when it is preset to 100°C (approximately). This result agrees with the assertion in the Encyclopedia of science and technology (1997) that the final moisture content of dry solid is usually less than 10%.

Figure 4.6, which is the variation of the moisture content against relative humidity reveals that the moisture content is directly proportional to the relative humidity. That is when the humidity is high, the moisture content is high and vice versa. The curves of a wet solid brought into contact with air of lower relative humidity also behave this way. The solid loses moisture and comes to equilibrium with the air. When the air is more humid than the solid, the solid absorbs moisture from the air until equilibrium is attained. The movement of moisture between the solid and air of different relative humidity is independent of temperature. It is therefore advisable that palm kernel nuts' oil should be extracted immediately after drying in order to avoid re-absorption of moisture the surrounding air.

**TABLE 4.1: Variation of temperature with time for the preliminary experiment**

| Time (minutes) | Experiment 1a Temp.($^{o}$C) | Experiment 1b Temp.($^{o}$C) | Experiments 2 Temp.($^{o}$C) | Experiment 3 Temp.($^{o}$C) |
|---|---|---|---|---|
| 0.0 | 32.0 | 34.0 | 99.0 | 99.0/100.0 |
| 0.5 | | | 85.0 | |
| 1.0 | 41.0 | 45.0 | 77.0 | 95.0 |
| 1.5 | | | 71.0 | |
| 2.0 | 50.0 | 59.0 | 66.0 | 91.0 |
| 2.5 | | | 62.0 | |
| 3.0 | 60.0 | 71.0 | 56.0 | 86.0 |
| 3.5 | | | 53.0 | |
| 4.0 | 70.0 | 82.0 | 51.0 | 79.0 |
| 4.5 | | | 49.0 | |
| 5.0 | 80.0 | 92.0 | 47.0 | 75.0 |
| 5.5 | | | 46.0 | |
| 6.0 | 90.0 | 98.0/99.0 | 45.0 | 71.0 |
| 6.5 | | | 44.0 | |
| 7.0 | 98.0 | 99.0/100.0 | 43.0 | 68.0 |
| 7.5 | | | 42.0 | |
| 8.0 | 99.0 | 99.0/100.0 | 41.0 | 66.0 |
| 8.5 | | | 41.0 | |
| 9.0 | | | 40.0 | 64.0 |
| 9.5 | | | 39.0 | |
| 10.0 | | | 39.0 | 62.0 |
| 10.5 | | | | |
| 11.0 | | | | 60.0 |
| 11.5 | | | | |
| 12.0 | | | | 59.0 |
| 12.5 | | | | |
| 13.0 | | | | 58.0 |
| 13.5 | | | | |
| 14.0 | | | | 56.0 |
| 14.5 | | | | |
| 15.0 | | | | 55.0 |
| 15.5 | | | | |
| 16.0 | | | | 54.0 |
| 16.5 | | | | |
| 17.0 | | | | 53.0 |
| 17.5 | | | | |
| 18.0 | | | | 52.0 |

| | | | | |
|---|---|---|---|---|
| 18.5 | | | | |
| 19.0 | | | | 51.0 |
| 19.5 | | | | |
| 20.0 | | | | 50.0 |
| 20.5 | | | | |
| 21.0 | | | | 49.0 |
| 21.5 | | | | |
| 22.0 | | | | 48.0 |
| 22.5 | | | | |
| 23.0 | | | | 48.0 |
| 23.5 | | | | |
| 24.0 | | | | 47.0 |
| 24.5 | | | | |
| 25.0 | | | | 47.0 |
| 25.5 | | | | |
| 26.0 | | | | 46.0 |
| 26.5 | | | | |
| 27.0 | | | | 46.0 |
| 27.5 | | | | |
| 28.0 | | | | 46.0 |
| 28.5 | | | | |
| 29.0 | | | | 45.0 |
| 29.5 | | | | |
| 30.0 | | | | 45.0 |
| 30.5 | | | | |
| 31.0 | | | | 45.0 |
| 31.5 | | | | |
| 32.0 | | | | 44.0 |
| 32.5 | | | | |
| 33.0 | | | | 44.0 |
| 33.5 | | | | |
| 34.0 | | | | 43.0 |

**TABLE 4.2: Results of the first experiment**

Weight of wet seeds originally loaded inside each tray = 1kg

| Temp. of Chamber °C / Time taken (minutes) | 40 | | 60 | | 80 | | 100 | |
|---|---|---|---|---|---|---|---|---|
| | Mass of nuts (g) | Wet-bulb Temp. °C | Mass (g) | Wet-Bulb Temp °C | Mass (g) | Wet-Bulb Temp. °C | Mass (g) | Wet-Bulb Temp. °C |
| 15 | 992.25 | 30 | 984.20 | 37 | 967.00 | 44 | 944.80 | 50 |
| 30 | 990.00 | 30 | 966.50 | 37 | 951.50 | 44 | 929.00 | 50 |
| 45 | 988.90 | 30 | 955.30 | 37 | 939.00 | 44 | 925.80 | 50 |
| 60 | 979.00 | 30 | 947.50 | 37 | 934.00 | 44 | 923.50 | 50 |

**TABLE 4.3: Showing the Relative Humidity from table 4.2**

| Wet-Bulb temp. °C / Dry-Bulb Temp. °C | 30 | 37 | 44 | 50 |
|---|---|---|---|---|
| 40 | 49 | - | - | - |
| 60 | - | 24 | - | - |
| 80 | - | - | 14 | - |
| 100 | - | - | - | 9 |

**TABLE 4.4: The Result of the second experiment**

| Temp. of Chamber °C / Time (minutes) | 60 | | 80 | | 100 | |
|---|---|---|---|---|---|---|
| | Mass of nuts (g) | Wet-Bulb Temp. °C | Mass (g) | Wet-Bulb Temp. °C | Mass (g) | Wet-Bulb Temp. °C |
| 20 | 979.00 | 40 | 970.80 | 45 | 960.00 | 49 |
| 40 | 975.70 | 40 | 946.70 | 45 | 933.30 | 49 |
| 60 | 969.50 | 40 | 933.50 | 45 | 928.10 | 49 |

**TABLE 4.5: Relative Humidity from table 4.4**

| Wet-Bulb Temp. °C / Dry-Bulb Temp. °C | 40 | 45 | 49 |
|---|---|---|---|
| 60 | 30 | - | - |
| 80 | - | 15 | - |
| 100 | - | - | 8 |

**TABLE 4.6: The overall result from tables 4.2 and 4.3**

| Dry-Bulb Temp. Tb (°C) | 40 | | | | | 60 | | | | | 80 | | | | | 100 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wet-Bulb Temp. Tw (°C) | 30 | | | | | 37 | | | | | 44 | | | | | 50 | | | | |
| (Tb-Tw) °C | 49 | | | | | 24 | | | | | 14 | | | | | 9 | | | | |
| Relative Humidity % | 10 | | | | | 23 | | | | | 36 | | | | | 50 | | | | |
| Time (Mins) | 0 | 15 | 30 | 45 | 60 | 0 | 15 | 30 | 45 | 60 | 0 | 15 | 30 | 45 | 60 | 0 | 15 | 30 | 45 | 60 |
| Wet-Kernel Mass (g) $\times 10^{3}$ | 10.00 | 9.92 | 9.90 | 9.89 | 9.79 | 10.00 | 9.84 | 9.67 | 9.55 | 9.48 | 10.00 | 9.67 | 9.55 | 9.39 | 9.34 | 10.00 | 9.45 | 9.29 | 9.26 | 9.23 |
| Moisture content $X^{1}$ ($\times 10^{-2}$) | 8.73 | 7.86 | 7.64 | 7.52 | 6.45 | 8.73 | 7.01 | 5.09 | 3.87 | 3.02 | 8.73 | 5.14 | 3.46 | 2.10 | 1.56 | 8.73 | 2.73 | 1.01 | 0.67 | 0.41 |
| Percentage Moisture (%) | 100 | 90 | 87 | 86 | 74 | 100 | 80 | 59 | 44 | 35 | 100 | 59 | 44 | 25 | 18 | 100 | 32 | 12 | 8 | 5 |

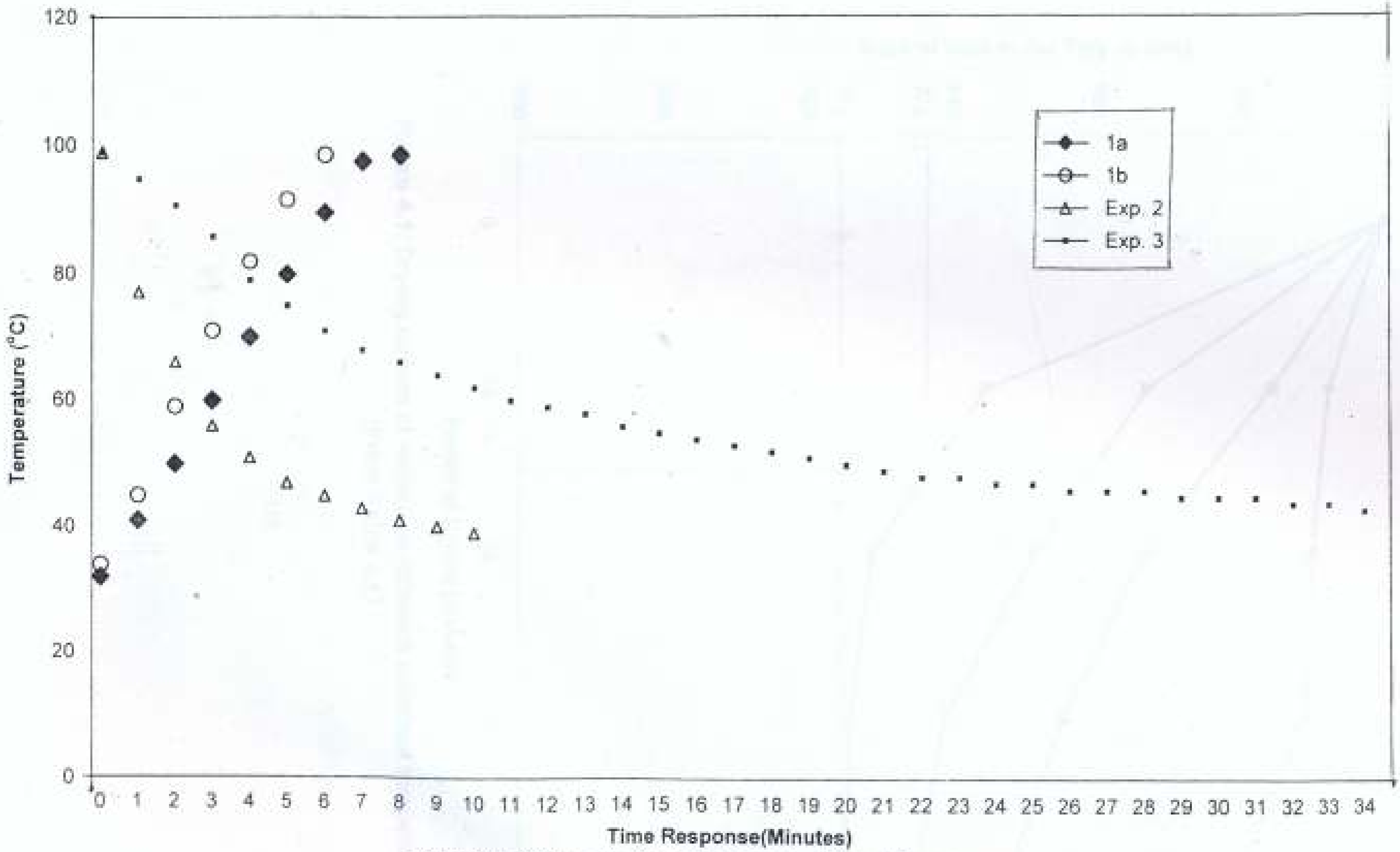


Figure 4.1: Graph of Temperature - Time Response

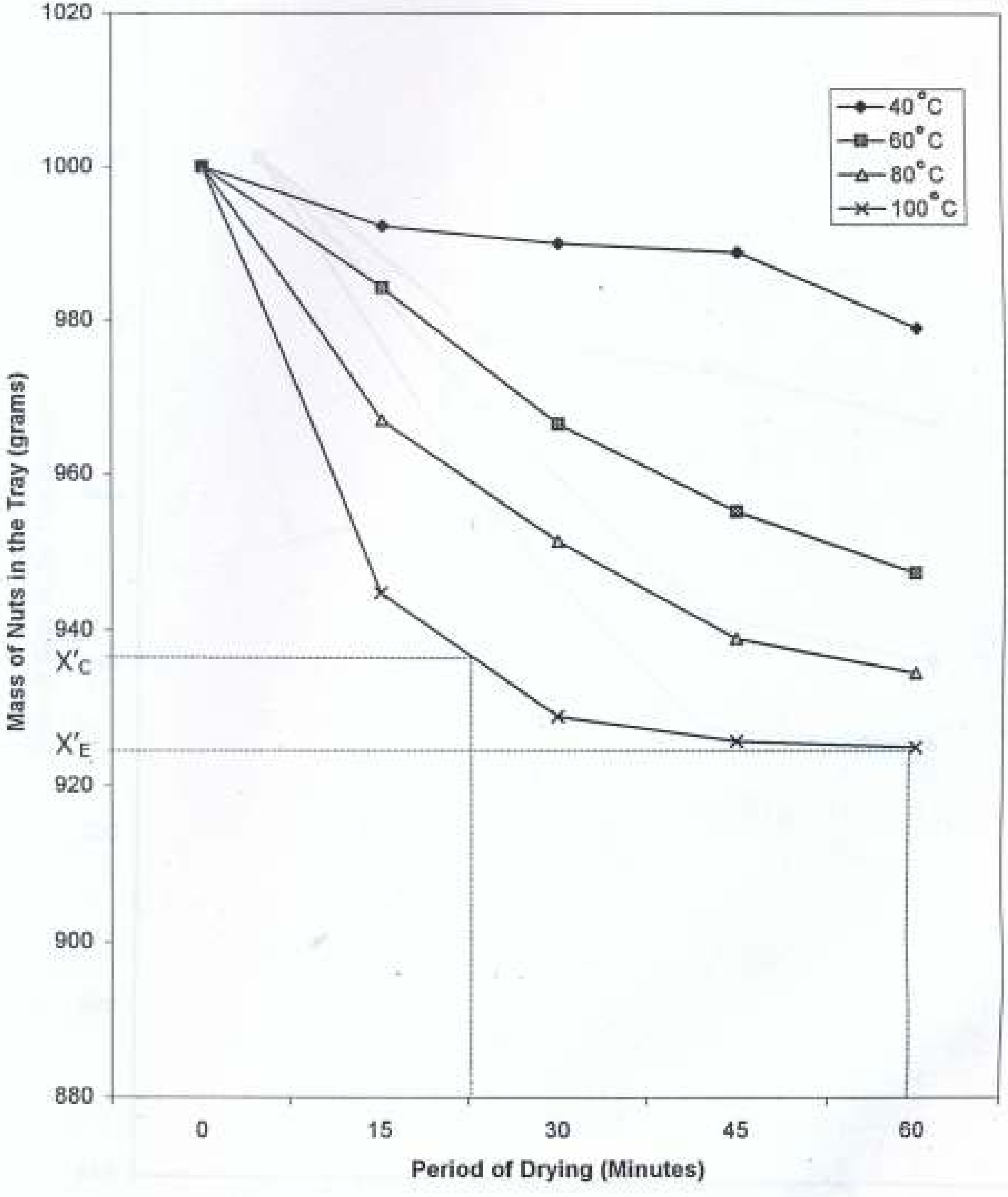



**Figure 4.1: Drying curves of kernels at different constant temperature (From Table 4.1)**

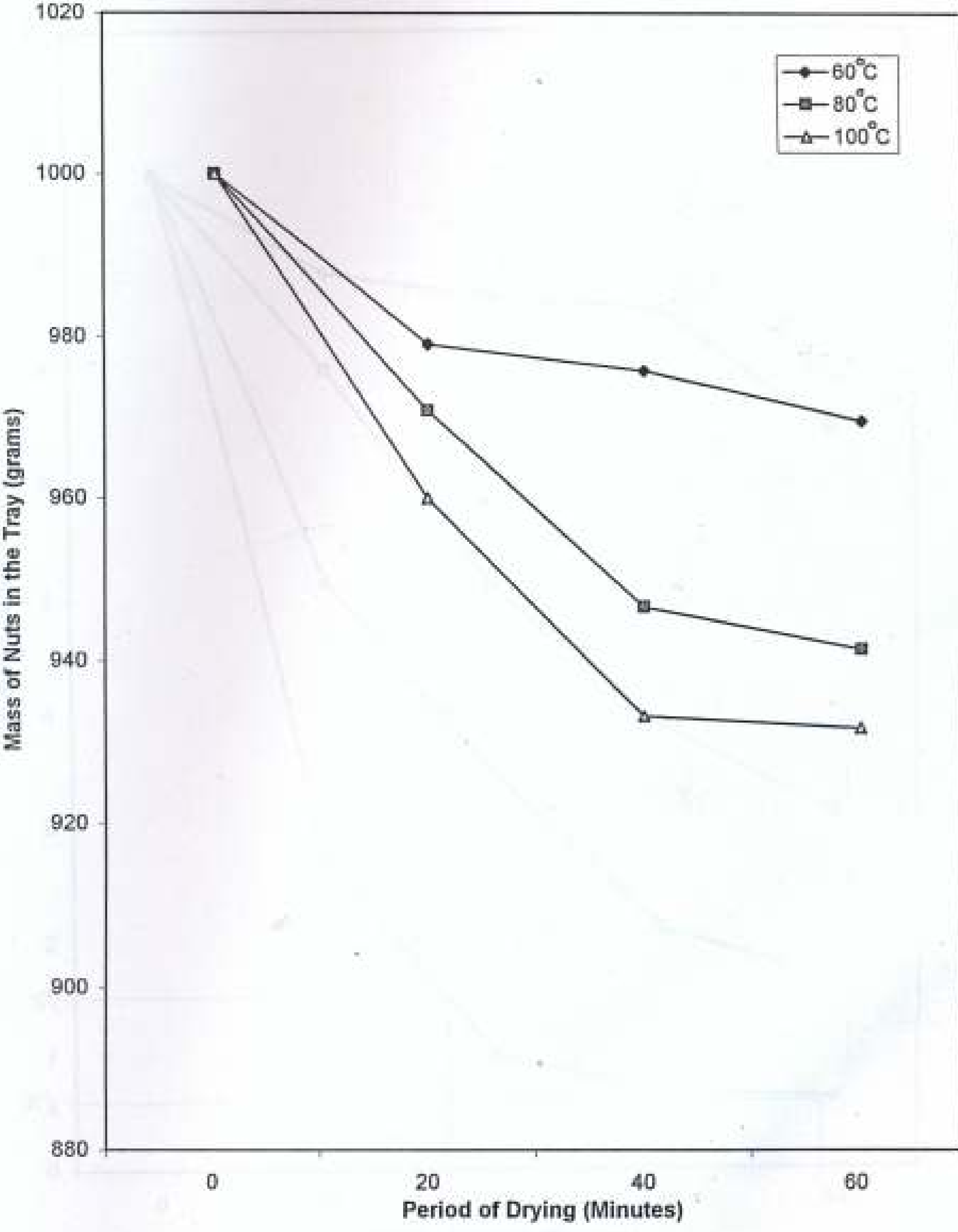



**Figure 4.2: A group of kernel drying curves at constant temperatures (From Table 4.3)**

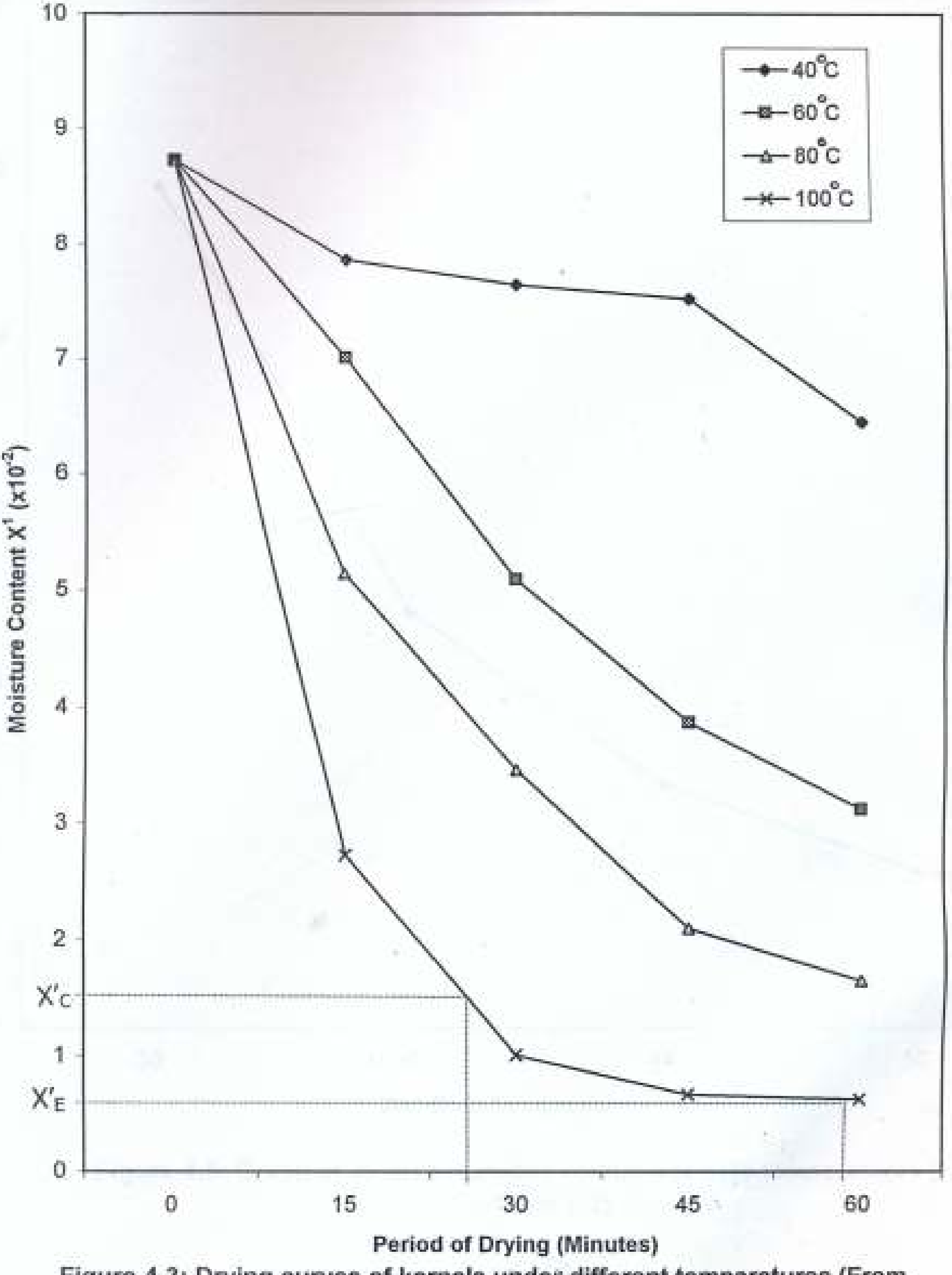



**Figure 4.3: Drying curves of kernels under different temperatures (From Table 4.5)**

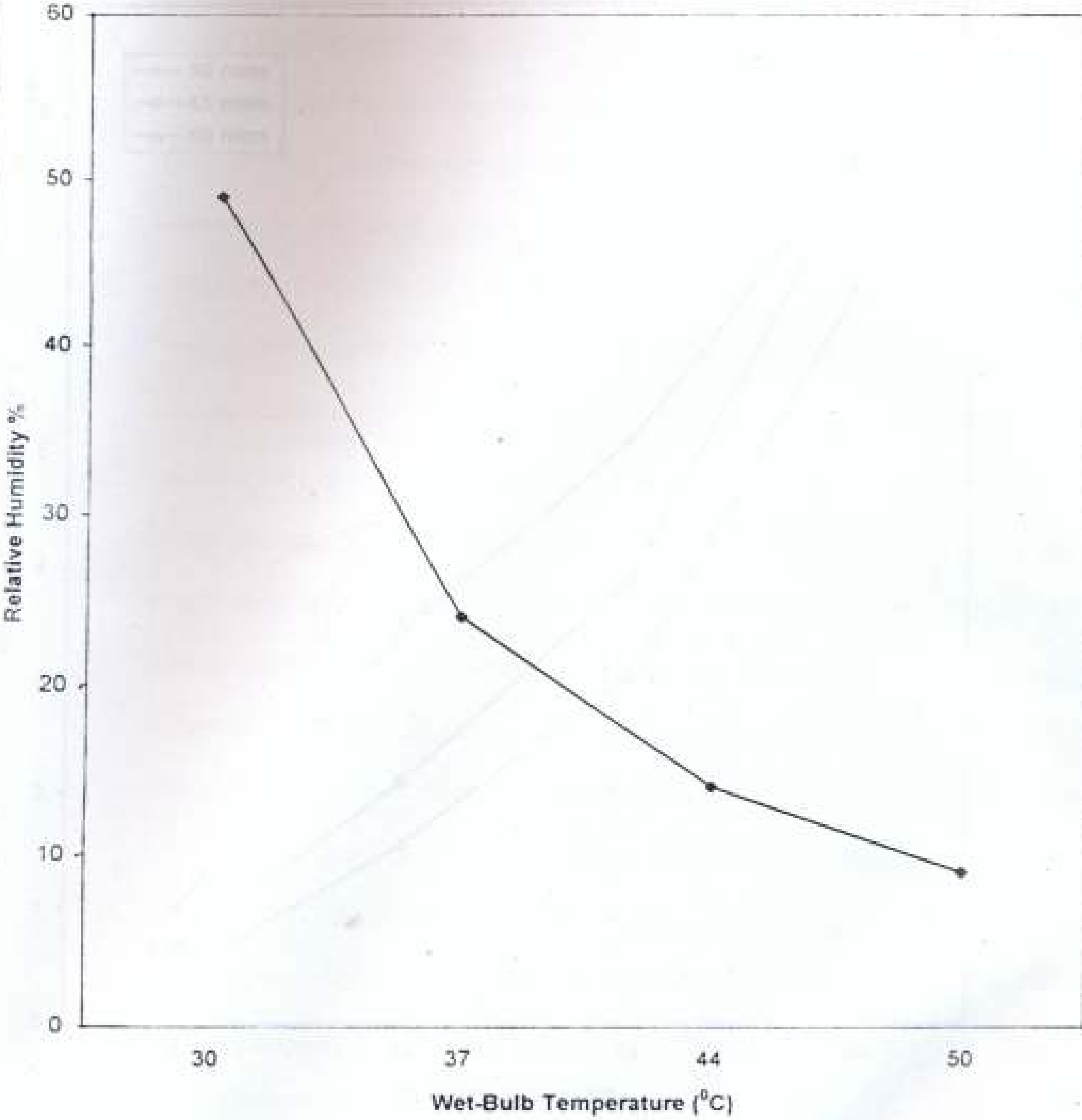



Figure 4.5: Graph of relative humidity versus wet-bulb temperatures (From Table 4.2)

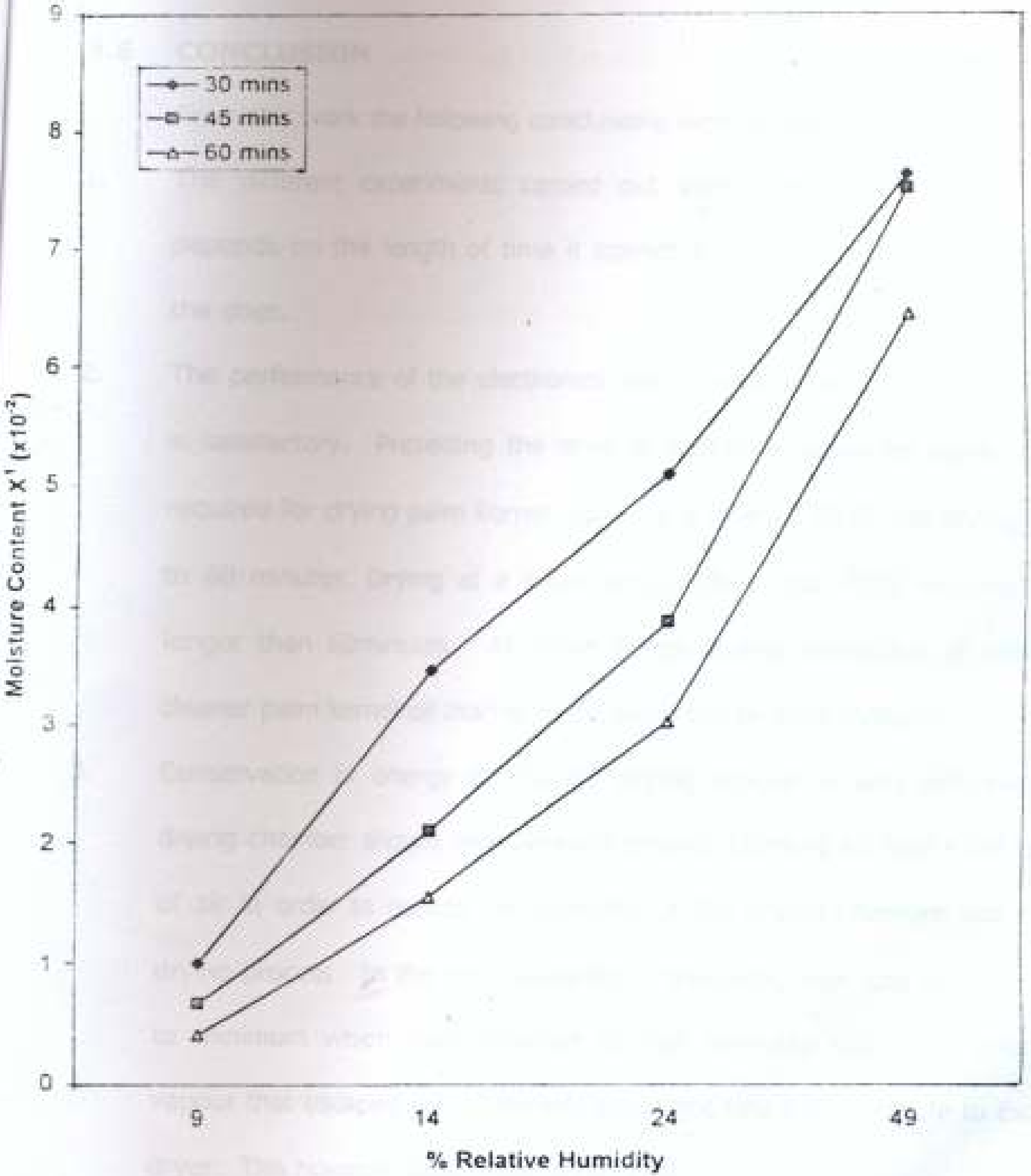



Figure 4.6: Graphical analysis of the variation of moisture content with relative humidity at constant time (From Table 4.5)

## 4.6 CONCLUSION

From this work the following conclusions were drawn.

1. The different experiments carried out show that the drying rate of any product depends on the length of time it spends in the drier and the preset temperature of the drier.
2. The performance of the electronics instrumentation and control systems of the drier is satisfactory. Presetting the drier at 100°C, a maximum period of 50 minutes is required for drying palm kernel nuts. For a drier at 80°C, the drying period increases to 60 minutes. Drying at a lower temperature than 60°C requires a drying period longer than 60minutes. At these temperatures, extraction of optically purer and cleaner palm kernel oil than hitherto extracted by local manufacturers is possible.
3. Conservation of energy during the drying process is well achieved. However, the drying chamber should provide wide enough opening for both inlet of air and outlet of air in order to reduce the humidity of the drying chamber and hence speed up drying process. In the drier designed in this work, heat loss was avoided or reduced to minimum which later resulted to high humidity inside the chamber since the vapour that escaped out of kernels could not find enough route to escape out of the dryer. This however lowers the drying rate.
4. The recommended ventilation type to adopt for many products (especially those whose properties are damageable with heat) is natural convection at 10-30°C above ambient temperature. The benefit of this is the preservation of the physical, biological as well as the chemical properties of the material been dried since the temperatures deviate only a little from the natural means of drying which is mainly by sun-dry.

5. It is possible to further reduce the drying period if a wet bulb thermometer is not in *the drying chamber and the relative humidity of the product* is determined using an independent source. It is also possible to increase the number of heaters to make the drying faster.

6. The capacity of the tray drier can be increased by increasing the size of the drier. The capacity extension most favourable for tray driers is in horizontal direction. The equipment can be adapted to the required size by some design changes for capacity and a more efficient fan for hot air circulation. The control circuit or the electronic instrumentation remains the same.

7. By merely changing the preset temperature the equipment can be adapted to dry many other agricultural products such as coffee, beans, cocoa, and maize to mention a few even at temperature higher than 100°C.

8. Apart from its high efficiency and dependability, the cost of production of tray driers is cheaper compare to many other forms of drier as stated in chapter two of this write-up. This makes it easily affordable (see appendix B).

## 4.7 RECOMMENDATIONS FOR FURTHER WORK

For greater efficiency and usage,

i. Trays should be made of stainless steel to allow wider usage of drier, for example in drying product which may have properties or constituent that can react with either paint or galvanized and ungalvanized metals to avoid poor end products.

ii. For a general-purpose tray drier, temperature range and size capacity should be wider and increased respectively.

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## APPENDIX A

## VALUE OF COMPONENTS

The following are the values of the different components used in the circuit employed.

a. **Resistors**

| | | |
|---|---|---|
| $R_1$ = 1kΩ | $R_{12}$ = 12kΩ | $R_{23}$ = 6.8kΩ |
| $R_2$ = 100kΩ | $R_{13}$ = 120kΩ | $R_{24}$ = 510Ω |
| $R_3$ = 2.2kΩ | $R_{14}$ = 680kΩ | $R_{25}$ = 10kΩ |
| $R_4$ = 560Ω | $R_{15}$ = 47μΩ | $R_{26}$ = 490Ω ≈ 470Ω |
| $R_5$ = 10Ω | $R_{16}$ = 51kΩ | $R_{27}$ = 390Ω |
| $R_6$ = 820kΩ | $R_{17}$ = 5.6kΩ | $R_{28}$ = 2.7kΩ |
| $R_7$ = 47kΩ | $R_{18}$ = 180Ω | $R_{29}$ = 150Ω |
| $R_8$ = 220Ω | $R_{19}$ = 8.2kΩ | $R_{30}$ = 1.2Ω |
| $R_9$ = 470kΩ | $R_{20}$ = 330Ω | $R_{31}$ = 1.5Ω |
| $R_{10}$ = 33kΩ | $R_{21}$ = 3.9kΩ | $R_{32}$ = 2.1kΩ |
| $R_{11}$ = 68kΩ | $R_{22}$ = 1.2kΩ | $R_{33}$ = 47Ω |

b. Capacitors

| | | |
|---|---|---|
| $C_1$ = 10μF | $C_6$ = 1.0nF | $C_{11}$ = 4.700pF |
| $C_2$ = 22μF | $C_7$ = 1.0μF | $C_{12}$ = 4.7μF |
| $C_3$ = 150pF | $C_8$ = 0.0669μF | $C_{13}$ = 6.800μF |
| $C_4$ = 10.5μF | $C_9$ = 0.1μF | $C_{14}$ = 4.7μF |
| $C_5$ = 0.01μF | $C_{10}$ = 100μF | |

c. Zener Diodes

| | | |
|---|---|---|
| $Z_1$ = 6.8V | $Z_4$ = 5.6V | $Z_7$ = 8.2V |
| $Z_2$ = 5.1V | $Z_5$ = 13V | $Z_8$ = 18V |
| $Z_3$ = 10V | $Z_6$ = 3.3V | $Z_9$ = 6.2V |

d. Pots

| | | |
|---|---|---|
| $RV_1$ = 100kΩ | $RV_3$ = 6.8kΩ | $RV_5$ = 2.2kΩ |
| $RV_2$ = 22kΩ | $RV_4$ = 2kΩ | $RV_6$ = 4.7kΩ |

## APPENDIX B

## COST ESTIMATE

This is the systematic break down of cost data. Cost can either be a detailed or a concise type. The purpose of preparing a cost analysis of a project is an attempt to reveal the cost relationship between the various sections of a project and also to allow for some comparability with others (Allan, 1988). The concise cost analysis of materials and components use in this project is as follows:

| | | | | N : k |
|---|---|---|---|---|
| 1. | Resistors - | (a) | Ordinary x 60 | 600.00 |
| | | (b) | Pots x 7 | 140.00 |
| 2. | Capacitor - | (a) | Small x12 | 300.00 |
| | | (b) | Big x 9 | 900.00 |
| 3. | Diodes- | (a) | Rectifiers x 4 | 40.00 |
| | | (b) | Zener x 11 | 275.00 |
| 4. | IC | (a) | Op-amp1/4 Lm324 x 5 or 2 IC | 120.00 |
| | | (b) | ADC 0804 x1 | 700.00 |
| | | (c) | 555 timer x 2 | 100.00 |
| | | (d) | 8 input NAND gate | 180.00 |
| | | (e) | Ex- OR x 2 | 500.00 |
| | | (f) | Inverters x 2 | 400.00 |
| | | (g) | 741 x2 | 90.00 |
| 5. | Transistor - | (1) | Driver x 5 | 150.00 |
| | | (2) | Power transistors x 6 | 540.00 |
| 6. | Photodiode x 2 | | | 20.00 |
| 7. | Photo resistor (ORP12)X 1 | | | 200.00 |
| 8. | Diac x 1 | | | 30.00 |
| 9. | Triac x 1 | | | 100.00 |
| 10. | Thrysistor x 1 | | | 50.00 |
| 11. | Opto - isolator x1 | | | 50.00 |
| 12. | Transformers x 2 | | | 550.00 |
| 13. | Relays x 3 | | | 450.00 |
| 14. | Heater x 2 | | | 1200.00 |
| 15. | Seven-segment Display x 1 | | | 150.00 |
| 16. | PCB x 7 | | | 1050.00 |
| 17. | Wires (1 metre) x 1 | | | 300.00 |
| 18. | Fan x 2 | | | 1500.00 |
| 19. | Connector x 4 | | | 200.00 |
| 20. | Thermocouple wires (Copper & constantan) | | | 150.00 |

| | | |
|---|---|---|
| 21. | Fuse x 2 | 20.00 |
| 22. | Fuse holder x 2 | 40.00 |
| 23. | Plug x 1 | 70.00 |
| 24. | Switches x 2 | 100.00 |
| 25. | Heat sinks | 100.00 |
| 26. | IC Socket (555 timer ₦15, LM324 ₦20 & 0804 ₦30) | 160.00 |
| 27. | Counter (2 binary, 2 decade) x 4 | 1000.00 |
| 28. | Latches x 4 | 720.00 |
| 29. | LED x 1 | 10.00 |
| 30. | Insulator (Saw-dust) | Free |
| 31. | Metal sheet x 5 | 1,000.00 |
| 32 | Body construction | 2,000.00 |
| 33. | Body smoothing and painting | 2,000.00 |
| 34. | Transportation | 5,000.00 |
| | **TOTAL** | **32,265.00** |

The correct analysis of the cost of this project provides us with the best guide f

determining optimum economy efficiency in the future.