ELECTRICAL METHODS OF MEASURING MOISTURE OF PAPER

A DISSERTATION

Submitted in partial fulfilment of the
requirements for the award of the Degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
(Measurement and Instrumentation)

By

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MARCH, 1984

CERTIFICATE

Certified that the dissertation entitled, "ELECTRICAL METHODS OF MEASURING MOISTURE OF PAPER", which is being submitted by Shri R.K. AGARWAL, in partial fulfilment for the award of the Degree of MASTER OF ENGINEERING in ELECTRICAL ENGINEERING (MEASURMENT AND INSTRUMENTATION) of the University of Roorkee, Roorkee is a record of student's own work carried out by him under our supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other degree or diploma.

This is to further certify that he has worked for about 4 $\frac{1}{2}$ months from November 1983 to March 1984 for preparing this dissertation at this University.

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ACKNOWLEDGEMENT

The author is highly indebted to Dr. R. N. Mishra, Reader in Electrical Engineering Department and Sri S. Mukherjee, Lecturer in Electrical Engineering Department, University of Roorkee, Roorkee for their unfailing help and able guidance.

The author is thankful to Dr. M. P. Dave, Professor and Head, Electrical Engineering Department for providing the necessary facilities.

He would like to take this opportunity to pay his sincere thanks to all those who in some way or the other encouraged and inspired him during the preparation of this dissertation work.

ABSTRACT

Moisture content of paper is important both for the manufacturers and users. Proper moisture content in paper is possible only with accurate instruments used both in production line and laboratory. The present dissertation work consists of the development of electrical type paper moisture meters both for on-line and laboratory applications and their performance analysis was undertaken. Developed instruments are based on resistance change of paper with moisture for on-line use and capacitance change of a parallel plate capacitor with change in the dielectric constant of paper with moisture for laboratory use. Encouraging results were obtained from their analysis. Based on this work, prototypes can be developed. Scope of future research in this area becomes clear and the developed instruments can also be improved to obtain better results.

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CHAPTER - 1

INTRODUCTION

From the dawn of civilization, betula (betulaceous, a family of trees having special thin bark) has been the medium for writing informations to preserve the valuable manuscripts and to transfer the messages from one place to the other. For the last many centuries paper production from wood pulp has been into existence, but one of the most difficult and persistent problems is the production of a uniform paper sheet containing 'right amount of moisture'. According to its degree of moistness, paper can display a number of peculiar physical and mechanical characteristics. If these characteristics are not controlled, undesirable economical and technical consequences can result for both manufacturers and users of paper, particularly in the highly specialized printing industry. Improper sheet moisture manifests itself on the paper machine by:

(a) Variation in finish, bulk, and density.

(b) Blackening of the paper sheet.

(c) Cockles, puckers, and grainy surfaces.

(d) Excessive breaks on the machine resulting in loss of production time.

(e) Non uniform strength properties such as burst, tear, and fold.

Printers and users also encounter difficulties due to improper sheet moisture, because of the followings:

(a) Development of curl.

(b) Poor strength properties.

(c) Large sheet dimensional change due to shrink or stretch.

(d) Poor coating and printing surfaces.

The first essential step toward control and moisture content is its measurment. However, paper web moisture is one of the most difficult process variables to be measured. This is, because practically all means of continuous moisture measurment are indirect, and are affected to a greater or lesser extent by other process variables such as temperature, composition, pH etc. None of the possible methods of measurment is universally applicable to all types of papers made from different raw materials because none is free of the extraneous effects of other variables. Therefore, the method to use is usually the one that provides the most reproducible results with the materials of interest and at the same time is least affected by other variables known to exist in the process.

The well accepted conventional method of moisture determination in paper is by weighing and is used for calibrating other (indirect) type of instruments. The sample is weighed when 'wet' and subsequently when dry by driving off the moisture by dessication. Percent moisture content (M) is then calculated from

$$M = \frac{W_{wet} - W_{dry}}{W_{wet}} \times 100\ \% \qquad (1.1)$$

This method is very slow and crude. It can not be used for online measurment of paper moisture, which is a must for controlling the moisture within a safe permissable limit.

The development of instrument technology for the measurment of the moisture content of the materials has undergone a radical change in recent years and there has been a revolution of methods and results these days in estimating moisture content of samples by the application of modern physical techniques such as infrared spectroscopy, nuclear magnetic resonance spectroscopy (NMR), neutron-scattering etc. These techniques have been developed based on some unique physical properties of water or that of hydrogen (H^+ proton) which forms its main constituent. Both online and laboratory measurments of paper moisture have been tried with some of these techniques and results obtained are quite encouraging. Since both manufacturers and consumers are not very quality concious in India, practically no paper moisture measuring instrument could be developed and marketed indigeneously so far. Some special types of papers are manufactured with proper moisture content using imported instruments. Through this dissertation work, a preliminary step toward indigenisation of technical know-how in this area has been taken.

1.1 ORGANISATION OF THE DISSERTATION WORK

The work embodied in this dissertation is divided in six chapters. After giving a brief introduction in the first chapter,

Chapter II deals with the cellulose-water relationship. In this chapter various properties of water and cellulose are described, which are important for moisture measuring system. The influence of interaction between solids (paper) and water on moisture measuring methods is also considered.

A critical uptodate review of moisture measuring methods (particularly applicable for paper) is made in Chapter III. Every attempt is made to cover up all the important moisture measuring methods for paper in this review chapter, space being the only limitation.

Chapter IV deals with the resistive type moisture meters developed for paper moisture measurment. The conventional resistive type moisture meter is not very much useful in the field because of its non-linear response characteristic. It is optimized and then linearized. Resistive transducer is used as sensor. It is an on-line method of paper moisture measurment, and the instrument can be directly used in the paper industry for the continuous moisture measurment of the paper. It is a simple, compact, portable and economic instrument.

Chapter V deals with the developments of capactive moisture meters. Parallel plate capactive transducer has been used as a sensor. A linearized capacitive moisture meter is developed for paper moisture measurment. This instrument is portable and can be used for paper moisture measurment intermittently or continuously. This is particularly useful as a laboratory type instrument.

Finally, in the chapter of conclusions, a complete summary of the work done by the author is given, which mainly consists the relative performance of the developed instruments. Scope of further work in this area is also included in this chapter.

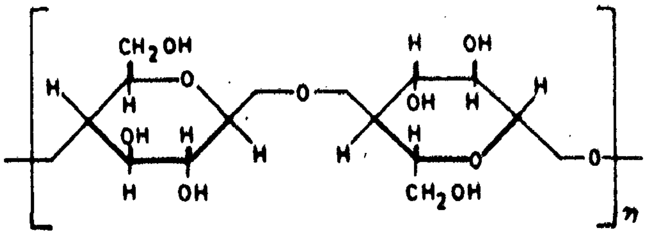
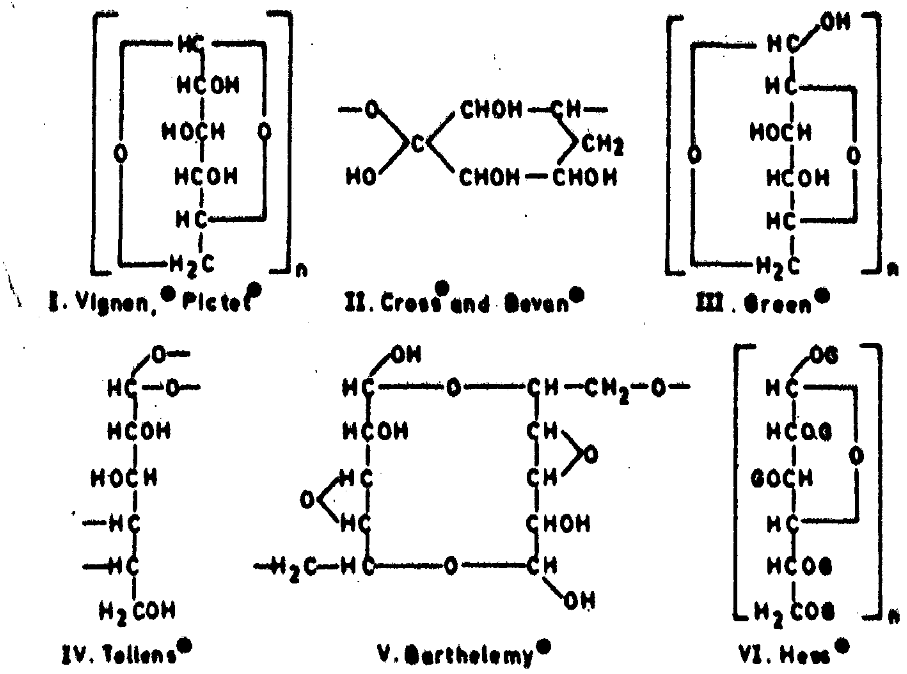


FIG. 2.1_ CHEMICAL STRUCTURE OF CELLULOSE.



I. Vignon, Pictet II. Cross and Bevan III. Green IV. Tollens V. Barthelemy VI. Hess

FIG. 2.2_ SOME EARLY FORMULAS PROPOSED FOR CELLULOSE.

CHAPTER- 2

PAPER (CELLULOSE) - WATER RELATIONSHIP AND THEIR PROPERTIES

The cellulose-water relationship is the most important relationship in the paper industry. The amount of water in the individual fibers affects the strength flexibility and sheet forming characteristics of the fibers. The moisture content of the paper affects the weight, strength, dimensional stability, and electrical properties of paper and is a highly important factor in the calendering, printing, coating and impregnation of paper.

The moisture content of paper stored under normal conditions is usually between 4 to 10 % at a relative humidity of 40 to 60 % . The quality of paper is determined by the cellulose-water relationship, therefore, the various aspects of the cellulose-water relationship are described here in brief.

2.1 CELLULOSE(2)

It is not easy to give a chemical definition of the word "Cellulose" which fits all the uses of the word. The 'ideal' cellulose is a linear polymer composed of individual anhydroglucose units (also called glucopyranose units) linked at the 1 and 4 positions through glucosidic bonds with the beta configuration. Thus, it has the repeated unit, with n having values ranging from about 50 to 5000 or more, as shown in Fig.2.1.Some

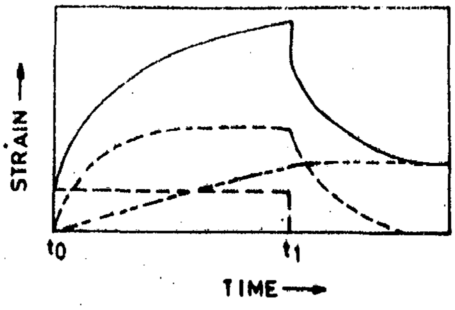


FIG.2.3_CREEP FUNCTION AND ITS COMPONENTS.
STRESS IMPOSED AT t_0: RELEASED AT t_1.

----IMMEDIATE ELASTIC DEFLECTION
-----PRIMARY CREEP
-------PERMANENT SET
———TOTAL DEFORMATION

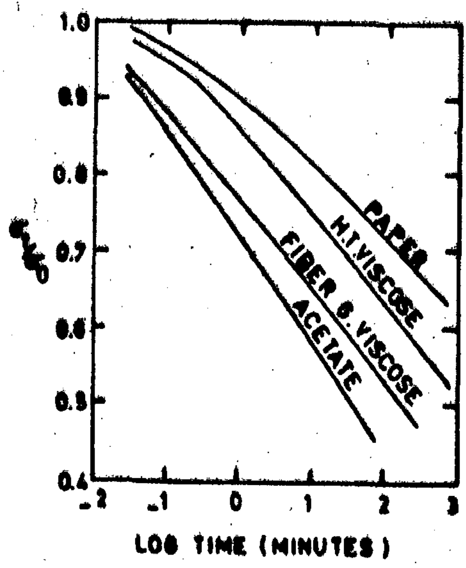


FIG.2.4_STRESS RELAXATION OF PAPER ETC. AT
65% R.H. AND 70 °F.

of the early formulas proposed for cellulose are also shown in Fig. 2.2.

2.2 PROPERTIES OF CELLULOSE(3,4)

2.2.1 PROPERTIES IN STATIC STRESS (CREEP)

The mechanical behaviour of cellulose under static stress is important because the resulting strain and breaking stress are time dependent. The continually increasing deformation, commonly known as creep, frequently results in undesirable dimensional changes or actual rupture of the structural element. On the other hand, a moderate amount of creep may be beneficial by relieving regions of highly localized stress, thus equalizing the load distribution.

Creep in tension may be simply observed by measuring elongation of the material at various times after a constant load has been applied. If the deforming stress is applied for a sufficiently long time, rupture occurs even when the stress is very low, as shown in Fig. 2.3.

2.2.2 PROPERTIES IN STATIC STRAIN (STRESS RELAXATION)

When high polymer material (e.g. paper) is rapidly deformed and held at constant deformation, the internal stress relaxes very rapidly at first and then more slowly as time goes on. This phenomenon is termed as "stress relaxation".

Stress relaxation is expressed by Maxwell's formula:

$$\sigma_t = \sigma_o \, e^{-t/\tau} \qquad (2.1)$$

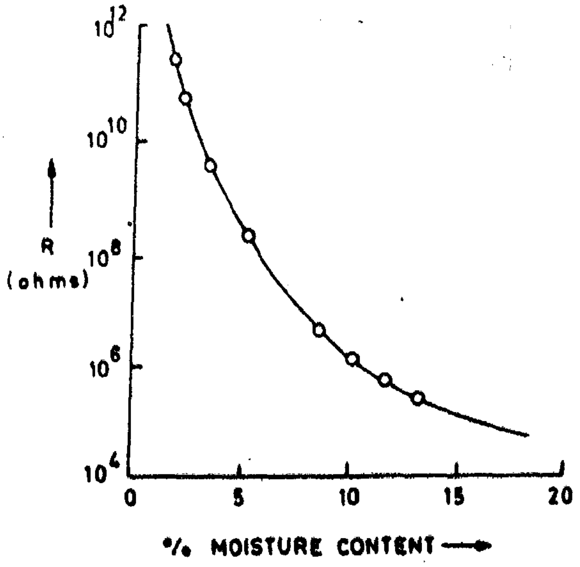


FIG. 2.5_VARIATION OF PAPER MOISTURE CONTENT AS A FUNCTION OF ITS RESISTANCE (R).

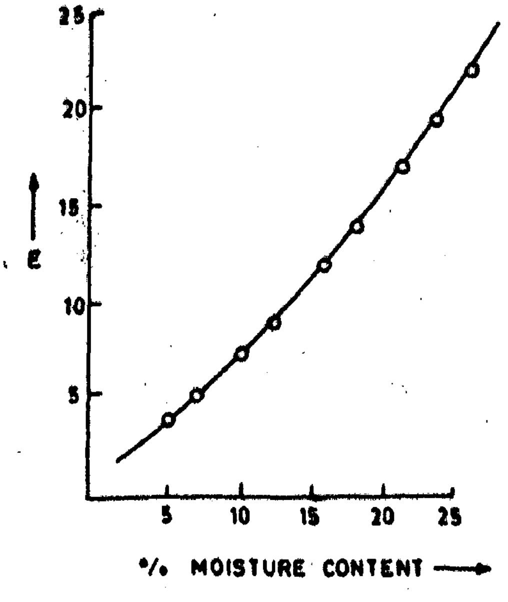


FIG. 2.6_VARIATION OF PAPER MOISTURE CONTENT AS A FUNCTION OF ITS DIELECTRIC CONSTANT (E)

where σ_t and σ_o are stresses at times t and 0, respectively, and τ is the time of relaxation in which the tension falls to 1/e of its original value. Fig.2.4 shows the stress relaxation function.

2.2.3 ELECTRICAL PROPERTIES OF CELLULOSE

Cellulose has two important electrical properties. First, the property of resistivity Anhydrous cellulose behaves as an insulator. It has the d.c. resistance value of about 10^{12} Ω when no moisture is present in the cellulose sample. As the amount of moisture increases in the cellulose sample, its resistance value decreases exponentialy. In the range of 15 to 20 % moisture content, the value of cellulose resistance is 10^5 to 10^6 Ω, as shown in Fig.2.5.

Second, cellulose is a dielectric material. It has a dielectric constant in between 2.7 to 3.3, when no moisture is present in the cellulose sample. As the moisture content in the cellulose sample increases, the dielectric constant of the sample increases at rate of 0.78 per one percent increase in the moisture content of the sample. The relationship between dielectric constant and moisture content present in the cellulose sample is almost linear, as shown in Fig.2.6.

2.3 WATER AND ITS GENERAL PROPERTIES(5,6)

2.3.1 WATER

The term 'water' refers in general to water in which the isotopes appear in their natural relative abundances. The molecular structure of water (H_2O) consists of highly directional

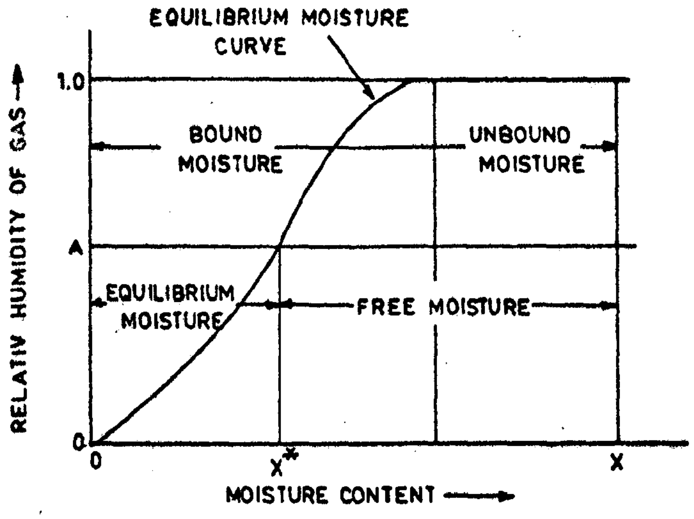


FIG.2.7_TYPESOF MOISTURE.

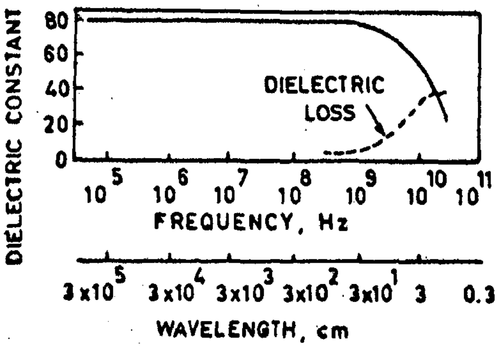


FIG.2.8_THE VARIATION OF THE DIELECTRIC CONSTANT OF WATER WITH FREQUENCY.

hydrogen bonds and is represented as:

$$H - O - H$$

2.3.2 NATURE OF WATER (MOISTURE) IN HYGROSCOPIC MATERIALS

Adsorbed moisture exists in many forms in the hygroscopic materials, shown in Fig.2.7.

Equilibrium Moisture (X^*): This is the moisture content of a substance when at equilibrium with a given partial pressure of the vapor.

Bound Moisture: This refers to the moisture contained by a substance which exerts an equilibrium vapor pressure less than that of the pure liquid at the same temperature.

Unbound Moisture: This refers to the moisture contained by a substance which exerts an equilibrium vapor pressure equal to that of the pure liquid at the same temperature.

Free Moisture: Free moisture is that moisture contained by a substance in excess of the equilibrium moisture: $X - X^*$.

2.3.3 SCATTERING AND ABSORPTION OF LIGHT WAVES BY WATER

When a layer of pure water is irradiated with a beam of monochromatic visible light, most of the light is either transmitted through the layer or reflected from the surface of the layer, but a fraction of light is scattered in other directions. The total light scattered by water is in the range of $\lambda = 2636$ to 5790 A^o and varies with λ. The absorption spetrum of water vapor extends from the far infrared to the far ultraviolet and consists of a series of bands, each composed of numerous lines.

2.4 ELECTRICAL PROPERTIES OF WATER(5)

2.4.1 CONDUCTIVITY OF WATER

The conductivity of pure water is due to hydrogen (H^+) and hydroxyl (OH^-) ions in equilibrium with water molecules. The conductivity of intrinsic water, theoretically estimated is 0.0548×10^{-6} mho/cm. at 25°C. Weiland obtained pure water having a conductivity of $0.05 - 0.07 \times 10^{-6}$ mho/cm. by distillation in quartz. In contact with air, water dissolves CO_2 and the conductivity rises at 25°C to about $.8 \times 10^{-6}$ mho/cm.

Water is a dipolar molecule. When an electric voltage (below breakdown strength) is applied, it shows conduction due to the presence of H^+ and OH^- ions. The conductivity, K, of a substance is the reciprocal of its volume resistivity, which is the longitudinal resistance per unit of length of a uniform cylinder of the substance of the unit cross-section area.

While employing electrical methods of moisture measurment, it is normal practicle to use the term 'resistance' or 'specific resistance' more often then the term 'conductivity'. This is because most electrical instruments operate on relationship between moisture content and the specific resistance of a hygroscopic material between two fixed points. Specific resistance is usually defined as the resistance between the opposite faces of a 1 cm^3 of the material.

2.4.2 DIELECTRIC PROPERTIES OF WATER

Water has high dielectric constant (80.0). No other liquid approaches it in this property. This accounts for the great ionizing power of water. The value of dielectric constant of water, expressed in electrostatic units, can be defined as the ratio of the mutual electrical capacity of a given pair of equipotential surfaces, fixed with reference to each other, when immersed in the dielectric (water) to their capacity and also when immersed in vacuum. If the polarization of the dielectric is accompanied by a dissipation of energy, the apparent dielectric constant is a complex quantity. In such cases the real part is commonly called the dielectric constant. In case of water, the dielectric constant at optical frequencies is much smaller than that under static conditions.

2.4.3 TEMPERATURE AND FREQUENCY VARIATION OF DIELECTRIC CONSTANT OF WATER

The approximate relationship between static dielectric constant (E_s) and temperature (T) is given by Kirwood's equation:

$$E_s \simeq \frac{19,000}{T} \qquad (2.2)$$

where T is expressed in Kelvin scale. This law has been experimentally verified, and the results are found to be in fairly good agreement with Kirkwood's theoretical calculations.

There is no satisfactory theoretical treatment of the frequency dependence of the dielectric properties of water as such. Experimentally it has been observed that dielectric

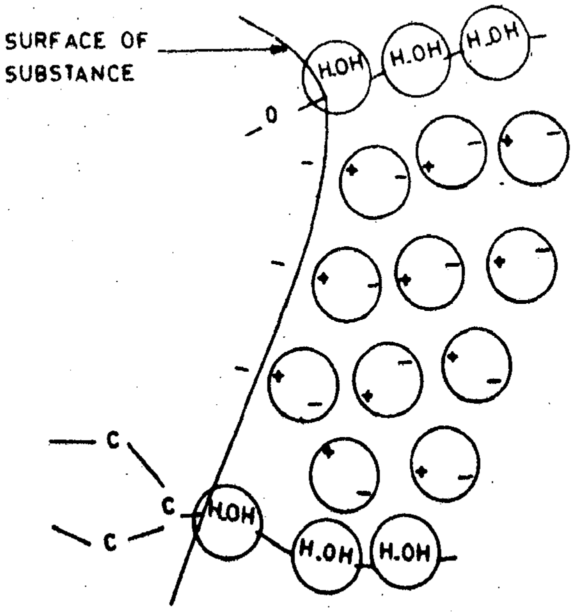


FIG.2.9_ DIAGRAMMATIC REPRESENTATION OF THE PHENOMENON OF WATER MOISTENING A SUBSTANCE.

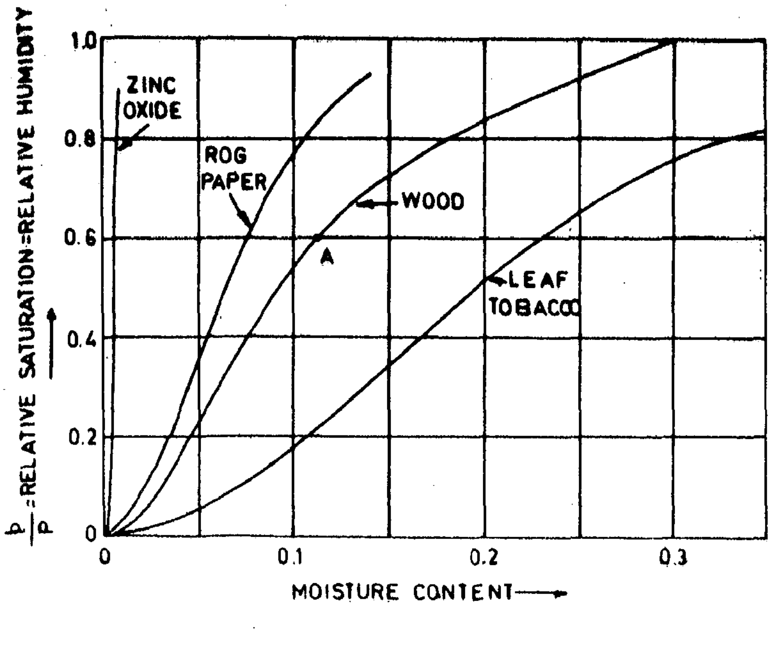


FIG 2.10_EQUILIBRIUM-MOISTURE RELATIONSHIP OF SOME COMMON SOLIDS.

constant of water remains constant at 81 upto 1,000 M Hz. Fig.2.8 shows the variation of dielectric constant and dielectric loss of water with change in frequency over a wide range of the frequencies. It can be observed that the dielectric constant remains nearly constant over a very wide range of frequencies.

2.5 INTERACTION OF WATER WITH CORPUSCULAR RADIATIONS(5)

Ionizing radiations in the form of α,β,γ, and X-rays or streams of fast moving neutrons, and other charged particles bring about decomposition of water into hydrogen, hydrogen peroxide, and oxygen. A steady state is reached where the rate of decomposition just matches the resynthesis rate of water.

In water vapor the range of the α particles is 0.77 times their range in air at the same temperature and pressure. The range of α particles from polanium in liquid water at 15°C is 32 μm. The range of α radiations in liquid water from RaC has been found to be 60 μm.

The coefficient of mass absorption of β rays from RaE in liquid water is 17.4 cm^2/g. The coefficient of absorption of neutrons in liquid water is 0.027 cm^{-1}.

2.6 ABSORPTION OF MOISTURE BY HYGROSCOPIC MATERIALS(5,6)

2.6.1 PHENOMENON OF WATER MOISTENING A SUBSTANCE

Fig.2.9 represents diagrammatically how water combines with a hygroscopic substance. A layer of molecules of water envelops the substance, fastening itself on the hydrophilous parts by electric action, potentials of contact, or exchange electrovalences. Molecules of water, being polar, are oriented by that bond; they present toward the exterior a polarized surface that is capable of affixing to it a new layer of molecules of water. Thus a second layer is capable of acting the same way, and there is formed a diffuse atmosphere of molecules attached to the substance.

The water molecules must be absorbed directly into the hydrophilic groups, or they may form further layers on top of the water molecules already absorbed. Water molecules directly attached will be firmly fixed, fitting tightly to the structure of molecules, and will therefore be limited in their movement. The indirectly attached water molecules will be more loosely held.

Water is absorbed in materials in three phases. The first phase to be absorbed is tightly bound to hydrophilic groups in the side chains of the molecule and has little effect on the rigidity of the structure of its electrical properties. The second phase is attached to groups in the main chain and replaces cross-links between molecules. The main effect is on rigidity. The third phase is more loosely attached and is only appreciable at high humidities.

2.6.2. EQUILIBRIUM-MOISTURE RELATIONSHIP AND HYSTRESIS

The moisture contained in a wet solid or liquid solution exerts a vapor pressure to an extent depending upon the nature of the moisture, the nature of the solid, and the temperature. If then a wet solid is exposed to a continual supply of fresh gas

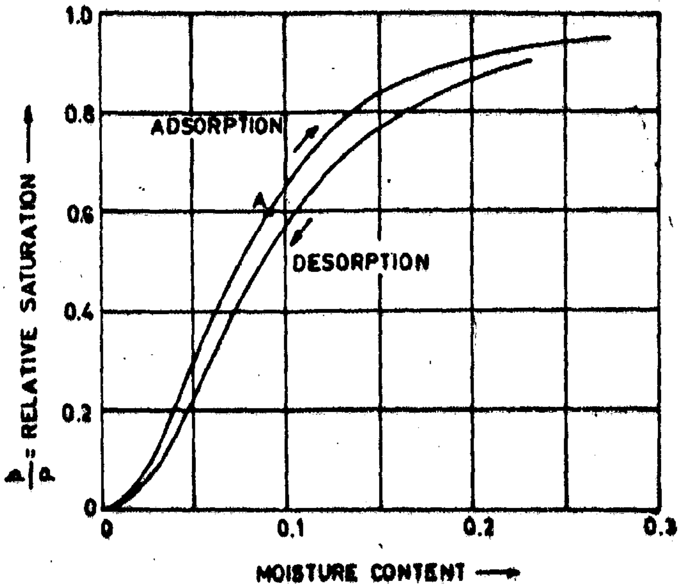


FIG. 2.11_EQUILIBRIUM WATER CONTENT OF A SULFITE PULP, SHOWING HYSTERESIS.

containing a fixed partial pressure of the vapor, p, the solid will either lose moisture by evaporation (desorption) or gain moisture (adsorption) from the gas until the vapor pressure of the moisture of the solid equals p. The solid and the gas are then in equilibrium, and the moisture content of the solid is termed its equilibrium-moisture content at the prevailing conditions. A few typical equilibrium-moisture relationships are shown in Fig.2.10, where the moisture in each case is water. Here the equilibrium partial pressure p of the water vapor in the gas stream is divided by the vapor pressure of pure water, P, to give the relative saturation or relative humidity of the gas.

Many substances exhibit different equilibrium-moisture characteristics depending upon whether the equilibrium is reached by condensation (adsorption) or evaporation (desorption) of the moisture. A typical example of hystresis is shown in Fig.2.11. In drying operations, it is the desorption equilibrium which is of particular interest, and this will always show the larger of the two equilibrium-moisture contents for a given partial pressure of vapor.

2.7 INFLUENCE OF INTERACTION BETWEEN SOLIDS AND WATER ON MOISTURE-MEASURING METHODS(5)

Most of the problems arising in moisture measurment are related to the material properties. Materials are mostly composite systems in which structure has a great effect on the interaction between material particles and water.

All materials can be classified into three groups:

(i) Colloidal materials - gelatins, pastes.

(ii) Materials with capillary pores - sands and soils.

(iii) Colloidal materials with capillary pores - This combines the properties of both groups (i) and (ii) and consists of capillaries with flexible walls, and therefore change their form and shape when absorbing or losing moisture. Fiberous materials (e.g. paper) fall in this group.

Three types of bonds exist between solids and water:

(i) Chemical Bond: The most energetically stable bond. The chemically bound water can only be separated by breaking down the chemical structure, resulting in a change of properties.

(ii) Physicochemical Bond: In this, water exists on the material surface. The formation of this type of bond is caused by electrical forces. In this case of hydrogen bonding, displacement of charges takes place.

(iii) Physical Bond: In this, water has the weakest bond with the material. Water bound in this way has little interaction with the material.

It is assumed that the dielectric constant of water is about 80. Nevertheless, in reality, the dielectric constant of pure water that is only made up of the tridymite structure is 80. The dielectric constant of water bound in a different way deviates from this value and changes inversely with the strength of binding. Thus, in the case of materials with a very strong water bond, the dielectric-constant versus moisture-content curve has a very low slope in the initial stages.

Unequal moisture distribution leads to incorrect measuring results, even with instruments based on measurment of conductivity (or resistivity). A value exceeding that of the mean moisture content is obtained if some parts of the sample contain higher moisture contents. Direct influence of water-solid interaction is apparent, since the logarithmic relation between resistivity and moisture content exists until hygroscopic saturation. After saturation, this relationship is represented by a flat curv and is not suitable for measurment.

CHAPTER- 3

A REVIEW OF MOISTURE MEASURING METHODS OF PAPER

The moisture measuring methods are broadly classified into two groups:

(i) Direct (Chemical) moisture measuring methods.
(ii) Indirect (Physical) moisture measuring methods.

In the direct methods moisture is normally extracted from the material by oven drying, desication, distillation and other chemical techniques, and its quantity found by weighing or by observing the pressure or temperature changes of the chemical reaction. Direct methods are usually employed in the laboratory and are found to be accurate. With proper precautions in sampling, in most of the cases, absolute values can be obtained. Some of the important direct methods are:

(i) Oven drying method of moisture measurment.
(ii) Distillation method of moisture measurment.
(iii) Titration method of moisture measurment.

In the indirect methods, the moisture content is not extracted from the material, instead properties of the wet solid dependent on the quantity of water present are measured. Some of the related properties on which a number of significant moisture measurment techniques have been developed are:

(i) Resistive method of moisture measurment.

(ii) Capacitive method of moisture measurment.
(iii) Microwave method of moisture measurment.
(iv) Infrared method of moisture measurment.
(v) N.M.R. method of moisture measurment.

A Comparison Between Direct and Indirect Methods

With the direct methods, it is possible to get very accurate and even absolute values of the moisture content, but the time taken in these methods is considerably large and the operations are mostly manual.

Indirect methods, though dependent in accuracy on the results of direct measurments against which they are calibrated, offer the quickest mode of moisture measurment. The continuous measurment and automatic control of moisture content is possible only with the indirect methods.

Today, the determination of moisture is more often achieved by instrumental (indirect) methods rather than by direct chemical analysis, because of the rapid developments in the field of electronic instrumentation.

3.1 DIRECT METHODS OF MOISTURE DETERMINATION(5,7)

3.1.1 DRYING METHODS

In these methods the paper is exposed to low relative humidity and decrease in weight occasioned by loss of moisture is determined. The common procedures are:

(i) Drying in an electrically heated oven at 100 to 125°C.

(ii) Drying in a vacuum oven in the range of 60 to 120°C

(iii) Drying at room temperature using anhydride P_2O_5 .

The oven drying method is the most commonly used procedure for determining the moisture content of the paper because of its ease and simplicity. For general use a temperature of 105 ± 2°C is recommended (TAPPI T412). Temperatures above 120°C are not advisable, because of possible decomposition of cellulose and certain other components of the paper. The paper sample is heated continuously for 1-hr. period or until the weight is constant. The moisture content of the paper is calculated by the Eq.(1.1).

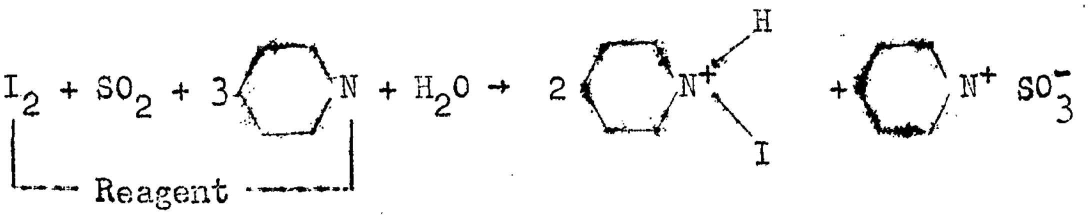
3.1.2 DISTILLATION METHODS

Moisture can be removed completely from the paper by distillation with a water-immiscible solvent. The distillate is condensed and collected in a trap. The solvent is returned continuously to the distillation flask, while the water remains in the trap and the volume is measured at the conclusion of the test.

This is a volumetric method and is especially suitable for materials which contain appreciable amounts of volatile substances other than water and for waxed or for varnished papers which are difficult to dry in an oven.

3.1.3 TITRATION METHODS

The Karl Fischer method is the most useful and generally applicable titration method. The Fischer reagent is a solution of iodine, pyridine, and sulfur dioxide in methanol. The reactio with water can be represented by:



In the determination, anhydrous methanol is added to the paper. The methanol removes the water and the solution is titrated with the Fischer reagent. The end point of the titration can be found visually. For accurate moisture content measurments, the dead-stop method of end-point detection is preferred and automatic titrators of this type are available from several manufacturers.

3.2 ELECTRICAL/ELECTRONIC METHODS OF MOISTURE MEASURMENT(1,8,9,10,11)

In section 2.4, we have seen that water has two important electrical properties: conductivity and dielectric. Moisture measuring methods and instruments based on these properties are described here.

3.2.1 D.C. CONDUCTIVITY OR RESISTANCE METHOD

Principle of Operation

There is a definite relationship between the moisture content of hygroscopic materials and their d.c. conductivity or d.c. resistance, which is logarithmic in nature and shown in Fig.2.5. Anhydrous paper has very high resistance value (10^{11} to 10^{12} ohms), whereas the resistance of the moist paper varies from about 25 KΩ to 50 MΩ for various grades of papers

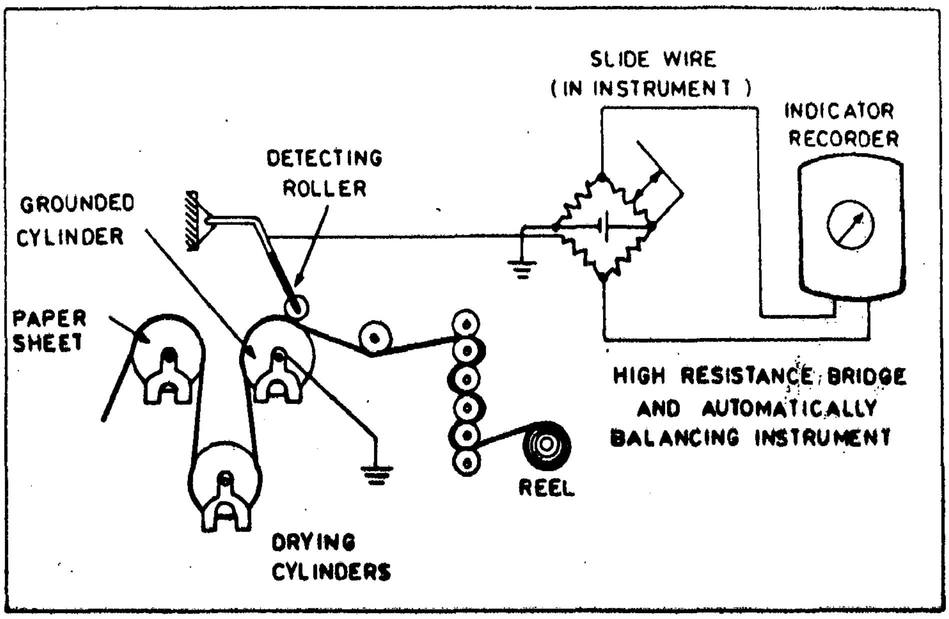


FIG.3.1_ON-LINE RESISTANCE TYPE MOISTURE MEASURING SYSTEM.

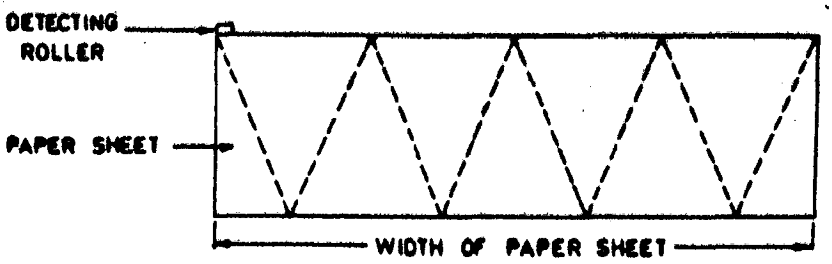


FIG.3.2_MOVEMENT PROFILE OF THE DETECTING ROLLER.(SHOWN BY----LINE)

with various moisture contents. This large change in resistance because of moisture variation is measurable and is a direct function of the moisture contents present in the sample.

On-Line Moisture Measurment of Paper

Fig. 3.1 shows a scheme which operates by measuring the electrical resistance through the paper. This scheme mainly consists of three units:

(i) The electrode system.
(ii) The electronic unit.
(iii) The indicating meter or recorder.

The electrode system consists of two electrodes. One electrode is grounded, called as grounded cylinder (roller) and the other electrode is placed against it, called as detecting roller. The sheet of paper passes through them. The detecting roller is installed against the sheet of paper in such a manner that the paper is used as a resistance between the grounded drying cylinder and the detecting roller.

Paper resistance forms one arm of the wheat stone bridge in the electronic unit. The change in the paper resistance, because of the change in the moistness of the paper, produces an out of balance voltage in the wheat stone bridge. This out of balance voltage is further amplified by the amplifiers and then the signal is fed to a suitable indicating or recording meter which is calibrated in terms of the percentage of the moisture content present in the paper. Calibration in terms of moisture content is established by a calibration curve, which is different

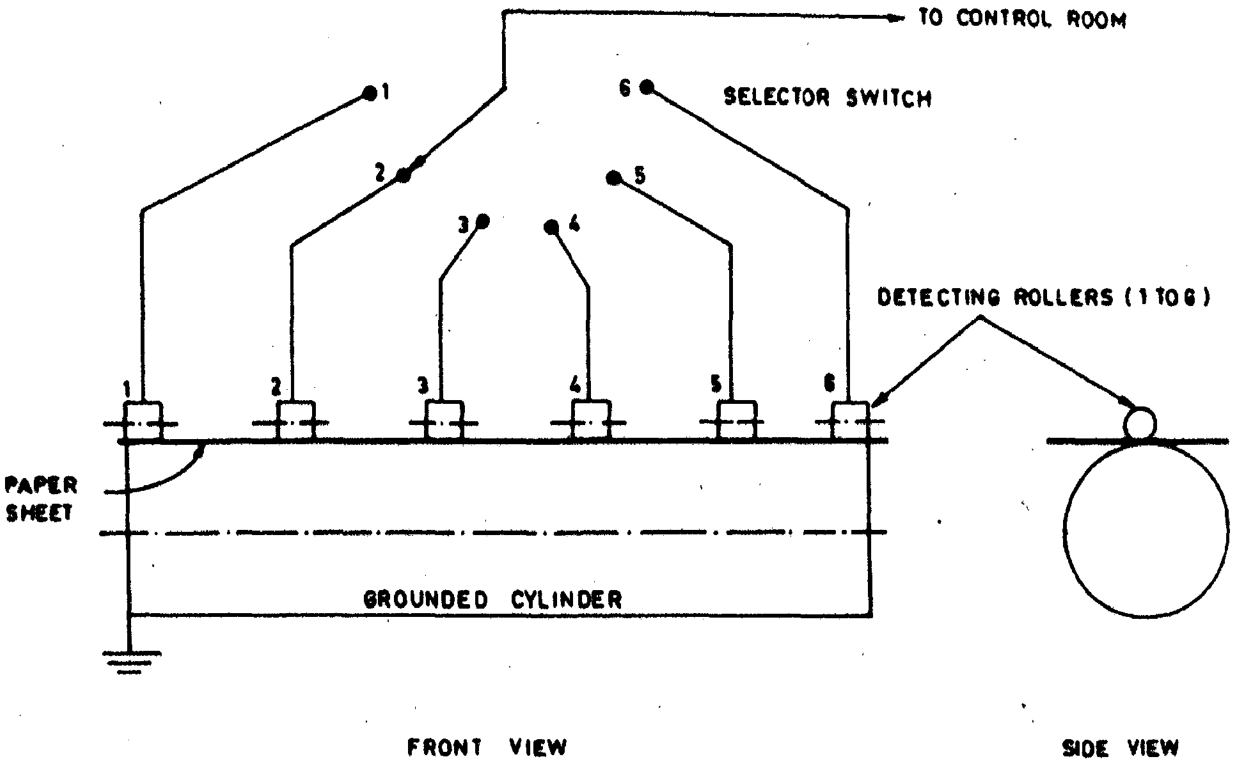


FIG.3.3_ MULTI DETECTING ROLLER RESISTANCE TYPE MOISTURE MEASURING SYSTEM.

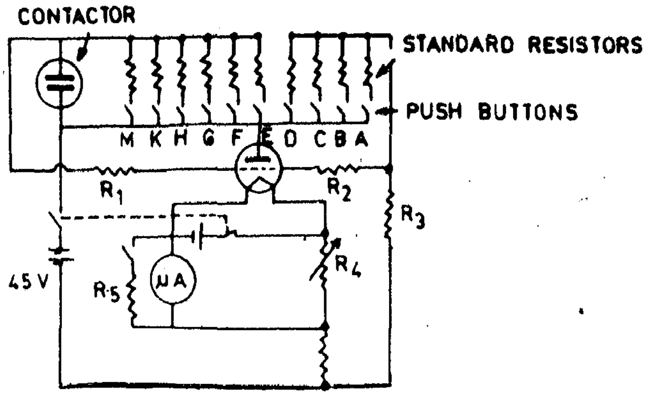


FIG 3 4_ELECTRICAL CIRCUIT OF HART MOISTURE METER.

for each grade of paper. Satisfactory measurments have been made on some papers with moisture contents as low as 2 percent and as high as 40 percent.

Only one detecting roller can be used in such a way that it can cover the whole of the width of the paper sheet, by using the mechanical gear and lever arrangment. The detecting roller, comes back at the initial position again after scanning whole of the width of the paper. A movement profile of such a detecting roller is shown in Fig.3.2. The advantage of using the detecting roller in this fashion is that it gives a continuous check of the moisture content at the different places of the paper sheet.

In the recent developments, a number of detecting rollers (usually six number) are used instead of using only one detecting roller. These rollers are placed on the width of the paper sheet at equal distances, as shown in Fig.3.3. Two rollers are placed at the edges of the paper sheet and rest four rollers are placed on the paper sheet such that the distance between the two rollers is 20 percent of the total width of the paper sheet. The control of such a scheme is usually in the control room, where the operator can put any one of the rollers in the operation just by moving the selector switch for a particular roller. When a particular roller is in contact with the paper sheet, other rollers remain in the lifted position. Thus, moisture content of the paper sheet can be monitered at its different places and accordingly it can be controlled.

Hart Moisture Meter

The same principle of change in resistance because of the change in the moistness of paper is applicable in Hart moisture meter. Paper forms one arm of the wheat stone bridge. The instrument is designed such that a series of known resistance can be incorporated into the balancing arm of the wheat stone bridge by pressing the button associated with that resistance The resistances are chosen to give uniform steps of approximately 0.1 % to 0.5 % moisture. Before use, the instrument must be calibrated with the papers of known moisture content. An electrical circuit of Hart moisture meter is shown in Fig.3.4, in which a direct voltage (10-45 Volts) is applied across the paper.

Factors Influencing the Moisture Measurment

For optimum results from the d.c. conductivity/resistance moisture meters, the following factors should be taken into consideration:

(i) Moisture Distribution

Moisture must be uniformly distributed throughout the sample, since resistance meters measure the path of least resistance and a single wet spot in the sample can vitiate the test results.

(ii) Range of Measurment

The accuracy of measurment is less in the samples having very low or very high moisture contents. Accurate measurments of ± 0.5 % can be made in the range of 3 to 30 % moisture contents.

(iii) Temperature

Normally, operation temperature should be 20 to 25°C. The electrical resistance of a hygroscopic material is an inverse function of its temperature, therefore, suitable temperature correction should be made.

(iv) Sampling

Sample should be in proper size and quantity because larger the sample, the more representative is the result.

(v) Purity of the Sample

The presence of small amounts of impurities in the form of an electrolyte drastically affect the conductivity of the sample and hence introduces the error in the test results.

(vi) Method of Measurment

Moisture content of the samples must be measured as rapidly as possible, where the current is passed directly through the sample. Delay in measurment will cause the heating of the sample and thus the incorrect results.

Merits and Demerits

(i) There is a large change in the resistance for a comparatively small change in the moisture content. An almost linear relationship holds between the moisture content and the logarithm of the resistance over the hygroscopic range, in which accurate moisture measurments can be made.

(ii) Resistance is a property which can be measured by simple, robust and reliable apparatus.

(iii) Moisture measurment is instantaneous after the sample is placed between the electrodes. Hence, continuous measurment and control of moisture can be made in an industrial process.

(iv) Moisture measurments are affected by the degree and efficiency of the contact between electrodes and sample. It is not always practicable to obtain uniform contact (due to the unevenness ~~of the~~ surface of the sample) and accuracy of measurment is of doubtful nature in such cases.

(v) The reading of the meter is very much affected by the presence of impurities in the form of electrolytes, and it is not possible to control these impurities as the moisture content may vary with the quality of water used in the processing of the material. This is a serious drawback in this type of meter.

3.2.2 A.C. CONDUCTIVITY METHOD

Paper containing no water is an insulator and produces effectively infinite resistance, or no conductivity. Pure water is also an insulator. However, water in paper is invariably contaminated by electrolytes in solution which make it conductive.

Using alternating current, the conductivity of paper can be measured over a range of moisture contents and kinds of paper. The change in conductivity with moisture content is large and the

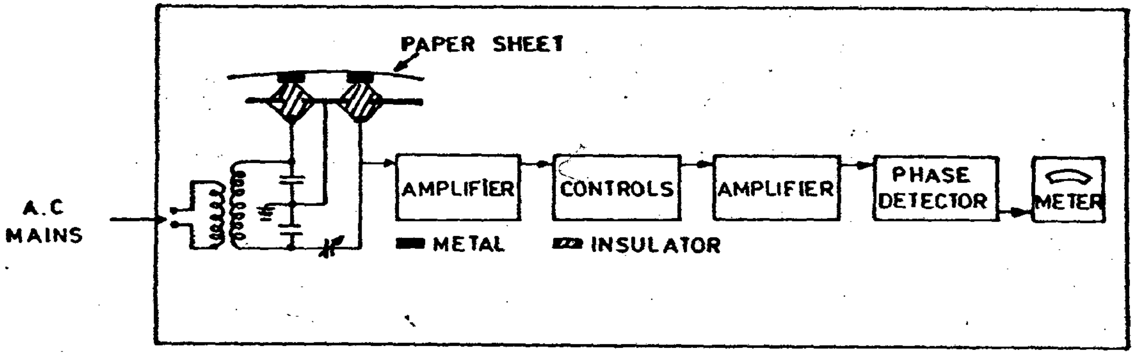


FIG.3.5_ BLOCK DIAGRAM OF A.C CONDUCTIVITY TYPE MOISTURE MEASURING SYSTEM.

relationship is exponential in form so that a shift of 1 percent in moisture causes conductivity to rise in five times its value at lower moisture content. A change of 2 percent in moisture at lower ranges change conductivity by 25 times. The block diagram in Fig.3.5 shows a moisture measurment system of this type. The measuring electrodes, applied to only one side of the sheet, form a part of a balanced capacity bridge energized with a voltage of about 1000 volts.

A small current, proportional to moisture content, passes through the paper spanning the electrodes and creates a voltage at the input of the first amplifier stage. Grade, temperature, and range controls are used in the next phase to adjust amplifier gain as required. The signal then passes through a second amplifier, then to a phase-sensitive detector, and finally to a secondary instrument which converts the signal to a linear percent moisture response within moisture range limits of 3 to 11 percent.

3.2.3 DIELECTRIC OR CAPACITIVE METHOD

Principle of Operation

The operating principle of the capacitive type moisture meter is based on the change occurring in the dielectric constant between its most and dry conditions. The variation of the dielectric constant of hygrosic materials with moisture content is approximately linear over a useful range of 0 to 35 % moisture content corresponding to a change in relative humidity of 30 to 90 % at 20°C. The dielectric constant of water is 81, whereas the dielectric constant of most of the hygroscopic materials varies from 2.2 to 4.0. Therefore, the presence of a very small quantity of water in the material causes a considerable change in the dielectric constant of the combined sample (mixture of material and water content).

Material-Water Mixture

Though the water absorbed by hygroscopic materials does not form a mixture in the true sense, the free water as well as the water mechanically held within the pores of the porous materials can be treated as forming a mixture with the solid material, and the composite dielectric constant of such a mixture can be theoretically estimated.

Under ideal conditions, the dielectric constant (E_m) of the mixture is given by the following relationship:

$$E_m = E_1 S_1 + E_2 S_2 \qquad (3.1)$$

where S_1 and S_2 are the volume-filling factors of each component into another to form the mixture, and E_1 and E_2 are the dielectric constant of the individual substance.

Capacitive Moisture Meters

Capacitive moisture meters are usually made of three units. They are

(i) An electrode system.

(ii) An electronic circuit.

(iii) An indicator or recorder.

(i) Electrode System

The geometry of the electrode system depends on the nature of the sample and type of measurment to be made. Plate-type electrodes are found to be most suitable for sheet materials for continuous measurments. One of the problems in the design of a parallel plate electrode is the prevention of fringing which causes error in the estimation of the capacity of the condenser from its parameters. Experimentally, fringing can be minimized by using a guard ring in the plane of one of the plates. The guard ring should be maintained at ground potential and its associated electrode should be kept at a low potential with respect to ground. By this arrangement, the fringing is confined to the guard ring only and the opposite electrode keeps the electrostatic lines of force straight between the upper and lower measuring electrodes.

(ii) Electronic Circuitry

Three electronic techniques are used for measuring the small capacitance changes obtained in the electrode system:

(a) Bridge circuit.

(b) Resonance circuit.

(c) Beat frequency circuit.

(a) Bridge Circuit

In the bridge circuit, a radio frequency oscillator is used. The use of high frequency in this method gives the advantage that impedence of the test capacitor is reduced to such a value that stability and accuracy can be obtained and very small changes in capacitance caused by small changes in moisture content can therefore be measured.

(b) Resonance Circuit

This method utilizes the characteristic of variation of voltage or current in a series or parallel resonant circuit, near its resonance frequency. Over a limited portion of the resonant curve, the voltage or current varies approximately linearly with the unknown value of the capacitance which is now forming a part of the resonant circuit and whose capacitance varies with change in moisture content of the sample.

(c) Beat Frequency Circuit

In this system, two oscillators, one having a fixed, preferably a crystal-controlled frequency, and the other having a variable frequency, are used. The test capacitor (made of sample) and a calibrated capacitor are connected to the variable oscillator. Initially both the oscillators have the same frequency i.e., show a zero beat. Before the sample is placed in the dielectric cell, the oscillator is made to oscillate. When the sample is placed in the dielectric cell, its capacitance changes and oscillation ceases. The change in the capacitance of the sample is compensated by adjusting the calibrated capacitor, which in turn directly gives the moisture content of the sample.

(iii) Indicating Meter or Recorder

It is a microampere meter or milliampere meter or recorder which indicates the moisture content of the sample into corresponding current variations.

Factors Influencing the Moisture Measurment

To get the best results from capacitance moisture meters, the following factors should be taken into consideration:

(i) Moisture Distribution

Moisture should be well distributed throughout the sample and the moisture content should preferably be under 40 % .

(ii) Presence of Electrolytes

Small concentrations of electrolytes do not introduce appreciable error in the moisture measurment; excessive concentration of additives in the form of electrolytes, lead to erroneous results by introducing dielectric losses which give a higher indicator reading.

(iii) Temperature

Dielectric constant of water is very sensitive to temperature changes, therefore, a temperature correction is necessary if the temperature at which measurments are made differs widely from the temperature at which the moisture meter has been calibrated.

Merits and Demerits

(i) The calibration of the capacitive moisture meter is not appreciably affected by the majority of additive agents encountered in the process.

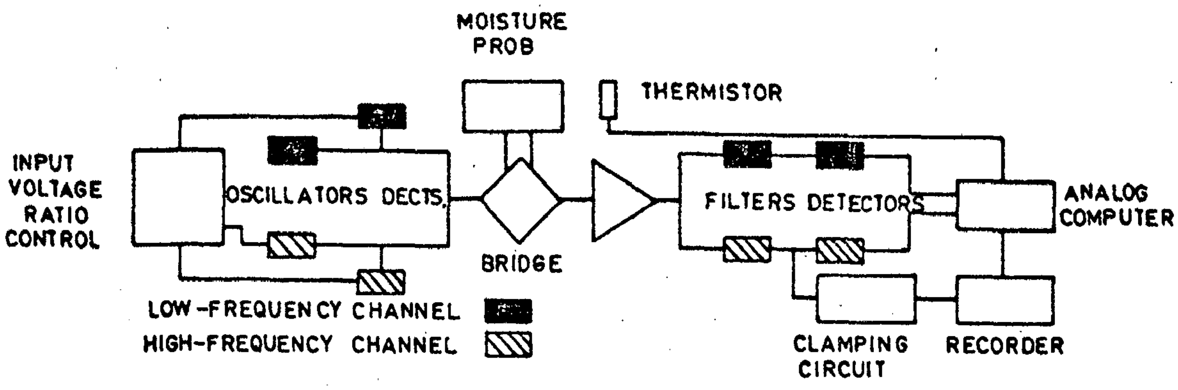


FIG. 3.6_TOTAL ADMITTANCE TYPE MOISTURE METER.

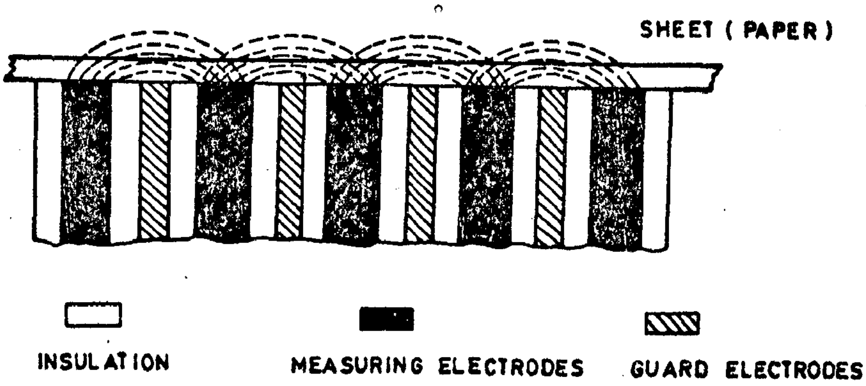


FIG. 3.7_FRINGE FIELD PROBE.

(ii) A large change in dielectric constant occurs for small changes in moisture content of most materials, hence very good sensitivity can be obtained.

(iii) It is not necessary that the material be in contact with both the electrodes. In the usual practice material contacts only one electrode, therefore, it is a very convenient method for continuous moisture measurment.

(iv) The electrode system can be modified in different ways to meet the requirments for sampling a large range of materials.

(v) When the moisture meter is exposed to abnormal temperature and tension variations, its calibration is affected, but such variations seldom occur under operating conditions.

(vi) It is possible to use the capacitance type moisture meter as a monitoring device as well as a measuring instrument.

3.2.4 TOTAL ADMITTANCE METHOD

It is a comparatively new technique which does not depend on one capacitance measurment alone, but determines total admittance at two frequencies simultaneously. These two values, plus a temperature measurment from a thermistor element, feed an analog computing circuit that produces a temperature-corrected output which is independent of the quality of the probe contact (Fig.3.6).

The primary measuring element is a fringe field capacitor probe (Fig.3.7) with a large surface containing many strips running in both the machine direction and across the machine. The probe is connected to a bridge circuit that is excited by two different oscillators operating at widely separated frequencies. After linear amplification, the two unbalanced signals from the bridge are filtered, further amplified and rectified. From the resulting d.c. signals, E_1 and E_2, a simple computing circuit produces a single out put voltage E according to the relation

$$E = (E_1 - E_2)E_1 \qquad (3.2)$$

which can be read out as percent moisture. The advantage of this type of moisture meter is that the temperature variations are corrected automatically, hence better results are obtained.

3.3 ELECTROLYTIC METHOD OF MOISTURE MEASURMENT(8,9)

Principle of Operation

This method is based on the principles of absorption of water in a suitable hygroscopic material followed by electrolysis of water to O_2 and H_2, the electrolysis current serving as a direct measure of water content.

According to Faraday's law of electrolysis, 0.5 g/mole of water (9.01 g) requires 96,500 coulombs of electricity for its electrolytic decomposition. The electrolysis current is proportional to the number of moles of water absorbed per unit time. If a flow rate of 100 ml/min. at NTP is maintained for ideal

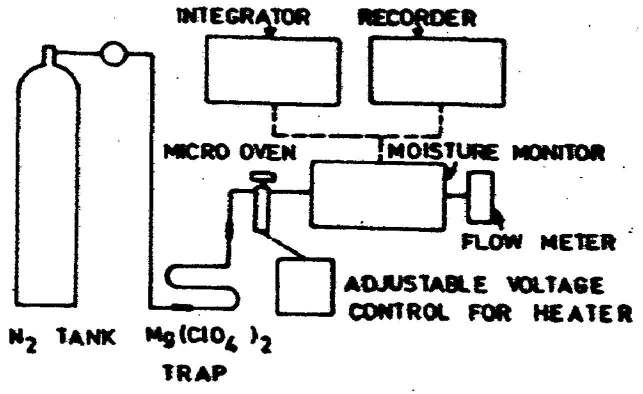


FIG. 3.8_ ARMSTRONG ELECTROLYTIC MOISTURE METER.

gaseous samples, the electrolysis current is 13.2 μA/ppm water by volume, which is measurable by electronic means.

Description of the Apparatus

The apparatus, 'Armstrong Electrolytic Moisture Meter', shown in Fig.3.8 consists of a tank of dry nitrogen, a magnesium perchlorate drying tube for the incoming nitrogen stream, a brass micro oven, a moisture monitor, a flowmeter, an integrator and a recorder. The micro oven heater is regulated by an automatic timer and an adjustable voltage control. The out put signal from the moisture monitor is recorded by the 10-mV Varian strip chart recorder and is simultaneously integrated by the integrator, which has a range of 0 to 1000 counts/min. corresponding to a signal output range of 0 to 10 mV.

3.4 HYGROMETRIC METHOD OF MOISTURE MEASURMENT(12I)

Principle of Operation

A porous material inside a closed space at a given temperature and relative humidity exchanges moisture with the atmosphere until an equilibrium of vapor pressure is attained. To This equilibrium corresponds a given moisture content in the material which depends on its characteristics. Conversely, the relative humidity of the material is a function of its moisture content.

If the function

$$W = f(H)$$

between the moisture content W and the relative humidity H is

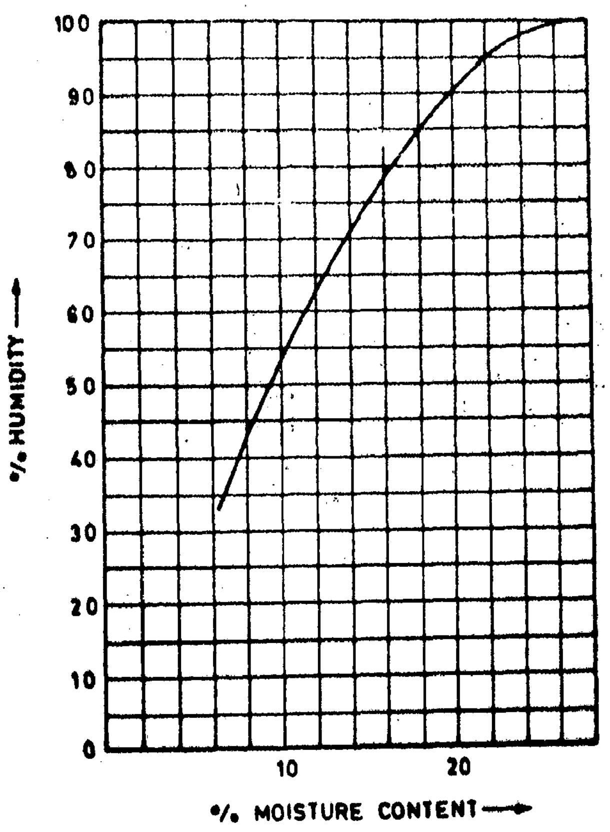


FIG. 3.9 _ HYGROMETRIC CURVE.

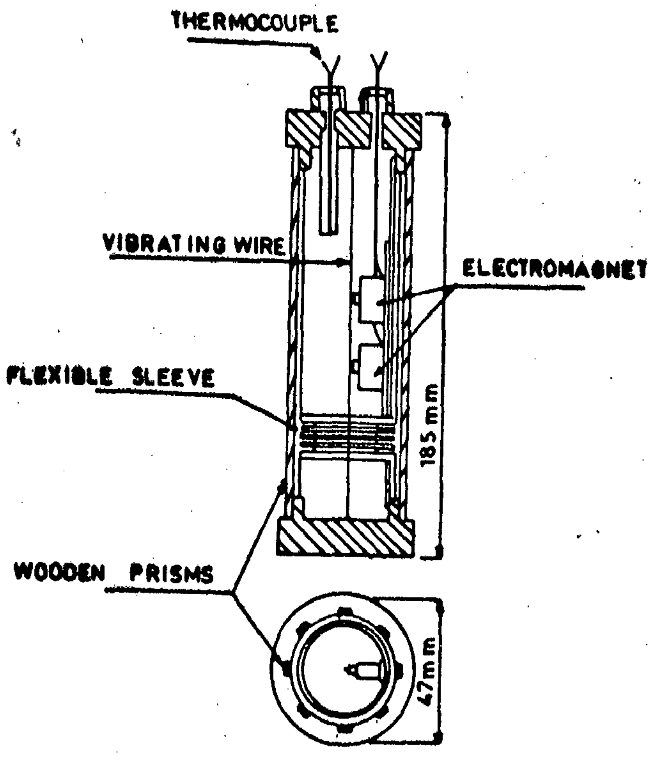


FIG. 3.10 _ DIAGRAMMATIC DRAWING OF A VIBRATING WIRE TELEHYGROMETER

known for this material, it is possible to obtain W from H. H can be determined without difficulty by means of a hygrometer. As the function W = f(H) depends on the characteristics of the material, the application of the method requires a previous plotting of a calibration hygrometric curve.

The field of application of the method is limited to the range of moisture contents corresponding to relative humidities below the saturation point (H = 100 %). The hygometric curve in Fig. 3.9 shows that the accuracy of the function H = f(W) decreases as the relative humidity approaches H = 100 percent.

Vibrating Wire Telehygrometer

The operation of the vibrating wire telehygrometer is based on the length variations undergone by certain hygroscopic materials on absorbing or losing moisture, and on the measurment of these strains by means of a vibrating wire, the vibration of which when excited by an electromagnet has a frequency which is a function of the stress in the wire.

A diagrammatic cross section of a telehygrometer is represented in Fig. 3.10 showing the wooden strips - the humidity sensitive element - arranged around two circular heads to which the vibrating fire is fixed. The length of the vibrating wire depends on the strains undergone by the wooden strips. The vibrating wire, the electromagnet that excites it and a temperature-measuring thermocouple are protected against moisture by a flexible sleeve.

3.5 INFRA-RED (SPECTRO-PHOTO-METRIC) METHOD OF MOISTURE MEASURMENT(4,8,12II,III,13,14)

Moisture measurment technique based on infra-red (IR) absorption is one of the most versatile and reliable method of the detection and quantitative measurment of water content of various substances. In recent years, a very reliable, accurate and sensitive moisture measurment technique particularly that of paper sheets has been developed using the IR transmission measurment.

The principle depends on the fact that water molecules have binding energy which corresponds to certain specific wavelengths in the IR-spectrum. Any IR radiation falling over water will show absorption lines corresponding to these lines. Water absorption bands occur at 0.76, 0.97, 1.18, 1.45, and 1.94 μ, as well as at longer wave-lengths. Shorter wave-lengths are more useful for measurment because of their higher penetration through the substance whose moisture content is to be measured.

One of the technique uses the ratio principle where two wave-lengths are chosen by rotating filter such that none of them are absorbed by the base material whereas one is absorbed by water. When transmitted through the sample one becomes the reference line while the other becomes the test or absorbed line. If the signal strengths measured by detector in the two cases are given by S_R and S_T respectively, then moisture content M is given by

$$M = \frac{S_T}{S_R} \qquad (3.3)$$

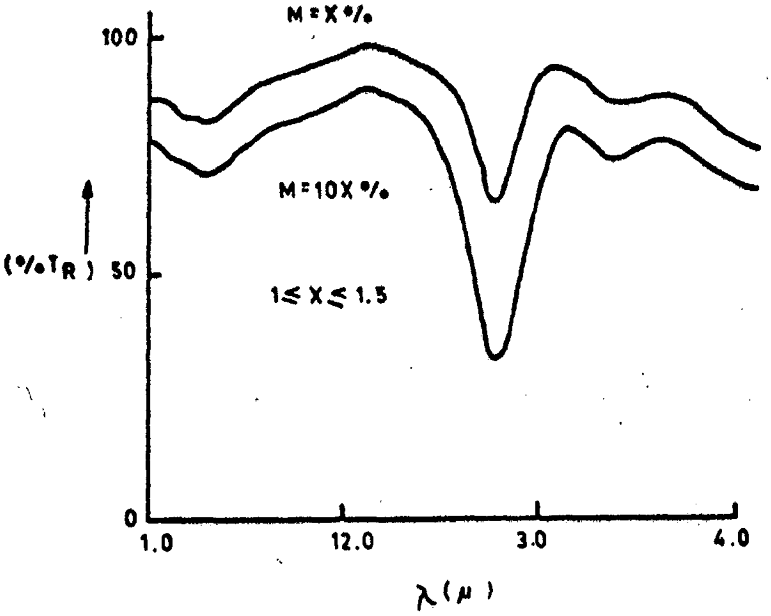
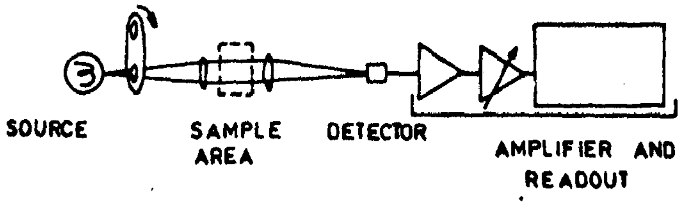


FIG.3.11_VARIATION OF TRANSMISSION RATIO (T_R) WITH WAVELENGTH FOR TWO SAMPLES HAVING DIFFERENT MOISTURE CONTENTS.

(A) FUNCTIONAL DIAGRAM



(B) SCHEMATIC DIAGRAM

FIG. 3.12_INFRARED MOISTURE MEASURING SYSTEM.

The ratio measurment technique is quite accurate as the measurment in the two cases will be equally affected, if any. The other technique is known as combination measurment and involves signal detection at dry and wet condition of the sample and a little more computation.

The law of absorption of radiation in a non-homogeneous material is given by

$$I_\lambda = I_{o\lambda} \exp\{-(\sum_{j=1}^{n} \alpha_{\lambda j} w_j + \sigma)x\} \qquad (3.4)$$

where $I_{o\lambda}$ is the intensity of the radiation for wavelength λ before absorption; I_λ, that after absorption; $\alpha_{\lambda j}$, the absorption coefficient for component j of material λ ; w_j the concentration of the component by weight; σ; the scattering coefficient; and x, the sample thickness. It is required in the ratio measurment that $I_{o\lambda 1}$ be made equal to $I_{o\lambda 2}$ such that a transmission ratio

$$T_R = I_{\lambda 1}/ I_{\lambda 2} \qquad (3.5)$$

can be evaluated as

$$T_R = \exp\ (- M\ \alpha_{\lambda 1}\ x) \qquad (3.6)$$

where M = moisture concentration by weight. Hence M is evaluated as

$$M = -\log_e T_R/ (x\ \alpha_{\lambda 1}) \qquad (3.7)$$

The T_R-λ curves for paper at two different moisture contents are shown in Fig.3.11.

Instrumentation

The functional and schematic diagrams of the IR moisture measurment technique for paper sheet are shown in Fig.3.12. The important constituent units of IR-spectrometer are:

(i) Monochromatic source of IR radiation.
(ii) Detector.
(iii) Amplifier and readout system.

For measurments in the 1.0 to 2.4 μ region, a simple spectrometer of very high efficiency is devised, using a wedge interference filter as the monochromator, a tungsten lamp as the radiant energy source, and a lead sulfide cell as the detector. The energy from the tungsten lamp is focused on the entrance slit placed directly above the wedge filter. The wedge filter, which is moved across the slit to obtain the desired monochromatic energy, is a Schott Veril S-200 filter designed for the 0.5 μ to 1.2 μ region. The detector is located as close as possible below the sample to collect the maximum amount of energy transmitted by the sample. The signal from the detector is amplified by a solid-state amplifier which is fed to an X-Y recorder for spectral scanning.

3.6 SONIC AND ULTRASONIC METHODS OF MOISTURE MEASURMENT(8)

3.6.1 SONIC METHOD OF MOISTURE MEASURMENT

Principle of Operation

The degree of absorption of sound energy is dependent on the medium through which it is transmitted. For many sheet

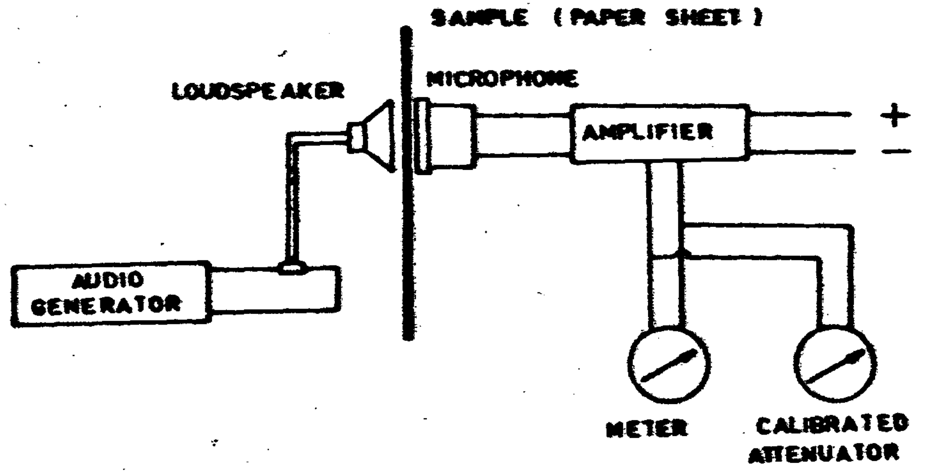


FIG. 3.13_ A SONIC MOISTURE METER FOR A WEB OF PAPER OR SHEET OF TEXTILE.

materials such as paper, textiles etc., sound absorption also depends on the quantity of water present in the sample.

Description of the Instrument

A sonic moisture meter for a web of paper is shown in Fig. 3.13. An audio frequency sound of a fixed frequency is generated by a phase-shift RC audiogenerator and fed to a loudspeaker. This generator is placed on one side of the web, and a reciever or microphone placed on the other side picks up the transmitted sound; the output of the microphone after passing through a sufficient number of stages of electronic amplification gives an adequate voltmeter reading. The resultant amplifier signal can also be utilized for electrical control of the web-forming process by automatic adjustments when the moisture content departs from a desired value.

3.6.2 ULTRASONIC METHOD OF MOISTURE MEASURMENT

Utilizing the same principle of sonic energy absorption, ultrasonic waves have been used for measurment of moisture content. Due to their high frequency (short wavelength), these waves have special properties of reflection, refraction, and absorption. They can be beamed and focused in a desired manner on the sample and the output from the sample can be processed to determine the moisture content of the sample.

In such devices the audio-generator is replaced by an ultrasonic generator comprising a radio frequency oscillator and a pizeoelectric transducer (quartz or ceramic crystal), the microphone being replaced by a pizeoelectric quartz receiver having the same resonant frequency as the generator. The ultrasonic waves, after passing through the web of material, are picked up by the pizeoelectric transducer and amplified by a suitable amplifier whose output is connected to a meter or a recorder.

3.7 MOISTURE BALANCE (12 IV)

Principle of Operation

Measurment of moisture content with a moisture balance is based on the fact that the volume displacement of a sample immersed in water is dependent on its moisture content and utilizes the buoyancy of the sample in water.

Specific gravity and moisture scales are graduated on the arms of the balance. The scale pan is hung at a point corresponding to the specific gravity of the anhydrous sample, and a vessel immersed in water is hung at the appointed point of the same arm.

The sample is placed on the pan, and a counter-weight of adjustable mass is hung at the appointed point of the other arm of the balance. The balance is brought into equilibrium by adjusting the mass of the counter weight.

The sample is then transferred from the pan into the vessel in water, and the equilibrium of the balance is restored by sliding the counterweight to a point of the moisture scale. The moisture content can then be read directly.

For the moisture measurment, the mass of sample does not have to be determined and so can be chosen arbitrarily. Moisture balance is suitable for both water-insoluble and water-soluble samples, the procedure of measurment is somewhat more complicated in the case of the latter. Moisture balance is more suitable for samples which have densities substantially greater than one.

Theoretical Considerations

Specific Volume of Water-Insoluble Sample

Let the density of insoluble sample in the dry state (anhydrous sample) be ρ, and the density of water be ρ_w, and let the sample of mass M be composed of anhydrous portion of mass m and water of mass m_w, then the moisture content x (percent) is given by

$$x = \frac{m_w}{M} \times 100 = \frac{m_w}{m+m_w} \times 100 \tag{3.8}$$

And the volume of this sample, V, is represented by

$$\begin{aligned} V &= \frac{m}{\rho} + \frac{m_w}{\rho_w} \\ &= M\left\{\frac{1}{\rho} - \frac{x}{100}\left(\frac{1}{\rho} - \frac{1}{\rho_w}\right)\right\} \end{aligned}$$

$$\frac{V}{M} = \frac{1}{\rho} - \frac{x}{100}\left(\frac{1}{\rho} - \frac{1}{\rho_w}\right) \tag{3.9}$$

where, $\frac{V}{M}$ is the specific volume of the sample.

Therefore, assuming that ρ and ρ_w are constant respectively, the specific volume of the sample $\frac{V}{M}$ is a linear function of x, and so x can be obtained by making use of the measured value of the specific volume $\frac{V}{M}$ and previously known values of ρ and ρ_w.

Specific Volume of Water-Soluble Sample

Let a sample of mass M be composed of solid of mass m^1 and liquid of mass m_ℓ, the liquid content x^1 is defined by

$$x^1 = \frac{m_\ell}{M} \times 100 = \frac{m_\ell}{m^1 + m_\ell} \times 100 \qquad (3.10)$$

Let the density of the liquid be ρ_ℓ (the density of the solid is still ρ), the specific volume of the sample is given by

$$\frac{V}{M} = \frac{1}{\rho} - \frac{x^1}{100} \left(\frac{1}{\rho} - \frac{1}{\rho_\ell}\right) \qquad (3.11)$$

The mass of water m_w included in the liquid of mass m_ℓ is given by

$$m_w = m_\ell \; (1 - \sigma) \qquad (3.12)$$

where σ is the concentration of the liquid.

Therefore, the moisture content x of the water-soluble sample is given by

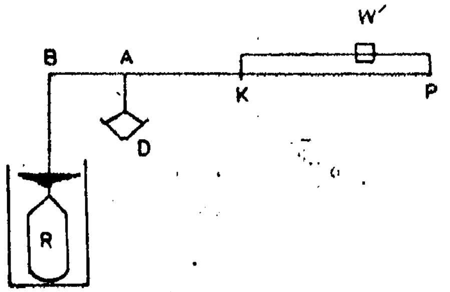
$$x = x^1 \; (1 - \sigma) \qquad (3.13)$$

Apparent Mass of Sample in Water or in Liquid

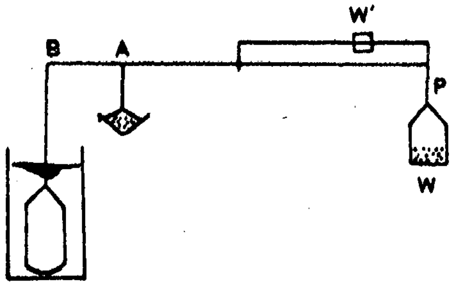
Apparent mass M_a in water of the insoluble sample is given by

$$M_a = M - V \rho_w$$

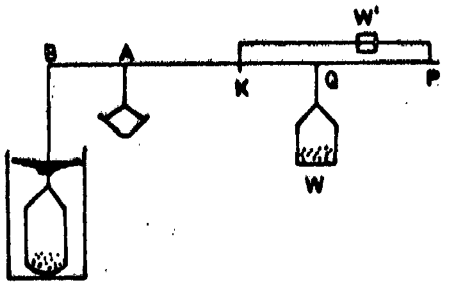
the apparently reduced mass $V \rho_w$ is due to buoyancy. The volume V of the sample can be represented as follows:



(a) WITHOUT SAMPLE



(b) WITH SAMPLE ON SCALE BEAM



(c) WITH SAMPLE IN VESSEL

FIG.3.14_ MOISTURE BALANCE IN VARIOUS STATES.

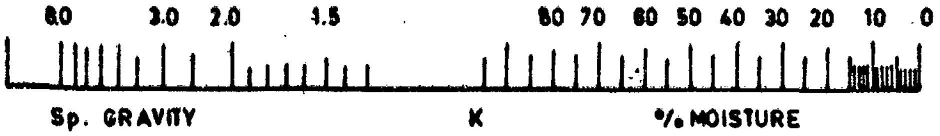


FIG.3.15_SPECIFIC GRAVITY SCALE AND MOISTURE SCALE.

$$V = \frac{1}{\rho_w}(M-M_a) \tag{3.14}$$

this equation gives, with Eq. (3.9)

$$\frac{V}{M} = \frac{1}{\rho_w}\left(1 - \frac{M_a}{M}\right)$$

$$= \frac{1}{\rho} - \frac{x}{100}\left(\frac{1}{\rho} - \frac{1}{\rho_w}\right)$$

and then we have

$$\frac{M_a}{M} = \left(1 - \frac{\rho_w}{\rho}\right) . \frac{(100-x)}{100} \tag{3.15}$$

corresponding to Eq.(3.15), the apparent mass M_a of the soluble sample in the liquid is given by

$$\frac{M_a}{M} = \left(1 - \frac{\rho_\ell}{\rho}\right) . \frac{(100-x^1)}{100} \tag{3.16}$$

Moisture Measurment with Moisture Balance

The moisture balance is an apparatus for obtaining the moisture content x by the ratio M_a/M, without measuring the mass of the sample.

Pan D is hung at point A on the arm of a balance fulcrum K, and versel R in water is hung at point B on the same arm of the balance as shown in Fig.3.14(a). The balance is put in equilibrium by auxiliary weight W^1, with no sample on the pan D or in the versel R.

The sample is placed on the pan D, a counterweight of adjustable mass w is hung at point P of the other arm of the balance, and then the balance is put in equilibrium by adjusting the mass w of the counterweight, as shown in Fig.3.14(b).

Let the distance of KA and KP be L and L_o respectively, then we have the relation

$$LM = L_o\ w \tag{3.17}$$

The sample is transferred from the pan D into the vessel R in water; the equilibrium of the balance is regained by changing the position of the counter weight w from the point P to point Q, as shown in Fig.3.14(c). Then we have

$$\ell_o\ M_a = \ell\ w \tag{3.18}$$

where ℓ_o and ℓ denote the distance KB and KQ respectively.

Combining Eqs.(3.17) and (3.18), we have

$$\frac{M_a}{M} = \frac{L}{\ell_o} \cdot \frac{\ell}{L} \tag{3.19}$$

and Eq.(3.19) gives, with Eq.(3.15)

$$\ell = \frac{\ell_o\ L_o}{L} \cdot \frac{(100-x)}{100} \cdot (1 - \frac{\rho_w}{\rho}) \tag{3.20}$$

The distance L is appointed to satisfy the relation

$$L = k(1 - \frac{\rho_w}{\rho}) \tag{3.21}$$

where k is an arbitrary proportional constant.

Putting L, given by Eq.(3.21), into Eq.(3.20), we have

$$\ell = \frac{\ell_o\ L_o}{k} \cdot \frac{(100-x)}{100}$$

or,

$$\ell = C(100-x) \tag{3.22}$$

where C is a proportionality constant.

Eq.(3.22) shows that ℓ varies proportionally to x and that the relation between ℓ and x is independent of the specific gravity of anhydrous sample.

For the sake of simplicity, it is assumed that

$$L_o = \ell_o = k$$

then Eq.(3.22) is rewritten in the form

$$\ell = \frac{L_o}{100} \cdot (100 - x) \tag{3.23}$$

In the case of water-soluble sample, taking ρ_ℓ and x' instead of ρ_w and x respectively, we have

$$\ell = \frac{L_o}{100} (100 - x') \tag{3.24}$$

Fig.3.15 shows the specific gravity scale and the moisture scale.

Merits

(i) Accurate measurment is possible.

(ii) The mass of the sample is arbitrary. It is unnecessary to measure the mass of the sample.

(iii) The measurment time is short (minutes).

(iv) The moisture balance provides a primary method of measuring moisture content.

Demerits

(i) The specific gravity of the anhydrous sample must be constant and known.

(ii) Continuous measurment is impossible.

(iii) Pores or voids in the sample which are not filled during the period of immersion prior to weighing in water causes an error.

3.8 MICROWAVE METHODS OF MOISTURE MEASURMENT(8,15,16)

3.8.1 A CHANGE IN ATTENUATION METHOD OF MOISTURE MEASURMENT

Principle of Operation

The principle of measuring attenuations (losses) at microwave frequencies, on which the method depends, is based on the fact that at centimeter wavelengths the loss tangent and dielectric constant of water are very high compared with those of most materials in which water is absorbed.

Theory

The loss of energy in a dielectric can be accounted for by considering the dielectric constant as a complex quantity of the form

$$\epsilon = \epsilon' - j\,\epsilon'' \qquad (3.25)$$

where

ϵ' = the real part of the dielectric.

ϵ'' = the imaginary part of the dielectric.

The loss tangent (or loss factor) is defined as

$$\tan\delta = \epsilon'' = \frac{\text{loss current}}{\text{charging current}} \qquad (3.26)$$

At normal temperatures in the frequency range 1 to 30 G.Hz the dielectric constant of water is between 40 and 80 and the loss tangent ranges from 0.15 to 1.2. Most dry materials have a dielectric constant ranging from 1 to 5 and a loss tangent between 0.001 and 0.05, unless some conducting material is present. Difference of the above order mean that the loss due to water is at least ten times greater than the loss in the material when no water is present.

Based on quantum-mechanical considerations, it is possible to calculate the relaxation frequency of the water molecules in the microwave region. The frequencies of absorption peaks are given by the relation:

$$f = \frac{1}{2\pi\tau} \qquad (3.27)$$

where

f = the frequency of electromagnetic radiation.

τ = the relaxation time of its molecular dipole.

Theoretically, τ is given by the following Debye's equation:

$$\tau = \frac{V\,3\,\eta}{KT} \qquad (3.28)$$

where

η = macroscopic viscosity of the liquid

V = the volume of a molecule of the liquid

K = the Boltzmann constant

T = the temperature (absolute scale)

Water at room temperature has a viscosity of about 0.01 P and the radius of molecule is 2 Å. Hence the value of τ of water is 0.25×10^{-10} sec. which corresponds to a wavelength of 1 cm.

In the case of water, it has been observed that the absorption band corresponds to a frequency of 2450 M Hz, which falls in the microwave region of the radio frequency spectrum.

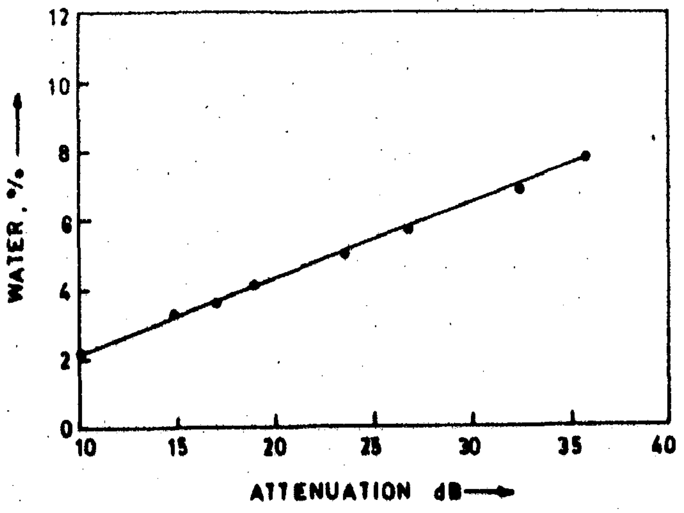


FIG. 3.16 _ CALIBRATION CURVE OF MOISTURE METER FOR PAPER SHEET.

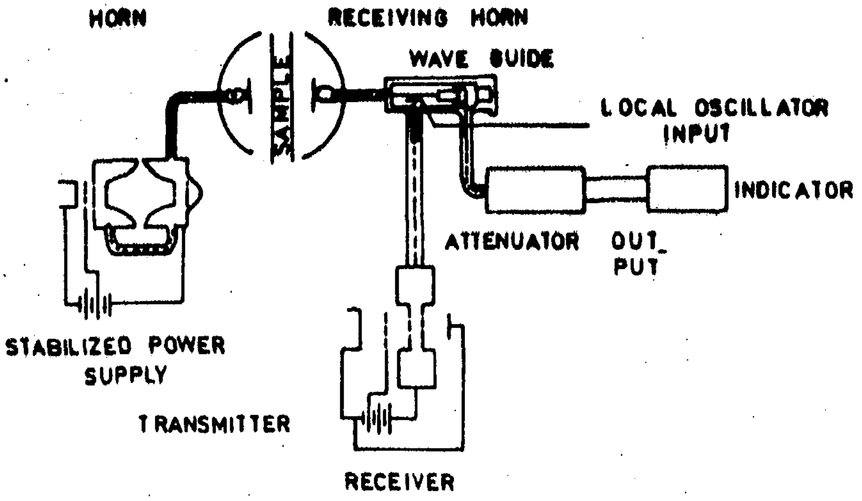


FIG. 3.17_ SCHEMATIC DIAGRAM OF A MICROWAVE METER (ATTENUATION TYPE)

Kinsey and Ellis reported that there is a linear relationship between the moisture content of hygroscopic materials and the absorption of microwaves having frequencies of 2450 M Hz (S band) and 10,680 M Hz (X band) as shown in Fig.3.16.

Description of the Equipment

The equipment consists of the following units:

(i) A constant source of microwave radiation of 2450 and 10,680 M Hz modulated by a square wave of 3 K Hz.

(ii) Wave guide terminating in a horn.

(iii) A micro-wave detector.

(iv) A microwave attenuator and amplifier.

(v) An indicating meter.

The experimental arrangment is shown in Fig.3.17. This is the usual transmitter-receiver combination, the specimen forming the absorbing medium. The commonly used source of microwave radiation is the reflex klystron oscillator. This oscillator gives a modulated power output of 0.5 watt and is coupled to a radiating horn by a quarter-wavelength waveguide system. The receiver consists of the receiving horn which is coupled to a 70-dB variable attenuator followed by crystal mixer, local oscillator, limiter, discriminator, and final amplifier. The moisture content value of the unknown sample is obtained from the calibration curve drawn earlier between attenuation readings and moisture content data obtained by standard oven drying method.

Merits

(i) Microwave absorption depends mainly on the moisture content and is not affected by the nature of the granular solid material.

(ii) The accuracy of this method lies between ± 2 and ± 3 %. of the actual amount of water present. Operational time is very less.

Demerits

The moisture meter readings are affected by the following factors:

(i) Leakage: If the size of test sample is smaller than the aperture of horn, leakage of energy takes place.

(ii) Particle size: Attenuation in granular material is due to two causes, the dielectric losses in the water and the scattering of the beam at the particular surfaces in the material. The scattered energy will be absorbed, but the degree of scattering, and hence the losses, depend on the particle size.

(iii) Polarization: The radiation from the moisture meter is polarized in one plane.

(iv) Soluble Salt Content: At low frequencies water shows an increase in loss when it contains dissolved salts, due to increased conductivity. Thus the variation of loss may occur with samples of different salt contents.

(v) Temperature: The loss factor of pure water decreases with increasing temperature. An individual calibration curve is required for particular temperature.

(vi) Frequency: The loss factor of pure water varies with the frequency, hence the measured attenuation is a function of frequency as well as of sample thickness.

3.8.2 AN IMPROVED MICROWAVE METHOD OF MOISTURE CONTENT MEASURMENT AND CONTROL

Kraszewski and Kulinski(16) described an improved method in which both the attenuation A and phase shift Ø of the electromagnetic waves are measured simultaneously and thus limits the demerits of the above method.

Theory

The definition of moisture content based on a wet basis is written as:

$$m_w = \frac{W_w}{W_o + W_w} = \frac{W_w/V}{\frac{W_o}{V} + \frac{W_w}{V}} \tag{3.29}$$

where

W_w = the weight of water.
W_o = the weight dry material.
V = the volume of the wet sample.

The density of wet material g may be written as:

$$g = \frac{W}{V} = \frac{W_o}{V} + \frac{W_w}{V} \tag{3.30}$$

where

$W = W_o + W_w$ = the weight of the wet sample.

Attenuation and phase shift of the electromagnetic wave passing through the sample of wet material are related to the thickness of the sample and to the dielectric properties of the material. The permitivity of the wet material is a function of its water content, density and physical properties. Thus, the measured value A and Ø may be presented in a general form

$$A = f_1(W_o, W_w) \quad \text{and} \quad Ø = f_2(W_o, W_w) \tag{3.31}$$

In the simplest case, when it may be assumed that the wet material is a homogeneous substance and that the attenuation A and phase shift Ø are linearly related to the weight of water and weight of dry substance, the case most often met inpractice, Eq. (3.31) may be written in the form

$$\begin{aligned} A &= t\left(\frac{W_w}{V} a_1 + \frac{W_o}{V} a_2\right), \\ Ø &= t\left(\frac{W_w}{V} a_3 + \frac{W_o}{V} a_4\right) \end{aligned} \tag{3.32}$$

where t denotes the thickness of the material layer, numerical coefficients a_n are specific for a particular material and its physical properties, A is the attenuation of the wet layer in dB and Ø is the phase shift in degrees. The numerical coefficients a_n are given for a volume of 1 cm^3, because the values of W_w/V and W_o/V are also referred to this volume.

By solving the Eq. (3.32), the following relations may be obtained

$$\begin{aligned} \frac{W_w}{V} &= \frac{1}{t}\left(\frac{A\ a_4 - Ø\ a_2}{a_1\ a_4 - a_2\ a_3}\right) \\ \frac{W_o}{V} &= \frac{1}{t}\left(\frac{Ø\ a_1 - A\ a_3}{a_1\ a_4 - a_2\ a_3}\right) \end{aligned} \tag{3.33}$$

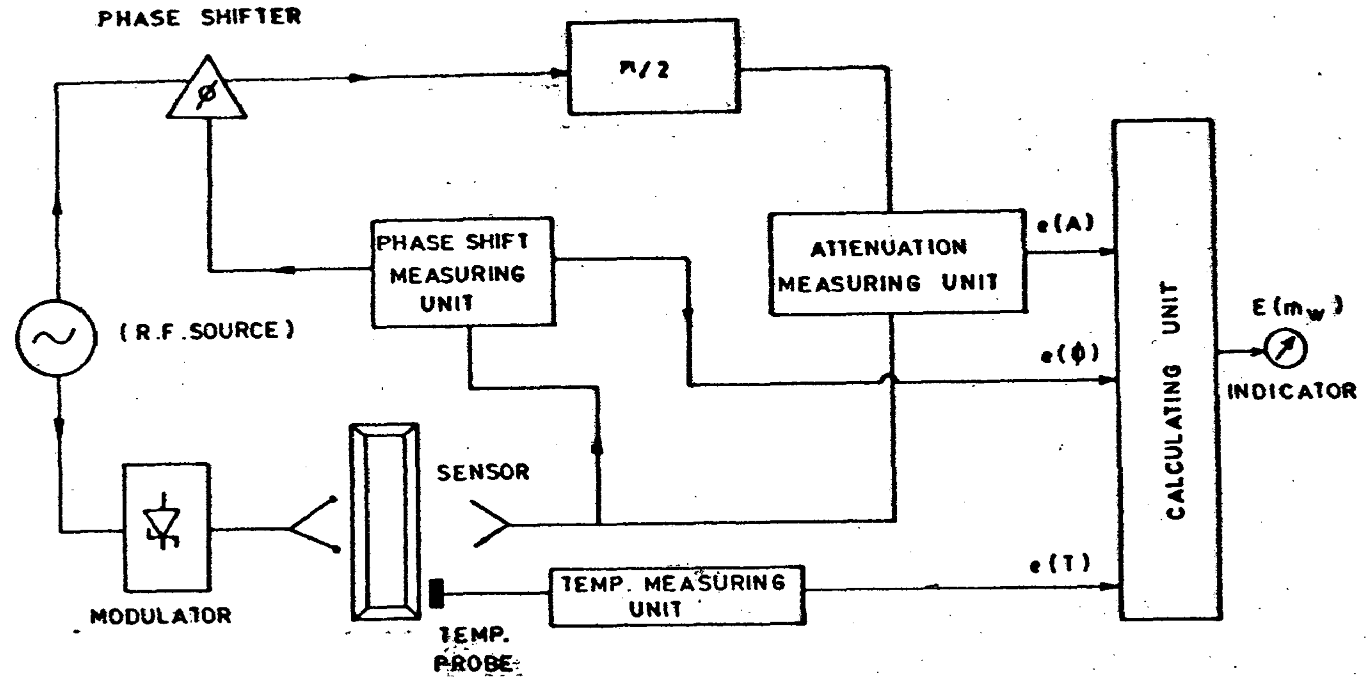


FIG. 3.18_ BLOCK DIAGRAM OF THE TWO PARAMETERS MEASURING SET UP WITH A CALCULATING UNIT AND TEMP. COMPENSATING DEVICE.

By substitution of Eq.(3.33) into Eq.(3.29), the simple expression for moisture content may be written as

$$m_w = \frac{A\, a_4 - \emptyset\, a_2}{\emptyset(a_1 - a_2) - A(a_3 - a_4)} \qquad (3.34)$$

It may be seen from the above expression that the moisture content determined according to this expression does not depend upon either thickness of the material or upon density of the material.

The values of a_n calculated for a sample (sand) at temperature of 20° and at frequency of 9.4 G Hz are as follows:

$$a_1 = 299.27\ ,\ a_2 = -1.42\ ,\ a_3 = 8177.43\ ,\ a_4 = 421.35$$

Substituting these values in Eq.(3.34), we have

$$m_w = \frac{4.21\ A + 0.014\ \emptyset}{3.01\ \emptyset - 77.56\ A} \qquad (3.35)$$

where

A = the attenuation of sample (in dB)
Ø = the phase shift introduced by sample.

A block diagram of complete measuring system is given in Fig.3.18. Inclusion of a thermometer probe sensing the material temperature to the calculating unit enables the correction of a_n values, according to the material temperature. The purpose of the calculating unit is continuous calculation of moisture content according to Eq.(3.35). The output of this unit is independent upon density of wet material, upon its layer thickness and upon its temperature.

This method has the limitation with the phase shift. In the case, where considerable changes of phase shift are introduced by wet material under test (when $\phi > 2\pi$), inaccuracy of the calculation of moisture content could be very high and might hide the advantages of this method.

3.9 N.M.R. METHOD OF MOISTURE MEASURMENT (8,12V)

Nuclear magnetic resonance (NM.R) is a new non-destructive method of moisture measurment in which the nuclear magnetism of the hydrogen atom is utilized. The nuclear magnetism of hydrogen is a useful property for the identification and quantitative analysis of hydrogen containing compounds in liquids or solids. The N.M.R. method of moisture measurment is quite unique in the sense that it is based on nuclear properties of the hydrogen atoms in water rather than on properties of the water molecule itself. The N.M.R. technique is based on the absorption of radio frequency energy by the nucleus of an atom placed in the constant magnetic field. The N.M.R. technique has a number of applications in industry and research connected with product identification in chemical analysis, as well as the measurment of the moisture content of hygroscopic materials.

Theory

N.M.R. depends for its existence upon the fact that most isotopes of the elements possess gyromagnetic properties i.e. they behave like spinning bar magnets. Some of atoms are: hydrogen, lithium, boron, carbon, nitrogen etc. The gyromagnetic property of the atom is the basis of the phenomenon of nuclear magnetic resonance which can be explained by the Larmor Precession Theorem.

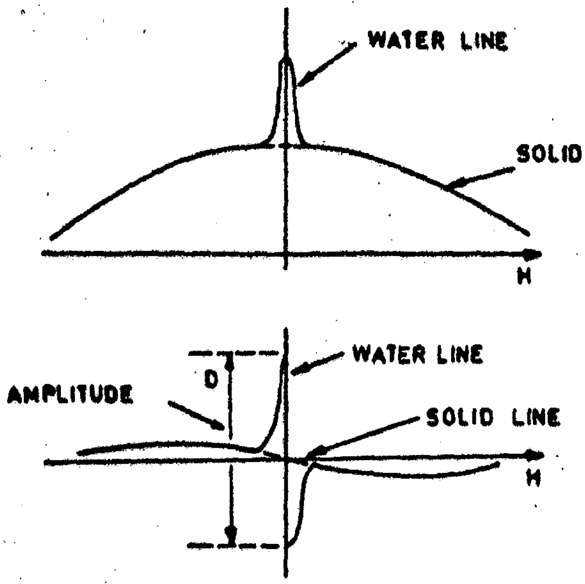
If these nuclei which have a magnetic moment and a spin 'I' are placed in a homogeneous magnetic field H, they behave like minute magnets having random orientations and allign themselves, depending upon the particular nuclei (e.g. hydrogen nuclei), either parallel or antiparallel to the direction of applied magnetic field. Larmor showed that the angular frequency of precession was directly proportional to H. The constant of proportionality is the ratio of magnetic moment of the spinning bar magnet to its angular momentum, called as the gyromagnetic ratio, v. Therefore, the Larmor Precession Theorem can be stated as follows

$$W_o = v\,H \qquad (3.36)$$

where

W_o = angular precession (Larmor) frequency
H = intensity of homogeneous magnetic field
v = gyromagnetic ratio

If these precessing nuclei are now subjected to a ratio frequency field placed at right angle to the applied magnetic field H, and if the radio frequency and Larmor W_o are equal, resonance occurs and the radio frequency energy is absorbed by the nuclei in proportion to their number. The quantity of radio frequency absorbed gives a measure of the abundance of hydrogen nuclei which in turn can be used as a measure of moisture content in a sample. The magnetic moment of the proton (H^+) is 1.4×10^{-23} ergs/g and thus for a magnetic field of 10,000 gauss,



TYPICAL OBSORPTION AND DERIVATIVE NMR CURVES OF A MATERIAL CONTAINING BOTH SOLID AND LIQUID.

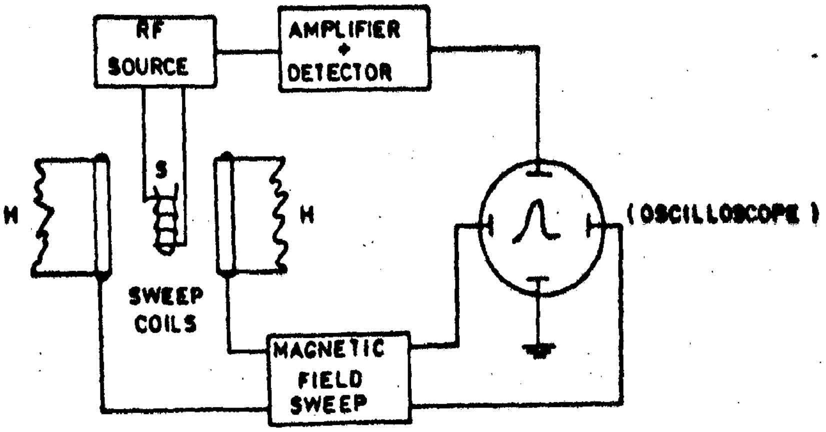
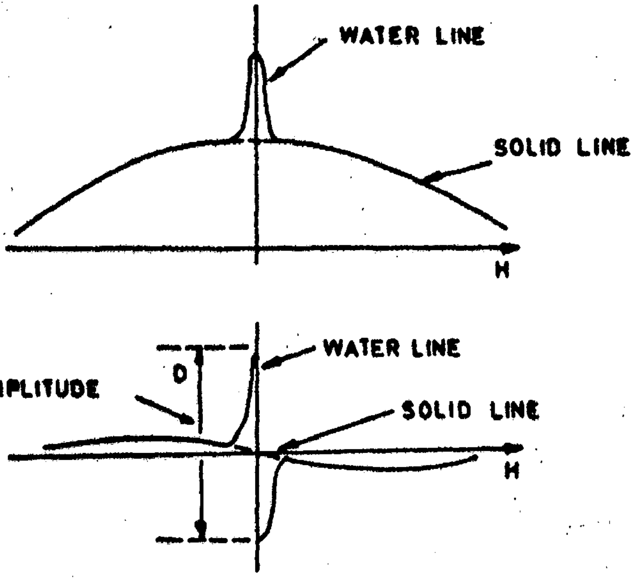


FIG. 3.19_SCHEMATIC DIAGRAM FOR THE MEASUREMENT OF NMR ABSORPTION FOR MOISTURE MEASURMENT.



TYPICAL OBSORPTION AND DERIVATIVE NMR CURVES OF A MATERIAL CONTAINING BOTH SOLID AND LIQUID.

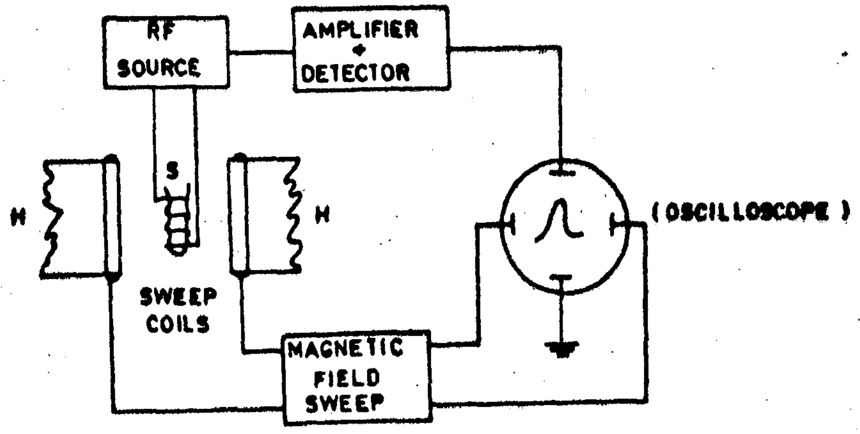


FIG. 3.19 _ SCHEMATIC DIAGRAM FOR THE MEASUREMENT OF NMR ABSORPTION FOR MOISTURE MEASURMENT.

the Larmor frequency W_o equals 42.4 M Hz which (W_o) can be generated by standard electronic techniques.

An Experimental N.M.R. Spectrometer

The experimental NMR apparatus developed by Leane is described in Fig. 3.19. The apparatus consists essentially of four units:

(i) A magnet capable of producing a very strong homogeneous magnetic field.

(ii) A means of continuously varying the magnetic field over a very small range.

(iii) A radio-frequency oscillator.

(iv) A radio-frequency reciever or detector.

(i) The Magnet

Both permanent and electromagnets are employed in N.M.R. spectroscopy. Leane used a permanent magnet having a magnetic field of 7000 G. The magnet had a square yoke of large dimensions to minimize the effects of external magnetic disturbances. The temperature of the poles was maintained almost constant at 27°C. It is desirable that the strength of this field should be as high as is practically possible because higher the field strength, better is the dispersion of the spectrum. High field strength gives rise to stronger absorption signals.

(ii) Magnetic Field Sweep System

The precessional frequency of the nucleus can be effected by varying the strength of the applied static magnetic field whereas the rotational frequency of the rotating magnetic field can be determined by varying the frequency of the rf-oscillator. The sweeping or scanning of the static field may be accomplished in two ways. First, it is possible to apply direct current to coils wound on the two pole pieces of the magnet. In the second method a direct current is fed to a pair of Helmholtz coils which flank the sample with their axes parallel to the direction of the static field. Either method allows the effective value of H to be varied over a small range. Scan time was varied from 6.1 sec. to 45 min. by Leane, and the range of scan was kept from 5 m G to 5 G.

(iii) Radio-Frequency Oscillator (Generator)

In order to induce a nuclear transition it is necessary to provide a rotating electromagnetic field, the magnetic component of which moves in a plane perpendicular to the direction of the applied magnetic field. A radio frequency oscillator capable of generating a signal of constant frequency but variable power is the source of radiant energy. A GT-cut 100-K Hz quartz crystal maintained at a constant temperature is used as the source of energy. This signal is fed to a coil situated in the pole gap of the magnet, with its axis perpendicular to the direction of the magnetic field. Such an arrangment provides for a magnetic component of electromagnetic field to rotate in a plane at right angles to the main field direction.

(iv) Radio-Frequency Reciever or Detector

The passage of radiation through the magnetized sample is associated with two phenomena, namely, absorption and dispersion. The observation of either dispersion or absorption enables the determination of resonance frequency. The function of the detector is two fold: First, it must separate the absorption signal from the dispersion signal; and second, it must separate the absorption signal from that originating from the rf-oscillator. Detector requires the use of a radio-frequency bridge which functions as a wheatstone bridge. The bridge network balances out the oscillator signal and allows the absorption or dispersion signal to appear as an out of balance signal electromotive force across the bridge. The out of balance signal can be amplified and rectified, and recorded or displayed on an oscilloscope.

Merits

(i) The NMR method of moisture determination is rapid, non-destructive, and presents the results in the form of an electrical signal which can be used to control automatically driers or blenders in the manufacturing plant.

(ii) This method does not depend on the sample size, compaction, or on the presence of moderate amounts of nonparamagnetic electrolytes.

(iii) Powdered materials and whole grains can be handled with equal facility.

(iv) No special precaution is required for preparing the test sample.

(v) This method is useful over the entire moisture range of a few percent to 100 % water.

Demerits

(i) Cost of equipment is high compared to that of other devices for measuring water content.

(ii) This method does not give a single standard curve for all types of materials.

(iii) The instrument is complex and requires skilled electronic technicians for its operation and maintenance.

CHAPTER - 4

DEVELOPMENT OF AN ON-LINE PAPER MOISTURE METER

4.1 PRINCIPLE OF OPERATION

The principle of operation of this moisture meter is based on the change occurring in the paper resistance between its moist and dry conditions. The resistance value of the dry paper is very high. Moisture decreases the resistance of the paper and this decrease is exponential in nature. The resistance of the paper varies from about 25 K Ω to 50 M Ω for various papers with various moisture contents(1). The useful range of resistance variation is from 1 to 3 M Ω for commercial papers when the moisture varies from 15-20 % to 6-8 % . Therefore, presence of a very small quantity of water in the paper causes considerable change in the resistance of the paper and it is this property of resistance variation which has been used in the moisture measuring instrument.

The change in resistance is sensed by a resistive transducer in terms of resistance. The resistive transducer forms one of the arms of the wheatstone bridge. The unbalanced signal caused by the change in resistance of the transducer due to moisture content of the sample is amplified and measured by a suitable voltmeter. This voltmeter reading shows a direct

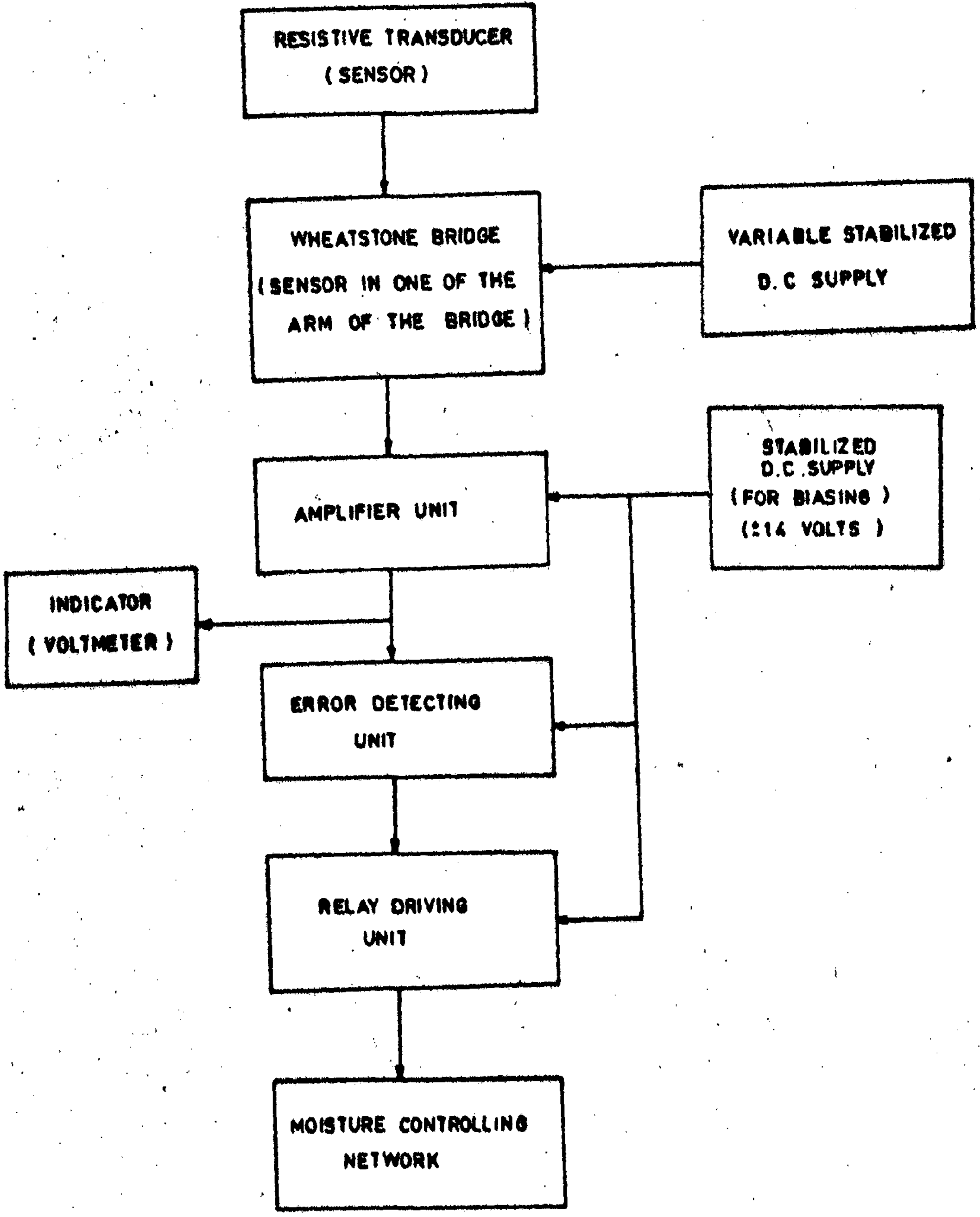


FIG. 4.1_ BLOCK DIAGRAM OF RESISTIVE MOISTURE METER.

relationship with the change in resistance, and hence with the moisture content of the paper.

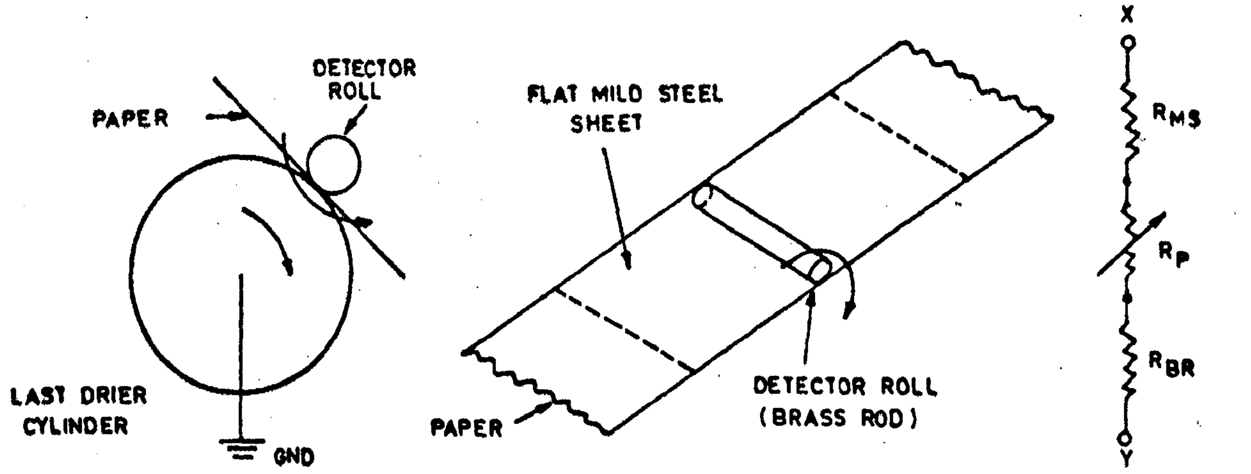
To control the moisture content of the paper, this measured signal (voltage) of the measuring circuit is compared with a reference voltage which is fixed for a particular percentage of moisture content. An output signal is obtained by the comparator depending upon the error signal caused by the comparison of both the measured and reference voltages which in turn either regulates the steam input to the drier or machine speed within predetermined limitations (relay action represents the controlling action for laboratory purpose).

4.2 SCHEME OF THE MOISTURE METER

The block diagram of the resistive moisture meter developed by the author is shown in Fig.4.1. This block diagram is applicable to all the three resistive moisture meters developed in different phases. It has the following units:

(i) Resistive Transducer.
(ii) Electronic Circuit:
  (a) Wheatstone bridge with supply.
  (b) Amplifier unit.
  (c) Error detecting unit.
  (d) Relay driving unit.
  (e) Stabilized d.c. supply for biasing (± 14 volts).
(iii) Indicator.

Details of each block, including design are discussed below individually.



(a) UNDER WORKING CONDITION IN THE PAPER M/C

(b) UNDER LABORATORY CONDITION

(c) ELECT. EQUIVALENT CIRCUIT

FIG.4.2_TRANSDUCER FOR RESISTIVE MOISTURE METER.

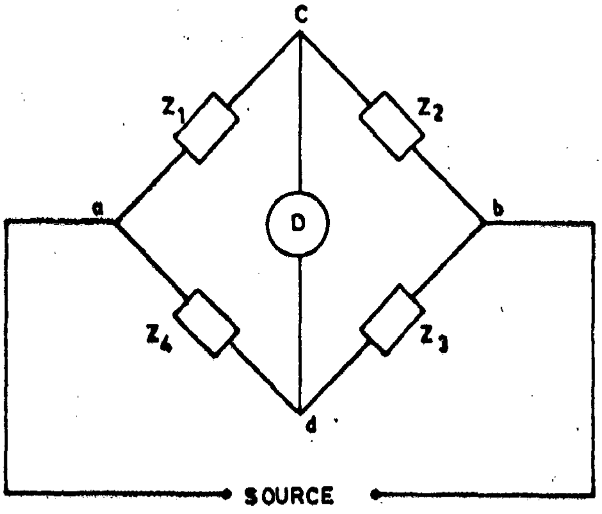


FIG.4.3_GENERAL FORM OF FOUR ARM W.STONE BRIDGE.

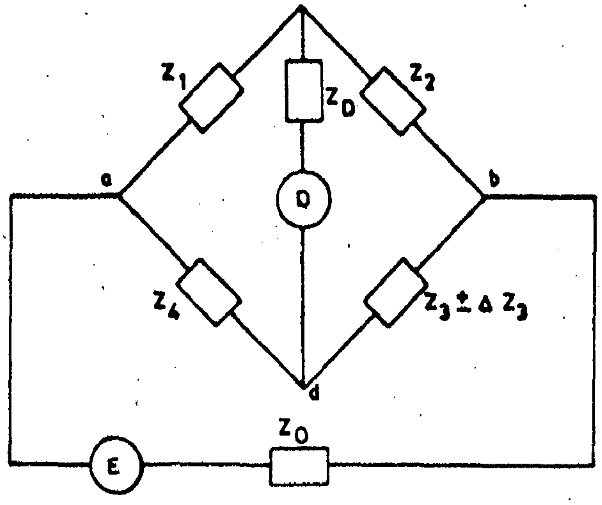


FIG.4.4_W.STONE BRIDGE FOR SENSITIVITY ANALYSIS.

4.2.1 RESISTIVE TRANSDUCER (SENSOR)

To simulate the actual situation in the laboratory conditions, a flat mild steel plate is used in place of the drier surface and a brass rod is used as the detecting rollor, as shown in Fig.4.2. In this scheme the drying cylinder and the detector roll will act as the two electrodes between which the paper moves. The arrangment is made such that the paper, which passes through both the electrodes behaves as a variable resistance with the variation of the moisture in the paper. From Fig.4.2

$$R_{XY} = R_{MS} + R_P + R_{BR}$$

where

R_{XY} = Total resistance between the terminals X and Y.

R_{MS} = Resistance of mild steel plant.

R_P = Resistance of paper (variable) in contact with both the electrodes.

R_{BR} = Resistance of the brass rod.

To minimize errors, paper between both the electrodes should move in a manner such that there is only the paper between the drying cylinder surface and detector roll without any air gap and also the detector roll should not touch the drying cylinder at any place. To achieve this condition, detecting roller should be heavy enough to press the paper against the grounded cylinder without effecting its physical properties and it should be able to make proper contact with the paper without leaving any air bubble in the paper.

Design (From Fig. 4.2)

$$R_{XY} = R_{MS} + R_P + R_{BR}$$

$$R_{MS} \ll R_P \quad \text{and} \quad R_{BR} \ll R_P$$

$$\therefore R_{XY} \simeq R_P$$

Mild steel plate (Grounded cylinder):

Surface Area = 30×25 cm.^{2}

Thickness of the sheet = 0.1 cm.

Resistivity of iron = 12 $\mu\Omega$ - cm.

Therefore, the resistance of the mild steel plate (R_{MS}) is approximately 150 $\mu\Omega$.

Brass Rod (Detecting roller):

Length of the rod = 28 cm.

Diameter of the rod = 2.1 cm.

Resistivity of brass $\simeq$ 50 $\mu\Omega$- cm. (depending upon the ratio of Cu and Zn).

Cross-sectional area of the rod = πr^2

= 3.464 cm.^{2}

Therefore, the resistance of the brass rod (R_{BR}) is approximately 400 $\mu\Omega$.

4.2.2 WHEAT STONE BRIDGE(17,18)

The general form of four-arm wheat stone bridge is shown in Fig. 4.3. From Fig. 4.3, the general balance equation of a general four-arm wheat stone bridge will be:

$$Z_1 . Z_3 = Z_2 . Z_4 \qquad (4.1)$$

In the polar form, $Z = |Z| \, e^{j\phi}$

where $|Z|$ represents the magnitude of a complex impedence, and ϕ its phase angle.

Therefore, Eq.(4.1) becomes:

$$|Z_1 \; Z_3| \; e^{j(\phi_1+\phi_3)} = |Z_2 \; Z_4| \; e^{j(\phi_2+\phi_4)} \qquad (4.2)$$

To satisfy this relationship, it is essential that

$$\left.\begin{aligned} &|Z_1 \; Z_3| = |Z_2 \; Z_4| \; ; \\ \text{and} \quad &(\phi_1+\phi_3) = (\phi_2+\phi_4) \end{aligned}\right\} \qquad (4.3)$$

Sensitivity

There are two types of voltage sensitivities: absolute and relative, defined below:

(i) Absolute voltage sensitivity, $S_V = \lim\limits_{|\Delta Z| \to o} \Delta V_{cd} | \Delta Z$ (4.4)

(ii) Relative voltage sensitivity, $$\left.\begin{aligned} S_V^o &= \lim_{|\Delta Z| \to o} \Delta V_{cd} | (\Delta Z/Z) \\ &= S_V . Z \end{aligned}\right\} \qquad (4.5)$$

where, ΔV_{cd} = Vector of change in voltage across detector circuit.

To determine these sensitivities, consider the bridge (Fig.4.4) thrown out of balance by a small change in the impedence (say ΔZ_3) of an arm (say Z_3)

when $$\Delta Z_3 \ll Z_3$$

$$\frac{\Delta Z_3}{Z_3} = \delta Z_3$$

where, δZ_3 = Unbalance factor

At balance, $Z_1 . Z_3 = Z_2 . Z_4$

$$\frac{Z_1}{Z_2} = \frac{Z_4}{Z_3} = A \qquad (4.6)$$

where, A = Arm ratio

$$\Delta V_{cd} = Vab \frac{Z_1(Z_3 + \Delta Z_3) - Z_2 Z_4}{(Z_1+Z_2)[(Z_3+\Delta Z_3)+Z_4]} \qquad (4.7)$$

At near balance condition

$$\Delta V_{cd} = V_{ab} . \delta Z_3 . \frac{A}{(1+A)^2} \qquad (4.8)$$

$$S_V^o = \frac{\Delta V_{cd}}{\delta Z_3} = V_{ab} . \frac{A}{(1+A)^2} \qquad (4.9)$$

If Eq.(4.9) is rearranged for ΔV_{cd}:

$$\Delta V_{cd} = S_V^o . \delta Z_3 = \delta Z.K.V_{ab} \qquad (4.10)$$

where, $K = \frac{A}{(1+A)^2}$ = Network factor

In the polar form, $A = d + jq = a e^{j\theta}$. We get:

$$K = \frac{a}{(1 + 2 a \cos \theta + a^2)} \qquad (4.11)$$

Design (From Fig.4.3)

For resistive wheat stone bridge, Z = R

Therefore, $R_1 . R_3 = R_2 . R_4$

Since, the resistance of paper varies from 1.0 to 3.0 M Ω when its moisture content varies from 15-20 % to 6-8 %, therefore, all the four arms of the wheat stone bridge should have the approximate 1 M Ω resistance value at the initial balance condition such that the condition $R_1 . R_3 = R_2 . R_4$ may be achieved.

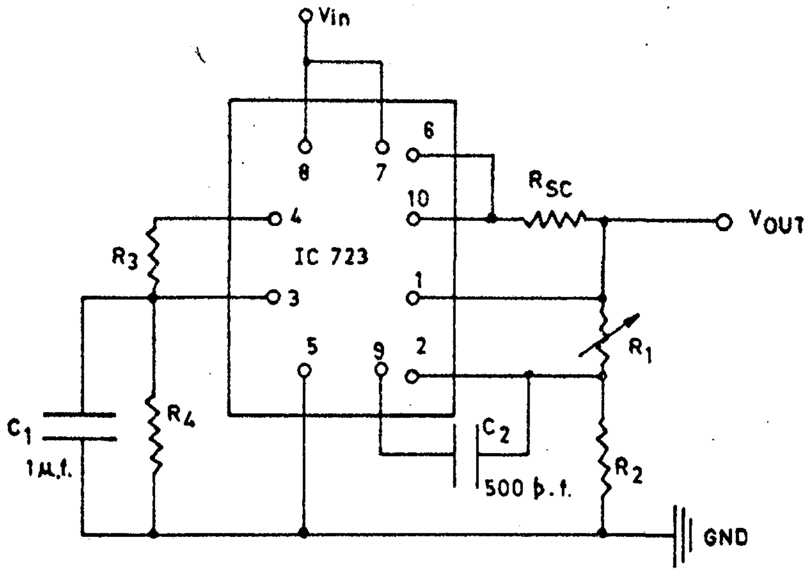


FIG.4.5_VARIABLE STABILIZED D.C. SUPPLY (USING I.C.723).

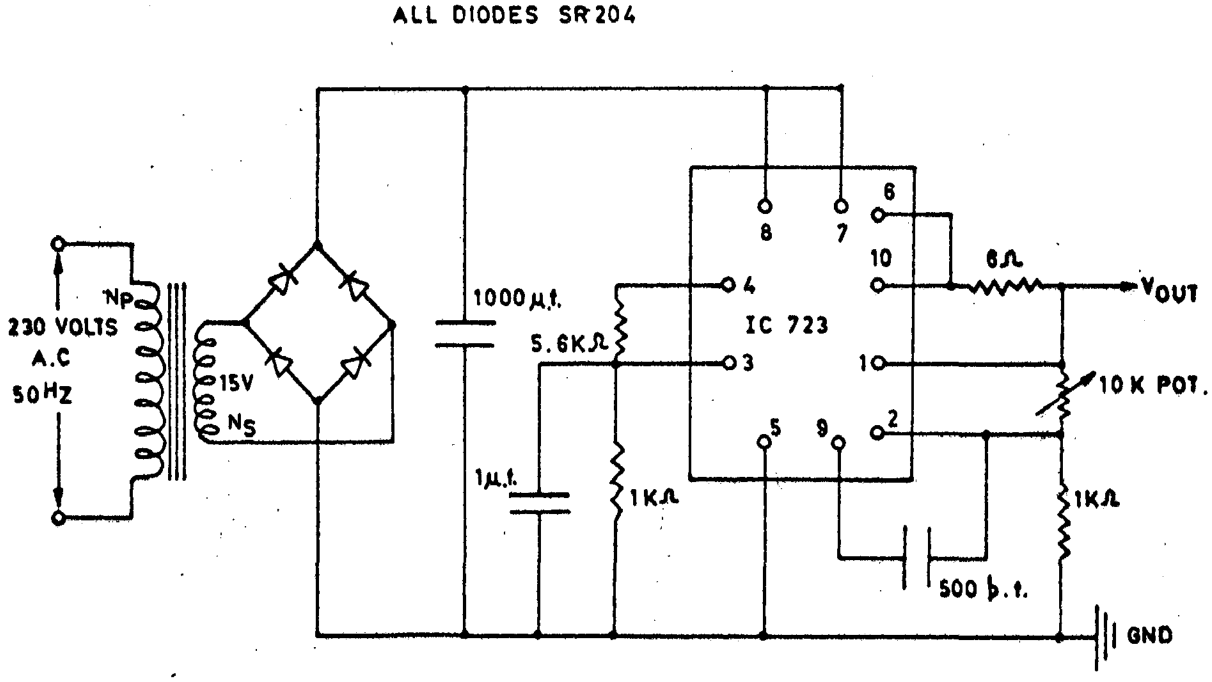


FIG.4.6_ CIRCUIT DIAGRAM OF VARIABLE STABILIZED D.C. SUPPLY (2-10V).

The final values are

R_1 = 1 MΩ + 10 KΩ preset

R_2 = 1 MΩ + 10 KΩ preset

R_3 = Resistive transducer unit + 10 KΩ preset

R_4 = 1 MΩ + 10 KΩ preset

Presets are used to achieve zero balance condition. From Fig.4.4:

$$\frac{R_1}{R_2} = \frac{R_4}{R_3} = A = 1.0$$

Therefore, $a = 1.0$ and $\theta = 0$

From Eq.(4.11), $K = .25$

$$\therefore \quad \Delta V_{cd} = .25\ \delta R\ V_{ab} \qquad (4.12)$$

where, V_{ab} is the variable stabilized d.c. supply for the bridge excitation, applied across the terminals a and b of the bridge circuit.

4.2.3 REGULATED D.C. SUPPLY FOR BRIDGE

The circuit diagram for variable stabilized d.c. supply using IC 723 (regulator) is shown in Fig.4.5.

Design (From Fig.4.5)

V_{Zener} (given) = 7 V

Variation required = 2V - 10 V

Short circuit current I_{sc} = 100 mA

Take $V_{ref} = 1.0$ V

$V_{ref} = 7 \times R_4/(R_3+R_4)$

$$\text{or } 1.0 = 7.0 \times \frac{R_4}{R_3 + R_4}$$

Take $R_4 = 1.0\ K\Omega$

Therefore,

$R_3 + 1.0 = 7.0$ or $R_3 = 6.0\ K\Omega$

$$R_{SC} \text{ (Short circuit resistance)} = \frac{V_{BE}}{I_{SC}} = \frac{0.6}{100 \times 10^{-3}}$$

$$\text{or } R_{SC} = 6\ \Omega$$

where, V_{BE} = Voltage drop across base to emitter.

$$V_{out} = V_{ref} \cdot \frac{(R_1 + R_2)}{R_2}, \quad R_2 = 1.0\ K\Omega \text{ (say)}$$

when $R_1 = 0$; $V_{out} = V_{ref}$

$$V_{out} = 1.0\ V$$

when $R_1 = 10.0\ K\Omega$; $V_{out} = 1.0 \times \frac{10.0 + 1.0}{1.0}$

$$= 11.0\ V$$

Therefore, the final values are:

$R_1 = 10.0\ K\Omega$ Pot., $R_2 = 1.0\ K\Omega$, $R_3 = 5.6\ K\Omega$,

$R_4 = 1.0\ K\Omega$, $R_{SC} = 6.0\ \Omega$, $C_1 = 1\ \mu$.f., $C_2 = 500$ p.f.

Transformer Design

To get the variable stabilized d.c. supply for bridge circuit, a transformer (230/15 Volts) is designed with the following specifications:

Stamping size = 15 no.

Primary voltage = 230 (P to P)

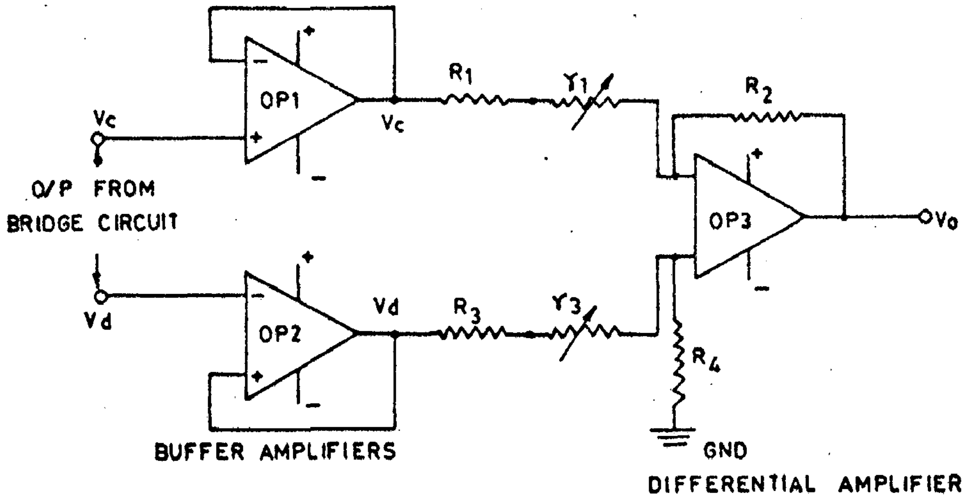


FIG. 4.7_ AMPLIFIER UNIT.

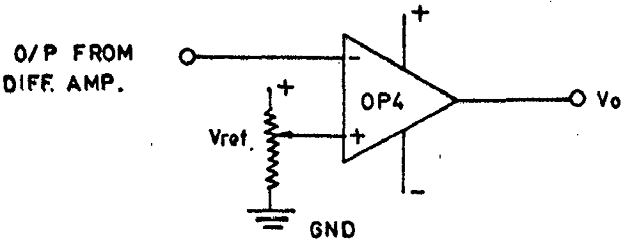


FIG. 4.8_ERROR DETECTING UNIT.

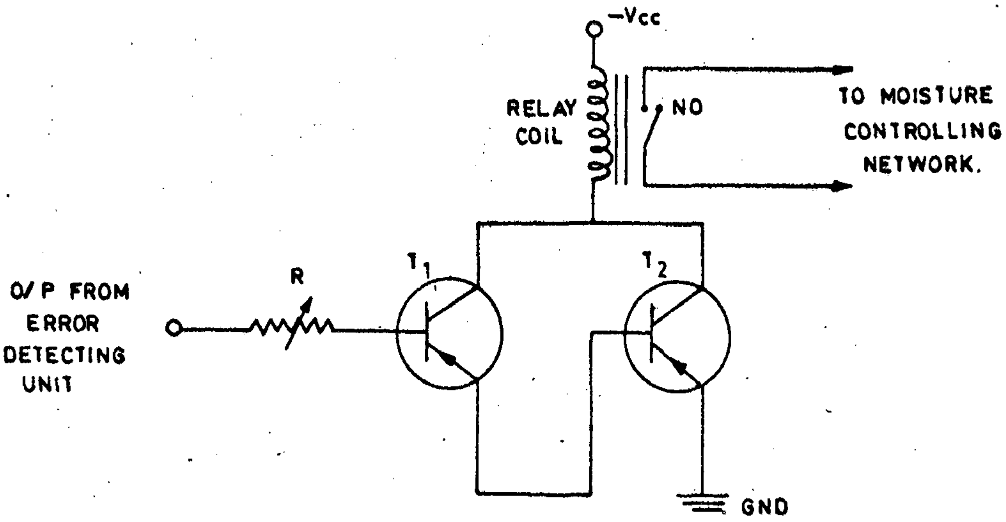


FIG. 4.9_RELAY DRIVING UNIT.

Secondary voltage = 15 (P to P)

Take $\phi = 1.2\ \mathrm{Wb/m^2}$

$$E_S = 4.44\,f.B.A.N_S$$

$$15 = 4.44 \times 50 \times 12 \times 2.5 \times 2.5 \times 10^{-4} \times N_S$$

$$N_S = 90$$

$$N_P = \frac{230}{15} \times 90$$

$$= 1380$$

Maximum secondary current = 100 mA.

Hence, wire gauge of secondary winding = 32 SWG.

Primary current $= \frac{15}{230} \times 100 \simeq 10$ mA.

Hence, gauge for primary winding = 43 SWG.

Vin, in Fig.4.5 is the unstabilized d.c. voltage, is obtained from the full wave rectifier circuit. 4 no. SR 204 diodes and one 1000 p.f. capacitor are used with the secondary of the transformer to get the unstabilized d.c. supply which is fed at the terminal no.8 of IC 723 . A complete circuit diagram of variable stabilized d.c. supply (2V to 10V) is shown in Fig.4.6.

4.2.4 AMPLIFIER UNIT(19)

An amplifier unit, shown in Fig.4.7 consists of buffer amplifiers and a differential amplifier. OP1 and OP2 are the buffer amplifiers to avoid any loading of the signals picked up from the c and d points of the bridge network. Buffer amplifiers are used in unity gain as voltage follower. Differential amplifier uses only one OP. AMP. (OP3) which is differential-input single-ended output instrumentation amplifier. From Fig.4.7

$$\text{If } \frac{R_2}{R_1 + r_1} = \frac{R_4}{R_3 + r_3} = n$$

$$\text{then, } V_o = n(V_c - V_d) \qquad (4.13)$$

Design (From Fig.4.7)

$R_2 = R_4 = 33.0\ \text{K}\Omega$ (say)

$R_1 = R_3 = 1.0\ \text{K}\Omega$

$r_1 = r_3 = 10.0\ \text{K}\Omega$ preset.

When, $r_1 = r_3 = 0;\ n = \frac{33.0}{1.0} = 33$

$r_1 = r_3 = 10.0\ \text{K}\Omega;\ n = \frac{33.0}{1.0 + 10.0} = 3$

Therefore, the gain of the differential amplifier can be adjusted anywhere in between 3 to 33.

4.2.5 ERROR DETECTING UNIT

It is a simple comparator which uses only one OP. AMP. and compares the two input signals (Fig.4.8). One of the input signals is the output obtained from the differential amplifier and is fed at the inverting terminal (2) of OP4. The other signal is the adjustable reference supply fed at the non-inverting terminal (3) of OP4. Both the input signals are compared and depending upon the error, an output signal is issued which in turn is used to drive the relay circuit for the controlling action.

Variable reference supply, $V_{ref.}$, is tapped from the IC 741 biasing supply (+14 Volts) through a 10K Ω linear Pot.

V_{ref} varies in the range of 0-14 volts. To control the moisture content of the paper sheet, V_{ref} can be adjusted at a particular value (from the calibration curve) for a predetermined value of moisture content.

4.2.6 RELAY DRIVING UNIT

The signal issued from the error detecting unit is not capable enough to drive the relay winding. Relay is used to represent the controlling action to control the moisture content of the paper sheet at the desired value. In actual practice, the control of moisture content is achieved either by regulating the machine speed or the steam input to the drying cylinders.

To drive the relay, the signal (current value) issued from the error detecting unit is strengthened (amplified) by using a darlington pair which consists of two cascaded emitter follower, shown in Fig.4.9.

For darlington pair, current gain (A_I):

$$A_I = A_{I1} \times A_{I2} \qquad (4.14)$$

where, A_{I1} and A_{I2} are the respective current gain of transistor T_1 and T_2.

Design (From Fig.4.9)

Relay: Electromagnetic type (12 volts d.c.)

Coil current = 80 mA.

Contact current = 1 Amp.

To drive the relay, following two transistors are used:

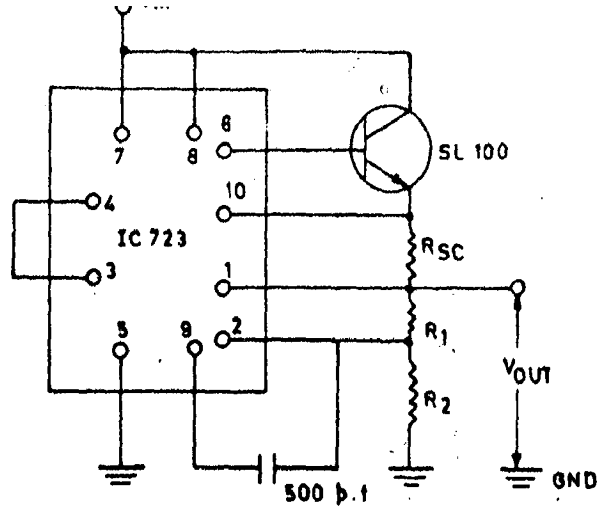


FIG.4.10_OP. AMP. EXCITATION SUPPLY USING IC 723 VOLTAGE REGULATOR AND SL 100 TRANSISTOR.

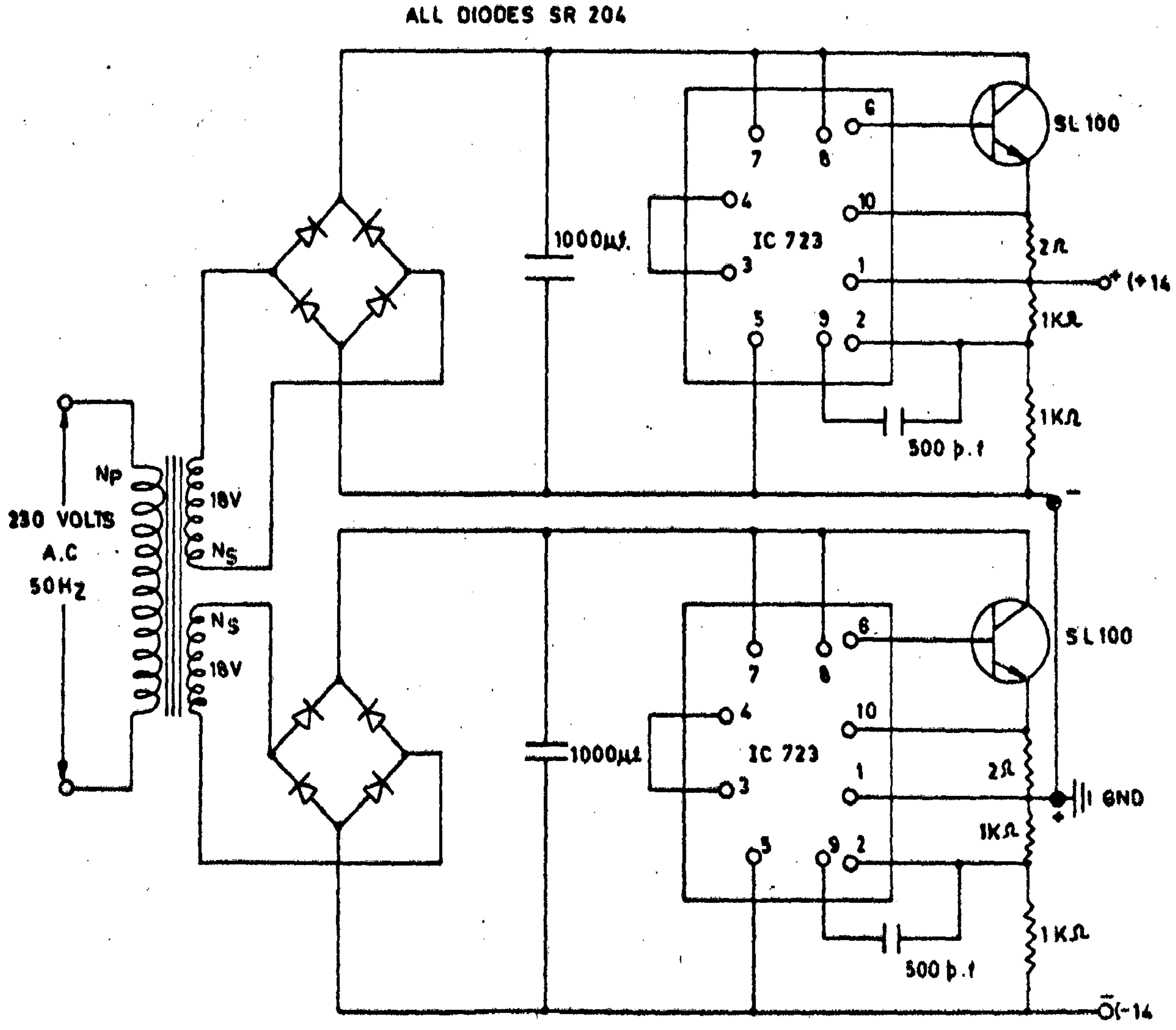


FIG. 4.11_OP. AMP. EXCITATION SUPPLY(±14V D.C. STABILIZED).

T_1 = SF 103 (PNP), $I_{c(Max.)}$ = 150 mA, h_{fe} = 50/280

T_2 = SK 100 (PNP), $I_{c(Max.)}$ = 500 mA, h_{fe} = 50/300

R = 10 KΩ preset (to regulate the current)

4.2.7 STABILIZED D.C. SUPPLY FOR BIASING (± 14 VOLTS)

A d.c. stabilized supply of ± 14 V is required for operational amplifiers. For this purpose two voltage regulators (723) are used.

Design: Circuit diagram using 723 regulator and SL 100 transistor is shown in Fig.4.10.

$$V_{out} = V_{ref} \cdot \frac{R_1 + R_2}{R_2}$$

V_{ref} = 7 V (given)

V_{out} = 14 V

$$14 = 7 \times \frac{R_1 + R_2}{R_2}$$

or $2R_2 = R_1 + R_2$ or $R_2 = R_1$

Take $R_2 = R_1 = 1K\Omega$

Let short circuit current, I_{SC} = 400 mA.

$$\therefore R_{SC} = \frac{V_{BE}}{400 \text{ mA}}$$

$$= \frac{0.6}{400 \times 10^{-3}} = 1.5 \ \Omega$$

Transistor used is SL 100.

Transformer Design

Transformer for dual power supply of OP. AMP. is designed with the following specifications:

Stamping size = 15 no.

Primary voltage = 230 (P to P)

Secondary voltage = 18V-0-18V (P to P)

To get dual out put, one primary and two secondary windings (i.e. central tap) are wound. Take Ø = 1.2 Wb/m^2

$$E_S = 4.44 \times f \cdot B \cdot A \cdot N_S$$

$$36 = 4.44 \times 50 \times 1.2 \times 2.5 \times 2.5 \times 10^{-4} \times N_S$$

$$N_S = 216$$

$$N_P = \frac{230}{36} \times 216$$

$$= 1380$$

Maximum secondary current = 250 mA.

Hence, wire gauge of secondary wdg. = 27 SWG.

Primary current = $\frac{36}{230} \times 250 \simeq 40$ mA.

Hence, gauge for primary wdg. = 38 SWG.

The 18 Volts secondary voltage of the transformer gives the unstabilized d.c. voltage of 16 Volts with SR 204 diodes and 1000 μ.f. capacitor. This unstabilized voltage, when applied at terminal 8 (Vin) of IC 723, gives the stabilized 14 Volts d.c. supply. A complete circuit diagram of stabilized dual d.c. supply (± 14 V) is shown in Fig.4.11.

4.2.8 INDICATOR

A 0-20 Volts d.c. voltmeter is used for the indication purpose. This voltmeter is calibrated in terms of the moisture content of the paper sample.

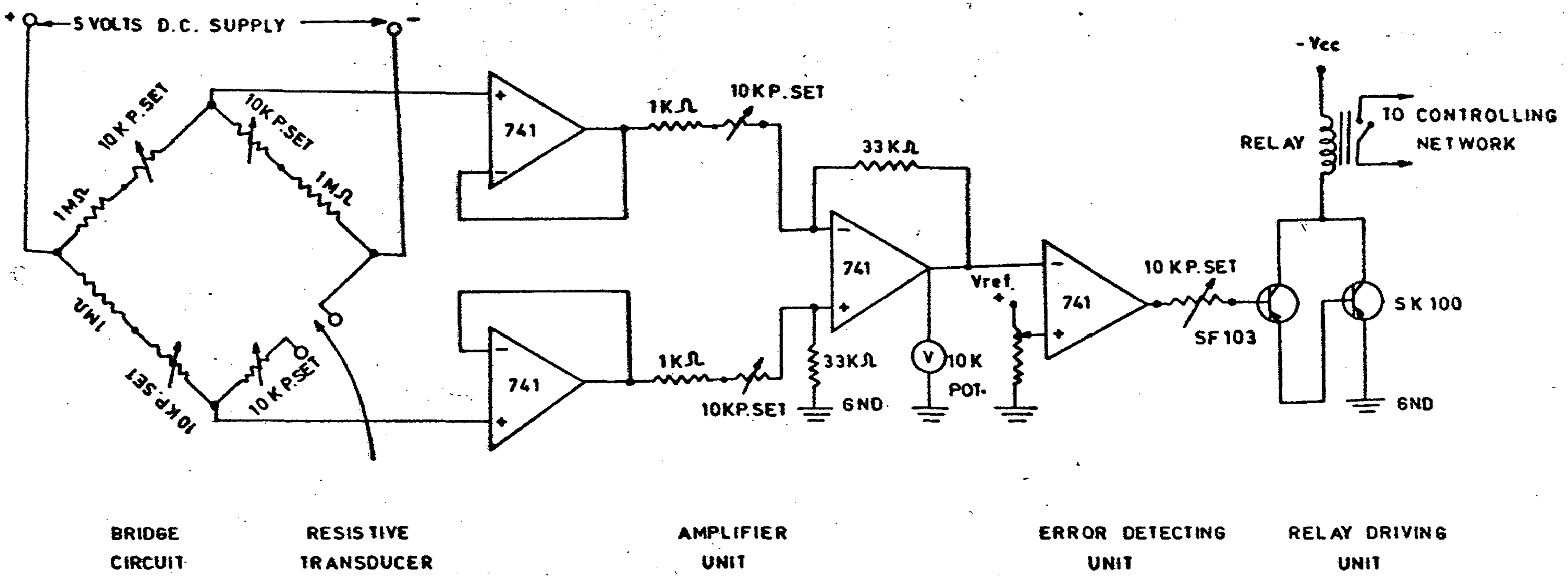


FIG.4.12_CIRCUIT DIAGRAM OF THE CONVENTIONAL RESISTIVE MOISTURE METER FOR PAPER.

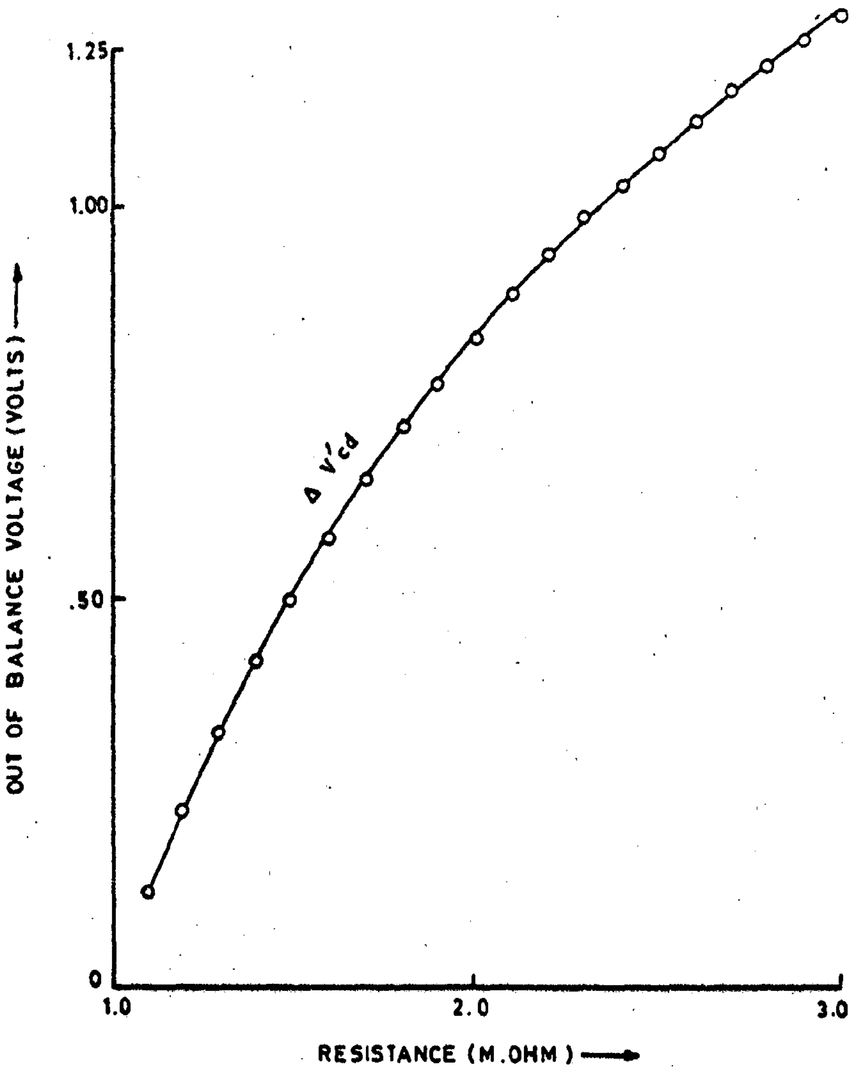


FIG.4.13_RESPONSE OF THE CONVENTIONAL BRIDGE (Vab=5.0 VOLTS)

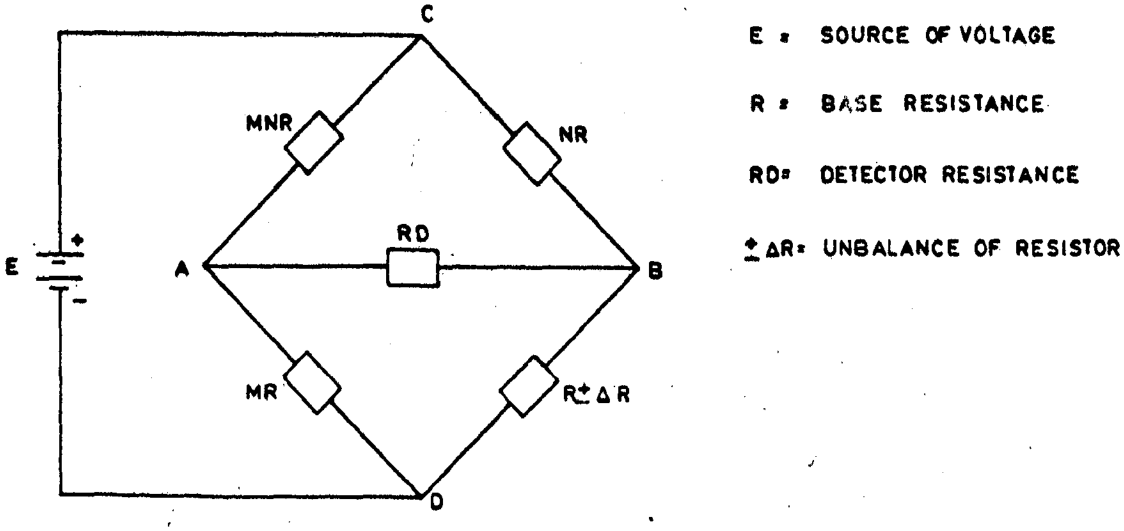


FIG.4.14_W.STONE BRIDGE WITH VARIATIONS IN THREE ARMS.

A complete circuit for the conventional paper moisture meter is shown in Fig.4.12.

4.3 ANALYSIS FOR THE BRIDGE OUTPUT

$$\Delta V_{cd} = V_{ab} \cdot \delta Z . K \qquad (4.10)$$

For resistive bridge, $\delta Z = \delta R$. Therefore, Eq.(4.10) becomes:

$$\Delta V_{cd} = V_{ab} \cdot \delta R . K \qquad (4.15)$$

Eq.(4.15) is applicable for near balance case only i.e. when $\Delta R \ll R$. But, in the present case, the above condition does not exist because the resistance of the paper sheet varies from 1.0 MΩ to 3.0 MΩ in the interested moisture content region. For large ΔR, ΔV_{cd} (say $\Delta V'_{cd}$) is calculated according to Eq.(4.7). For resistive bridge $Z = R$. Therefore, Eq.(4.7) becomes:

$$\Delta V'_{cd} = V_{ab} \cdot \frac{R_1 (R_3 + \Delta R_3) - R_2 R_4}{(R_1 + R_2)[(R_3 + \Delta R_3) + R_4]} \qquad (4.16)$$

Impedence of the detector is assumed infinity. Fig.4.13 shows the curve for $\Delta V'_{cd}$ ($V_{ab} = 5.0$ Volts) for the different values of $(R_3 + \Delta R_3)$. $\Delta V'_{cd}$ is the out of balance voltage of the bridge. It is clear from the Fig.4.13 that as the value of resistance increases, the out of balance voltage increases in accordance with Eq.(4.16).

4.4 OPTIMIZATION OF THE BRIDGE SENSITIVITY (20,21,22)

A wheatstone bridge is used to measure an unknown resistor or indirectly some other quantity such as moisture content. It is important to achieve the largest output voltage for a given bridge unbalance. In other words, optimization of bridge sensitivity is desirable. By choosing the proper value for the bridge arms this optimum condition may be achieved but at the expense of the bridge's input power.

The values of the resistive elements in the bridge are in general a function of power dissipation. The analysis deals with the power distribution among the four bridge elements as a function of maximum bridge sensitivity. Hence, a compromise must be made between bridge sensitivity and power.

4.4.1 BRIDGE SENSITIVITY

The wheat stone bridge as shown in Fig.4.14 consists of four resistive elements where one bridge leg has a resistance of R and the other three legs are expressed in terms of R and two factors, M and N. By restricting these elements to positive values, R, M and N attributes to ± Δ R which is assumed small as compared to R. If the detector is treated as the load, a mathematical expression using Thevenin's Theorem can be derived between the voltage appearing across the detector and ± Δ R(22). The result is

$$\Delta E_{AB} = [E(\pm \Delta R)/R) x (KN/N(M+1)(N+1)+K(N+1)^2)] \qquad (4.17)$$

where K represents the ratio of the detector's resistance, R_D to R, and the other quantities are defined in Fig.4.14.

A normalized sensitivity can be defined such that it will be applicable for all bridges that fit the circuit configuration in Fig.4.14 and can be expressed as

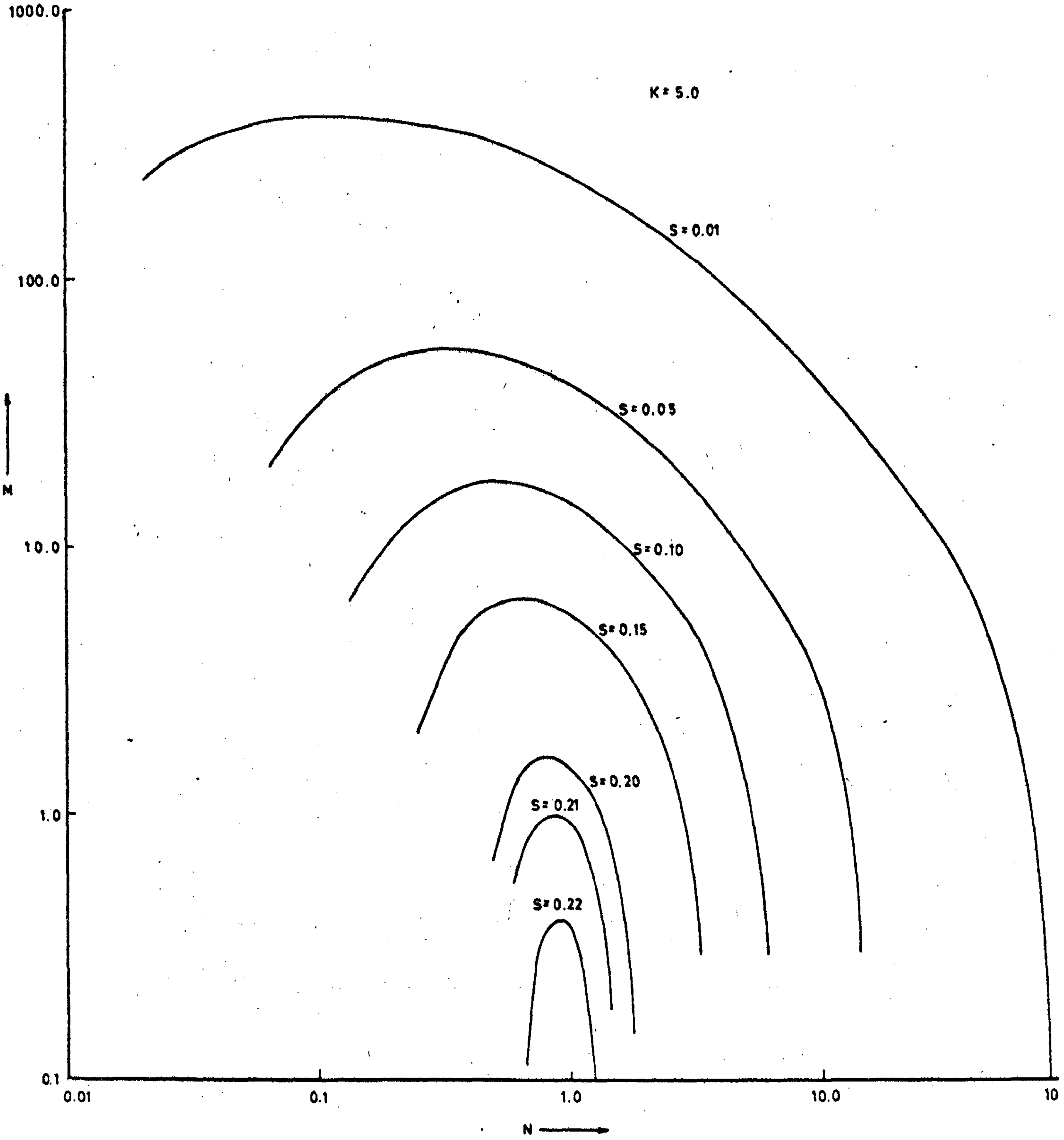


FIG.4.15_CURVES OF CONSTANT BRIDGE SENSITIVITY (K= 5.0).

$$S = (\Delta E_{AB} / E)/(\pm \Delta R/R) \quad (4.18)$$

Using the above definition, the bridge sensitivity can be expressed in terms of K, M and N in the following manner:

$$S = KN/[N(M+1)(N+1)+K(N+1)^2] \quad (4.19)$$

If S is considered to be a parameter, a family of constant sensitivity curves can be plotted for a given K. For K = 5.0, the results are shown in Fig.4.15. As the numerical value of S increases, the bridge becomes more sensitive. Fig.4.15 also shows the relation between M and N. It can be noted that the sensitivity passes through a maximum value of M for an increasing N. This maximum can be found by setting the first derivative of Eq.(4.19) with respect to N equal to zero. The value of N for maximum sensitivity is

$$N = [K/(K+M+1)]^{1/2} \quad (4.20)$$

Solving Eq.(4.20) for (M+1) and substituting the results into Eq.(4.19), we have

$$S_{Max} = [N/(N+1)]^2 \quad (4.21)$$

The largest value of N for maximum sensitivity may be found by the following expression:

$$N = [K/(1+K)]^{1/2} \quad (4.22)$$

From Eqs.(4.20) and (4.22), as K approaches infinity, N approaches unity and the corresponding value for S_{Max} is 0.25. In Fig.4.15, all maximum sensitivities are to the left of N = 1 regardless the value of K. As K increases, the sensitivity contours shift

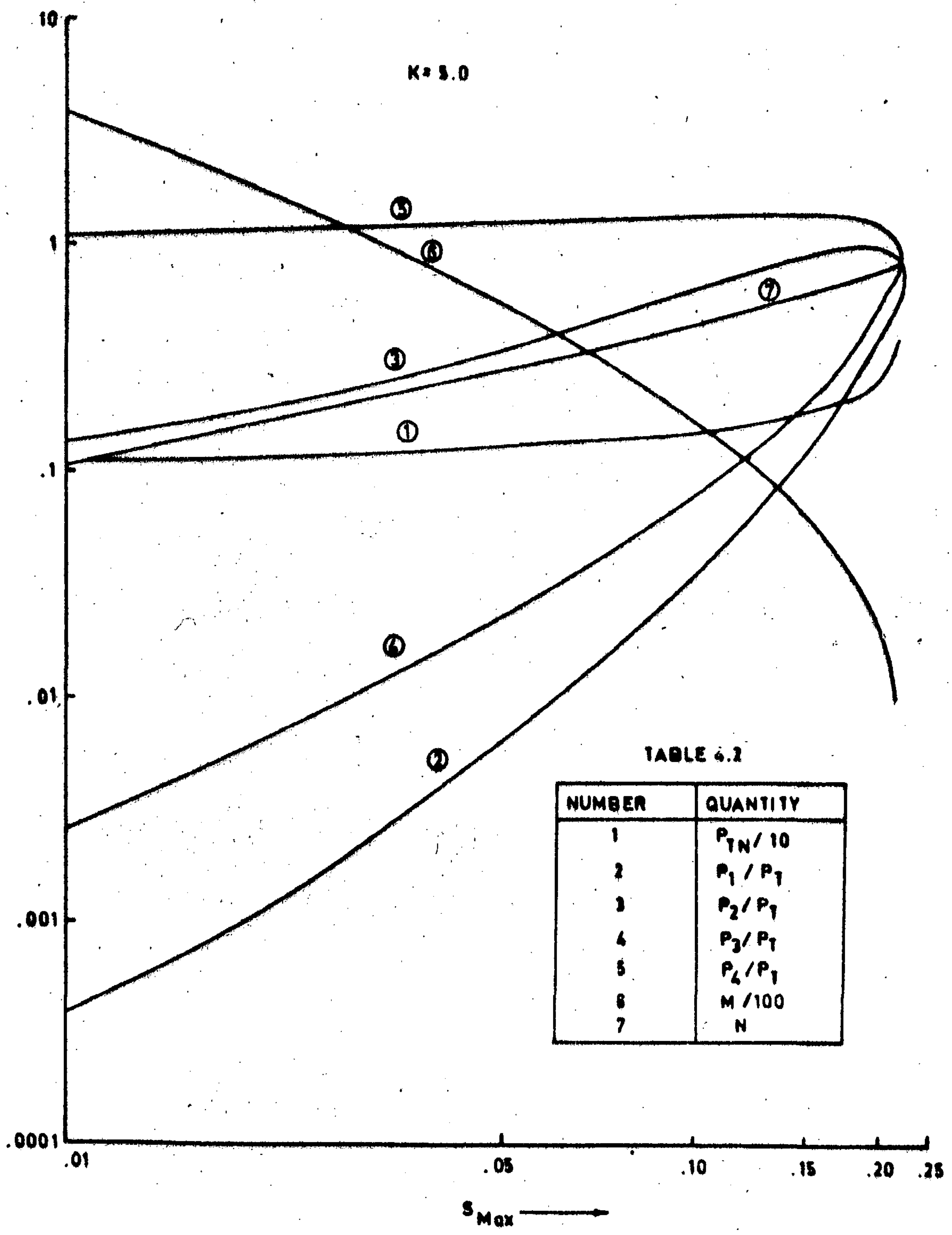


TABLE 4.2

NUMBER	QUANTITY
1	$P_{TN}/10$
2	P_1/P_T
3	P_2/P_T
4	P_3/P_T
5	P_4/P_T
6	M /100
7	N

FIG. 4.16_NORMALIZED POWER DISTRIBUTION AS A FUNCTION OF S_{Max}.

upward. With the restriction that the bridge elements must be positive, the bridge sensitivity will approach to maximum (0.25) under the limiting conditions $K \rightarrow \infty$ and $N \rightarrow 1$.

4.4.2 POWER DISSIPATION

The actual, normalized, and total power dissipation are shown in Table (4.1) in terms of E,R,M and N. It is assumed that the power dissipation in the detector is small as compared to the power dissipation in the bridge elements. This is true only if Δ R is much less than R.

TABLE 4.1

Bridge Element	Actual Power Dissipation (Watts)	Normalized Power Dissipation
MNR	$P_1 = (E^2/R)x(N/(M(N+1)^2))$	$P_1/P_T = N/((M+1)x(N+1))$
NR	$P_2 = (E^2/R)x(N/(N+1)^2)$	$P_2/P_T = NM/((M+1)x(N+1))$
MR	$P_3 = (E^2/R)x(1/(M(N+1)^2))$	$P_3/P_T = 1/((M+1)x(N+1))$
R	$P_4 = (E^2/R)x(1/(N+1)^2)$	$P_4/P_T = M/((M+1)x(N+1))$
Total Power Input	$P_T = (E^2/R)x(M+1)/(Mx(N+1))$	$P_{TN} = (M+1)/(Mx(N+1))$

4.4.3 POWER DISTRIBUTION

The distribution of input power among the four bridge elements depends on the sensitivity of the bridge. Generally, P_1/P_T and P_3/P_T increases with sensitivity because N is increasing. Fig.4.16 represents the power distribution, normalized power P_{IN}, M, and N as a function of maximum bridge sensitivity. Table (4.2) indicates the corresponding meaning of each number in Fig.4.16.

Curve 1, represents the bridge's normalized input power. The normalized power dissipation associated with resistor MNR, curve 2, increases with increasing maximum bridge sensitivity. This is due to increasing N. The same general argument holds for curve 4.

Curve 3, the normalized power in resistor NR, shows that the power dissipation reaches a maximum in Fig.4.16. This is due to the fact that this power is essentially proportional to the product MN. Since M and N are decreasing and increasing respectively with S_{Max}, the product produces a maximum condition.

The normalized power dissipation associated with resistor R, Curve 5, is essentially proportional to M. Curves 6 and 7 follow the results by Eqs.(4.20) and (4.21).

4.5 DESIGN OF AN OPTIMIZED METER

From Figs.4.15 and 4.16, we conclude that a maximum sensitivity of 0.22 (for K = 5.0) can be achieved with the following values of N and M.

N	M
0.65	0.0818
0.70	0.2261
0.80	0.3763
0.90	0.4062
1.00	0.3636

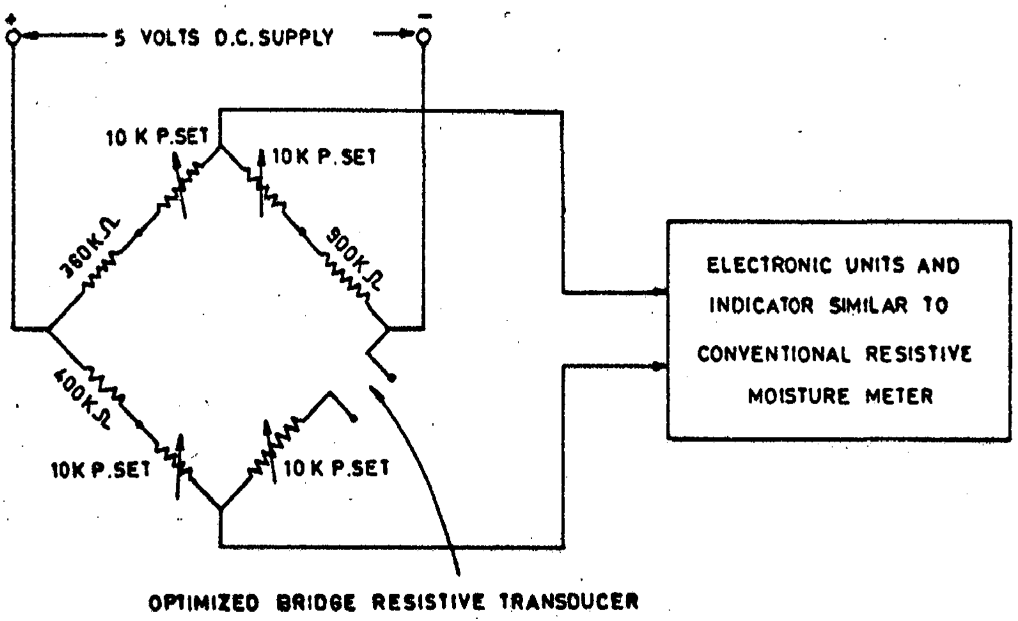


FIG. 4.17_ OPTIMIZED RESISTIVE MOISTURE METER FOR PAPER.

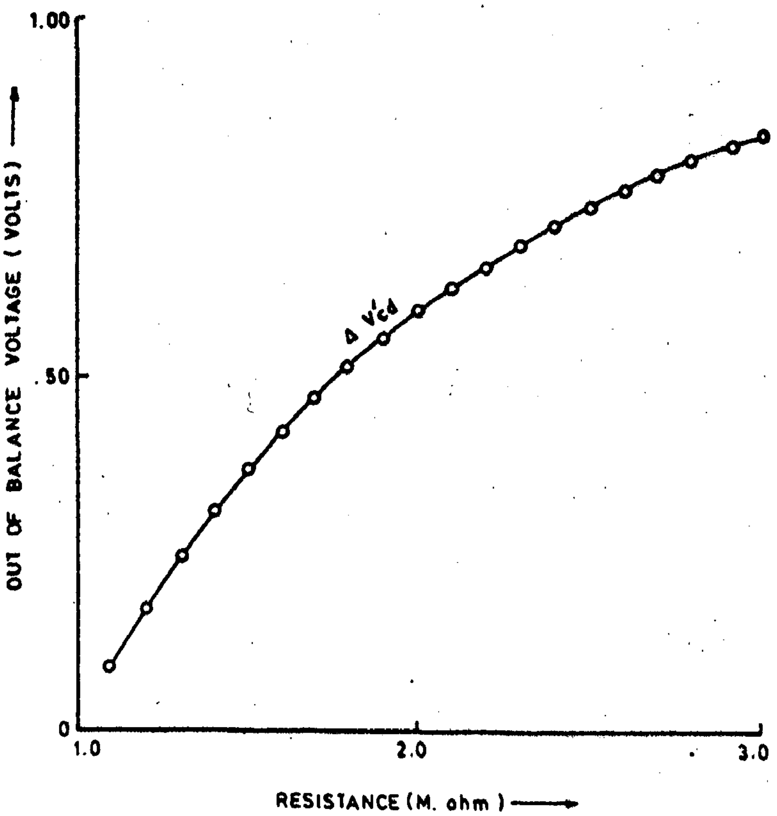
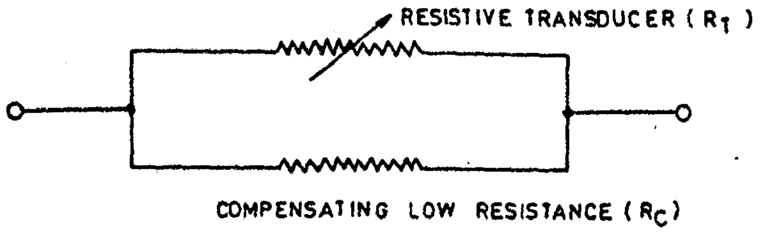
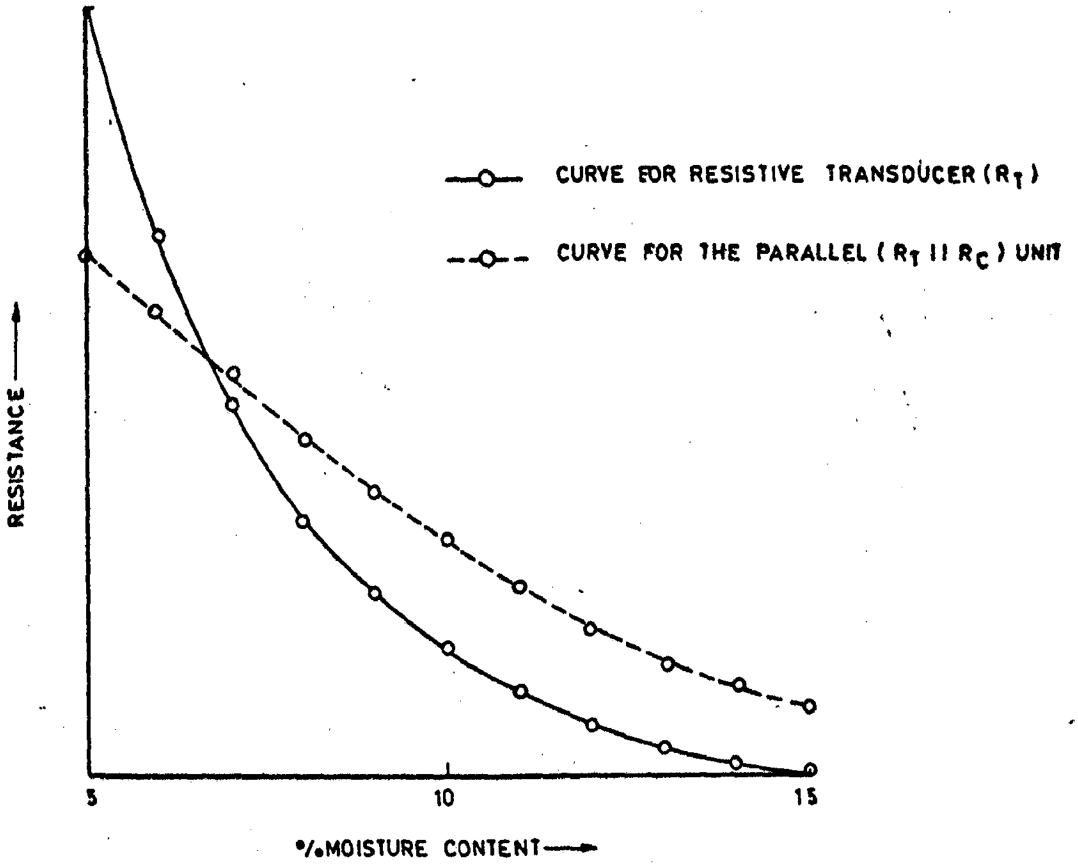


FIG. 4.18_ RESPONSE OF THE OPTIMIZED BRIDGE (Vab = 5.0 VOLTS).



(a) A SCHEME OF PARALLELING RESISTIVE TRANSDUCER WITH A LOW RESISTANCE.



(b) UNCOMPENSATED AND COMPENSATED RESISTIVE TRANSDUCER CHARACTERISTIC.

FIG.4.19_COMPENSATION FOR NON-LINEARITY OF RESISTIVE TRANSDUCER RESPONSE.

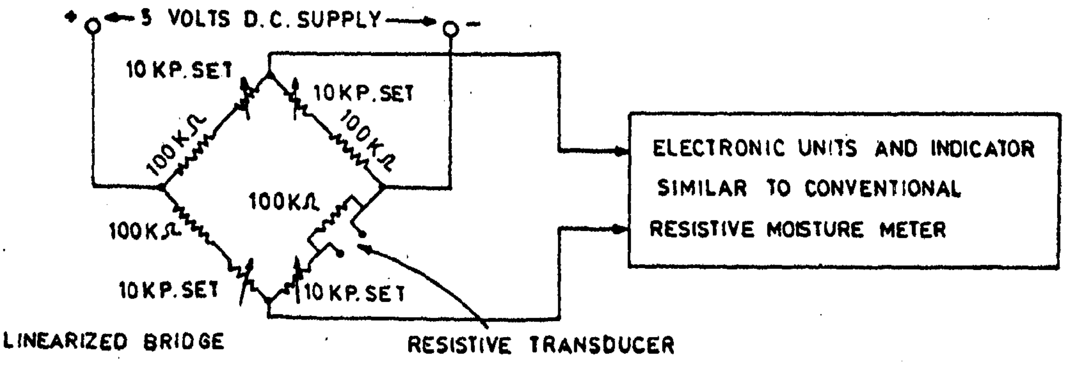


FIG.4.20_LINEARIZED RESISTIVE MOISTURE METER FOR PAPER.

The optimum values fall to the left of $N = 1$ in the Fig.4.15 such that N approaches unity. Hence, the optimum values of N and M (for $K = 5.0$) are chosen as below:

$$N = 0.90 \quad \text{and} \quad M = 0.40$$

Therefore, the bridge elements are chosen of the following values:

$NR = 900\ K\Omega + 10\ K\Omega$ preset
$MR = 400\ K\Omega + 10\ K\Omega$ preset
$MNR = 360\ K\Omega + 10\ K\Omega$ preset
$R =$ Resistive transducer $+ 10\ K\Omega$ preset

Fig.4.17 shows the optimized wheat stone bridge unit with the chosen values of N and M for the paper moisture measurment. This bridge is used in the optimized resistive moisture meter. Rest of the electronic units remain same as that of the conventional resistive moisture meter discussed earlier. Fig.4.18 shows the out of balance voltage of the optimized bridge using Eq.4.16.

4.6 LINEARIZATION OF THE METER OUTPUT(4)

The disadvantage of the resistive type transducer for moisture measurment is its nonlinear scale over the entire range of operation. This, however, is to some extent annulled by the compensation techniques. A simple compensation technique is to parallel the resistive transducer with a low resistance. This reduces the sensitivity but increases linearity. Fig.4.19 shows the scheme and the curves of uncompensated and compensated resistive transducer characteristics for comparison. The physical concept is that the parallel combination has much less resistance value and hence its percentage change will also be less. This can be calculated theoretically with approximation.

4.6.1 DESIGN FOR LINEARIZED WHEATSTONE BRIDGE

Variation of transducer resistance (R_T) = 1.0 to 2.5 MΩ.

Let, $R_C = 100$ KΩ is used for compensation.

At $R_T = 1.0$ MΩ, $R_T||R_C = 90.909$ KΩ

$R_T = 2.5$ MΩ, $R_T||R_C = 96.153$ KΩ

For maximum sensitivity, the bridge should be symmetrical at the balance condition.

$$R_1 = R_2 = R_3 = R_4 = 100 \text{ K}\Omega \text{ (say)}$$

To get the zero balance condition (at $R_T = 1.0$ MΩ), a preset of 10 KΩ (fixed at 9.091 KΩ) is used in series with the transducer compensated arm such that the total resistance of the arm is 100 KΩ.

Fig.4.20 shows the linearized bridge circuit for the paper moisture measurment. Rest of the electronic circuitry is similar to the conventional resistive moisture meter except that the gain of the Diff. Amp. is adjusted nearly 100.

4.7 CALIBRATION OF THE METERS

Following three resistive moisture meters were developed for calibration:

(i) Conventional resistive moisture meter.
(ii) Optimized resistive moisture meter.
(iii) Linearized resistive moisture meter.

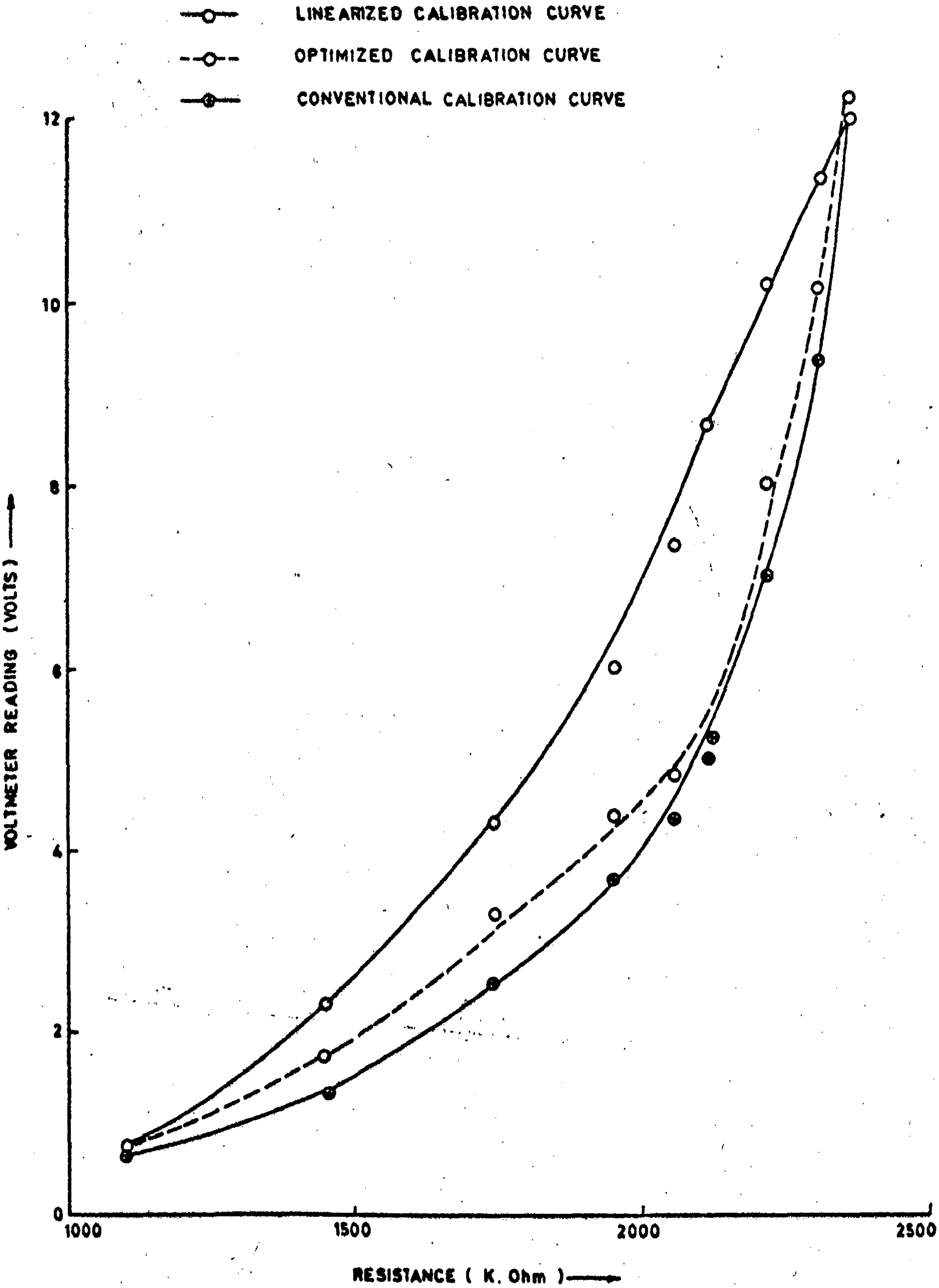


FIG.4.21_RELATION BETWEEN RESISTANCE AND VOLTMETER READING.

The instruments developed were first calibrated in terms of resistance. For this purpose, transducer is replaced by the known variable resistance and the voltmeter reading is recorded for different values of resistance. Then the calibration of the instruments is done with the help of the paper sheet samples of the known moisture percentage.

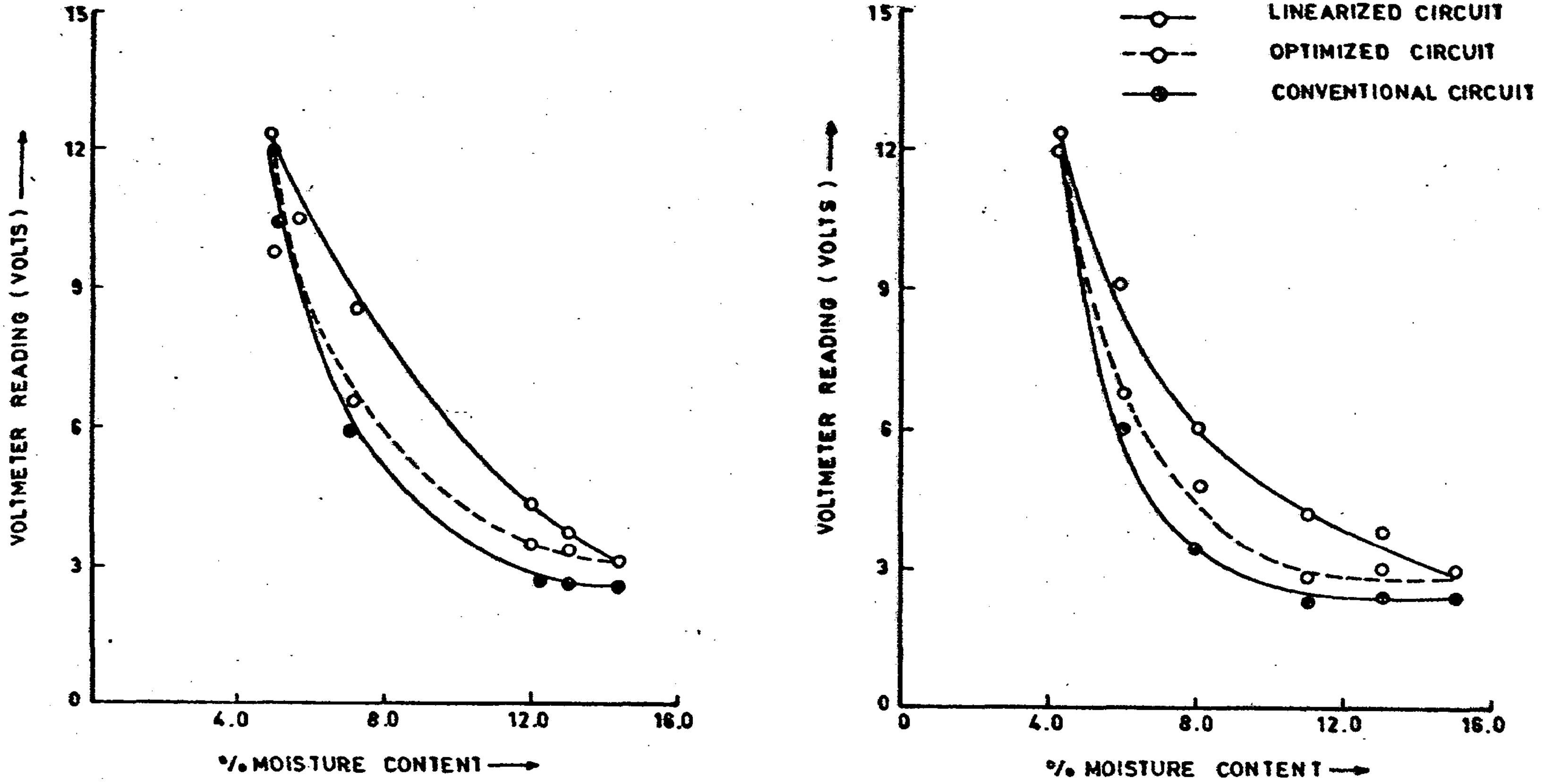
4.7.1 CALIBRATION IN TERMS OF RESISTANCE

Resistance decade boxes and linear pots (10 to 1000 KΩ) in the range of 1.0 to 2.5 MΩ were used in place of the transducer and full scale deflection in the voltmeter was obtained. Table (4.3) shows the voltmeter readings noted for different values of the resistance.

TABLE 4.3

S. No.	Resistance (KΩ)	Voltmeter Reading (Volts)		
		Conventional Moist. Meter	Optimized Moist.Meter	Linearized Moist.Meter
1	1095	.7	.7	.8
2	1450	1.3	1.7	2.3
3	1740	2.5	3.3	4.3
4	1950	3.7	4.4	6.0
5	2055	4.4	4.8	7.3
6	2110	5.0	5.3	8.6
7	2205	7.0	8.0	10.2
8	2295	9.4	10.2	11.4
9	2355	12.0	12.2	12.0

Calibration curves are shown in Fig.4.21.



(a) FOR KRAFT PAPER

(b) FOR WRITING AND PRINTING PAPER

FIG.4.22. RELATION BETWEEN % OF MOISTURE CONTENT IN PAPER & VOLTMETER READING.

4.7.2 CALIBRATION IN TERMS OF MOISTURE PERCENTAGE

Paper samples of known moisture percentage (by oven method) were placed between the two electrodes of the resistive transducer, which forms one arm of the bridge and the corresponding voltmeter readings were noted in Table (4.4).

TABLE 4.4

(a) For Kraft Paper

S. No.	Moisture % of paper	Voltmeter Reading (Volts)		
		Conventional Moist. Meter	Optimized Moist.Meter	Linearised Moist.Meter
1	4.96	12.1	12.0	12.4
2	5.10	10.2	9.8	10.5
3	7.16	6.0	6.7	8.4
4	12.04	2.8	3.6	4.4
5	13.18	2.7	3.5	3.8
6	14.45	2.7	3.1	3.1

(b) For Writing and Printing Paper

S. No.	Moisture % of paper	Voltmeter Reading (Volts)		
		Conventional Moist. Meter	Optimized Moist.Meter	Linearized Moist.Meter
1	4.22	12.2	12.0	12.6
2	5.06	6.0	6.7	9.0
3	7.98	3.7	4.7	6.0
4	10.96	2.4	2.9	4.2
5	13.00	2.4	3.0	3.7
6	15.11	2.4	2.9	2.9

Fig.4.22 shows the relationship between the moisture percentage of the paper samples and the voltmeter readings.

4.8 MERITS AND DEMERITS OF THE METERS

4.8.1 MERITS

The developed resistive moisture meters for the paper moisture measurment has the following merits:

(i) The moisture meter is simple, compact and portable.

(ii) There is considerably large change in resistance for a comparatively small change in the moisture content.

(iii) A simple resistive transducer is used as sensor. It is simple in construction. Length and diameter of the detector roll can be modified easily depending upon the dimensions of the paper machine.

(iv) The use of low resistance in parallel with the transducer makes the response approximately linear.

(v) Continuous moisture measurment is possible instantaneously after the paper starts passing through the detector roll.

(vi) The instrument is expected to be cheaper than other types using different transducers.

4.8.2 DEMERITS

(i) The initial response of the instrument is non-linear.

(ii) With non-uniform moisture distribution, satisfactory results are not likely to be obtained.

(iii) Paper sample must be in firm contact with both the electrodes of the transducer. Any gap between them will cause wrong results.

(iv) The presence of electrolytes, salts or acids in the paper sample reduces its resistivity and hence leads to wrong results.

(v) Resistance depends on the temperature. Hence, any change in the temperature of the operation of the instrument will give erroneous results. A temperature correction is necessary.

(vi) If the paper sample is placed for longer periods between the electrodes of the transducer, current passing through the paper will cause its heating and the moisture content of the sample may vary.

CHAPTER- 5

DEVELOPMENT OF A LABORATORY TYPE PAPER MOISTURE METER

5.1 PRINCIPLE OF OPERATION

Dielectric constant of dry paper varies between 2.7 and 3.5, whereas the dielectric constant of water is 81. Hence, the dielectric constant of the moist paper varies from 3.5 onwards depending upon the moisture content present in the paper sample. This change in dielectric constant has linear relationship with the moisture content. For one percent increase in the moisture content, the dielectric constant of the paper increases by 0.78. The change in dielectric constant due to the change in the moisture content of the paper is being utilized for the capacitive moisture meter.

The change in dielectric constant is sensed by a capacitive transducer in terms of capacitance and is measured by a bridge. The unbalanced signal caused by the change in capacitance of the transducer due to moisture is amplified, filtered, rectified and given to a d.c. microammeter. The microammeter reading shows the change in capacitance, which is proportional to the moisture content in the paper sample upto a considerable range of moisture percentage.

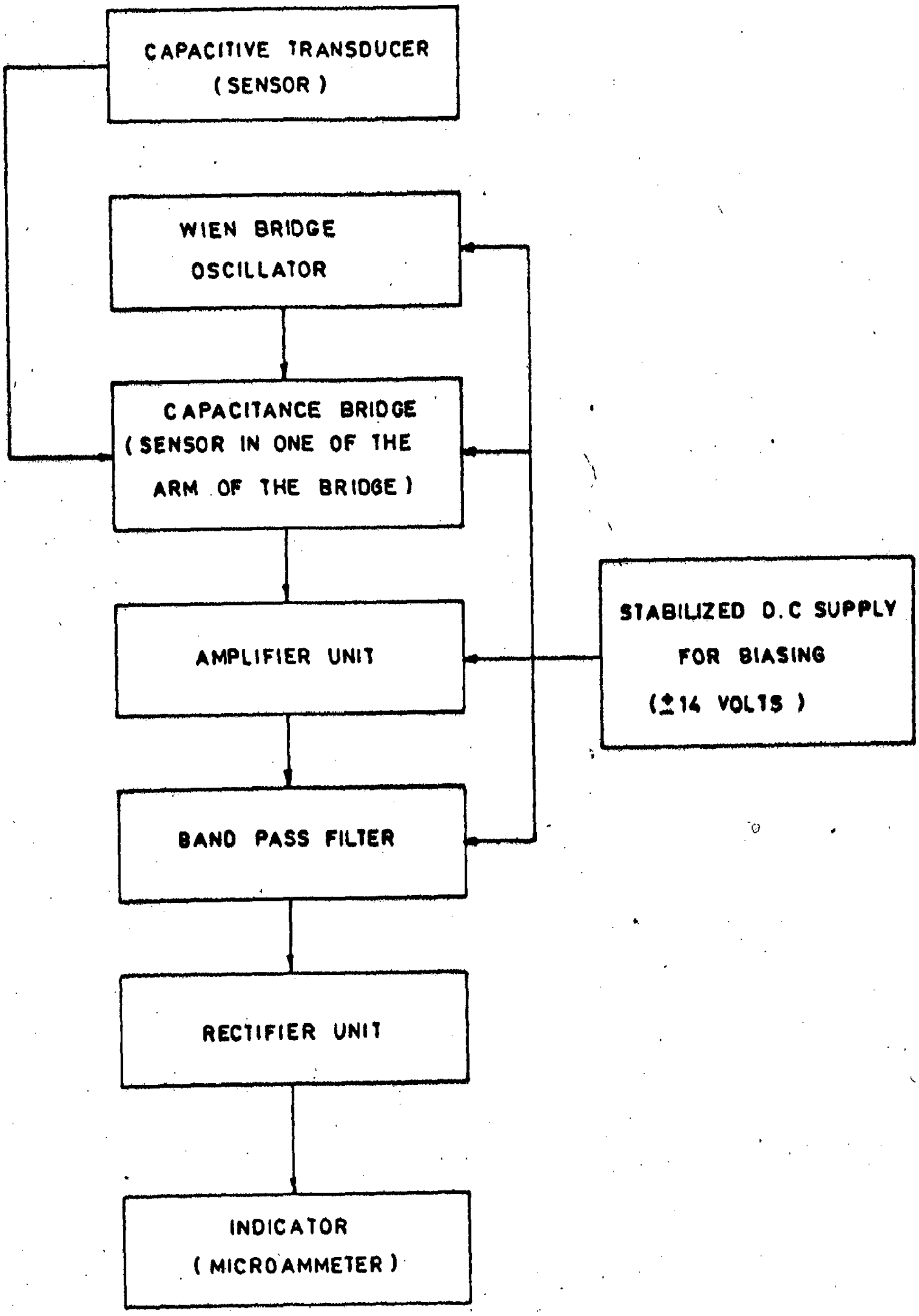
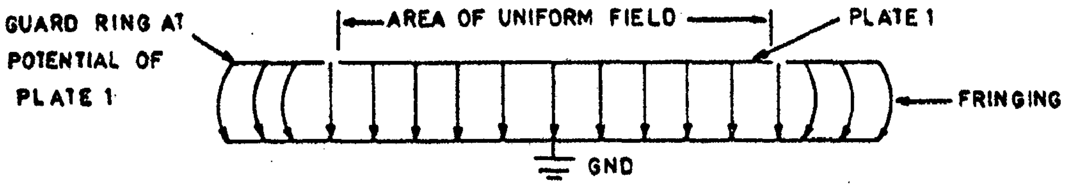


FIG. 5.1_ BLOCK DIAGRAM OF CAPACITIVE MOISTURE METER.



PARALLEL PLATE CAPACITOR WITH GUARD RING.

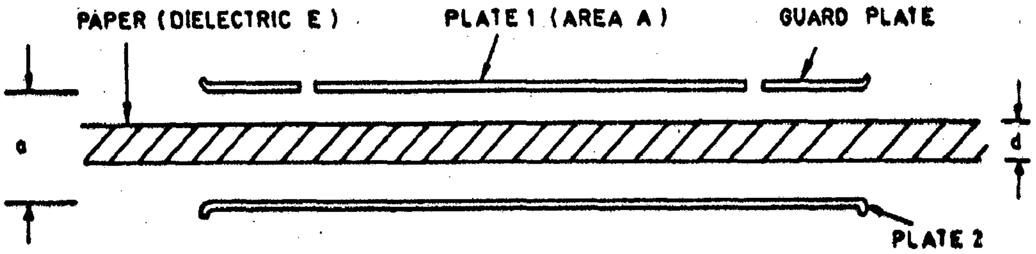


FIG.5.2_PARALLEL PLATE CAPACITOR (PAPER AS DIELECTRIC).

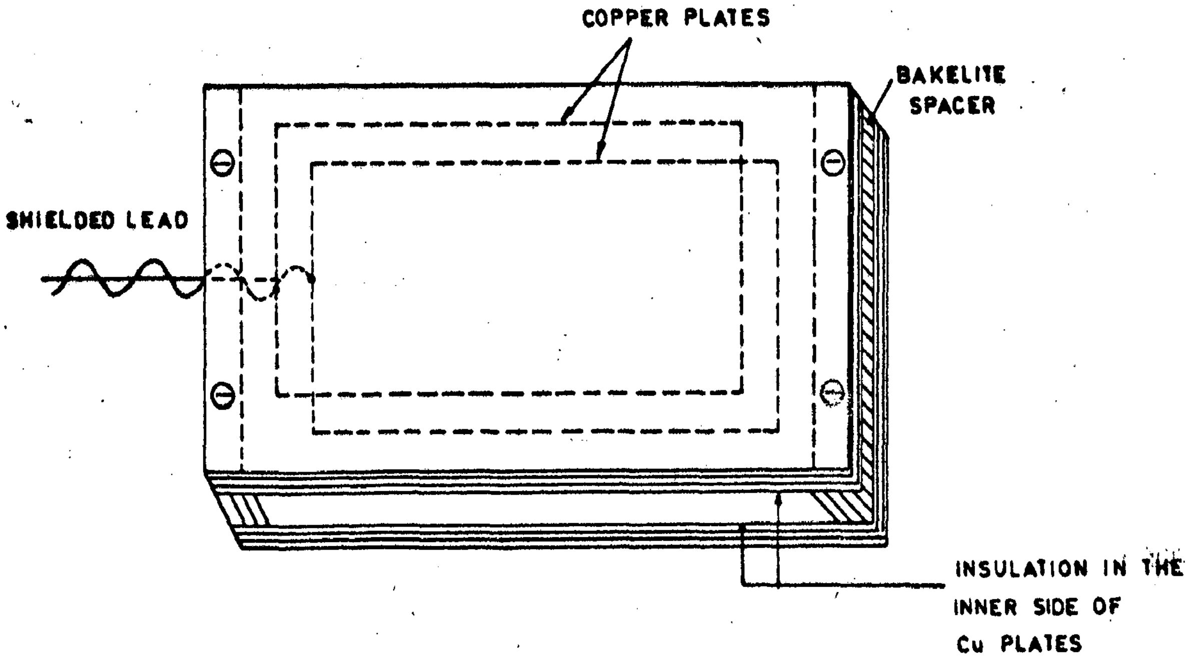


FIG.5.3_CAPACITIVE TRANSDUCER FOR PAPER MOISTURE MEASURMENT

5.2 SCHEME OF THE MOISTURE METER

The block diagram of the capacitive moisture meter developed by the author is shown in Fig. 5.1. It has the following units:

(i) Capacitive Transducer.

(ii) Electronic Circuit:

- (a) Wien bridge oscillator.
- (b) Capacitance bridge.
- (c) Amplifier unit.
- (d) Bandpass filter.
- (e) Rectifier unit.
- (f) Stabilized d.c. supply for biasing (± 14 Volts).

(iii) Indicator.

Details of each block, including design are discussed below individually.

5.2.1 CAPACITIVE TRANSDUCER (SENSOR)(23,28)

For paper moisture measurment, parallel plate capacitive transducer is used in which paper acts as the dielectric media. By the use of guard plate arrangment (Fig. 5.2) the capacitance of a condenser with two parallel plates is given by

$$C = \frac{0.885\ A}{a - d + d/E} \qquad (5.1)$$

where

C = Capacitance in p. farads.

A = Active area of one plate in cm^2.

a = Distance between plates in mm.

d = Thickness of paper in mm.

E = Dielectric constant of the moist paper.

An increase in permittivity of the moist paper by δE will increase the capacitance by δC,

$$C + \delta C = \frac{0.885\ A}{a-d+d/(E+\delta E)}$$

Hence, the fractional change in capacity $\delta C/C$,

$$\frac{\delta C}{C} = \frac{\delta E}{E} N_2 \cdot \frac{1}{1 + N_3(\delta E/E)}$$

where, $N_2 = \frac{1}{1 + E(a-d)/d}$ = Sensitivity factor

$N_3 = \frac{1}{1+[d/E(a-d)]}$ = Non-linearity factor

and $d/(a-d)$ is called the gap ratio of the transducer.

Design (From Fig. 5.2)

For measurable capacitance change, an area of 150 $cm.^2$ (15 cm.x10 cm.) will be suitable for parallel plates of the capacitive transducer.

For $A = 150\ cm.^2$, $a = d = 2$ mm.

$C(\text{for } E = 3.0) \simeq 200$ p.f.

$C(\text{for } E = 30.0) \simeq 2000$ p.f.

The capacitance of the transducer varies from 200 p.f. to 2000 p.f. when the moisture content of the paper varies approximately upto 20%. The parallel plate capacitive transducer is constructed by using two copper clad plates ($15 \times 10\ cm.^2$) having a separation of 2 mm. of bakelite, as shown in Fig. 5.3. The distance between the two plates is kept small compared with the dimensions of the plates

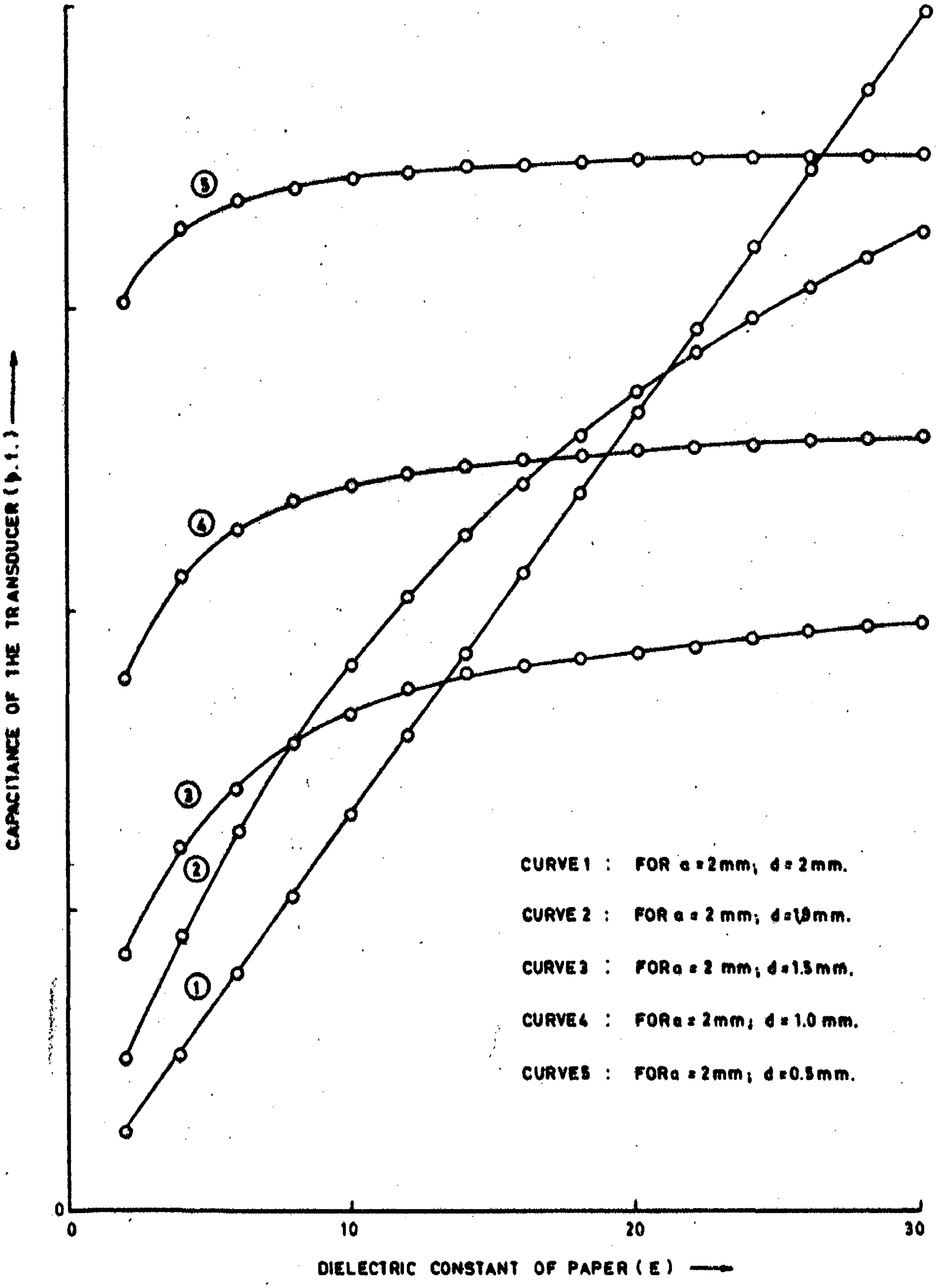


FIG.5.4_RESPONSE CHAT. FOR THE VARIATION OF THE THICKNESS OF THE PAPER SHEET (d).

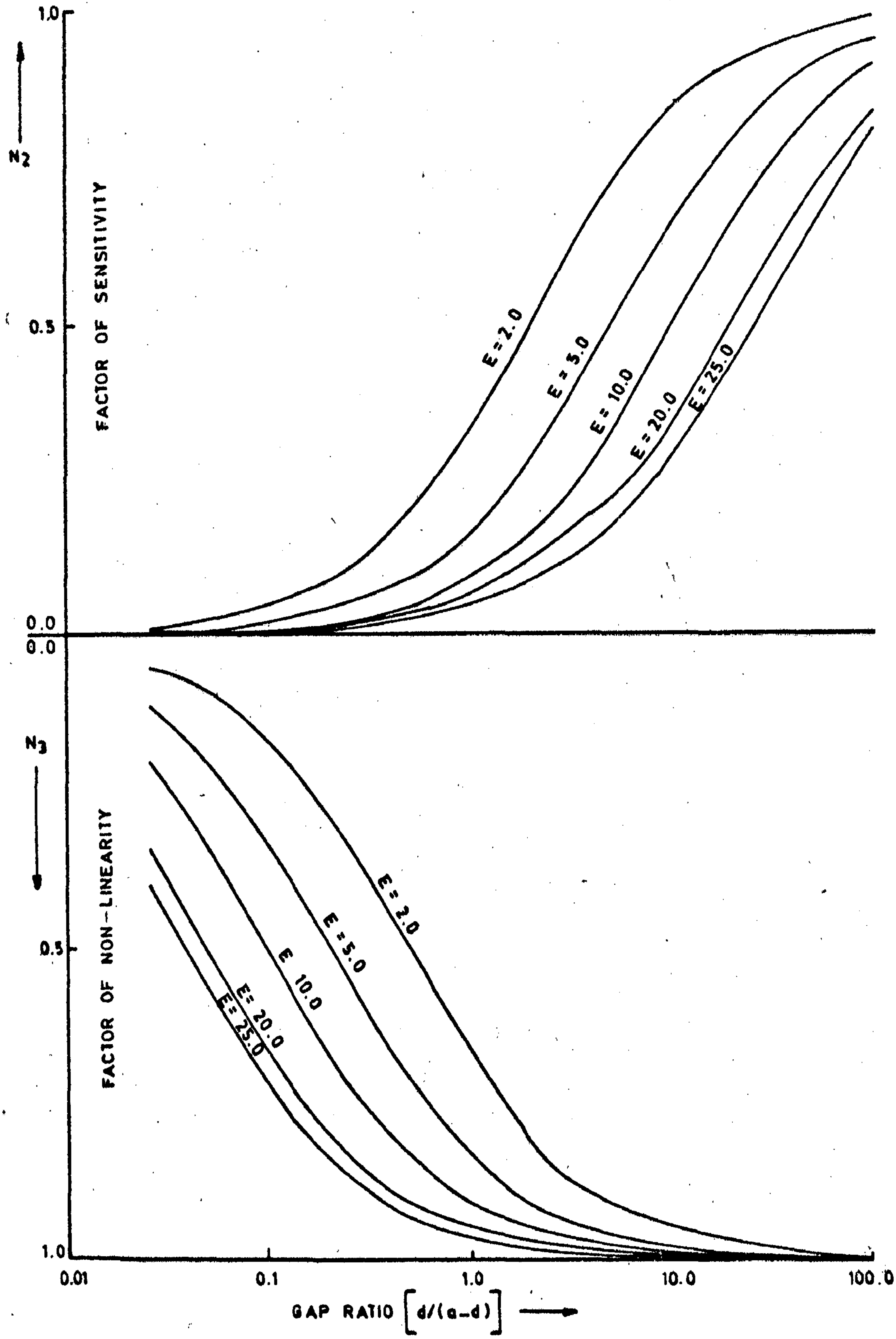


FIG.5.5_EFFECT OF GAP RATIO ON SENS. FACTOR (N_2) AND NON-LIN. FACTOR (N_3) OF THE TRANSDUCER.

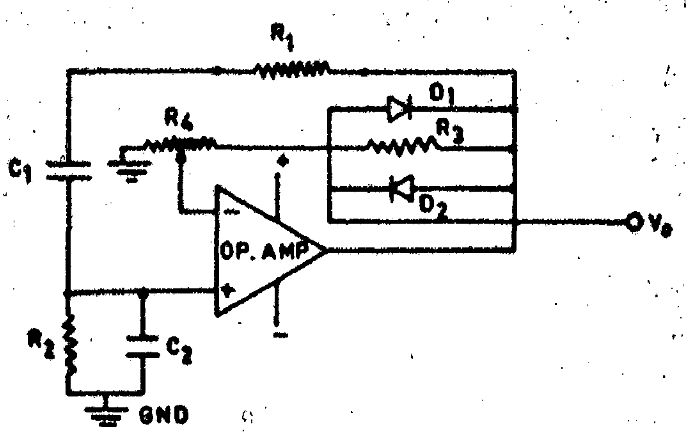


FIG.5.6_WIEN BRIDGE OSCILLATOR.

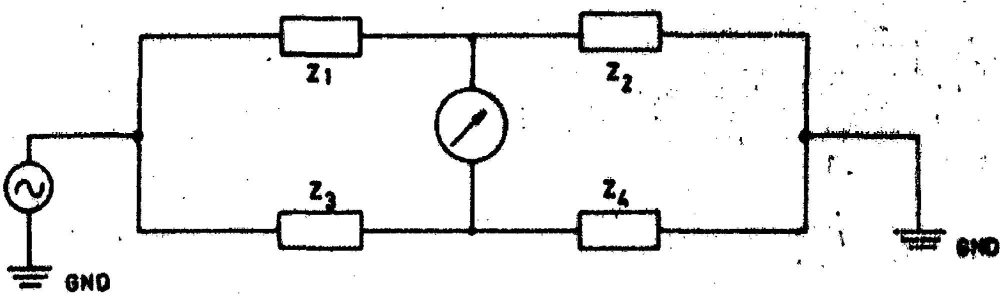


FIG.5.7_BLOCK DIAGRAM OF ORDINARY CAPACITANCE BRIDGE.

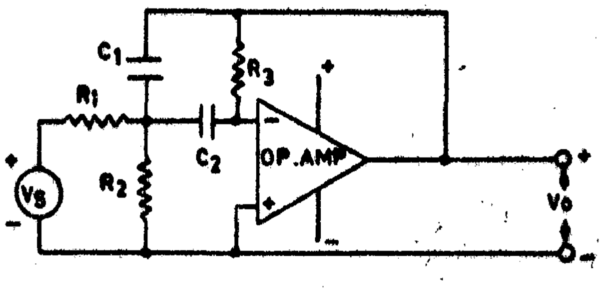


FIG.5.8_ AN ACTIVE RC BAND PASS FILTER.

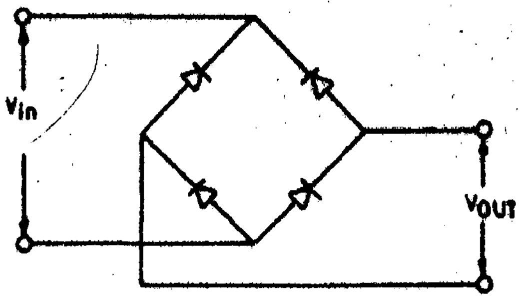


FIG.5.9_ RECTIFIER UNIT.

in order to avoid the fringing effect at the edges of the plates. To avoid the stray capacitance effects due to the connecting leads, shielded wires have been used to connect the transducer to an arm of the bridge.

Effect of the Thickness of the Paper (d)

Fig. 5.4 is plotted to show the effect of the variation in the thickness of the paper sheet on the value of capacitance of the transducer. It is clear from Fig. 5.4 that as the value of d reduces by a, the response characteristic is not linear. For a = d, the response characteristic is a straight line. Therefore, for good results, the gap between the parallel plates of the transducer must be fully filled with the sample of the paper sheet.

Analysis for Sensitivity Factor and Non-linearity Factor of the Transducer

The sensitivity factor and the non-linearity factor are plotted in Fig. 5.5 against the gap ratio d/(a-d) for various permittivities. Best results are obtained with high d/(a-d) ratios, i.e. d is greater than (a-d). High gap ratio can be achieved by thick layers of the paper and narrow air gap between the plates of the transducer.

5.2.2 WIEN BRIDGE OSCILLATOR(19,27,30)

Wien bridge oscillator (Fig. 5.6) is the simplest precision sine wave generator of constant frequency, required for the operation of the capacitance bridge. With an OP. Amp. (active element) as a gain element, such an oscillator will have a frequency that is precisely controlled by bridge elements. The oscillation results at the frequency

$$f = 1/2\pi\sqrt{R_1 \; R_2 \; C_1 \; C_2} \quad \text{at } \beta = \frac{1}{3}$$

where, β is the feed back factor

If $R_1 = R_2 = R$ and $C_1 = C_2 = C$

$$f = 1/2\pi \, RC$$

For sustained oscillations β should be slightly less than 1/3.

$$\beta = R_4 / (R_3 + R_4) \leq \frac{1}{3}$$

Design (From Fig. 5.6)

Let $w = 10^4$ rad/sec ($f = 1.59$ K Hz)

$$R = \frac{1}{10^4 \times .01 \times 10^{-6}} \quad ; \; C_1 = C_2 = C = 0.01 \; \mu.\text{f.} \text{(say)}$$

or $R = 10 \; K\Omega$

$R_3 = 10 \; K\Omega$ and $R_4 = 4.7 \; K\Omega$ preset for $\beta < \frac{1}{3}$

5.2.3 CAPACITANCE BRIDGE (24, 25)

An ordinary bridge for capacitance measurment is shown in Fig. 5.7. Assuming that the detector is of high impedence, the transfer function of the ordinary bridge is given by:

$$T = \frac{Z_2}{Z_1 + Z_2} - \frac{Z_4}{Z_3 + Z_4} \tag{5.2}$$

It is well known that close to balance, the transfer function may be considered as a linear function of the impedance responsible for the departure from the balance. On the other hand, if large deviations from balance are contemplated, linear behaviour is not generally attained. However, if the transfer function is rewritten as:

$$T = \frac{Z_2/Z_1}{1 + Z_2/Z_1} - \frac{Z_4/Z_3}{1 + Z_4/Z_3} \qquad (5.3)$$

then it is easily seen that linearity at the detector is possible for large deviations from balance under the conditions: $Z_2/Z_1 \ll 1$ and $Z_4/Z_3 \ll 1$.

In such a situation the transfer function may be written approximately as

$$T \simeq \frac{Z_2}{Z_1} - \frac{Z_4}{Z_3} \qquad (5.4)$$

Design: Z_1 = Capacitive transducer and 0.001 μ.f. capacitor in parallel + 1 MΩ resistance in series.

Z_3 = 0.001 μ.f. capacitor and trimmer (for zero setting) in parallel + 1 MΩ resistance in series.

$Z_2 = Z_4$ = 0.001 μ.f. capacitor in parallel with 1 MΩ resistance.

$Z_2 = Z_4 = 10^4 (1 - 10j)$ ($w = 10^4$ rad/sec.)

$Z_3 = 10^5 (10 - j)$ when trimmer at zero position.

$Z_1 = 10^5 (10 - j.833)$ for dry paper.

$= 10^5 (10 - j.333)$ for 20% ($E = 30.0$) moist paper.

Therefore, $\frac{Z_2}{Z_1} \simeq 0.10$ and $\frac{Z_4}{Z_3} \simeq 0.10$

5.2.4 AMPLIFIER UNIT

Similar amplifier unit as described in sect. 4.2.4 of Chapter- 4 is used here.

5.2.5 BAND PASS FILTER(19)

To measure the signal, noise must be filtered out. A narrow band pass filter is a circuit designed to pass signals only in certain band of frequencies while rejecting all signals outside this band. Fig. 5.8 shows an active RC band pass filter.

Design (From Fig. 5.8)

The design equations are:

$$R_1C_1 = \frac{Q}{W_o \; A_o}$$

$$R_3 \frac{C_1 \; C_2}{C_1 + C_2} = \frac{Q}{W_o}$$

$$R^1 \; R_3 \; C_1 \; C_2 = \frac{1}{W_o^2}$$

where $R^1 = R_1 || R_2$

We have $W_o = 10^4$ rad/sec.

Let, band with B = 100 Hz

Therefore, quality factor $Q = \frac{10^4}{100} = 100$

Let maximum gain of OP.AMP.$(A_o) = 50$

$C_1 = C_2 = 0.01$ μ.f. (say)

$$R_1 = \frac{1}{.01 \times 10^{-6}} \times \frac{100}{10^4 \times 50} = 20 \text{ K}\Omega$$

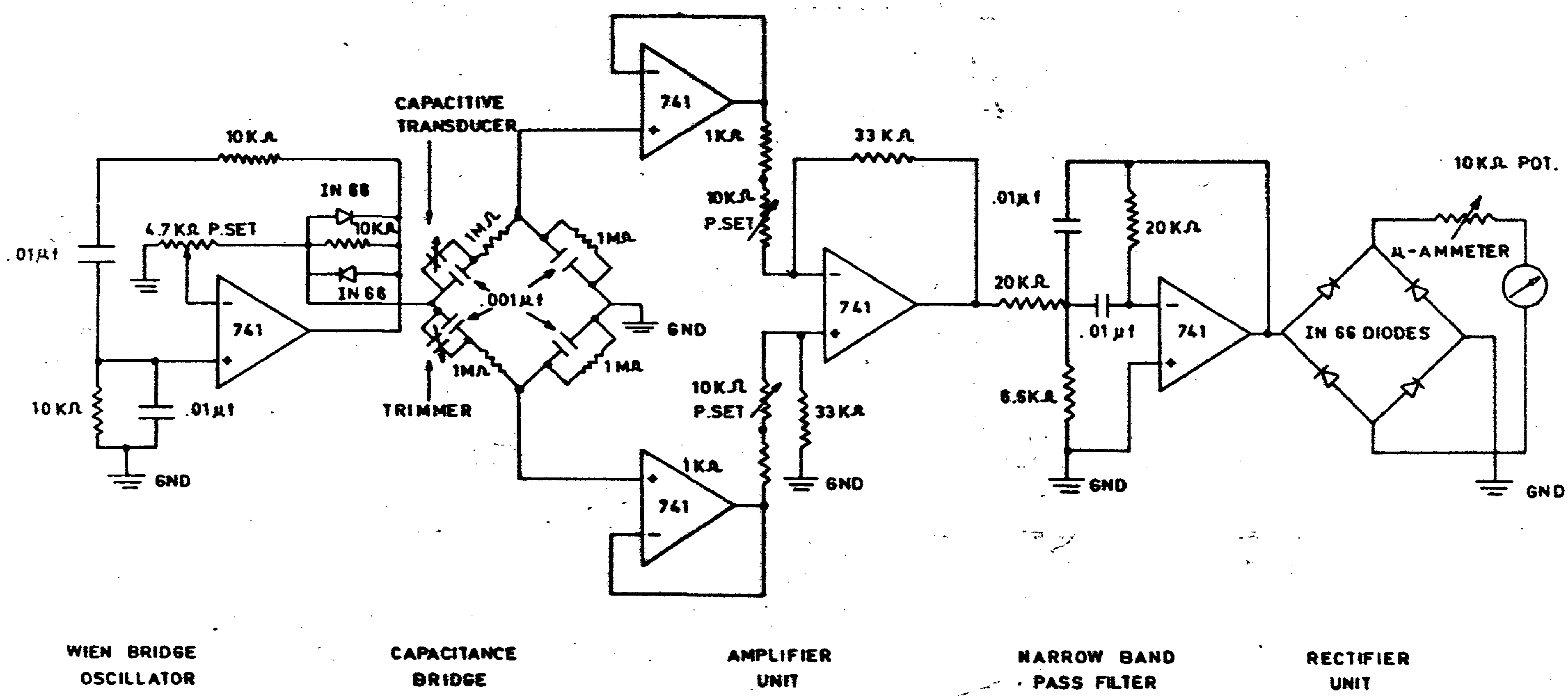


FIG. 5.10_CIRCUIT DIAGRAM OF THE CONVENTIONAL CAPACITIVE MOISTURE METER FOR PAPER.

$$R_3 \times \frac{.01 \times 10^{-6} \times .01 \times 10^{-6}}{.01 \times 10^{-6} + .01 \times 10^{-6}} = \frac{100}{10^4}$$

$$R_3 = 20\ K\Omega$$

$$\frac{20 \times 10^3 \times R_2}{20 \times 10^3 + R_2} \times 20 \times 10^3 \times .01 \times 10^{-6} \times .01 \times 10^{-6} = \frac{1}{(10^4)^2}$$

$$R_2 = 6.6\ K\Omega$$

Therefore, the final values are:

$$C_1 = C_2 = 0.01\ \mu.f.;\ R_1 = R_3 = 20\ K\Omega,\ R_2 = 6.6\ K\Omega$$

5.2.6 RECTIFIER UNIT(19)

The output obtained from the band pass filter is to be rectified for the microammeter niddle deflection. A rectifier unit (Fig. 5.9) converts the sinusoidal input waveform (whose average value is zero) into a unidirectional waveform, with a non zero average component. In the rectifier unit 4 no. IN 66 diodes are used.

5.2.7 INDICATOR

The output of the bridge rectifier unit is given to a d.c. microammeter (0-100 μA) through a variable resistor (10 KΩ Pot) in series which gives the average value of current corresponding to the change in moisture content in paper.

The complete circuit diagram of the conventional capacitive moisture meter for paper is shown in Fig. 5.10.

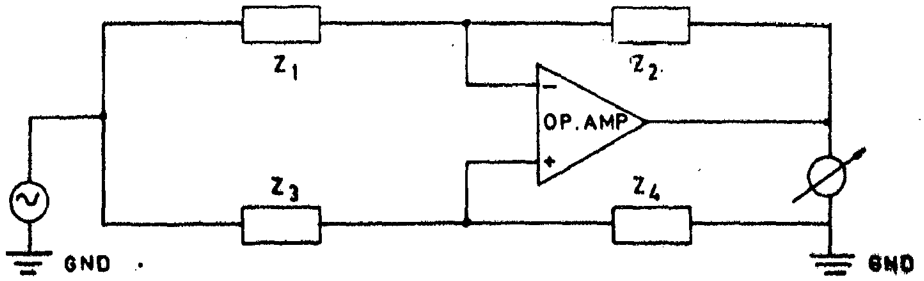


FIG.5.11_ BLOCK DIAGRAM OF PSEUDO BRIDGE.

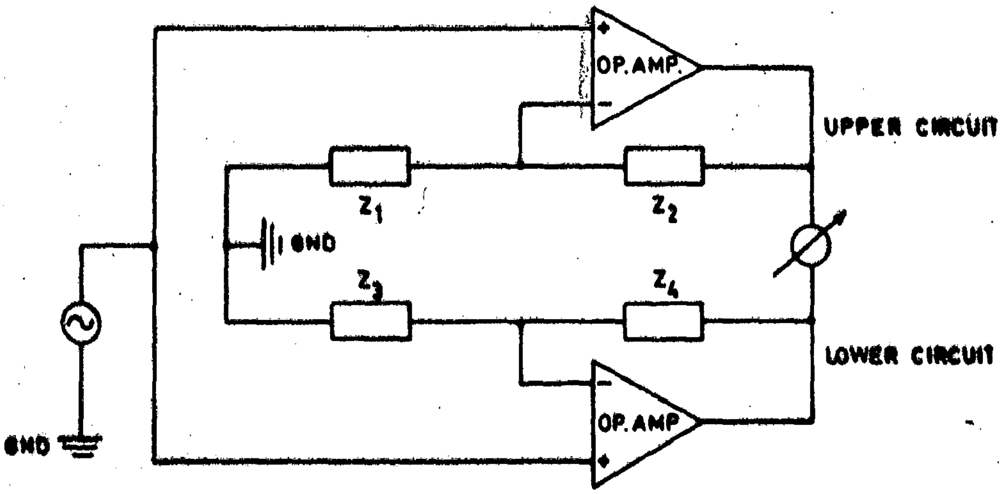


FIG.5.12_ BLOCK DIAGRAM OF IMPROVED BRIDGE WITH LINEAR OUTPUT.

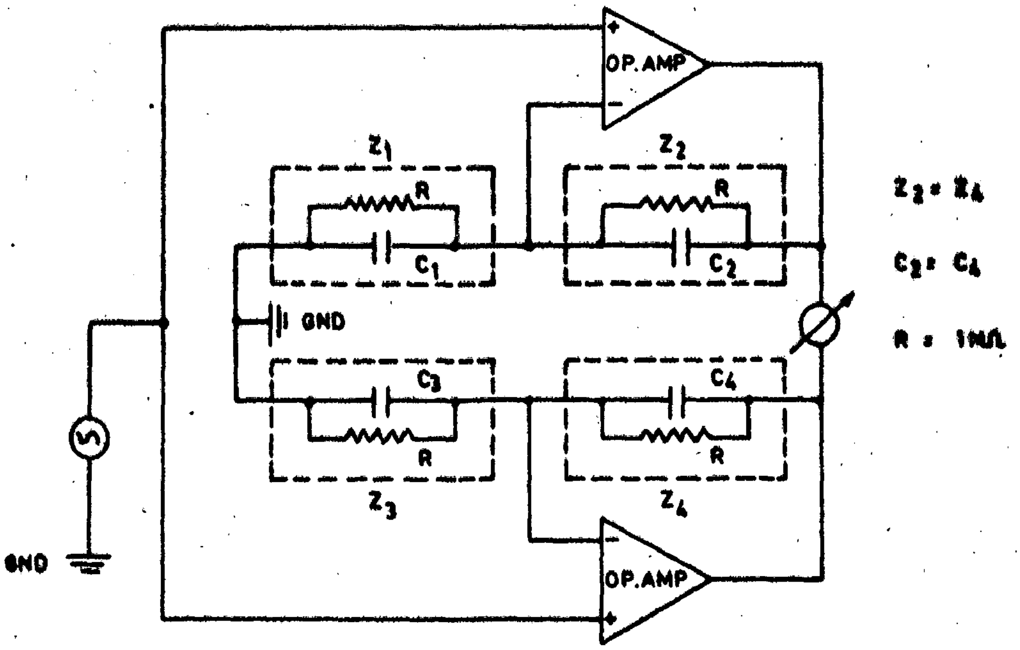


FIG.5.13_IMPLEMENTATION OF THE IMPROVED BRIDGE
FOR CAPACITANCE MEASURMENT.

5.3 LINEARIZATION OF THE METER OUTPUT

The ordinary bridge described in sect. 5.2.3 is not very much practicable. Linearity in this case can only be achieved with a possible loss of sensitivity.

In contrast, linearity can be preserved in the pseudo bridge (Fig. 5.11), whose transfer function is given as

$$T = \frac{Z_4/Z_3 - Z_2/Z_1}{1 + Z_4/Z_3} \qquad (5.5)$$

An improved bridge which comprises two similar feed back amplifier circuits has been used (Fig. 5.12). For upper and lower circuits, the transfer functions are respectively

$$T_U = \frac{Z_1 + Z_2}{Z_1} \quad , \quad T_L = \frac{Z_3 + Z_4}{Z_3}$$

The combined transfer function of the bridge is $T = T_U - T_L$. Hence,

$$T = \frac{Z_2}{Z_1} - \frac{Z_4}{Z_3} \qquad (5.6)$$

If impedances Z_1 and Z_3 are purely capacitive, and equal to $1/jwC_1$ and $1/jwC_3$ respectively, then

$$T = jw(Z_2 C_1 - Z_4 C_3)$$

If $Z_2 = Z_4 = Z$, then

$$T = j w Z(C_1 - C_3) \qquad (5.7)$$

which is simply proportional to the difference between the two oppositely varying capacitors. Due to stability consideration,

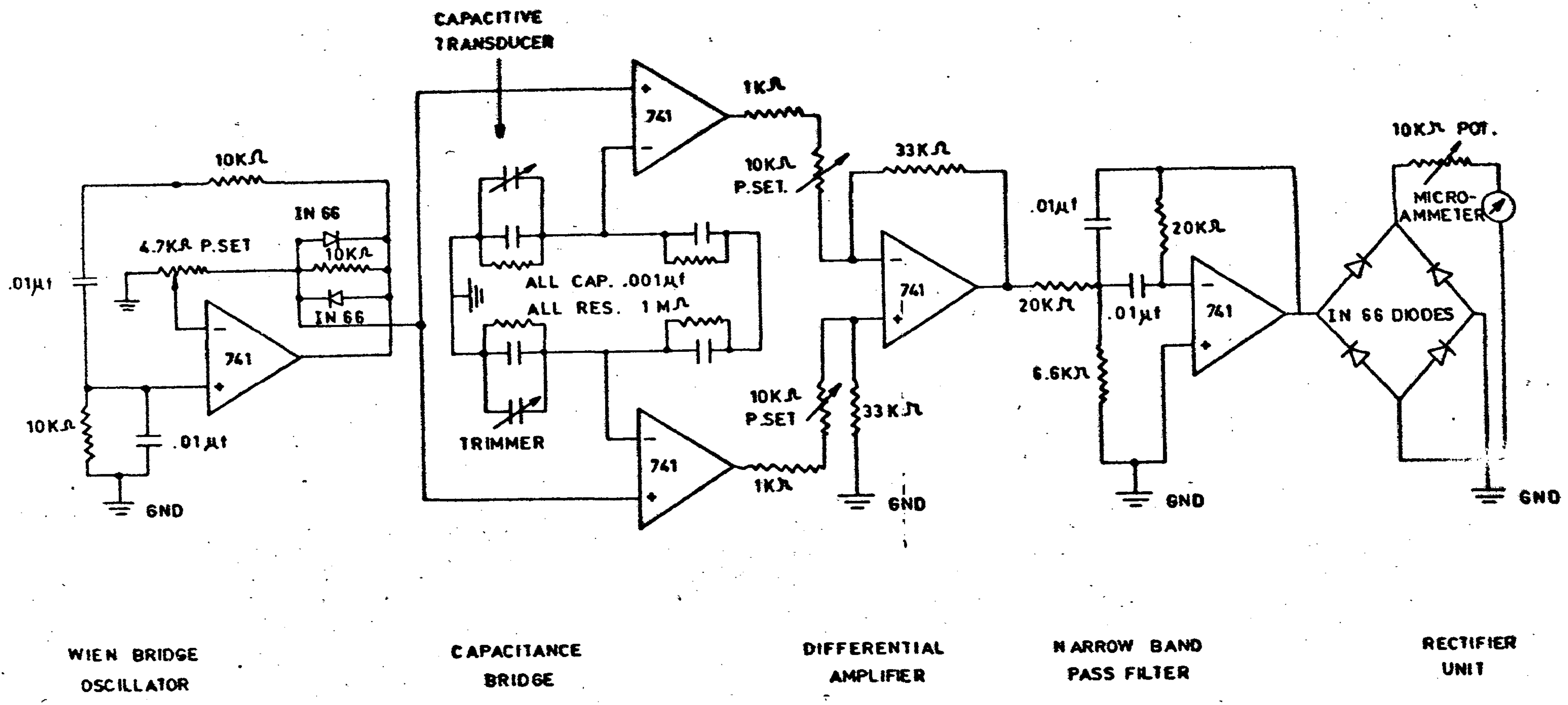


FIG.5.14_ CIRCUIT DIAGRAM OF THE LINEARIZED CAPACITIVE MOISTURE METER FOR PAPER.

some high resistance is added to each side.

$Z_2 = Z_4 = Z$, $Z_1 = 1/(1/R + jw\,C_1)$ and $Z_3 = 1/(1/R + jw\,C_3)$

consequently,

$$T = Z[(\frac{1}{R} + jw\,C_1) - (\frac{1}{R} + jw\,C_3)]$$

and therefore, $T = jw\,Z(C_1 - C_3)$

which preserves the same form as Eq.(5.7).

Implementation of the Improved Bridge for Capacitance Measurment

Fig. 5.13 shows the circuit in which the improved bridge with linear output is implemented. Bridge arms are chosen as follow:

Z_1 = Parallel unit of capacitive transducer + 0.001 μ.f. capacitor + 1 MΩ resistance.

Z_3 = Parallel unit of 0.001 μ.f. capacitor + trimmer (for zero setting) + 1 MΩ resistance.

$Z_2 = Z_4$ = 0.001 μ.f. capacitor in parallel with 1 MΩ resistance.

The complete circuit diagram of the linearized capacitive moisture meter for paper is shown in Fig. 5.14. Electronic units are similar to conventional capacitive moisture meter.

5.4 CALIBRATION OF THE METERS

Following two capacitive moisture meters were developed for calibration:

(i) Conventional capacitive moisture meter.

(ii) Linearized capacitive moisture meter.

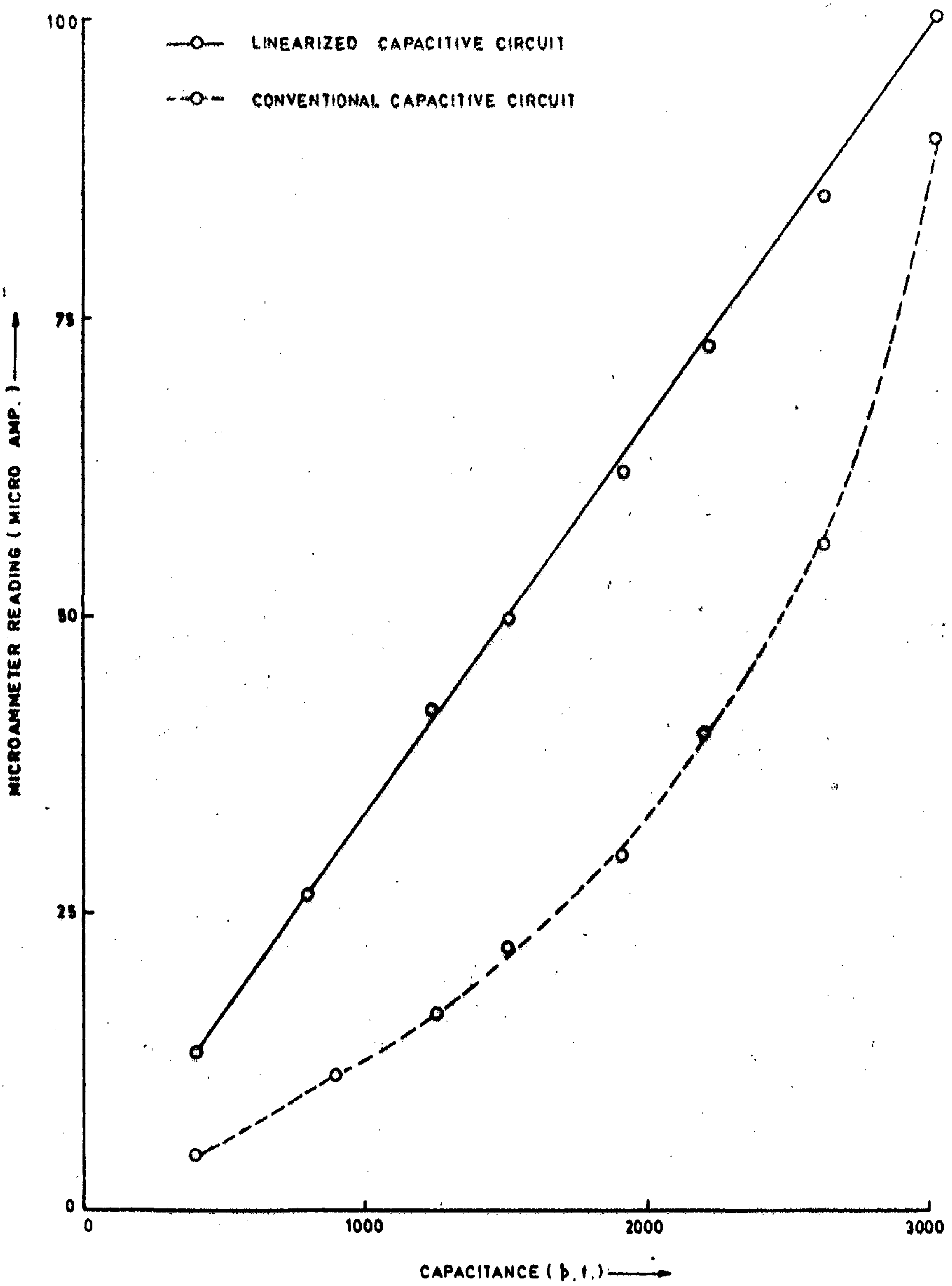


FIG.5.15_RELATION BETWEEN CAPACITANCE AND MICROAMMETER READIN

The instruments were first calibrated in terms of capacitance. For this purpose, transducer is replaced by the known variable capacitance and the microammeter reading is recorded for different values of capacitance. Then the calibration of the instruments is done with the helps of the paper sheet samples of the known moisture percentage.

5.4.1 CALIBRATION IN TERMS OF CAPACITANCE

A variable capacitor of value 0.003 μ.f. was used in place of the transducer and full scale deflection in the microammeter was obtained. Table (5.1) shows the microammeter readings noted for the different values of the capacitance.

TABLE 5.1

S. No.	Capacitance p.f.	Microammeter Reading (μ.A.) Conventional Moist. Meter	Microammeter Reading (μ.A.) Linearized Moist. Meter
1	400	5	13
2	900	11	26
3	1250	17	42
4	1500	22	50
5	1900	30	67
6	2200	40	72
7	2600	56	85
8	3000	90	100

Calibration curves are shown in Fig. 5.15.

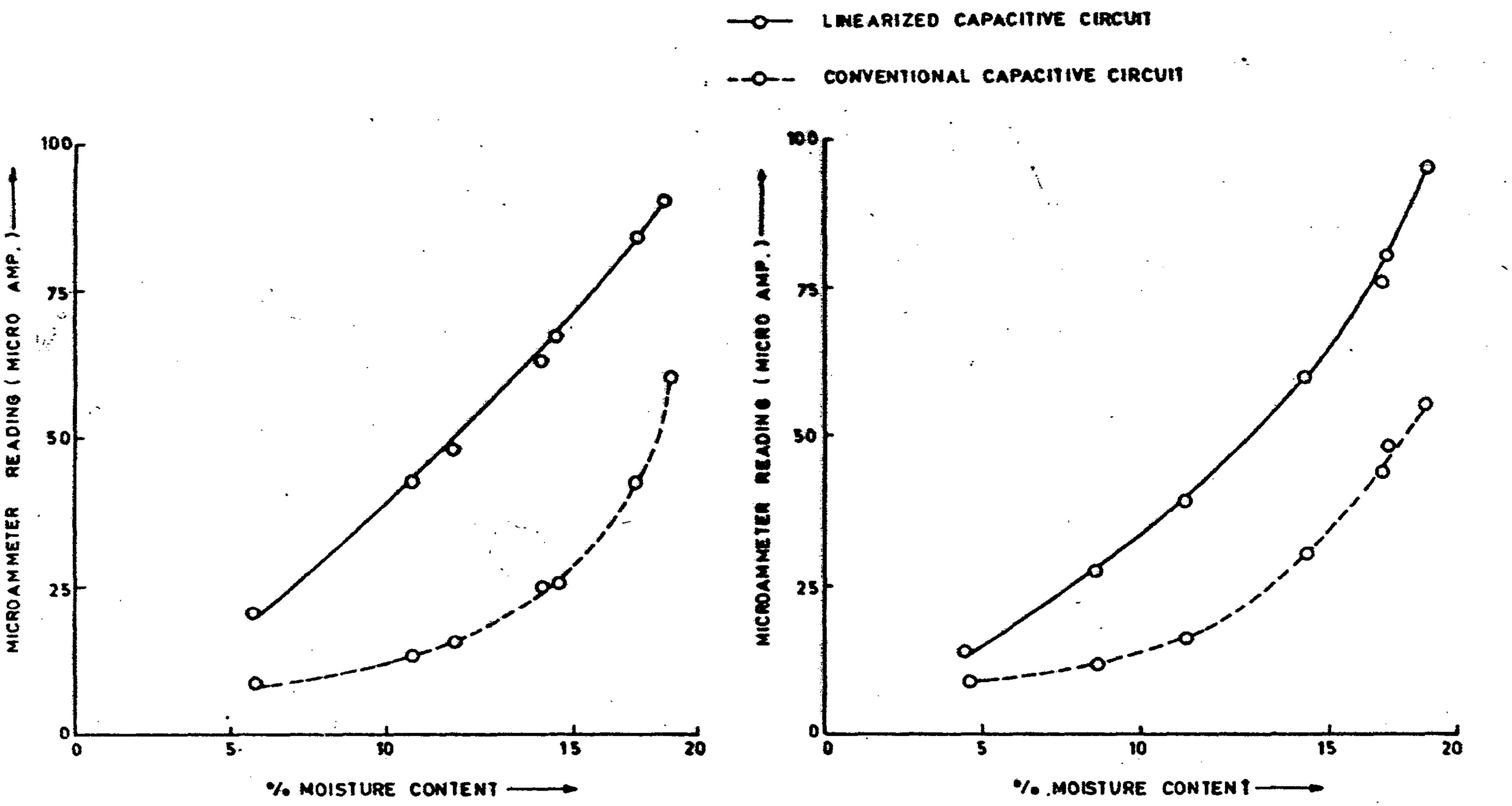
5.4.2 CALIBRATION IN TERMS OF MOISTURE PERCENTAGE

Paper samples of known moisture percentage (by oven method) were place between the parallel plates of the capacitive transducer, which forms one arm of the bridge and the corresponding micro-ammeter readings were noted in Table (5.2).

TABLE 5.2

(a) For Kraft Paper

S. No.	Moisture % of Paper	Microammeter Reading (μ.A.) Conventional Moist. Meter	Microammeter Reading (μ.A.) Linearized Moist. Meter
1	5.82	9	20
2	10.98	14	43
3	12.40	16	48
4	15.14	25	63
5	15.74	25	67
6	18.01	43	84
7	18.96	61	90



(a) FOR KRAFT PAPER

(b) FOR WRITING AND PRINTING PAPAER

FIG. 5.16_ RELATION BETWEEN MOISTURE % IN PAPER AND MICROAMMETER READING.

TABLE 5.2

(b) For Writing and Printing Paper

S. Nos.	Moisture % of Paper	Microammeter Reading (μ.A.) Conventional Moist. Meter	Microammeter Reading (μ.A.) Linearized Moist. Meter
1	4.42	9	14
2	8.60	12	27
3	11.38	16	39
4	15.24	30	59
5	17.60	44	76
6	17.83	47	80
7	18.89	55	94

Fig. 5.16 shows the relationship between the moisture percentage of the paper samples and the microammeter readings. The response of the conventional moisture meter is not linear whereas the linearized moisture meter shows the approximate linear relationship.

5.5 MERITS AND DEMERITS OF THE METERS

5.5.1 MERITS

(i) The moisture meter is simple, compact and portable. This does not require any accessory.

(ii) There is a large change in capacitance for a small change in the moisture content. Change in capacitance is proportional to the change in moisture content. Hence, linear relationship exists.

CHAPTER- 6

CONCLUSIONS AND FUTURE SCOPES

After having surveyed the work done in the area of moisture measurment of paper, the author got exposed to the ideas used by various research workers. An attempt was made in the present work towards developing both on-line and laboratory type paper moisture meters based on well known principles of variable resistance and capacitance for moisture measurment. At present none of such measuring instruments are manufactured in the country, hence, the development work undertaken is a positive step towards indigenisation of technical know-how which will lead to development of prototypes in future for imports substitution.

Performance analysis of both the instruments showed quite satisfactory results and they are going to be quite economical too when manufactured in large quantities.

The present work opens the door for future research in this area which may be listed as follows:

(i) Development of a closed loop control system for on-line control of moisture of paper.

(ii) Development of a microprocessor based system to control paper moisture when it is being manufactured.

(iii) A simple parallel plate capacitive transducer is used as sensor. It's construction is simple and can be easily modified.

(iv) The moisture measurment is instantaneous after the sample is placed between the parallel plates of the transducer.

(v) In comparison to resistive moisture meter, the main advantage of the capacitive moisture meter is that the presence of electrolytes, salts or acids in the paper sample does not affect the moisture measurment.

(vi) It is not necessary that the paper sample should be in contact with both the plates of the transducer.

(vii) The use of an improved capacitance bridge with OP. AMP. and high resistance makes the system more stable.

(viii) Capacitive moisture meter can be used both for on-line and latoratory purpose.

(ix) The instrument is economical.

5.5.2 DEMERITS

(i) Fringe field capacitance at the end of the plates and the stray capacitance between the leads may introduce error.

(ii) Paper sheet should be of uniform thickness.

(iii) Improvement of the capacitor type instrument by considering the change in phase angle due to the change in capacitance.

(iv) Development of both on-line and laboratory type instruments using sensing elements with Infrared, Microwave and Ultrasonic sources.

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