EVALUATION OF MOISTURE CONTENT IN WOOD FIBER AND RECOMMENDATION OF THE BEST METHOD FOR ITS DETERMINATION

By

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SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
AT
HELWAN UNIVERSITY
AIN HELWAN, CAIRO
JANUARY 2006

HELWAN UNIVRSITY
FACULTY OF SCIENCE
DEPARTMENT OF PHYSICS

APPROVAL SHEET

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Title: **Evaluation of moisture content in wood fiber and recommendation of the best method for its determination**

Degree: **Master of Science (Pysics)**

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Thesis Approval Date: / / 2005
Faculty Council Approval: / / 2005
University Council Approval: / / 2005

HELWAN UNIVERSITY

Date: **January 2006**

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Department: **Physics**

Degree: **M.Sc.** Convocation: **May** Year: **2006**

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Signature of Author

To my parent, brothers, wife Amany, ...and my son Ahmed

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Summary

This thesis was done at thermometry laboratory to satisfy the Egyptian economy needs for a calibration system of moisture content meters in wood.

The present thesis contains three chapters and appendix.

Chapter 1 contains an introduction and the definition of moisture content in wood, its measurement importance, a green wood and fiber saturation point and moisture content of wood and ambient environment. Also the chapter contains the relationships between moisture content of wood and its physical properties, as thermal properties, electrical properties, friction coefficient, and interaction of nuclear radiation with wood. Moreover this chapter includes different moisture content measurement methods, as oven-drying method which is the primary standard calibration method for other methods, distillation method, with their advantages and disadvantages with respect to destructive and time consuming. The common commercial moisture meters are also described such as conductance- and capacitance-type meters which are rely on the relationship between electrical properties of wood and its moisture content (MC), and Inferred meter that is rely on the absorbance of wood to inferred radiation and its relation with the MC.

Chapter 2 deals with the experimental procedures and studies done for realizing and characterizing of NIS calibration system (oven-dry method) for MC in wood. The developed system was then used to calibrate the most used meters in the Egyptian market for measuring the MC in Mosky, Zan, Aro, and Mogna woods, namely conductance and capacitance-meters. The experimental work shows that conductance meters have many advantages over capacitance meters. It is more accurate, easy in

use and maintain, and is much cheaper. This leads to the following recommendations

1-Conductance moisture meters are the best to be used

2-They should be checked periodically and recalibrated when necessary.

3-The moisture meters importing companies should ask manufacture to calibrate the meters to adopt the wood kinds in the Egyptian market.

Chapter 3 Include a qualitative physical model for the relationship between electrical conductance of wood and its MC. This was derived by the application of Anderson-Stuart model for ionic conduction in amorphous materials. The resultant equation from this model was found to be in agreement with experimental data for the relationship between conductance and MC of wood. The result of this study was published in scientific periodical Egyptian Journal of Solids. This result suggested a new calibration model for conductance meter, which is of a low cost and easy to use.

The appendix contains a copy of the first certificate given from the thermometry laboratory in NIS using the developed system, to an Egyptian company.

Abstract

The measurement of moisture content is important for its influence on wood properties. In this work calibration facilities has been established for measurement of moisture content in wood satisfy Egyptian economy needs. The system was used to calibrate and compare between the most two commonly used meters in the Egyptian market namely Conductance and capacitance-meters. The experimental work show that conductance meters have many advantages over capacitance meters. It is more accurate, easy in use and maintain, and is more cheaper. This leads to the following recommendations

1-Conductance moisture meters are preferable

2-Moisture meters should be checked periodically and recalibarted when necessary.

3-The moisture meters manufactures have to adopt their calibration to the Egyptian wood kind.

This work shows experimentally that the direct current (D.C.) conductance in wood below fiber saturation point as a function of MC, can be explained using Anderson-Stuart model for ionic conduction in amorphous materials. The calculated values using this model is in a good agreement with experimental observation behavior of MC and the literature values. This gives a new calibration model, for conductance type meters, that is easy to use, low cost, and not time consumed.

Key words: **Moisture content, wood, oven-dry, Anderson-Stuart model, ionic conduction, conductance types meters, capacitance-types meters.**

Acknowledgements

I would like to express my sincere thanks to

Mohamed Mohamed Mansure El-Nicklawy

Professor of Physics, Faculty of Science, Helwan University

Prof. Dr. Nabila Ismail El-Sayed

Vice president, Head of Chemical division, Head of Thermometry Laboratory, National Institute for Standards

Prof. Dr. Amin Fahim Hassan

Professor of Physics, Faculty of Science, Helwan University

Dr. Madiha Halawaa

Thermometry Laboratory, National Institute for Standards

For suggesting the subject investigated and for supervision, continuous advises valuable discussion, and there helping in presenting this thesis and

Dr. Mostafa Makawy

Thermometry Laboratory, National Institute for Standards

For continuous advices, support supervision and good guidance

Dr. Essam E. Mahmoud

Thermometry Laboratory, National Institute for Standards

For continuous advices, support supervision and good guidance

I would like to extend my gratitude to thermometry laboratory staff for their kind support.

Aim of the work

One of the principal functions of National Institute for Standards (NIS) is to give technical leadership and advice upon request to industry and other sectors in problems relating to measurements and calibration of high precision measuring devices for scientific, legal, industrial and technical laboratories.

Thermal Metrology Department is responsible for the maintenance and dissemination of thermal, humidity, and viscosity measurement standards to a wide range of industry and scientific institutions.

As globalization and cross-border business increases, so industrial sectors require equivalent and acceptable measurements.

The thermometry laboratory started several years ago to have its own research on humidity, moisture and calibration of its instruments.

Wood has its important in manufacturing of furniture, floor and wall cover. During the last few years the Egyptian industry sectors need to have a calibrated equipments for measuring moisture content (MC). As it is known that MC is one of the most important technical specification for quality in wood industry. The measurement of MC of wood is important due to its influence on the properties that affect the performance of wood in service. Mechanical properties, dimensional change, the propensity for the development of a given drying defect, or the conditions necessary for biological deterioration, are all influenced by moisture content.

In order to respond the increased request for calibration of moisture content in wood, a calibration facility was set up at NIS. It can provide accurate calibrations of practically all types of moisture meters

The aim of this thesis is to compare between different types of moisture meters with respect to their high accuracy, simplicity, and low cost sensor, and develop a physical model for its determination.

Chapter 1

Introduction

Throughout the history, the unique characteristics and comparative abundance of wood have made it a natural material for homes and other structures, furniture, tools, vehicles, and decorative objects. Today, for the same reasons, wood is prized for a multitude of uses.

All wood is composed of cellulose 40%, lignin 21%, hemicelluloses 30%, and minor amounts (5% to 10%) of extraneous materials contained in a cellular structure [18, 62]. Variations in the characteristics and volume of these components and differences in cellular structure make woods heavy or light, stiff or flexible, and hard or soft. The properties of a single species are relatively constant within limits; therefore, selection of wood by species alone may sometimes be adequate. However, to use wood to its best advantage and most effectively in engineering applications, specific characteristics or physical properties must be considered and measured with high accuracy.

1.1 Physical properties of wood and moisture content

Moisture content of wood (MC) is defined as the weight of water in wood expressed as a fraction, usually a percentage, of the weight of ovendry wood [18].

$$MC\% = \frac{\text{Wet weight} - \text{Ovendry weight}}{\text{Ovendry weight of wood}} \times 100 \tag{1.1.1}$$

Weight, shrinkage, strength, and other properties depend upon the moisture content of wood. In trees, moisture content can range from about 30% to more than 200% of the weight of wood substance. In softwoods, the moisture content of sapwood is usually greater than that of heartwood.

1.1.1 A green wood and fiber saturation point

Moisture can exist in wood as liquid water (free water) or water vapor in cell lumens and cavities and as water held chemically (bound water) within cell walls (figure 1.1). Green wood is often defined as freshly sawn wood in which the cell walls are completely saturated with water; however, green wood usually contains additional water in the lumens [47]. The moisture content at which both of the cell lumens and cell walls are completely saturated with water is the maximum possible moisture content. Specific gravity is the major determinant of maximum moisture content. Lumen volume decreases as specific gravity increases, so maximum moisture content also decreases as specific gravity increases because there is less room available for free water. Maximum moisture content MC_{max}[18] for any specific gravity can be calculated from

$$\mathrm{MC}_{max} = 100 \times \frac{1.54 - G_b}{1.54 G_b} \tag{1.1.2}$$

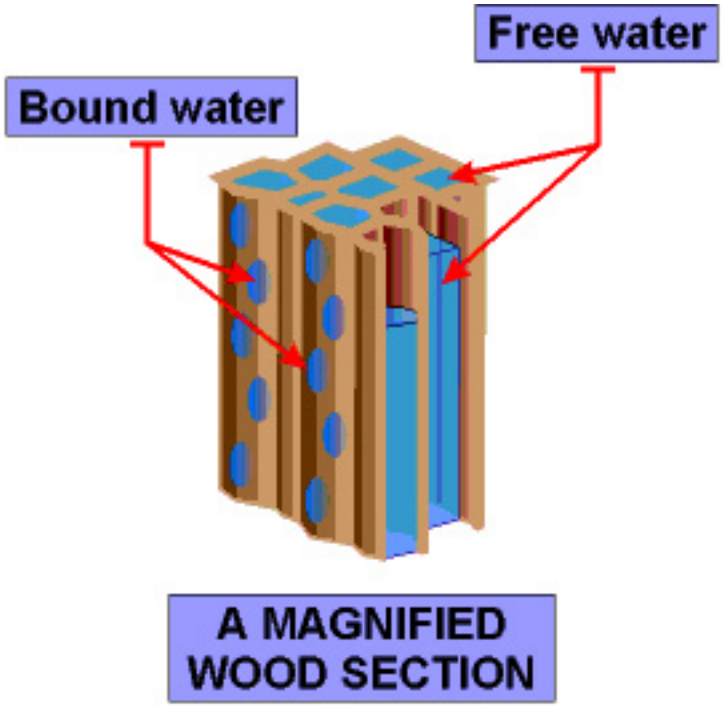

Figure 1.1: Free and bound water in wood

where G_b is basic specific gravity (based on ovendry weight and green volume) and 1.54 is specific gravity of wood cell walls. Maximum possible moisture content varies from 267% at specific gravity of 0.30 to 44% at specific gravity 0.90. Maximum possible moisture content is seldom attained in trees. However, green moisture content can be quite high in some species naturally or through waterlogging. The moisture content at which wood will sink in water can be calculated by [18]

$$\mathrm{MC}_{sink} = 100 \times \frac{1 - G_b}{G_b} \tag{1.1.3}$$

The fiber saturation point (FSP) is the moisture content at which only the cell walls are completely saturated (all bound water) but no water exists in cell lumens. While a useful concept, the term fiber saturation point is not very precise. In concept, it

distinguishes between the two ways water is held in wood. In fact, it is possible for all cell lumens to be empty and have partially dried cell walls in one part of a piece of wood, while in another part of the same piece, cell walls may be saturated and lumens partially or completely filled with water. It is even probable that a cell wall will begin to dry before all the water has left the lumen of that same cell. The fiber saturation point of wood averages about 30% moisture content, but in individual species and individual pieces of wood it can vary by several percentage points from that value. The fiber saturation point also is often considered as that moisture content below which the physical and mechanical properties of wood begin to change as a function of moisture content. During drying, the outer parts of a board can be less than fiber saturation while the inner parts are still greater than fiber saturation.

1.1.2 Moisture content of wood and ambient environment

Water vapor is always present in the air. The amount of water vapor air can hold depends upon its temperature: warm air can hold more than cold air [56]. The maximum amount of water vapor that air of a given temperature can hold is called its absolute humidity at saturation. Except when foggy or rainy, air seldom contains the maximum amount of water vapor that it could. The amount of water vapor actually held in air of a given temperature is termed the absolute humidity.

Importantly, changes in wood moisture content are keyed to changes in relative humidity, not absolute humidity. Relative humidity is the ratio of the actual amount of water vapor contained in air of a given temperature to the maximum amount of water vapor that air at that same temperature could hold, expressed as a percent. In other words, relative humidity is the absolute humidity divided by the absolute humidity at saturation of air at the same temperature.

Wood is a hygroscopic material. Always containing water, it constantly exchanges water vapor with the air, picking it up when atmospheric relative humidity is high, and giving it off when relative humidity is low. Since wood swells as it adsorbs water, and shrinks as it releases water, both its moisture content and its dimensions are controlled by the relative humidity of the surrounding air [56].

Though air temperature and relative humidity can change radically in a short time, the moisture content of unfinished wood changes slowly. Moisture content changes in finished wood happen even more slowly because water vapor must first diffuse through the coating. Because of the time lag between changes in atmospheric conditions and changes in wood moisture content, short-lived fluctuations in relative humidity usually have no appreciable effect on wood moisture content. But with prolonged exposure -weeks to months- wood will eventually stabilize at an equilibrium moisture content dictated by the average ambient relative humidity.

Despite wide day-to-day fluctuations, average outdoor relative humidity actually changes little from season to season. As a result, the moisture content of wood used or stored outdoors, but protected from direct wetting, varies little through the seasons. It's inside homes however, where the relative humidity of outdoor air drawn inside is drastically altered by heating it and cooling it without humidification or dehumidification, that wide seasonal swings in relative humidity, and hence, wood moisture content and dimensions, occur [56].

1.1.3 Equilibrium moisture content (EMC)

The moisture content of wood below the fiber saturation point is a function of both relative humidity and temperature of the surrounding air (figure1.2) [18].

Equilibrium moisture content is defined as the moisture content at which the wood is neither gaining nor losing moisture; i.e. an equilibrium condition has been reached. The relationship between EMC, relative humidity, and temperature can be approximated by the following equation which may be applied to wood of any species [18]:

$$\mathrm{EMC} = \frac{1800}{W}\left[\frac{kh}{1-kh} + \frac{k_1 kh + 2k_1 k_2 k^2 h^2}{1 + k_1 k_2 k^2 h^2}\right] \tag{1.1.4}$$

where h is relative humidity (%/100), and EMC is equilibrium moisture content (%).

For temperature T in Celsius, where

$$\begin{aligned} W &= 349 + 1.29T + 0.0135T^2 \\ k &= 0.805 + 0.000736T - 0.00000273T^2 \\ k_1 &= 6.27 - 0.00938T - 0.000303T^2 \\ k_2 &= 1.91 + 0.0407T - 0.000293T^2 \end{aligned}$$

Wood in service is exposed to both long-term (seasonal) and short-term (daily) changes in relative humidity and temperature of the surrounding air. Thus, wood is always undergoing at least slight changes in moisture content. These changes usually are gradual, and short-term fluctuations tend to influence only the wood surface. Moisture content changes can be retarded, but not prevented, by protective coatings,

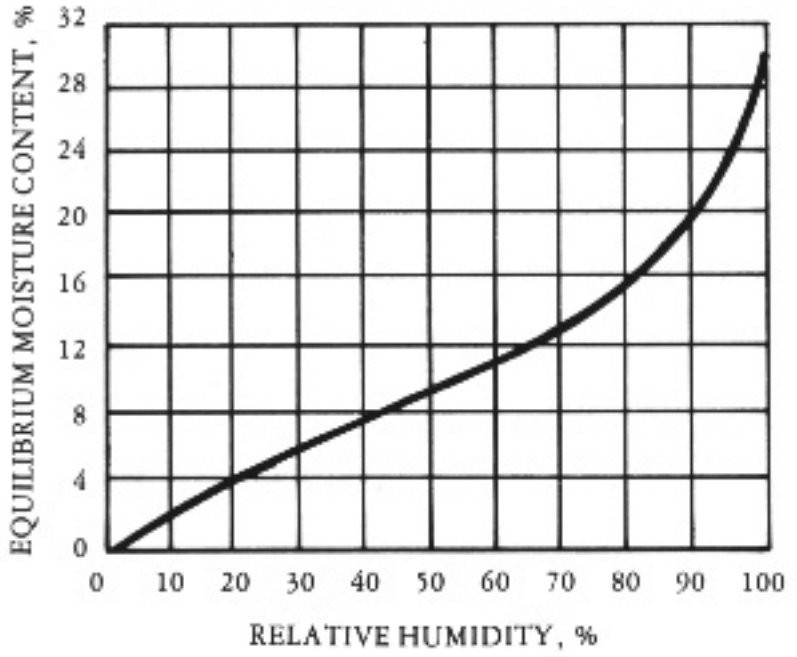

Figure 1.2: Changes in wood equilibrium moisture content with changes in relative humidity

such as varnish, lacquer, or paint. The objective of wood drying is to bring the wood close to the moisture content a finished product will have in service.

1.1.4 Thermal properties

There are four important thermal properties of wood, which are thermal conductivity, specific heat, thermal diffusivity, and coefficient of thermal expansion [18] which can be affected by MC.

Thermal Conductivity

Thermal conductivity is the measure of the rate of heat flow through one unit thickness of a material subjected to a temperature gradient. The thermal conductivity of

common structural woods is much less than the conductivity of metals with which wood often is mated in construction. It is about two to four times that of common insulating material. For example, the conductivity of structural softwood lumber at 12% moisture content is in the range of 0.1 to 1.4 W/(m.K) compared with 216 for aluminum, 45 for steel, 0.9 for concrete, 1 for glass, 0.7 for plaster, and 0.036 for mineral wool.

The thermal conductivity of wood is affected by a number of basic factors: density, moisture content, extractive content, grain direction, structural irregularities such as checks and knots, fibril angle, and temperature. Thermal conductivity increases as density, moisture content, temperature, or extractive content of the wood increases.

Specific Heat

Specific heat is defined as the amount of energy needed to increase one unit of mass (kg) one unit in temperature (K). The specific heat of wood depends on the temperature and moisture content of the wood but it is practically independent of density or species [18].

The specific heat of wood that contains water is greater than that of dry wood. Below fiber saturation, it is the sum of the specific heat of the dry wood C_{p0} and that of water (C_{pw}) and an additional adjustment factor A_c that accounts for the additional energy in the wood-water bond [18]:

$$C_p = \frac{C_{p0} + 0.01 C_{pw} \mathrm{MC}}{1 + 0.01 \mathrm{MC}} + A_c \tag{1.1.5}$$

where MC is moisture content (%). The specific heat of water is about 4.19 kJ/kgK. The adjustment factor can be derived from [18]

$$A_c = \text{MC } (b_1 + b_2 t + b_3 \text{MC }) \tag{1.1.6}$$

with $b_1 = -0.06191$, $b_2 = 2.36 \times 10^{-4}$, and $b_3 = -1.33 \times 10^{-4}$ with t temperature in kelvin. These formulas are valid for wood below fiber saturation at temperatures between 7°C and 147°C. The moisture above fiber saturation contributes to specific heat according to the simple rule of mixtures [18].

Thermal diffusivity

Thermal diffusivity is a measure of how quickly a material can absorb heat from its surroundings; it is the ratio of thermal conductivity to the product of density and heat capacity. Diffusivity is defined as the ratio of conductivity to the product of heat capacity and density; therefore, conclusions regarding its variation with temperature and density are often based on calculating the effect of these variables on heat capacity and conductivity [18].

Thermal expansion coefficient

The coefficient of thermal expansion is a measure of the change of dimension caused by temperature change. The thermal expansion coefficients of completely dry wood are positive in all directions; that is, wood expands on heating and contracts on cooling. Limited research [18] has been carried out to explore the influence of wood property variability on thermal expansion. The thermal expansion coefficient of ovendry wood parallel to the grain appears to be independent of specific gravity and species. In tests of both hardwoods and softwoods, the parallel-to-grain values have ranged [18] from about 0.000031 to 0.0000045 per K.

Wood that contains moisture reacts differently to varying temperature than does

dry wood. When moist wood is heated, it tends to expand because of normal thermal expansion and to shrink because of loss in moisture content. Unless the wood is very dry initially (perhaps 3% or 4% moisture content or less), shrinkage caused by moisture loss on heating will be greater than thermal expansion, so the net dimensional change on heating will be negative. Wood at intermediate moisture levels (about 8% to 20%) will expand when first heated, then gradually shrink to a volume smaller than the initial volume as the wood gradually loses water while in the heated condition.

Even in the longitudinal (grain) direction [18], where dimensional change caused by moisture change is very small, such changes will still predominate over corresponding dimensional changes as a result of thermal expansion unless the wood is very dry initially. For wood at usual moisture levels, net dimensional changes will generally be negative after prolonged heating.

1.1.5 Electrical properties

The most important electrical properties of wood are conductivity, dielectric constant, and dielectric power factor. The conductivity of a material determines the electric current that will flow when the material is placed under a given voltage gradient. The dielectric constant of a nonconducting material determines the amount of potential electric energy, in the form of induced polarization, that is stored in a given volume of the material when that material is placed in an electric field. The power factor of a nonconducting material determines the fraction of stored energy that is dissipated as heat when the material experiences a complete polarize-depolarize cycle [18].

Examples of industrial wood processes and applications in which electrical properties of wood are important include crossarms and poles for high voltage powerlines, utility workers tools, and the heat-curing of adhesives in wood products by high

frequency electric fields. Moisture meters for wood utilize the relationship between electrical properties and moisture content to estimate the moisture content.

Electrical conductivity

The electrical conductivity of wood varies slightly with applied voltage and approximately doubles for each temperature increase of 10°C. The electrical conductivity of wood (or its reciprocal, resistivity) varies greatly with moisture content, especially below the fiber saturation point. As the moisture content of wood increases from near zero to fiber saturation, electrical conductivity [18] increases (resistivity decreases) by 10^{10} to 10^{13} times. Resistivity is about 10^{14} to 10^{16} Ω·m for ovendry wood and 10^{3} to 10^{4} Ω·m for wood at fiber saturation. As the moisture content increases from fiber saturation to complete saturation of the wood structure, the further increase in conductivity is smaller and erratic, generally amounting to less than a hundredfold.

When wood contains abnormal quantities of water-soluble salts or other electrolytic substances, such as preservative or fire-retardant treatment, or is in prolonged contact with seawater, electrical conductivity can be substantially increased. The increase is small when the moisture content of the wood is less than about 8% but quickly increases as the moisture content exceeds 10% to 12%.

Dielectric constant

The dielectric constant is the ratio of the dielectric permittivity of the material to that of free space; it is essentially a measure of the potential energy per unit volume stored in the material in the form of electric polarization when the material is in a given electric field. As measured by practical tests, the dielectric constant of a material is the ratio of the capacitance of a capacitor using the material as the dielectric to the

capacitance of the same capacitor using free space as the dielectric [24].

The dielectric constant of ovendry wood ranges from about 2 to 5 at room temperature and decreases slowly but steadily with increasing frequency of the applied electric field. It increases as either temperature or moisture content increases, with a moderate positive interaction between temperature and moisture. There is an intense negative interaction between moisture and frequency. At 20 Hz, the dielectric constant may range from about 4 for dry wood to near 1,000,000 for wet wood; at 1 kHz, from about 4 when dry to about 5,000 when wet; and at 1 MHz, from about 3 when dry to about 100 when wet. The dielectric constant is larger for polarization parallel to the grain than across the grain [18].

Dielectric power factor

When a nonconductor is placed in an electric field, it absorbs and stores potential energy. The amount of energy stored per unit volume depends upon the dielectric constant and the magnitude of the applied field. An ideal dielectric releases all this energy to the external electric circuit when the field is removed, but practical dielectrics dissipate some of the energy as heat. The power factor is a measure of that portion of the stored energy converted to heat. Power factor values always fall between zero and unity. When the power factor does not exceed about 0.1, the fraction of the stored energy that is lost in one charge-discharge cycle is approximately equal to 2π times the power factor of the dielectric; for larger power factors, this fraction is approximated simply by the power factor itself [18].

The power factor of wood is large compared with that of inert plastic insulating materials, but some materials, for example some formulations of rubber, have equally large power factors. The power factor of wood varies from about 0.01 for dry, low

density woods to as large as 0.95 for dense woods at high moisture levels. The power factor is usually, but not always, greater for electric fields along the grain than across the grain.

The power factor of wood is affected by several factors, including frequency, moisture content, and temperature. These factors interact in complex ways to cause the power factor to have maximum and minimum values at various combinations of these factors [18].

1.1.6 Coefficient of friction

The coefficient of friction depends on the moisture content of the wood and the roughness of the surface. It varies little with species except for those species, such as lignumvitae, that contain abundant oily or waxy extractives [18].

On most materials, the coefficients of friction for wood increase continuously as the moisture content of the wood increases from ovendry to fiber saturation, then remain about constant as the moisture content increases further until considerable free water is present. When the surface is flooded with water, the coefficient of friction decreases.

Static coefficients of friction are generally greater than sliding coefficients, and the latter depend somewhat on the speed of sliding. Sliding coefficients of friction vary only slightly with speed when the wood moisture content is less than about 20%; at high moisture content, the coefficient of friction decreases substantially as the speed increases .

Coefficients of sliding friction for smooth, dry wood against hard, smooth surfaces commonly range [18] from 0.3 to 0.5; at intermediate moisture content, 0.5 to 0.7; and near fiber saturation, 0.7 to 0.9.

1.1.7 Nuclear radiation

Radiation passing through matter is reduced in intensity according to the following relationship [18]:

$$I = I_o e^{-\mu x} \tag{1.1.7}$$

where I is the reduced intensity of the beam at depth x in the material, I_o is the incident intensity of a beam of radiation, and μ is the linear absorption coefficient of the material, which is the fraction of energy removed from the beam per unit depth traversed. When density is a factor of interest in energy absorption, the linear absorption coefficient is divided by the density of the material to derive the mass absorption coefficient. The absorption coefficient of a material varies with the type and energy of radiation. The linear absorption coefficient of wood for γ radiation is known to vary directly with moisture content and density and inversely with the γ ray energy. As an example, the irradiation of ovendry yellow-poplar with 0.047-MeV γ rays yields linear absorption coefficients ranging from about 0.065 to about 0.11 cm^{-1} over the ovendry specific gravity range of about 0.33 to 0.62. An increase in the linear absorption coefficient of about 0.01 cm^{-1} occurs with an increase in moisture content from ovendry to fiber saturation. Absorption of γ rays in wood is of practical interest, in part for measuring the density of wood [18].

The interaction of wood with β radiation is similar in character to that with γ radiation, except that the absorption coefficients are larger. The linear absorption coefficient of wood with a specific gravity of 0.5 for a 0.5-MeV β ray is about 3.0 cm^{-1}. The result of the larger coefficient is that even very thin wood products are virtually opaque to β rays [18].

The interaction of neutrons with wood is of interest because wood and water contain compounds of hydrogen, and hydrogen has a relatively large probability of interaction with neutrons. Higher energy neutrons lose energy much more quickly through interaction with hydrogen than with other elements found in wood. Lower energy neutrons that result from this interaction are thus a measure of the hydrogen density of the specimen. Measurement of the lower energy level neutrons can be related to the moisture content of the wood.

When neutrons interact with wood, an additional result is the production of radioactive isotopes of the elements present in the wood. The radioisotopes produced can be identified by the type, energy, and half-life of their emissions, and the specific activity of each indicates the amount of isotope present. This procedure, called neutron activation analysis, provides a sensitive nondestructive method of analysis for trace elements [18].

1.2 Measurement of moisture content in wood

The measurement of moisture content in wood is in so far important as it influences all its major properties that affect its performance in service. For instance mechanical properties, dimensional change, the propensity for the development of a given drying defect, or the conditions necessary for biological deterioration, are all influenced by moisture content. The most accurate methods for determining moisture content include ovendrying and distillation, but these methods take too much time for many processes, and they also require that a sample be sacrificed in order to make the determination. Quicker methods have been developed that are nondestructive or are accomplished with minimal intrusion. Unfortunately, most of the methods are not as accurate as the time-consuming destructive procedures. One can select a method that provides an estimate of moisture content adequate for a particular application. The objective when selecting and using a nondestructive method is to have an understand of the advantages and limitations of that method [42].

Due to this fact, the common commercially available moisture meters are separated into groups depending on the property to be measured to estimate the moisture content. Conductance- and capacitance-type meters is rely on the relationships between an electrical property and the moisture in wood. Conductance meters measure the resistance to the flow of direct current, or low frequency alternating current, and capacitance-type meters measure some functions of the dielectric constant. Infrared meters measure differences between incident and reflected intensities for selected wavelengths. The particular wavelengths utilized by these meters will depend on the property or characteristic being measured [42].

Each of these meters has positive features that make it preferable for some applications, and each has limiting features that may make them less preferable for other applications.

The methods of determining moisture content of wood are covered in ASTM D4442.

1.2.1 Oven-drying and distillation methods

In the oven-drying method, specimens are taken from representative boards or pieces of a quantity of lumber at least 500 mm from its end. They should be free from knots and other irregularities, such as bark and pitch pockets. Specimens from lumber should be full cross sections and 25 mm long. Specimens from larger items may be representative sectors of such sections or subdivided increment borer or auger chip samples. Convenient amounts of chips and particles can be selected at random from larger batches, with care taken to ensure that the sample is representative of the batch. Veneer samples should be selected from four or five locations in a sheet to ensure that the sample average will accurately indicate the average of the sheet. Each specimen should be weighed immediately, before any drying or reabsorption of moisture has taken place. If the specimen cannot be weighed immediately, it should be placed in a plastic bag or tightly wrapped in metal foil to protect it from moisture change until it can be weighed. After weighing, the specimen is placed in an oven heated to 103 $\pm$ 2 ^{o}C and kept there until no appreciable weight change occurs in 3 hour weighing intervals. A lumber section 25 mm along the grain will reach a constant weight in a time span ranging from 12 to 48 hour. Smaller specimens will take less time. The weight of the oven dried specimen and its weight as it was cut are used to determine

the percentage of moisture content according to the formula [2]

$$MC\% = \frac{\text{Wet weight} - \text{Ovendry weight}}{\text{Ovendry weight of wood}} \times 100 \tag{1.2.1}$$

This method is the most precise one and therefore taken as the primary standard method for calibrating instruments used directly for measuring moisture content.

If wood has been treated or impregnated with chemicals, ovendrying moisture measurements may be inaccurate. An impregnant that is volatile at oven temperatures will evaporate during ovendrying, and the resulting weight loss can be misinterpreted as due to evaporated water. An impregnant that is nonvolatile will remain in the wood and so increase the apparent ovendry weight of the wood. For treated wood, the distillation method may be more accurate than ovendrying [3] for measuring moisture content. In distillation method, water is removed from the wood specimen in a closed system, in which the water is collected and measured directly. Any extraneous organic materials in the wood are dissolved out of the specimen by an organic solvent during the water extraction process. The distillation method is also more accurate than the ovendry method for some species that naturally contain large amounts of volatile materials other than water.

The disadvantages of these methods that they are time consuming (the drying period alone is at least 12 h), they require expensive apparatus and considerable skilled persons, moreover they destroy the specimen. These problems have prompted the search for other simpler and faster methods for measuring moisture content.

1.2.2 Common moisture meters

Some early methods, tried as substitutes for the ovendry method, used humidity sensors or indicators to estimate wood moisture content from the humidity at the surface or inside the wood. Others used chemicals to extract water from a pulverized wood specimen, using various means to determine the amount of water adsorbed by the extracting chemical. The potential value of electric conductance as a moisture indicator became evident when Suits and Dunlap (1931) [59] studied the dependence of electric conductance of wood on its moisture content.

A conductance-type (resistance-type) moisture meter differs from an ordinary ohmmeter only in the unusually high values of resistance (low conductance) that must be measured when checking wood with moisture content below about 10 percent. First attempts to develop a portable instrument capable of measuring such low conductance began in the late 1920's and led to the blinker-type meter[22]. This device consisted of a neon lamp in parallel with a high-quality capacitor that was charged through the wood specimen as a series conductor. When the capacitor voltage reached the firing voltage of the lamp, the lamp conducted briefly, thereby discharging the capacitor and starting the process over again. The time required to charge the capacitor increased as the series conductance decreased, so the rate of flashing of the neon lamp indicated the electric conductance of the wood. After the blinker-type meter, a high-resistance vacuum-tube bridge was developed that led to the modern direct-reading conductance-type moisture meters [14]. These instruments are basically conductance bridge circuits, using a wide range of standard resistors and a high-resistance electronic voltmeter to measure the bridge output. At about the same

time as direct-reading conductance-type meters appeared on the market, dielectric-type meters were developed. These types of meter operate on the relationship between the dielectric properties and moisture content of wood. To day, three types of electric moisture meter, each based on the fundamental relationship between moisture content and a different electric property, have been developed: the conductance-type (resistance-type), which uses the relationship between moisture content and direct current conductance; the power-loss type, which uses the relationship between moisture content and the dielectric loss factor of the wood and the capacitance type, which uses the relationship between moisture content and the dielectric constant of the wood. The latter two types of meter are classed as dielectric types. Meters that use the relationship between moisture content and electric conductance have been referred to traditionally as "resistance-type" meters. However, it is conductance that increases with increasing moisture content, so wood technologists are beginning to use the more descriptive term "conductance-type" for these meters. Conductance is simply the reciprocal of resistance.

Conductance and capacitance types

Conductance type meters typically utilize pins that are driven into the material. These pins come in varying lengths, but are usually either 1.3 cm, 2.5 cm, or 7.6 cm long. They can either be insulated using a nonconducting coating (common with the 1.3-and 2.5-cm, pins) or uninsulated (common with the 1.3 cm pins)[42]. When using insulated pins, the moisture content that is measured will be at the pin tips; but, with the uninsulated pins the moisture content that is measured will be at the wettest location along the pin shank. Because of the moisture gradient that usually

develops in wood during drying, the wettest location will typically be at the pin tip, but if water comes in contact with the surface of the material, then that would likely be the wettest spot.

The use of insulated pins allows the user to determine the moisture content gradient by taking intermittent readings while driving the pins to full depth. This flexibility is a distinct advantage when measuring materials of varying thickness. The availability of the 7.6-cm long pins makes this type of meter useful when examining large beams and timbers in service, particularly in exposed conditions or other areas where beams may be wetted. An added advantage with the 7.6-cm pins is the ability to monitor driving resistance of the pins when using the slide hammer. Low-density regions resulting from intermediate to advanced levels of fungal decay can usually be detected, as can termite and beetle damage, if severe enough.

Conductance meters are dependent on the temperature of the wood where the reading is made, and a correction factor must be used to adjust the measurement if different from the 25^{o}C calibration (some meters will apply a temperature correction based on an operator adjusted value). Since the actual temperature at the pins is not always know, the use of an estimated temperature can result in some error in the readings. Conductance and capacitance meters are inaccurate above the fiber saturation point (a moisture content between 26% and 30% for most species). Although the meter may register higher amounts, readings above 26 to 30 percent only indicate that the material is above this moisture content. For many uses, this kind of accuracy is sufficient, but this is not the case where green sorting or drying of lumber is concerned. The accuracy of both types of meters are roughly the same, varying between 1 to 3 percent moisture content. This accuracy applies to both hand-held

and in-line meters [6, 10, 46, 63]. The accuracy has been shown to be a function of the moisture content, both meters are more accurate at moisture contents above 6 to 7 % up to fiber saturation point (30%).

Measurements using capacitance-type hand-held meters are quick and completely nondestructive (i.e., no holes). Multiple measurements on a given board using a hand-held meter is accomplished with less effort. Use of these meters would also be desirable where appearance is important. Capacitance meters are sensitive to surface moisture and are also dependent on material density. Improved accuracy can be obtained by correcting for density [38, 46], but this is often impractical, except for incorporating general species or species-group corrections. When normal (parabolic-shaped) moisture content gradients exist in the material, or when the material is uniformly equilibrated, the meter will perform adequately. However, if high moisture content regions occur in the core, either resulting from bacterially infected wet wood or other situations that result in a high core moisture content, both meters may have difficulty. Although the conductance meter could detect it if the pins enter the affected area, the pockets are typically localized, and the probability that a pocket of wet wood would be missed is high. Whether or not the capacitance meter would detect a wet area, even if directly over it, would depend on the size and location of the wet region. Studies have shown that wet regions can be detected if they are located within 0.95 cm from the surface, they remain undetected if they are located at roughly 2.54 cm below the surface [44, 45]. Some capacitance-type meters have been shown to be extremely sensitive to surface moisture [35]. Longitudinal feed in-line meters, with heads above and below the material, would have a better chance in detecting wet cores. Both meters respond to higher than normal levels of salts in the wood, and it

is crucial that the user be aware of situations where such conditions could exist. The influence of some preservative and fire-retardant salts of meter performance have been documented. Another example showing the effect of water-soluble electrolytes (i.e., salts) on meter performance was observed in a recent examination of a commercial waterslide/water park. The moisture meter readings on the exposed surface of the plywood deck sheathing indicated that the material was very wet, both at the surface and in the core.

Infrared moisture meters

Infrared moisture sensing systems are sometimes confusing because of the terminology associated with them. Moisture meters are commercially available that measure changes in absorption of incident energy in the infrared band (i.e., wavelengths between 1 and 2.5 m). Meters that use this principle are most commonly used for particles and fibers in composite mills, such as particleboard and fiberboard manufacturing facilities. Other systems measure temperatures or temperature changes at the surface of a material utilizing infrared sensors, or infrared thermography. These systems can estimate moisture content by measuring the temperature difference after subjecting the surface to a heat source [61], or infer relative differences in moisture by mapping the temperature at many points on the surface of the material. For example, infrared thermography could be used to map the sides or roof of a dry kiln in order to find leaks in the building envelope. Leaks would result in increased moisture in the insulation and would cause local changes in the heat transfer characteristics of the surface (e.g., when the kiln is operating, a wet area would be warmer because of the increased heat transfer). In either case, use of this technology would only provide

a qualitative measure of moisture at the surface. This system is not limited to use below fiber saturation point, and theoretically could provide very accurate data above the fiber saturation point, although no published information on accuracy is available [42].

The infrared measurement system provides certain benefits to the user, it is nondestructive, it provides moisture content information quickly, it is relatively independent of physical properties (compared to conductance- and capacitance-type meters), and it is not limited to use below the fiber saturation point. The main disadvantages are that it can only measure surface moisture and is relatively more expensive than the electrical moisture meters [42].

Chapter 2

Realization of NIS system for calibration of MC meters in wood and comparison between conductance and capacitance type meters

In order to achieve the required accuracy for MC measurements, the MC meters have to be calibrated.

Calibration is the process of comparing the output of the MC meters against standard of known accuracy. Oven-dry method [2, 3] is the reference (primary) standard method for MC measurements and can be used to calibrate meters this is because in this method the quantities used for defining moisture content are directly measured.

The following parts give a detailed description of the used system:

2.1 Apparatus and samples

2.1.1 Wood samples

Five samples of each of the following wood species; Mosaky, Zan, Aro, and Mogna were cut in, samples of dimensions of 2 x 3 x 5 cm^3. The Samples were subjected to an atmospheres of 33.9, 37.7, 43.2, and 84.6% relative humidities for a time long enough to establish equilibrium. These humidity values were obtained from different saturated salt solutions of magnesium chloride, potassium acetate, potassium carbonate, and potassium sulphate at an average temperature of about 25 ^oC.

2.1.2 Oven

E. Schulz & Co. (Apparatebau Berlin) oven of dimensions 50 cm x 50 cm x 32 cm outside and 37 cm x 37 cm x 27 cm inside allowing temperature range from 20 to 200^oC with accuracy of 2^oC was used. The oven was controlled at a temperature of 103^oC to dry the samples. Type (T) thermocouple was used as a sensor in contact with the oven. The thermocouple was calibrated according to ITS-90 to be sure of its correct reading.

2.1.3 Balance

Mettler Toledo AT201 balance with readability of 0.01 mg and weighing capacity 205 g was used in the experimental work. The balance was calibrated at mass laboratory NIS.

2.1.4 Capacitance moisture meter

The Humitest MC-100S is a capacitance measuring moisture meter with range from 0 to 85%. It works on the principle of measuring the dielectric constant. A high frequency electrical field penetrates the material to be measured and produces a signal which is related to the moisture content. The signal is evaluated by the microprocessor and the zero point is corrected. When the correct material group is selected, the moisture content is determined and displayed at once.

2.1.5 Electrical resistance moisture meter

The Testo 606 is an electrical resistance measuring moisture meter suitable for measuring from 6% to 44% in wood. It works on the principle of measuring the electric resistance. Two metal electrodes penetrates inside the material, to be measured, and produces a signal which is related to the moisture content. The signal is evaluated by the microprocessor, the moisture content is determined and displayed at once.

2.1.6 Humidity and temperature sensor

A capacitive polymers sensor manufactured by Testo was placed inside the chambers to determine the humidity and the temperature of the chambers. This sensor was tested using saturated salt solution. The procedure of checking was repeated every 6 months. In order to achieve the traceability to the international units.

2.1.7 Saturated salt solutions

The four values of relative humidities used in this work, were obtained according to ASTM [5], form saturated salt solutions to give an equilibrium state fixed humidity points. Because the saturated vapor pressure of water decreases when salt is dissolved in it according to Raoult's law [36] and the salt concentration in the water is maximum as saturation is achieved in this case the relative humidity of air in the container is given by:

$$RH = \frac{e_w}{e_{ws}} \cdot 100\% = (1 - X_s) \cdot 100\% \tag{2.1.1}$$

Where e_w, X_s, e_{ws} are the effective vapor pressure of water in the air, the solubility of the salt and saturation vapor pressure of water, respectively. The solution is assumed to be an ideal solution. The equation implies that the relative humidity value is dependent only on the solubility of the salt at the temperature of the container and the traceability is linked to the SI base units through the realization of the mole.

2.1.8 Chambers

Chambers are constructed from low thermal conductivity material with dimensions 50 cm x 50 cm x 30 cm. To insure reliable EMC values for wood samples. This was necessary to insure isolation of the system from the temperature and humidity of the environment. Testo 625 sensor was used to measure the humidity and temperature of the chambers. A small hole was made in the center of upper side of the the chambers. A fan was fixed in the center of the middle shelf to circulate the air to obtain homogeneses relative humidity. The humidity inside the chambers was changed using four different salt solutions maintained inside four dishes. The satiability of the

chambers was studied during the experiment and the curves of its stability are shown in the experimental work.

2.1.9 Salts

The purity of all used salts was at least 98%. The chemical and physical properties of used salts are as follows:

Magnesium Chloride: A white, odorless solid flake. It has a melting point of 113°C.

Potassium Acetate: A white, deliquescent, crystalline powder, odorless, its solubility is 200 gm/100 gm of water, and its melting point is 292°C

Potassium Carbonate: A fine white granules, odorless, it is soluble in equal parts of cold water. It has a melting point of 891°C and it decomposes when it boils.

Potassium Sulphate: A white powder, odorless, its solubility is 10 gm/ 100 gm of water. It has a boiling point of 1670°C.

2.2 Experimental procedure

Samples for wood species with dimensions 2 x 3 x 5 cm^3 were prepared; to be used for calibration of MC meters. It is known that the moisture content of wood below the fiber saturation point is a function of both relative humidity and temperature of the surrounding air. To attained EMC values (6.2%, 7.7%, 8.5% and 17.4%) through the samples [4], chambers ware constructed, with dimensions 50 x 50 x 30 cm^3 and a suitable pinhole was drained suitable for Testo 625 sensor. The chambers

are made from low conductive thermal material to insure isolation of the system from temperature and humidity of ambient environment. A fan fixed on the center of the middle shelf to circulate the air to obtain homogenous relative humidity inside the chambers. Four values of relative humidity 33.9, 37.7, 43.2, and 84.6% were generated and controlled by using different saturated salt solutions of Magnesium Chloride, Potassium Acetate, Potassium Carbonate, and Potassium Sulphate respectively [5]. The salt solutions were kept in dishes inside the chambers at an average temperature of 25^{o}C. The wood samples were placed in the chambers for 60 days to attain the required EMC values [4]. The conditions in the chambers have to be stabilized before and during the experiment. For handling and weighing procedure, samples have been stored in a desiccator until they have reached room temperature. The weight of the samples was done using Mettler balance of high precision. The MC of the samples was measured and registered using both Testo 606 and Humitest MC-100S meters then it were placed in the oven for 3 hour drying intervals, the weighting and drying was repeated until the mass loss at the a 3-h drying was found to be equal to or less than twice the balance sensitivity, i.e. the endpoint was considered to be reached.

2.3 Results and discussion

2.3.1 Stability of the chambers

The humidity and temperature sensor Testo 625 was calibrated before and during the experiment using saturated salt solution fixed points techniques [36, 5].

The four chamber were tested for stability and good tightness. The readings of Testo 625 were taken for 60 days and drawn in figures. Figures from 2.1 to 2.8 show good stability of the chambers during the experiment.

From this figures it can be seen that the humidity inside the first chamber is stable at 33.9 ± 1.3 % RH and temperature of 24.8 ^{o}C for a period of 60 days using Magnesium Chloride. For the second chamber the value of RH% is 37.7 ± 0.9 using Potassium Acetate at 24.8 ^{o}C. The third chamber was stable at 43.2 ± 1.8 RH% at the same temperature. While the fourth chamber was found to be stable at 84.6 ± 2.5 RH% at a temperature 24.8 ^{o}C.

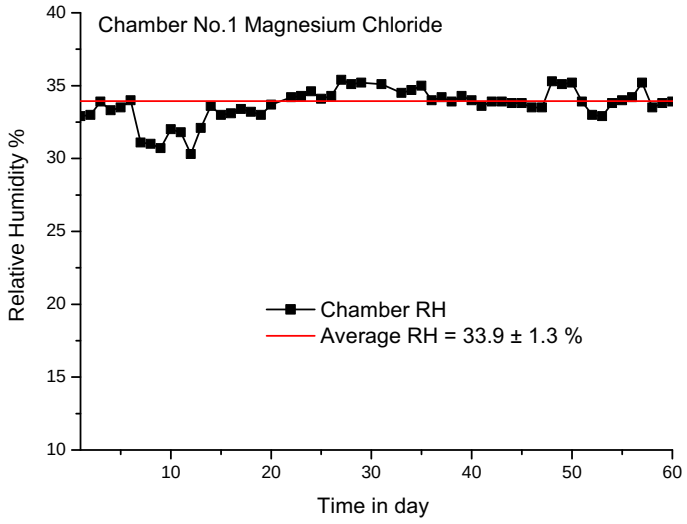

Figure 2.1: Relative humidity stability for chamber 1

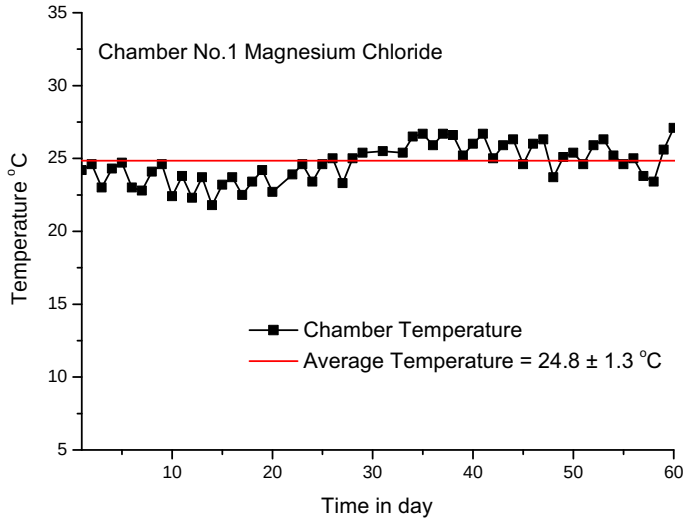

Figure 2.2: Temperature stability for chamber 1

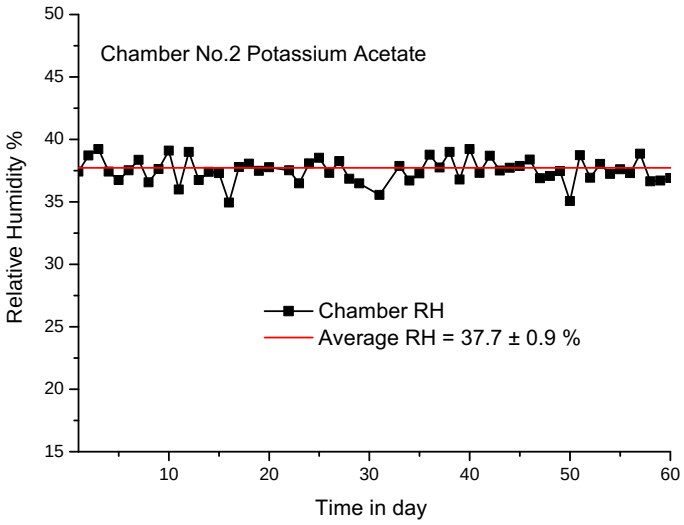

Figure 2.3: Relative humidity stability for chamber 2

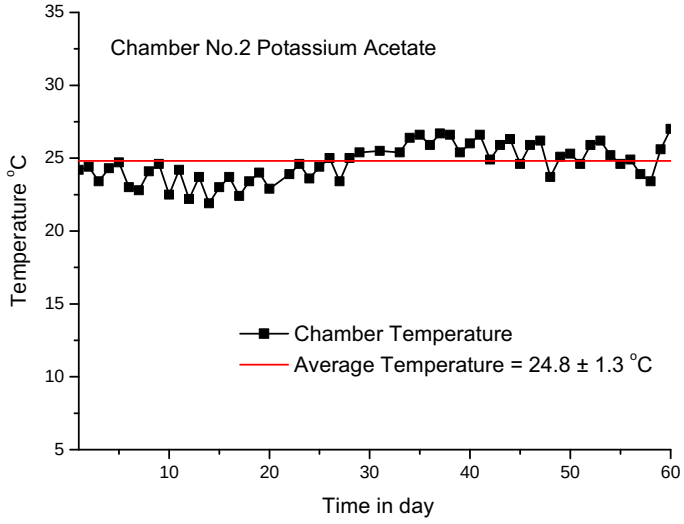

Figure 2.4: Temperature stability for chamber 2

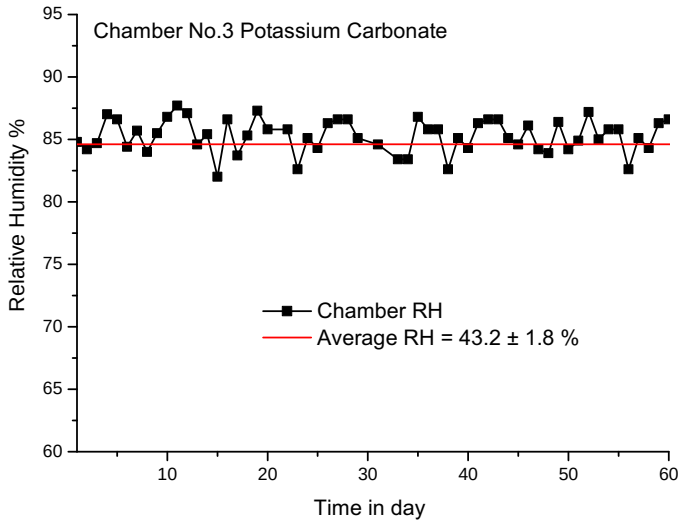

Figure 2.5: Relative humidity stability for chamber 3

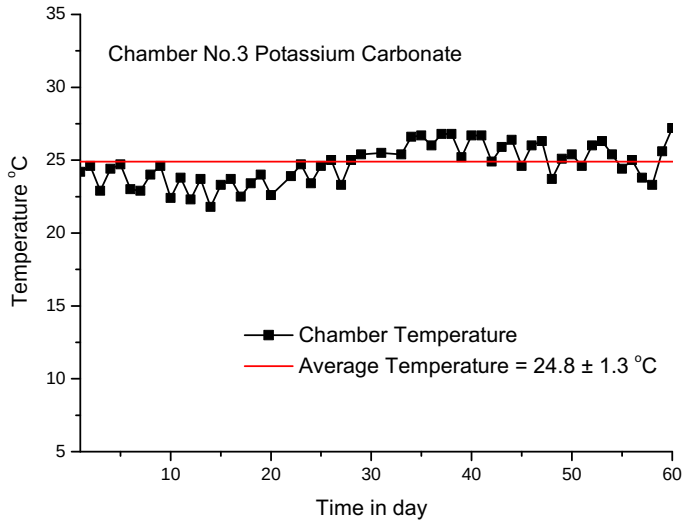

Figure 2.6: Temperature stability for chamber 3

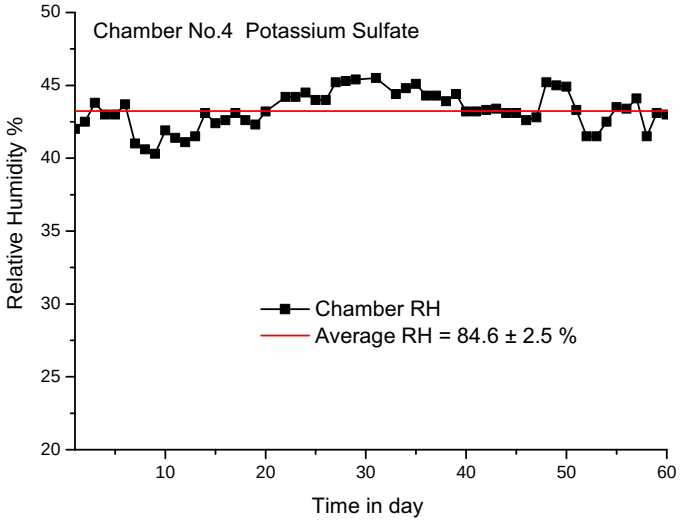

Figure 2.7: Relative humidity stability for chamber 4

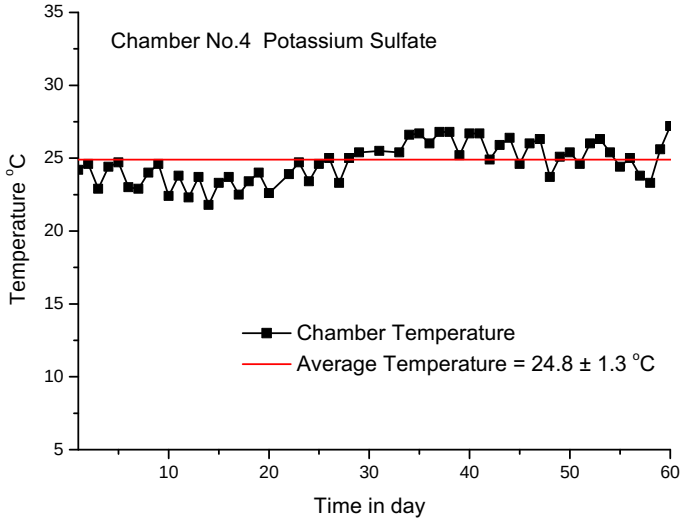

Figure 2.8: Temperature stability for chamber 4

2.3.2 Results of wood samples

The weights written in tables 2.1 and 2.2 are the weights under vacuum using the following equation [41]

$$W_{vac.} = W_{air}\left[1 + \left(\frac{\rho_{air}}{\rho_s} - \frac{\rho_{air}}{\rho_w}\right)\right] \tag{2.3.1}$$

where

$W_{vac.}$	:	Weight of sample in vacuum
W_{air}	:	Weight of sample in air
ρ_s	:	Density of sample
ρ_w	:	Density of weights
ρ_{air}	:	Density of air at 22.2°C and 76.8 mm Hg

This equation was used to avoid the parameters of vapor pressure, temperature, pressure which effect the weights, to be able to subtract and comparative weights without any correction and to reduced the uncertainty values of the standard method.

The wood samples were kept inside the chambers to compare between the different types of sensors i.e., capacitance and conductance against the standard method (Oven dry method). An example of the reading done is given in Tables 2.1 and 2.2

Results of Mosky Samples:-

Table 2.1 shows an example of calculation of the results of MC% for Mosky wood samples taken using capacitance meter. The samples were kept of 43.2% RH and temperature of 24.8 °C for 60 days. This results are compared with the results of oven dry method. The values were calculated with its uncertainty.

Table 2.1: Comparison between the results of MC% using capacitance meter with oven dry method for 5 Mosky samples kept at 43.2% RH and temperature of 24.8 °C for 60 days

Samples	Wet weight gm	Dry weight gm	MC_S %	MC_M %	Δ MC% $MC_S - MC_M$
1	37.4222	34.3492	8.95	8.2	0.75
2	36.6534	34.2809	6.92	6.0	0.92
3	36.5959	34.2878	6.73	6.4	0.33
4	34.8711	32.6337	6.86	6.8	0.06
5	34.9115	32.6349	6.98	6.0	0.98
Average	36.0908	33.6373	7.29±0.2	6.68±0.36	0.61

where

Wet weight : is weight before drying

Dry weight : is weight after drying
$MC_S\%$: is percentage of MC calculated using oven dry method
$MC_M\%$: is percentage of MC measured using capacitance meter
Δ MC% : is $MC_S - MC_M$

Table 2.2 shows an example of calculation of the results of MC% for Mosky wood samples taken using conductance meter. The samples were kept of 43.2% RH and temperature of 24.8 °C for 60 days. This results are compared with the results of oven dry method. The values were calculated with its uncertainty.

Table 2.2: Comparison between the results of MC% using conductance meter with oven dry method for 5 Mosky samples kept at 43.2% RH and temperature of 24.8 °C for 60 days

Samples	Wet weight gm	Dry weight gm	MC_S %	MC_M %	Δ MC% $MC_S - MC_M$
1	37.4222	34.3492	9.0	8	1.0
2	36.6534	34.2809	6.9	7	-0.1
3	36.5959	34.2878	6.7	6	0.7
4	34.8711	32.6337	6.9	7	-0.1
5	34.9115	32.6349	7.0	7	0.0
Average	36.0908	33.6373	7.3±0.2	7.0 ±0.62	0.3

where
$MC_M\%$: is percentage of MC measured using conductance meter
Δ MC% : is $MC_S - MC_M$

Table 2.3 shows the experimental results of MC% for Mosky wood samples using capacitance sensor. The samples were kept inside chamber 1 at relative humidity of 33.9% RH and temperature of 24.8 °C for 60 days.

Table 2.3: Comparison between the results of MC% using capacitance meter with oven dry method for 5 Mosky samples kept at 33.9% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	7.85	7.1	0.75
2	5.49	6.2	-0.71
3	5.16	6.1	-0.94
4	5.50	6.2	-0.70
5	5.09	6.0	-0.91
Average	5.82 $\pm$0.20	6.32 $\pm$0.36	-0.50

It is seen from this table that maximum difference between the two methods is -0.94% and the minimum is 0.70% using capacitance sensor at moisture content percent of 5.82

Table 2.4 shows the experimental results of MC% for Mosky wood samples using conductance sensor. The samples were kept inside chamber 1 at relative humidity of 33.9% RH and temperature of 24.8 °C for 60 days.

Table 2.4: Comparison between the results of MC% using conductance meter with oven dry method for 5 Mosky samples kept at 33.9% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	7.9	7	0.9
2	5.5	6	-0.5
3	5.2	6	-0.8
4	5.5	6	-0.5
5	5.1	6	-0.9
Average	5.8 $\pm$0.20	6.2 $\pm$0.62	-0.4

It is seen from this table that maximum difference between the two methods is -0.9% and the minimum is -0.5% using conductance sensor at moisture content percent of 5.8

From tables 2.3 and 2.4 it can be says that the conductance moisture meter is better than capacitance meter

Table 2.5 shows the experimental results of MC% for Mosky wood samples using capacitance sensor. kept inside chamber 2 at relative humidity of 37.7% RH and temperature of 24.8 °C for 60 days.

Table 2.5: Comparison between the results of MC% using capacitance meter with oven dry method for 5 Mosky samples kept at 37.7% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	8.20	8.4	-0.20
2	6.49	6.1	0.39
3	6.70	6.8	-0.10
4	6.69	6.5	0.19
5	6.69	6.7	-0.01
Average	6.95 $\pm$0.20	6.90 $\pm$0.36	0.05

It is seen from this table that maximum difference between the two methods is 0.39% and the minimum is -0.01% using capacitance sensor at moisture content percent of 6.95

Table 2.6 shows the experimental results of MC% for Mosky wood samples using conductance sensor. The samples were kept inside chamber 2 at relative humidity of 37.7% RH and temperature of 24.8 °C for 60 days.

Table 2.6: Comparison between the results of MC% using conductance meter with oven dry method for 5 Mosky samples kept at 37.7%RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	8.2	8	0.2
2	6.5	7	-0.5
3	6.7	6	0.7
4	6.7	7	-0.3
5	6.7	6	0.7
Average	7.0 $\pm$0.2	6.8 $\pm$0.62	0.2

It is seen from this table that maximum difference between the two methods is 0.7% and the minimum is 0.2% using conductance sensor at moisture content percent of 7.0

Table 2.7 shows the experimental results of MC% for Mosky wood samples using capacitance sensor. The samples were kept inside chamber 3 at relative humidity of 43.2% RH and temperature of 24.8 °C for 60 days.

Table 2.7: Comparison between the results of MC% using capacitance meter with oven dry method for 5 Mosky samples kept at 43.2% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	8.95	8.2	0.75
2	6.92	6.0	0.92
3	6.73	6.4	0.33
4	6.86	6.8	0.06
5	6.98	6.0	0.98
Average	7.29±0.2	6.68±0.36	0.61

It is seen from this table that maximum difference between the two methods is 0.75% and the minimum is 0.06% using capacitance sensor at moisture content percent of 7.29

Table 2.8 shows the experimental results of MC% for Mosky wood samples using conductance sensor. The samples were kept inside chamber 3 at relative humidity of 43.2% RH and temperature of 24.8 °C for 60 days.

Table 2.8: Comparison between the results of MC% using conductance meter with oven dry method for 5 Mosky samples kept at 43.2% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	8.9	8	0.9
2	6.9	7	-0.1
3	6.7	6	0.7
4	6.9	7	-0.1
5	7.0	7	0.0
Average	7.3±0.2	7.0 ±0.62	0.3

It is seen from this table that maximum difference between the two methods is 0.9% and the minimum is 0.0% using conductance sensor at moisture content percent of 7.3

Table 2.9 shows the experimental results of MC% for Mosky wood samples using capacitance sensor. The samples were kept inside chamber 4 at relative humidity of 84.6% RH and temperature of 24.8 °C for 60 days.

Table 2.9: Comparison between the results of MC% using capacitance meter with oven dry method for 5 Mosky samples kept at 84.6% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	16.31	16.5	0.19
2	13.68	14.10	-0.42
3	13.87	13.90	-0.03
4	14.02	14.30	-0.28
5	14.22	14.90	-0.68
Average	14.42 $\pm$0.20	14.74 $\pm$0.36	-0.32

It is seen from this table that maximum difference between the two methods is -0.68% and the minimum is -0.03% using capacitance sensor at moisture content percent of 14.42

Table 2.10 shows the experimental results of MC% for Mosky wood samples using conductance sensor. The samples were kept inside chamber 4 at relative humidity of 84.6% RH and temperature of 24.8 °C for 60 days.

Table 2.10: Comparison between the results of MC% using conductance meter with oven dry method for 5 Mosky samples kept at 84.6% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	16.3	16	0.3
2	13.7	14	-0.3
3	13.9	13	0.9
4	14.0	14	0.0
5	14.2	14	0.2
Average	14.4 ±0.2	14.2 ±0.62	0.2

It is seen from this table that maximum difference between the two methods is 0.9% and the minimum is 0.0% using conductance sensor at moisture content percent of 14.4

Table 2.11 shows the experimental results of MC% for Zan wood samples using capacitance sensor. The samples were kept inside chamber 1 at relative humidity of 33.9% RH and temperature of 24.8 °C for 60 days.

Table 2.11: Comparison between the results of MC% using capacitance meter with oven dry method for 5 Zan samples kept at 33.9% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	7.47	7.1	0.37
2	5.84	5.10	0.74
3	5.50	5.20	0.30
4	5.64	5.10	0.54
5	5.24	4.90	0.34
Average	5.94±0.20	5.48 ±0.36	0.46

It is seen from this table that maximum difference between the two methods is 0.74% and the minimum is 0.30% using capacitance sensor at moisture content percent of 5.94

Table 2.12 shows the experimental results of MC% for Zan wood samples using Conductance sensor. The samples were kept inside chamber 1 at relative humidity of 33.9% RH and temperature of 24.8 °C for 60 days.

Table 2.12: Comparison between the results of MC% using conductance meter with oven dry method for 5 Zan samples kept at 33.9% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	7.5	8	-0.5
2	5.8	6	-0.2
3	5.5	6	-0.5
4	5.6	6	-0.4
5	5.2	6	-0.8
Average	5.9 ±0.2	6.4 ±0.62	-0.5

It is seen from this table that maximum difference between the two methods is -0.8% and the minimum is -0.2% using conductance sensor at moisture content percent of 5.9

Table 2.13 shows the experimental results of MC% for Zan wood samples using capacitance sensor. The samples were kept inside chamber 2 at relative humidity of 37.7% RH and temperature of 24.8 °C for 60 days.

Table 2.13: Comparison between the results of MC% using capacitance meter with oven dry method for 5 Zan samples kept at 37.7% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	8.44	8.3	0.14
2	5.95	6.20	-0.25
3	6.10	6.80	-0.70
4	6.04	6.70	-0.66
5	6.19	6.50	-0.31
Average	6.54 $\pm$0.20	6.9 $\pm$0.36	-0.36

It is seen from this table that maximum difference between the two methods is -0.70% and the minimum is 0.14% using capacitance sensor at moisture content percent of 6.54

Table 2.14 shows the experimental results of MC% for Zan wood samples using Conductance sensor. The samples were kept inside chamber 2 at relative humidity of 37.7% RH and temperature of 24.8 °C for 60 days.

Table 2.14: Comparison between the results of MC% using conductance meter with oven dry method for 5 Zan samples kept at 37.7% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	8.4	8	0.4
2	6.0	6	0.0
3	6.1	6	0.1
4	6.0	6	0.0
5	6.2	6	0.2
Average	6.5 $\pm$0.20	6.4 $\pm$0.62	0.14

It is seen from this table that maximum difference between the two methods is 0.4% and the minimum is 0.0% using conductance sensor at moisture content percent of 6.5

Table 2.15 shows the experimental results of MC% for Zan wood samples using capacitance sensor. The samples were kept inside chamber 3 at relative humidity of 43.2% RH and temperature of 24.8 °C for 60 days.

Table 2.15: Comparison between the results of MC% using capacitance meter with oven dry method for 5 Zan samples kept at 43.2% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	8.23	8.3	-0.07
2	6.24	7.20	-0.96
3	6.25	7.00	-0.75
4	6.39	6.80	-0.41
5	6.38	6.50	-0.12
Average	6.70 $\pm$0.20	7.16 $\pm$0.36	-0.46

It is seen from this table that maximum difference between the two methods is -0.96% and the minimum is -0.12% using capacitance sensor at moisture content percent of 6.70

Table 2.16 shows the experimental results of MC% for Zan wood samples using Conductance sensor. The samples were kept inside chamber 3 at relative humidity of 43.2% RH and temperature of 24.8 °C for 60 days.

Table 2.16: Comparison between the results of MC% using conductance meter with oven dry method for 5 Zan samples kept at 43.2% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	8.2	8	0.2
2	6.2	6	0.2
3	6.3	6	0.3
4	6.4	7	-0.6
5	6.4	7	-0.6
Average	6.7 $\pm$0.2	6.8 $\pm$0.62	-0.1

It is seen from this table that maximum difference between the two methods is -0.6% and the minimum is 0.2% using conductance sensor at moisture content percent of 6.7

Table 2.17 shows the experimental results of MC% for Zan wood samples using capacitance sensor. The samples were kept inside chamber 4 at relative humidity of 84.6% RH and temperature of 24.8 °C for 60 days.

Table 2.17: Comparison between the results of MC% using capacitance meter with oven dry method for 5 Zan samples kept at 84.6% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	16.63	16.1	0.53
2	13.74	14.0	-0.26
3	13.74	14.5	-0.76
4	14.71	14.6	0.11
5	13.74	13.9	-0.16
Average	14.51±0.2	14.62 ±0.36	-0.11

It is seen from this table that maximum difference between the two methods is -0.76% and the minimum is 0.11% using capacitance sensor at moisture content percent of 14.51

Table 2.18 shows the experimental results of MC% for Zan wood samples using Conductance sensor. The samples were kept inside chamber 4 at relative humidity of 84.6% RH and temperature of 24.8 °C for 60 days.

Table 2.18: Comparison between the results of MC% using conductance meter with oven dry method for 5 Zan samples kept at 84.6% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	16.6	16	0.6
2	13.7	14	-0.3
3	13.7	14	-0.3
4	14.7	15	-0.3
5	13.7	14	-0.3
Average	14.5±0.2	14.6 ±0.62	-0.1

It is seen from this table that maximum difference between the two methods is 0.6% and the minimum is -0.3% using conductance sensor at moisture content percent of 14.5

Table 2.19 shows the experimental results of MC% for Aro wood samples using capacitance sensor. The samples were kept inside chamber 1 at relative humidity of 33.9% RH and temperature of 24.8 °C for 60 days.

Table 2.19: Comparison between the results of MC% using conductance meter with oven dry method for 5 Aro samples kept at 33.9% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	7.77	7.2	0.57
2	5.71	6.10	-0.39
3	5.76	5.60	0.16
4	5.21	6.20	-0.99
5	5.30	5.60	-0.30
Average	5.95±0.20	6.14 ±0.36	-0.19

It is seen from this table that maximum difference between the two methods is -0.99% and the minimum is 0.16% using capacitance sensor at moisture content percent of 5.95

Table 2.20 shows the experimental results of MC% for Aro wood samples using conductance sensor. The samples were kept inside chamber 1 at relative humidity of 33.9% RH and temperature of 24.8 °C for 60 days.

Table 2.20: Comparison between the results of MC% using conductance meter with oven dry method for 5 Aro samples kept at 33.9% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	7.8	7	0.8
2	5.7	6	-0.3
3	5.8	6	-0.2
4	5.2	6	-0.8
5	5.3	6	-0.7
Average	6.0±0.2	6.2 ±0.62	-0.2

It is seen from this table that maximum difference between the two methods is 0.8% and the minimum is -0.2% using conductance sensor at moisture content percent of 6.0

Table 2.21 shows the experimental results of MC% for Aro wood samples using capacitance sensor. The samples were kept inside chamber 2 at relative humidity of 37.7% RH and temperature of 24.8 °C for 60 days.

Table 2.21: Comparison between the results of MC% using capacitance meter with oven dry method for 5 Aro samples kept at 37.7% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	8.74	8.6	0.14
2	6.12	6.3	-0.18
3	6.03	6.6	-0.57
4	6.17	6.5	-0.33
5	6.08	6.7	-0.62
Average	6.63±0.2	6.94±0.36	-0.31

It is seen from this table that maximum difference between the two methods is -0.62% and the minimum is -0.18% using capacitance sensor at moisture content percent of 6.63

Table 2.22 shows the experimental results of MC% for Aro wood samples using conductance sensor. The samples were kept inside chamber 2 at relative humidity of 37.7% RH and temperature of 24.8 °C for 60 days.

Table 2.22: Comparison between the results of MC% using conductance meter with oven dry method for 5 Aro samples kept at 37.7% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	8.7	9	-0.3
2	6.1	6	0.1
3	6.0	6	0.0
4	6.2	6	0.2
5	6.1	6	0.1
Average	6.6 $\pm$0.2	6.6 $\pm$0.62	0.0

It is seen from this table that maximum difference between the two methods is -0.3% and the minimum is 0.0% using conductance sensor at moisture content percent of 6.6

Table 2.23 shows the experimental results of MC% for Aro wood samples using capacitance sensor. The samples were kept inside chamber 3 at relative humidity of 43.2% RH and temperature of 24.8 °C for 60 days.

Table 2.23: Comparison between the results of MC% using capacitance meter with oven dry method for 5 Aro samples kept at 43.2% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	8.72	9.1	-0.38
2	7.78	7.9	-0.12
3	7.33	7.5	-0.17
4	6.97	7.4	-0.43
5	6.65	7.3	-0.65
Average	7.49 $\pm$0.20	7.84 $\pm$0.36	-0.35

It is seen from this table that maximum difference between the two methods is -0.65% and the minimum is -0.38% using capacitance sensor at moisture content percent of 7.49

Table 2.24 shows the experimental results of MC% for Aro wood samples using conductance sensor. The samples were kept inside chamber 3 at relative humidity of 43.2% RH and temperature of 24.8 °C for 60 days.

Table 2.24: Comparison between the results of MC% using conductance meter with oven dry method for 5 Aro samples kept at 43.2% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	8.7	9	-0.3
2	7.8	7	0.8
3	7.3	7	0.3
4	7.0	7	0.0
5	6.7	7	-0.3
Average	7.5 ±0.2	7.4 ±0.62	0.1

It is seen from this table that maximum difference between the two methods is 0.8% and the minimum is 0.0% using conductance sensor at moisture content percent of 7.5

Table 2.25 shows the experimental results of MC% for Aro wood samples using capacitance sensor. The samples were kept inside chamber 4 at relative humidity of 84.6% RH and temperature of 24.8 °C for 60 days.

Table 2.25: Comparison between the results of MC% using capacitance meter with oven dry method for 5 Aro samples kept at 84.6% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	15.13	15.3	-0.27
2	13.11	13.8	-0.69
3	13.13	14.1	-0.97
4	13.03	14.0	-0.97
5	13.10	13.9	-0.80
Average	13.50±0.2	14.22 ±0.36	-0.72

It is seen from this table that maximum difference between the two methods is -0.97% and the minimum is -0.27% using capacitance sensor at moisture content percent of 13.50

Table 2.26 shows the experimental results of MC% for Aro wood samples using conductance sensor. The samples were kept inside chamber 4 at relative humidity of 84.6% RH and temperature of 24.8 °C for 60 days.

Table 2.26: Comparison between the results of MC% using conductance meter with oven dry method for 5 Aro samples kept at 84.6% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	15.1	15	0.1
2	13.1	13	0.1
3	13.1	14	-0.9
4	13.0	13	0.0
5	13.1	14	-0.9
Average	13.5 $\pm$0.2	13.8 $\pm$0.62	-0.3

It is seen from this table that maximum difference between the two methods is -0.9% and the minimum is 0.1% using conductance sensor at moisture content percent of 13.5

Table 2.27 shows the experimental results of MC% for Mogna wood samples using capacitance sensor. The samples were kept inside chamber 1 at relative humidity of 33.9% RH and temperature of 24.8 °C for 60 days.

Table 2.27: Comparison between the results of MC% using capacitance meter with oven dry method for 5 Mogna samples kept at 33.9% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	8.20	8.6	-0.4
2	6.42	6.5	-0.08
3	6.47	6.6	-0.13
4	6.12	6.4	-0.28
5	5.46	6.3	-0.84
Average	6.53 $\pm$0.2	6.88 $\pm$0.36	-0.35

It is seen from this table that maximum difference between the two methods is -0.84% and the minimum is -0.08% using capacitance sensor at moisture content percent of 6.53

Table 2.28 shows the experimental results of MC% for Mogna wood samples using conductance sensor. The samples were kept inside chamber 1 at relative humidity of 33.9% RH and temperature of 24.8 °C for 60 days.

Table 2.28: Comparison between the results of MC% using conductance meter with oven dry method for 5 Mogna samples kept at 33.9% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	8.2	8	0.2
2	6.4	6	0.4
3	6.5	7	-0.5
4	6.1	6	0.1
5	5.5	6	-0.5
Average	6.5 $\pm$0.2	6.6 $\pm$0.62	-0.1

It is seen from this table that maximum difference between the two methods is -0.5% and the minimum is 0.1% using conductance sensor at moisture content percent of 6.5

Table 2.29 shows the experimental results of MC% for Mogna wood samples using capacitance sensor. The samples were kept inside chamber 2 at relative humidity of 37.7% RH and temperature of 24.8 °C for 60 days.

Table 2.29: Comparison between the results of MC% using capacitance meter with oven dry method for 5 Mogna samples kept at 37.7% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	9.41	9.5	-0.11
2	6.88	7.4	-0.52
3	6.96	7.3	-0.34
4	7.02	7.5	-0.48
5	7.21	7.8	-0.59
Average	7.50 $\pm$0.2	7.90 $\pm$0.36	-0.40

It is seen from this table that maximum difference between the two methods is -0.59% and the minimum is -0.11% using capacitance sensor at moisture content percent of 7.50

Table 2.30 shows the experimental results of MC% for Mogna wood samples using conductance sensor. The samples were kept inside chamber 2 at relative humidity of 37.7% RH and temperature of 24.8 °C for 60 days.

Table 2.30: Comparison between the results of MC% using conductance meter with oven dry method for 5 Mogna samples kept at 37.7% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	9.4	9	0.4
2	6.9	6	0.9
3	7.0	7	0.0
4	7.0	7	0.0
5	7.2	7	0.2
Average	7.5±0.2	7.2 ±0.62	0.3

It is seen from this table that maximum difference between the two methods is 0.9% and the minimum is 0.0% using conductance sensor at moisture content percent of 7.5

Table 2.31 shows the experimental results of MC% for Mogna wood samples using capacitance sensor. The samples were kept inside chamber 3 at relative humidity of 43.2% RH and temperature of 24.8 °C for 60 days.

Table 2.31: Comparison between the results of MC% using capacitance meter with oven dry method for 5 Mogna samples kept at 43.2% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	10.01	10.3	-0.29
2	7.92	8.10	-0.18
3	8.27	8.70	-0.43
4	8.77	9.10	-0.33
5	8.27	8.50	-0.23
Average	8.65 $\pm$0.2	8.94 $\pm$0.36	-0.29

It is seen from this table that maximum difference between the two methods is -0.43% and the minimum is -0.18% using capacitance sensor at moisture content percent of 8.65

Table 2.32 shows the experimental results of MC% for Mogna wood samples using conductance sensor. The samples were kept inside chamber 3 at relative humidity of 43.2% RH and temperature of 24.8 °C for 60 days.

Table 2.32: Comparison between the results of MC% using conductance meter with oven dry method for 5 Mogna samples kept at 43.2% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	10.0	10	0.0
2	7.9	8	-0.1
3	8.3	8	0.3
4	8.8	9	-0.2
5	8.3	8	0.3
Average	8.7 $\pm$0.2	8.6 $\pm$0.62	0.1

It is seen from this table that maximum difference between the two methods is 0.3% and the minimum is 0.0% using conductance sensor at moisture content percent of 8.7

Table 2.33 shows the experimental results of MC% for Mogna wood samples using capacitance sensor. The samples were kept inside chamber 4 at relative humidity of 84.6% RH and temperature of 24.8 °C for 60 days.

Table 2.33: Comparison between the results of MC% using capacitance meter with oven dry method for 5 Mogna samples kept at 84.6% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	16.30	16.5	-0.20
2	14.14	13.9	0.24
3	14.02	14.2	-0.18
4	14.22	14.5	-0.28
5	14.86	15.3	-0.44
Average	14.71±0.2	14.88 ±0.36	-0.17

It is seen from this table that maximum difference between the two methods is -0.44% and the minimum is -0.20% using capacitance sensor at moisture content percent of 14.71

Table 2.34 shows the experimental results of MC% for Mogna wood samples using conductance sensor. The samples were kept inside chamber 4 at relative humidity of 84.6% RH and temperature of 24.8 °C for 60 days.

Table 2.34: Comparison between the results of MC% using conductance meter with oven dry method for 5 Mogna samples kept at 84.6% RH and temperature of 24.8 °C for 60 days

Samples	MC_S% (S)	MC_M% (M)	Δ MC% $MC_S - MC_M$
1	16.3	16	0.3
2	14.1	14	0.1
3	14.0	14	0.0
4	14.2	14	0.2
5	14.9	15	-0.1
Average	14.7 $\pm$0.2	14.6$\pm$0.62	0.1

It is seen from this table that maximum difference between the two methods is 0.3% and the minimum is 0.0% using conductance sensor at moisture content percent of 14.7

Table 2.35 shows the average moisture content percent using oven dry method and the results measured by conductance MC_{RM} and capacitance MC_{CM} meters for Mosky wood samples ranging from ≈ 5 up to 14%

Table 2.35: Average moisture content percent using oven dry method and the results measured by conductance MC_{RM} and capacitance MC_{CM} meters for Mosky wood samples

Chamber Humidity RH%	MC_S %	MC_{RM} %	MC_{CM} %
33.9	5.82	6.2	6.32
37.7	6.95	6.8	6.90
43.2	7.29	7.0	6.68
84.6	14.42	14.2	14.74

Table 2.36 shows the average moisture content percent using oven dry method and the results measured by conductance MC_{RM} and capacitance MC_{CM} meters for Zan wood samples ranging from ≈ 5 up to 14%

Table 2.36: Average moisture content percent using oven dry method and the results measured by conductance MC_{RM} and capacitance MC_{CM} meters for Zan wood samples

Chamber Humidity RH%	MC_S %	MC_{RM} %	MC_{CM} %
33.9	5.94	6.4	5.48
37.7	6.54	6.4	6.9
43.2	6.70	6.8	7.16
84.6	14.51	14.6	14.62

Table 2.37 shows the average moisture content percent using oven dry method and the results measured by conductance MC_{RM} and capacitance MC_{CM} meters for Aro wood samples ranging from ≈ 5 up to 14%

Table 2.37: Average moisture content percent using oven dry method and the results measured by conductance MC_{RM} and capacitance MC_{CM} meters for Aro wood samples

Chamber Humidity RH%	MC_S %	MC_{RM} %	MC_{CM} %
33.9	5.95	6.2	6.14
37.7	6.63	6.6	6.94
43.2	7.49	7.4	7.84
84.6	13.50	13.8	14.22

Table 2.38 shows the average moisture content percent using oven dry method and the results measured by conductance MC_{RM} and capacitance MC_{CM} meters for Mogna wood samples ranging from ≈ 5 up to 14%

Table 2.38: Average moisture content percent using oven dry method and the results measured by conductance MC_{RM} and capacitance MC_{CM} meters for Mogna wood samples

Chamber Humidity RH%	MC_S %	MC_{RM} %	MC_{CM} %
33.9	6.53	6.6	6.88
37.7	7.50	7.2	7.90
43.2	8.65	8.6	8.94
84.6	14.71	14.6	14.88

2.3.3 Uncertainty of measurement

In every measurement - even the most careful- there is always a margin of doubt. This is because there will be some inaccuracy inherent in the measurement [8, 11, 17](e.g. Instrument construction errors, environmental error, Operating error ...). Uncertainty is an estimate of the range of values which contains the true value of a measured quantity. Uncertainty is reported in terms of the probability (*confidence level*) that the true value lies within a state range of values (*interval*).

The International Organization for Standardization (ISO) definited the uncertainty as:

Parameter, associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to measurand. The result of measurement after correction for recognized systematic effects is still only an estimate of the value of the measurand because of the uncertainty arising from random effects and from imperfect correction of the result for systematic effect.

Standard uncertainty is representing each component of uncertainty that contributes to the uncertainty of a measurement result by an estimated standard deviation.

The uncertainty of the result of a measurement generally consists of several components which are grouped into two categories according to the method used to estimate their numerical values: type(A) those which are evaluated by statistical methods and type(B) those which are evaluated by other means.

Type A evaluation of standard uncertainty

A type A evaluation of standard uncertainty may be based on any valid statistical method for treating data. In most cases, the best available estimate of the expectation or expected value μ_q of a quantity q that varies randomly, and for which n independent observations q_k have been obtained under the same condition of measurement, the arithmetic mean or average $\overline{q}$ of the n observation:

$$\overline{q} = \frac{1}{n}\sum_{k=1}^{n} q_k \tag{2.3.2}$$

Thus, for an input quantity X_i estimated from n independent repeated observations $X_{i,k}$, the arithmetic mean $\overline{X_i}$ obtained from equation (2.3.2) is used as the input estimate x_i in equation $y = f(x_1, x_2, ..., x_N)$, to determine the measurement result y; that is, $x_i = \overline{X_i}$. Those input estimates not evaluated from repeated observations must be obtained by other methods.

The individual observation q_k differ in value because of random variation in the influence quantities, or random effects. The experimental variance of the observations, which estimates the variance U^2 of the probability distribution of q, is given by

$$U^2(q_k) = \frac{1}{n-1}\sum_{k=1}^{n}(q_k - \overline{q})^2 \tag{2.3.3}$$

this estimate of variance and its positive square root $U(q_k)$, termed the experimental standard deviation, characterize the variability of the observed values q_k, or more specifically, their dispersion about their mean $\overline{q}$.

The best estimate of the variance of the mean, is given by

$$U^2(\overline{q}) = u^2/n \tag{2.3.4}$$

the experimental variance of the mean $U^2(\overline{q})$ and the experimental standard deviation of the mean $U(\overline{q})$, equal to the positive square root of $U^2(\overline{q})$, the $U(\overline{q})$ and $U^2(\overline{q})$ are called type A standard uncertainty and type A variance

Sources of errors and uncertainties for electric moisture meters

The accuracy of an electric moisture meter in good condition is neither limited by the ability of the meter to respond precisely to the fundamental electrical property of wood on which its calibration is based, nor by the precision to which the dial can be read [22]. The accuracy of a meter is limited by the influence of factors other than moisture content on the readings of the meter, insofar as these factors are unknown or not properly taken into account.

One such factor is the calibration of the meter. This is usually considered to the responsibility of the manufacturer, since the user accepts the calibration data supplied with the meter. The accuracy of calibration, especially in regard to sampling and specimen control, is usually unknown to the user. Unless the user is willing to run an involved calibration procedure [27, 28], the influence of this factor is uncontrollable.

Temperature

As the temperature of wood increases so does its electrical conductance, and vice versa [13, 24, 25, 31]. Temperature corrections should be made when using a conductance-type meter on specimens that are warmer than 32^oC or cooler than 21^oC. The amount of correction depends on both temperature and moisture content, so it is best to determine the correction from a chart [22]. If a chart is not available, a rough correction can be made by subtracting 1 percent moisture content from the reading for every

7^oC the specimen temperature is above the calibration temperature specified by the manufacturer, and adding 1 percent for every 7^oC the specimen temperature is below the calibration temperature.

The effect of temperature on power loss and capacitive admittance is more complicated than its effect on conductance, so temperature corrections for these meters are not as simple as for conduct ante meters. Temperature corrections for power-loss and capacitive admittance meters can be made using charts, such as shown in [22], or special tables that provide readings corrected for temperature [9].

When using any type of electric moisture meter, the meter indication should first be corrected for temperature, and then the established room temperature-species corrections or calibration factors should be applied.

Temperature of the lumber also affects the calibration of in-line systems for monitoring moisture of lumber moving along conveyors. The limit settings should be adjusted for the temperature of the wood being monitored.

Evaluation of type B sources

A type B evaluation of standard uncertainty is usually based on scientific judgment using all the relevant information available, which may include previous measurement data, experience with, or general knowledge of, the behavior and property of relevant materials and instruments, manufacturers specifications, data provided in calibration and other reports, and uncertainties assigned to reference data taken from handbooks.

Combined standard uncertainty

The combined standard uncertainty of a measurement result is taken to represent the estimated standard deviation of the result. It is obtained by combining the individual standard uncertainties (and covariances as appropriate), whether arising from a type A evaluation or a type B evaluation, by

$$U_c = \sqrt{U_1^2 + U_2^2 + ... + U_N^2} \tag{2.3.5}$$

Expanded uncertainty

It is often required that a measure of uncertainty that defines an interval about the measurement result y within which the value of the measurand Y is confidently believed to lie. The measure of uncertainty intended to meet this requirement is termed expanded uncertainty U, and is obtained by multiplying $U_c(y)$ by a coverage factor k. Thus $U = kU_c(y)$ and it is confidently believed that $y - U < Y < y + U$, which is commonly written as $Y = y \pm U$.

Table 2.39: Uncertainty budget at confidence level 95% (k=2) for oven-dry

Source of uncertainty	Type	Value	Probability distribution	Divisor	Standard uncertainty
Standard uncertainty	A	0.1	Normal	1	0.1
Calibration of Balance	B	0.02	Normal	2	0.01
Combined standard uncertainty			Assumed normal		0.10
Expanded uncertainty			Assumed normal		0.20

Table 2.40: Uncertainty budget at confidence level 95% (k=2) for Humitest

Source of uncertainty	Type	Value	Probability distribution	Divisor	Standard uncertainty
Standard uncertainty	A	0.17	Normal	1	0.17
Resolution size	B	0.05	Rectangular	$\sqrt{3}$	0.029
Temperature effect	B	0.1	Rectangular	$\sqrt{3}$	0.058
Combined standard uncertainty			Assumed normal		0.18
Expanded uncertainty			Assumed normal		0.36

Table 2.41: Uncertainty budget at confidence level 95% (k=2) for Testo

Source of uncertainty	Type	Value	Probability distribution	Divisor	Standard uncertainty
Standard uncertainty	A	0.13	Normal	1	0.13
Resolution size	B	0.5	Rectangular	$\sqrt{3}$	0.28
Temperature effect	B	0.01	Rectangular	$\sqrt{3}$	0.006
Combined standard uncertainty			Assumed normal		0.31
Expanded uncertainty			Assumed normal		0.62

2.3.4 Traceability

The traceability is: The property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.

The traceability of the instruments used in the measurement is as following

All the temperatures reading values were measured according to ITS's-90 which mean that the reading is traceable to the SI units.

Hygrmoeters were calibrated by using Testo 650, which are transfer standard traceable to IMGC-Italy.

Balance used in weighting process traceable to Mass, Pressure & Density Department of NIS

2.3.5 Discussion

The chambers were studied for its stabilities for a period of 60 days. All the chambers were stable except Potassium Acetate chamber which was stable only, for 20 days, that is because the salt starting to absorb moisture. This was avoided by changing the salt solution three times to reach 60 days for the same conditions to meet ASTM D 4933.

Regarding the tables of results 2.3-2.34 the difference of results of the first value than the others may explained as this value was taken without the heating of the sample (using oven dry method process) and the wood samples may contain some volatile solutions. It can also be noticed that the Last four values are very near to each other which may be due to the fact that the samples were subjected to the same process. It is noticed that the highest difference of the MC% between the standard method (oven dry) and conductance sensor for MC is -0.9 while the maximum difference of capacitance sensor is -0.99 for MC. Also Tables 2.40 and 2.41 show that the uncertainty type A is 0.13 for conductance meter and it is 0.17 for capacitance meter which mean that the conductance sensor is better than capacitance sensor.

Chapter 3

New calibration system for moisture content conductance meters

3.1 Introduction

The common commercially moisture meters are conductance-type meters rely on the relationship between electrical conductance and the MC of wood. Because there is no existent physical theory give quantitative and qualitative relationship between an electrical conductance and the MC of wood below fiber saturation point; the existent calibration methods for those meters are long time and high cost consuming; due to the needs of great number of points between MC, and electrical conductance to draw the calibration curve.

To find out a physical theory between an electrical conductance and the MC of

wood, a physical similarity between wood and amorphous material as both are non crystals formed from networks, lead us to suggest the using Anderson-Stuart model for ionic conduction in amorphous materials

3.2 Ionic conduction theory for wood using Anderson-Stuart model for ionic conduction in amorphous materials

The chemical structure of wood is cellulose 40%, lignin 21%, hemicelluloses 30%, and others materials, which are natural polymers. An important step in determining the nature of the conduction mechanism in wood is identification of the charge carrier(s). A key indicator of ionic (including proton) conduction is the existence of electrolytic effects [12]. Phenomena such as polarization and the dependence of conductivity on voltage, the metal used for electrodes and the time of application of voltage have been widely observed in cellulosic materials like wood. The electric conductance of wood increases as the temperature of the wood increases [13, 25]. This is opposite to the effect of temperature on resistance in metals and suggests that in wood the mechanism of conduction is by charge carriers whose number or mobility is increased by thermal activity. Thus, the conduction of current by wood is likely to be ionic. Murphy [39] in an electrolysis experiment proved that conduction in dry cellulose is ionic and probably protonic, and reached the same conclusion for humidified cellulose. Hence the evidence supports the conclusion that conduction in cellulosic materials containing sorbed water is predominantly electrolytic and that the charge carriers are therefore ionic.

To explain the ionic conduction wood, a physical similarity between wood and amorphous material as non crystals formed from networks, suggesting the applying Anderson-Stuart model for ionic conduction in amorphous materials [15], in this model the ionic conductivity on wood written in the form

$$\sigma = nq\mu \tag{3.2.1}$$

where n is the concentration of mobile ionic species carrying charge q, and μ is the mobility. A simple expression for the ionic conductivity may be obtained by assuming that the ionic motion occurs by field-enhanced, thermally activated hopping between equivalent sites in the structure. The action of the applied electric field E is to lower the energy of a site by an amount equal to qEa, where a is the intersite spacing. Therefore, the probability of ionic hopping in the direction of the field increases, and the net number of ions per volume hopping in the direction of the field, averaged over all space, is then

$$\phi = \frac{nqaE\nu_o}{6k_BT} \exp\left(-\frac{W}{k_BT}\right) \tag{3.2.2}$$

where W is the mobility activation energy, i.e. the barrier to hopping (diffusion) between two sites, ν_o is the pre-exponential term in the hopping rate expression (essentially equal to the 'rattling' vibrational frequency of an ion trapped in the potential well at a site), T temperature in Kelvin, k_B Boltezman constant, and it has been assumed that $qaE \ll k_BT$. The current density is simply

$$J = qa\phi, \tag{3.2.3}$$

and the ionic conductivity is then given by

$$\sigma = \frac{J}{E}$$

$$\sigma = \frac{n\nu_o q^2 a^2}{6k_B T} \exp\left(-\frac{W}{k_B T}\right) \tag{3.2.4}$$

The ionic carrier concentration may be itself thermally activated:

$$n = n_o \exp\left(-\frac{E_c}{k_B T}\right) \tag{3.2.5}$$

where E_c is the ionic carrier concentration activation energy, and so the d.c. conductivity activation energy E_σ in this picture is given in general by the sum of two terms:

$$E_\sigma = W + E_c \tag{3.2.6}$$

substituting from equations (3.2.5) and (3.2.6) in (3.2.4) we get

$$\sigma = \frac{n_o\nu_o q^2 a^2}{6k_B T} \exp\left(-\frac{E_\sigma}{k_B T}\right) \tag{3.2.7}$$

It should be noted that the activation energies E_c, and W are in fact enthalpies, and the corresponding entropy terms associated with the individual processes are subsumed into the pre-exponential terms n_o and ν_o.

Using Anderson-Stuart model [1, 15] which have been proposed to account for activation energy of the ionic d.c. conductivity E_σ, (or the diffusion coefficient): cation for example H^+ coming from water linked to cellulose hydroxyl group is presumed to hop from an occupied site in the vicinity of a negatively charged counterion, such as the cellulosic hydroxyl group site in wood, to a vacancy near another cellulosic hydroxyl group site, passing through a 'gateway' formed by bridging molecules. The model suggested that E_σ may be regarded as consisting of two terms, an electrostatic binding energy E_b, required to remove a cation (H^+) from a cellulosic hydroxyl group, and a strain term E_s associated with the long-range mobility ('gate-passing'). Thus, E_σ can be written as $E_\sigma = E_s + E_b$ or

$$E_\sigma = \frac{\alpha Z_+ Z_- e^2}{4\pi\varepsilon\varepsilon_o r_o} - \frac{2Z_+ Z_- e^2}{4\pi\varepsilon\varepsilon_o (r_p/2)} + \frac{\pi G r_p}{2}(r_+ - r_d)^2 \tag{3.2.8}$$

where

Z_+ **and** Z_- are the charge states of cation and cellulosic hydroxyl group respectively

e is the electron charge

$r_o = (r_+ + r_-)$ the sum of the cation (H^+) and hydroxyl group radii respectively

r_d is the 'gateway' radius between hydroxyl groups

G is the shear modulus

ε the dielectric constant of the host

ε_o the dielectric constant of free space

r_p is a jump length

α is Madelung like constant of the order unity

Elliott [15] has argued that, for d.c. conductivity, the correct choice for r_p is the critical percolation radius, which in three dimensions is given by

$$r_p = \left(2.7 \times \frac{3}{4\pi n}\right)^{\frac{1}{3}} \tag{3.2.9}$$

where n is the site concentration which equal to moisture contain MC as each water molecule H_2O give H^+, The first term in (3.2.8) represents the energy required to remove a cation from a hydroxyl group site and place it at infinity (the constant α is of the order of unity), reduced by the second term, the attractive electrostatic

potential experienced by a cation midway between two hydroxyl group sites; the sum of these two terms is thus equal to the electrostatic binding energy of the cation at a site. The third term is the strain energy as calculated by McElfresh and Howitt [15] for enlargement of a cylindrical hole (of length r_p) from radius r_d to r_+, and represents the strain associated with an ion moving between two sites.

Thus, as the site (cation) concentration MC increases, the d.c. conductivity activation energy E_σ is predicted from (3.2.8) to decrease. Some of those parameters values in Eq. (3.2.8) are differentiating wood species like n_o, ν_o, G, r_d, and ε.

r_p could be written in the form

$$r_p = \frac{0.864}{\sqrt[3]{MC}} \tag{3.2.10}$$

substituting r_p from eq (3.2.10) to (3.2.8) we get

$$E_\sigma = \frac{\alpha Z_+ Z_- e^2}{4\pi\varepsilon\varepsilon_o r_o} - \frac{2Z_+Z_-e^2}{4\pi\varepsilon\varepsilon_o(0.432)}\sqrt[3]{MC} + \frac{\pi G}{2}\frac{0.864}{\sqrt[3]{MC}}(r_+ - r_d)^2 \tag{3.2.11}$$

For constant temperature Eq. (3.2.7) can be written in form

$$\sigma = \frac{n_o \nu_o q^2 a^2}{6k_B T} \times \tag{3.2.12}$$

$$\exp\left(-\frac{\alpha Z_+ Z_- e^2}{4\pi k_B T\varepsilon\varepsilon_o r_o} + \frac{2Z_+Z_-e^2}{4\pi k_B T\varepsilon\varepsilon_o(0.432)}\sqrt[3]{MC} - \frac{\pi G}{2k_B T}\frac{0.864}{\sqrt[3]{MC}}(r_+ - r_d)^2\right)$$

As the experimental data for wood in the literature are given in electrical conductance C rather than conductivity σ, the above Eq.(3.2.12) can be given in term of Conductance. For conductor of a cross section area A and length L conductance C:

$$C = \frac{A}{L}\sigma \tag{3.2.13}$$

Thus Eq. (3.2.12) in terms of conductance rather than conductivity can be written as:

$$C = \frac{A}{L}\frac{n_o \nu_o q^2 a^2}{6k_B T} \times \tag{3.2.14}$$

$$\exp\left(-\frac{\alpha Z_+ Z_- e^2}{4\pi k_B T \varepsilon \varepsilon_o r_o} + \frac{2Z_+ Z_- e^2}{4\pi k_B T \varepsilon \varepsilon_o (0.432)}\sqrt[3]{MC} - \frac{\pi G}{2k_B T}\frac{0.864}{\sqrt[3]{MC}}(r_+ - r_d)^2\right)$$

Taking the log C we get

$$\log C = \log\left[\frac{A}{L}\frac{n_o \nu_o q^2 a^2}{6k_B T}\right]\log e \times \tag{3.2.15}$$

$$\left(-\frac{\alpha Z_+ Z_- e^2}{4\pi k_B T \varepsilon \varepsilon_o r_o} + \frac{2Z_+ Z_- e^2}{4\pi k_B T \varepsilon \varepsilon_o (0.432)}\sqrt[3]{MC} - \frac{\pi G}{2k_B T}\frac{0.864}{\sqrt[3]{MC}}(r_+ - r_d)^2\right)$$

for constant temperature Eq. (3.2.15) can be written as:

$$\log C = I + J\sqrt[3]{MC} - \frac{K}{\sqrt[3]{MC}} \tag{3.2.16}$$

where

$$I = -\log\left[\frac{A}{L}\frac{n_o \nu_o q^2 a^2}{6k_B T}\right]\log e \times \frac{\alpha Z_+ Z_- e^2}{4\pi k_B T \varepsilon \varepsilon_o r_o},$$

$$J = \log\left[\frac{A}{L}\frac{n_o \nu_o q^2 a^2}{6k_B T}\right]\log e \times \frac{2Z_+ Z_- e^2}{4\pi k_B T \varepsilon \varepsilon_o (0.432)},$$

and

$$K = \log\left[\frac{A}{L}\frac{n_o \nu_o q^2 a^2}{6k_B T}\right]\log e \times \frac{0.864\ \pi G}{2k_B T}(r_+ - r_d)^2.$$

Eq. (3.2.16) give the direct current conductance as a function of MC for wood according to this ionic conduction model. To obtain the values of this three parameters for a given wood specie at certain temperature, three simultaneous equations with different three experimental date sets of (C, MC) substituted in eq. (3.2.16) needed to be solved.

3.3 The suggested new calibration method

A new calibration method for MC conductance meters using Eq. (3.2.16) is as follows:

3.3.1 Apparatus and samples

Samples for wood species with dimensions 2 x 3 x 5 cm^3 were prepared; for which the MC meter needed to be calibrated. The moisture content of wood below the fiber saturation point is a function of both relative humidity and temperature of the surrounding air. To attained three EMC values (7%, 16%, and 25%) through the samples [4], three chambers ware constructed, with dimensions 50 x 50 x 30 cm^3 and a suitable pinhole to humidity and temperature Testo 625 sensor. The chambers are made from low conductive thermal material to insure isolation of the system from thermal and humidity ambient environment, and a fan fixed on the center of the shelf to circulate the air to obtain homogenous relative humidity air. Three values of relative humidity (43.2, 84.3, 97.3) % are generated and controlled by three different saturated salt solutions (Potassium Carbonate, Potassium Chloride, and Potassium Sulphate respectively) [5], being in dishes inside the chambers at average temperature 25^oC. The samples are placed in the chambers for 60 days to attain the required equilibrium moisture content values [4]. The conditions in the chambers have to be stabilized before and during the experiment.

3.3.2 Experimental work

The resistances of the samples were measured using the Ohm-meter to be calibrated. The measurements were carried out at 25^oC between a pair of needle electrodes 2.5-0.6

cm apart and driven to a depth of 0.8 cm in the sample. The reciprocals of these data are the conductance in micro siemens. The MC of the samples was measured using the oven dry method. The procedure involves simply weighing the sample before and after oven drying to constant weight at 103^{o}C. Constant weight is achieved as no further weight loss was observed after further drying the samples in intervals of 3 h. The measuring accuracy was 0.2 % [2]. Because the moisture content was measured directly, this method is the most precise one.

3.3.3 Results and discussion for new calibration system

Applying equation (3.2.16) using the experimental values obtained from literature [22] resistances data are represented in Table 3.1 (The reciprocals of these data are the conductance in micro siemens) for the five wood species samples (Baldcypress, Red Pine, Bigtooth Aspen, Mahogany, and Black Walnut) having 7%, 16%, and 25% MC values. Three linear equations containing the three parameters I, J, and K for each of the five wood species ware solved. The obtained values for I, J, and K are listed in Table 3.2.

Substituting the values of the obtained parameters given in table 3.2 for each wood specie in Eq. (3.2.16)., C as a function of MC, can be calculated. To compar between the calculated and experimental values Log$C$ was plotted against MC for the investigated wood samples and given in Figs. 3.1, 3.2, 3.3, 3.4, and 3.5. From this comparison, it is clear that the experimental data match very good the calculated one. This simplified model need only three measured values of conductance at different MC, to give the parameters that a complete calibration curve for MC conductance meter can be obtained.

Table 3.1: Exp. MC% and corresponding resistance MΩ at 25 ^{o}C

MC %	7	16	25
Wood Specie	Resistance MΩ		
Baldcypress	12600	11.2	0.42
Red Pine	70000	28.0	0.67
Bigtooth Aspen	30000	8.6	0.26
Mahogany	20900	12.3	0.26
Black Walnut	51300	12.9	0.38

Table 3.2: Obtained I, J, and K values.

Wood Specie	I	J	K
Baldcypress	-0.5020	0.6925	20.8950
Red Pine	15.7617	1.9154	16.4227
Bigtooth Aspen	21.9493	-3.2861	51.9177
Mahogany	-5.3990	-2.1087	45.0935
Black Walnut	5.4157	-0.2665	29.8725

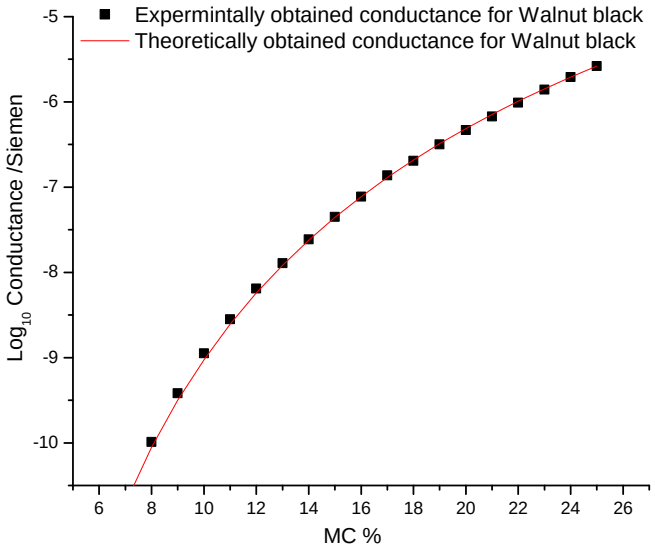

Figure 3.1: Log C vs MC for Walnut black

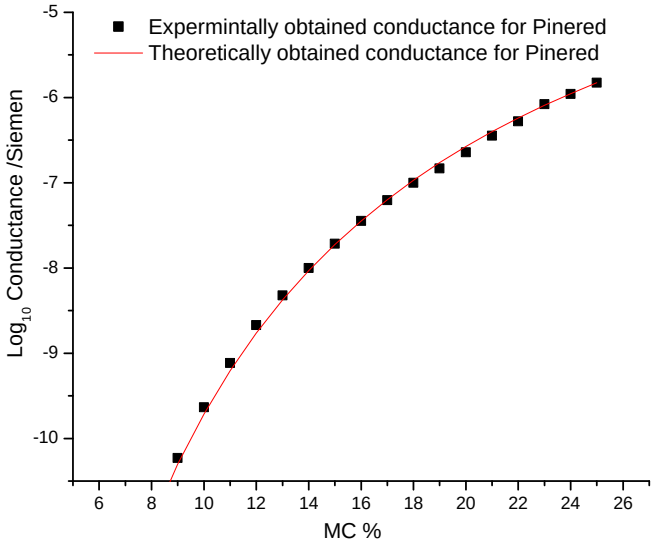

Figure 3.2: Log C vs MC for Pinered

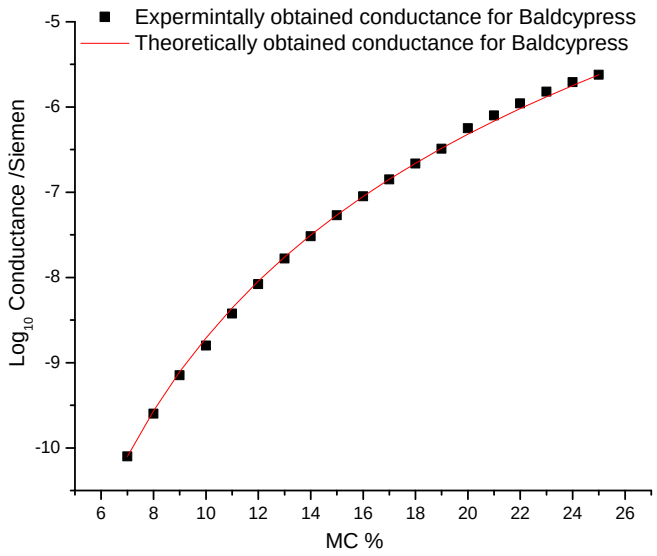

Figure 3.3: Log C vs MC for Bald cypress

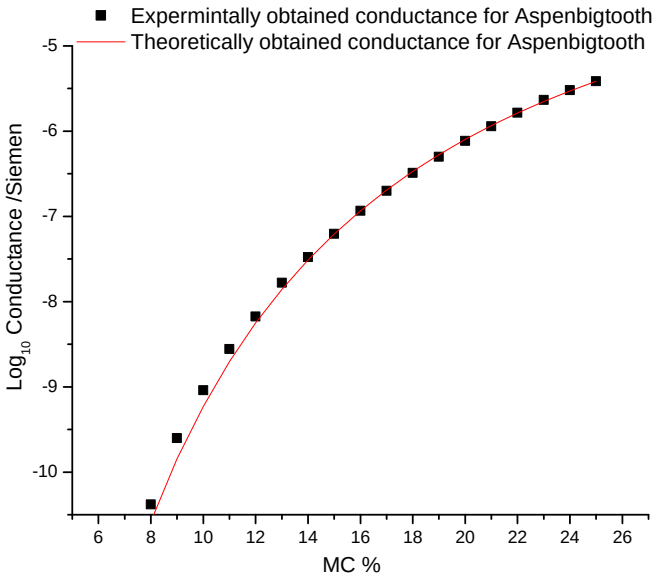

Figure 3.4: Log C vs MC for Aspen big tooth

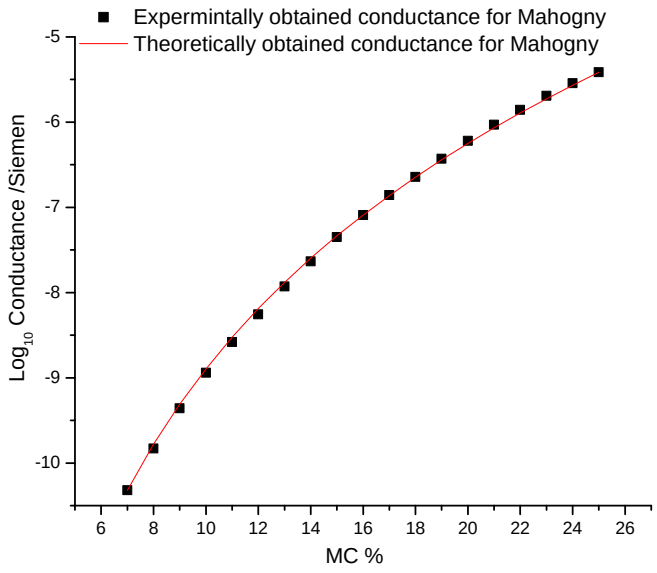

Figure 3.5: Log C vs MC for Mahogany

3.3.4 Conclusion for new calibration method

The direct current conductance of wood below fiber saturation point as a function of moisture content (MC)% is explained using the modified Anderson-Stuart model for ionic conduction in amorphous materials. The obtained theoretical results are found to be in a good agreement with experimental observed behavior of the conduction against MC % for the investigated wood spices. The obtained results leads to the conclusion that this calibration method is much cheaper and not so time consumed than the method ASTM D 4444-92 "Standard test methods for use and calibration of hand-held moisture meters".

3.4 Conclusion

1- The commercial sensors for measuring the moisture content of wood can be used for quick measurements of percentage moisture content in the range from 5% to 14% with uncertainty type A 0.13 for conductance meter and 0.17 for capacitance meter

2- The conductance sensor is more accurate than capacitance one

3- The calibration of commercial sensor can done using equation (3.2.16) and three samples of wood kept in chambers of difference values of humidity to be sure of the correct values of the moisture content. This method shorten the time of calibration and enable thermometry department of NIS to improve its capability as it is one of its responsibilities

4- This research project is one of projects that serve the wood industry in Egypt which is one of the important field of industry

References

[1] Anderson, O. L. and Stuart, D. A. 1954. "Calculation of activation energy of ionic conductivity in silica glasses by classical methods". J. Am. Ceram. Soc. 37, 573-580.

[2] ASTM D 4442-92, 2002. Standard test methods for direct moisture content measurement of wood and wood-base materials, ASTM.

[3] ASTM D 4444-92, 2002. Standard test methods for use and calibration of hand-held moisture meters, ASTM.

[4] ASTM D 4933-99, 2002. Standard guide for moisture conditioning of wood and wood-based materials, ASTM.

[5] ASTM E 104-85, 2002. Standard practice for maintaining constant relative humidity by means of aqueous solutions, ASTM.

[6] Beall, F.C., R.S. Parker, and S.K. Kaluzny. 1983. Development of a new lumber unstacker moisture meter. Proceedings Western Dry Kiln Association. pp. 37-47.

[7] Bell, Earl and Krueger, Norman. 1949. Effect of plywood glue lines on the accuracy of moisture meter indications. In: Proceedings, Forest Products Research Society Vol. 3, p. 85.

[8] Bell, Stephanie 1999. A beginner's guide to uncertainty of measurement, NPL.

[9] Bramhall, G.; Salamon, M. 1972. Combined species-temperature correction tables for moisture meters. Rep. VP-X-103. Vancouver, B. C.: Western Forest Products Laboratory Davidson.

[10] Breiner, T.A., D.G. Arganbright, and WY. Pong. 1987. Performance of in-line moisture meters. Forest Prod. J. 37(4) p.16.

[11] Bolton, W. 1996. Measurement and instrumentation systems, Elsevier group.

[12] Christie, J.H. and Woodhead, I.M. 2002. A New model of the dc conductivity of hygroscopic solids. Part I Cellulosic Materials. Text. Res. J. 72: 273-278.

[13] Davidson, R. W. 1958. Effect of temperature on the resistance of wood. Forest Products Journal. 8(5) p.160.

[14] Davies, I. I. 1937. A wide range vacuum-tube resistance bridger. Instruments. 10 p.261.

[15] Elliott S.R. 1990. Physics of amorphous materials, Longman Scientific & Technical.

[16] Fell, J.; Hill, J. L. 1980. Sampling levels for hardwood kiln drying control. Forest Products Journal. 30(3): 32-36.

[17] Fluk 1994. Calibration: Philosophy in practice, Fluk Corporation.

[18] Forest Products Laboratory 1999. Wood handbook: Wood as an engineering material. Gen. Tech. Rep. FPLGTR113. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

[19] Freese, Frank. 1967. Elementary statistical methods for foresters. Agriculture Handbook 317. Washington, DC: U.S. Department of Agriculture.

[20] Green, D.W. and Kretschmann, D.E. 1994. Moisture content and the properties of clear southern pine. Res. Pap. FPLRP531. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

[21] ISO 1993. Guide to the expression of uncertainty in measurement, International Organization for Standardization, Geneva, Switzerland.

[22] James, William L, 1988. Electric moisture meters for wood, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

[23] James, William L., 1980. Effects of wood preservatives on electric moisture-meter readings,Gen. Tech. Rep. FPL-0106. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

[24] James, William L. 1974. The dielectric properties of wood and hardboard; variation with temperature, frequency, moisture content, and grain orientation. Res. Pap. FPL 245. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

[25] James, William L. 1968. Effect of temperature on readings of electric moisture meters. Forest Products Journal. 18 (10) 23.

[26] James, William L. 1966. Effects of wood preservatives on electric moisture-meter readings. Res. Note FPL-0106. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

[27] James, William L. 1964. Calibration of electric moisture meters for some wood species grown in Hawaii. Res. Note FPL-061. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

[28] James, William L. 1961. Calibration of electric moisture meter for jack and red pine, black spruce, paper birch, black ash, eastern hemlock, and bigtooth aspen.

FPL Rep. 2208. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

[29] James, William L. and Yen, You-Hsin; King, Ray J. A. 1985. Microwave method for measuring moisture content, density, and grain angle of wood. Res. Note FPL-0250. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

[30] Kabir, Mohammed F. Wan M. Daud, Kaida B. Khalid and Aziz H. A. Sidek 2000. Equivalent circuit modeling of the dielectric properties of rubber wood at low frequency, Wood and Fiber Science, 32(4), pp. 450457.

[31] Keylwerth, R.; Noack, D. 1956. Uber den einflus hohrer temperature auf die electrische holzfeuchtigkeitsmessung nach dem widerstandsprinzip. [On the influence of higher temperatures on the electric measurement of wood moisture content using the resistance principle.] Holz als Rob- und Werkstoff. 14(5): 162.

[32] Labb, Nicole, Bernard De Jso, Jean-Claude Lartigue, Grard Daud, Michel Ptraud and Max Ratier 2002. Moisture content and extractive materials in Maritime pine wood by low field ^{1}H NMR, Holzforschung Vol. 56, pp.2531.

[33] Lienhard IV, Johan H., Johan H.Lienhard,V. 2004. A heat transfer textbook, `http://web.mit.edu/lienhard/www/ahtt.html`.

[34] Ludwig, N., V. Redaelli, E. Rosina, F. Augelli 2004. Moisture detection in wood and plaster by IR thermography, Infrared Physics & Technology, inpress.

[35] Mackay, J.F.G. 1976. Effect of moisture gradients on the accuracy of power-loss moisture meters. Forest Products Journal. 26(3): 49-52.

[36] Mahmoud, Essam E. 2003. Study and characterizing of relative humidity fixed points cells in the range from 11% to 97%, PhD thesis, Ain Shams University.

[37] Mallick, H. and Mallick, A. 2000. An experimental investigation of electrical conductivities in biopolymers, Bull. Mater. Sci., Vol. 23, No. 4, pp. 319-324.

[38] Milota, M.R. 1994. Specific gravity as a predictor of species correction factors for a capacitance-type moisture meter. Forest Prod. J. 44(3):63-68.

[39] Murphy, E. J. 1963. Conduction and electrolysis in cellulose, Can. J. Phys. Vol. 41, pp.1022-1035.

[40] Parker, R.S. 1984. Electrical scanning in wood application to moisture content gauging. In: Scanning Technology for the Eighties. Special Publication No. SP 21. Forintek Canada Corporation, Vancouver, B.C. pp. 8-62.

[41] Perkin, M., Davidson, S. and Buckley, M., 2004, The Measurement of Mass and Weight, Measurement Good Practice Guide No.71, National Physical Laboratory

[42] Quarles, Stephen L. 2003. Physical limitations of moisture meters, Forest Products Society

[43] Quarles, S.L. and T.A. Breiner. 1992. Operational characteristics of a capacitive-admittance type in-kiln moisture meter. Forest Prod. J. 42(3):15-22.

[44] Quarles. S.L. 1990. Sensitivity of two transverse feed inline moisture meters to wet pockets. Forest Prod. .J. 40(2):34-38.

[45] Quarles. S.L. 1990. Sensitivity of handheld dielectric moisture meters to a wet core. Forest Prod. J. 41(3):33-36.

[46] Quarles, S.L. andT.A. Breiner. 1989. Effect of density on in-line and handheld moisture meters. Forest Prod. J. 39(5):5 1-54.

[47] Reeb, James E. 1995. Wood and moisture relationships, EM 8600 Oregon state University extension service.

[48] Simpson, William T. and Jen Y. Liu 1999. Two-stage moisture diffusion in wood with constant transport coefficients, Drying Technology, 17(1&2), 257-269.

[49] Simpson, William T. 1998. Equilibrium moisture content of wood in outdoor locations in the United States and worldwide. Res. Note FPL-RN-0268. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

[50] Simpson, William T. 1998. Relationship between speed of sound and moisture content of red oak and hard maple during drying, Wood and Fiber Science, 30(4), pp. 405-413.

[51] Simpson, William T. and Jen Y. Liu 1997. An optimization technique to determine red oak surface and internal moisture transfer coefficients during drying, Wood and Fiber Science, 29 (4), pp. 312-318.

[52] Simpson, William T. 1994. Resistance moisture meter correction factors for four tropical wood species. Res. Note FPL-RN-0260. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

[53] Simpson, William T. 1993. Specific gravity, moisture content, and density relationship for wood. Gen. Tech. Rep. FPL-GTR-76. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

[54] Simpson, William T.; Sagoe, John A. 1991. Relative drying times of 650 tropical woods: Estimation by green moisture content, specific gravity, and green weight density. Gen. Tech. Rep. FPL-GTR-71 . Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

[55] Simpson, W. T. and J. Y. Liu 1991. Dependence of the water vapor diffusion coefficient of aspen (Populus spec.) on moisture content, Wood Sci. Technol. 26:9-21.

[56] Smulski, Stephen 1996. Humidity, temperature, and wood moisture content, Building Materials and Wood Technology publichation, Natural Resources Center, University of Massachusetts.

[57] Skaar, C. 1988. Woodwater relations. New York: SpringerVerlag. New York, Inc.

[58] Skaar, C. 1964. Some factors involved in the electrical determination of moisture gradients in wood. Forest Products Journal. 14(6): 239-243.

[59] Suits, C. G.; Dunlap, M. E. 1931. Determination of the moisture content of wood by electrical means. General Electric Review; p. 706.

[60] Taylor, Barry N. and Kuyatt, Chris E. 1994. Guidelines for evaluating and expressing the uncertainty of NIST measurement results, NIST Technical Note 1297.

[61] Troughton, G.E. and M.R. Clarke. 1987. Development of a new method to measure moisture content in unseasoned veneer and lumber. Forest Prod. J. 37(1):13-19.

[62] Ullmann's encyclopedia of industrial chemistry 6Th edition 2002. electronic release, WILEY-VCH.

[63] Wengert, G. and P. Bois. 1997. Evaluation of electric moisture meters on kiln-dried lumber. Forest Prod. J. 47(6):60-62.