University of Southern Queensland

Faculty of Engineering and Surveying

Measuring Moisture Content of Biofilter Media using Capacitance

A dissertation submitted by

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Abstract

A biofilter operates by passing contaminated air through a moist medium like woodchips, saw dust, soil or artificial material. Maintaining moisture content within this medium is critical for biofilter operation. To date, most biofilters use a timer system and sprinklers to apply water to the medium which may lead to under-watering or over-watering.

The moisture content of the filter medium in small and in research biofilters has been controlled gravimetrically using load cells. However, for full scale application of biofilters, this technique would be overly expensive and impractical. Some research is being undertaken to develop capacitor plates to monitor moisture levels within the biofilter medium. This technique shows promise and needs further development.

This project will reviews the literature on biofilters and biofilter control methods, and also on capacitance-based and other possible moisture measurement techniques. Based on this research, designs are developed for the measurement of the moisture content of the selected biofilter media such as wood chips and soil. It is concluded that the completion of this project has demonstrated the advantages of using the capacitive sensor as the basis for the design and proved the feasibility of the capacitive sensing system in determining the moisture content of the biofilter media.

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Limitations of Use

Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any course or institution, except where specifically stated.

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Signature

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Date

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CHAPTER 1

INTRODUCTION

The stench from livestock facilities is an issue for many communities especially livestock producers. In the past, sparse human population and livestock spread out over a large land area had made odour less of an issue. Now, with the advent of farms with large numbers of animals confined to a smaller area, the issue of odour and contaminants are becoming more serious. In addition, many areas formerly zoned for agriculture are being inhibited by more non-farm rural residents. This trend results in odour issues for livestock producers that in the past were minor or even a non issue. (Nicolai et al., 2005)

The odour, gas and dust emissions from livestock and poultry facilities may result in complaints from neighbours or exceed state or federal ambient air quality standards. In fact, people do not like events they have no control over, especially when it comes to handling the smell of livestock manure. Very little information is available on the impact of odour and airborne contaminants from livestock operations on human health. MWPS-18 (2002) studies indicated that odours might alter a person's mood and it is still unclear if this mood change is a psychological or physiological response to odour. Therefore it is essential to find adequate solutions to eliminate or minimise the odour problem.

Technologies to control odours are available to producers. However, there are significant economic barriers for these technologies to be implemented. These technologies range from simple to complex, from low maintenance to high maintenance, and from inexpensive to expensive. Some of these technologies have demonstrated odour reduction based on scientific measurements while the effectiveness of other technologies is supported only by anecdotal evidence and testimonials.

One of the more recent practices to reduce odour emissions is the use of biofilter. This is an air pollution control technology that uses micro-organisms to breakdown gaseous contaminants and produce innocuous end products. They are effective in reducing odour and hydrogen sulphide emissions from livestock facilities (Nicolai and Janni, 2000). Biofilters have also been used to control biodegradable volatile organic compounds from industrial and commercial sources (Leson and Winer, 1991). Organic acids and phenols (like those found in swine odour) have been characterized by Bohn (1993) as rapidly biodegradable and moderately biodegradable, respectively, making biofiltration of swine odour an attractive control option.

The key factors influencing biofilter performance are the amount of time the odorous air spends in the biofilter and the moisture content of the filter material (Schmidt et al., 2004). The flow rate of the air can be easily managed and maintained but the moisture level of a biofilter is more complicated. Hence there is a need to have an automatic control system in maintaining the moisture level of the biofilter.

1.1 Research Objectives

The overall aim is to identify and implement a capacitance-based sensor to measure the moisture content of the biofilter effectively. The specific objectives of this research project are:

- Examine the literature research of the biofilter and biofilter control methods.

- Evaluate the various possible moisture measurement techniques that are used in biofilters.

- Explore how capacitance-based moisture measurement technique works and alternatives for implementing capacitance-based moisture measurement.

- Design a measurement system using a capacitance-based sensing to determine the moisture level deep within the biofilter.

- Analyse on the feasibility of the proposed moisture sensing system (or alternative systems).

- Identify and implement a moisture sensor suitable for incorporation in a system built to automatically control the moisture level of a biofilter. (optional, if time permits)

1.2 Dissertation Outline

The first chapter of this dissertation provides an introduction to the problem of livestock odour and through using biofilter as a way to minimise and resolve the issue.

Chapter 2 outlines the literature and methodology of biofilter; discuss on the design methods, understanding of biofilter media, composition of a biofilter and finally the health and safety concerns.

Chapter 3 outlines various moisture measurement techniques that are based on the research of soil content.

Chapter 4 outlines the fundamental theory of capacitance and explain the basic concept of dielectric constant.

Chapter 5 presents some of the different configurations of capacitance plates that are used to build various types of sensors.

Chapter 6 discusses on the basic circuit building blocks of a capacitive sensor.

Chapter 7 outlines of how capacitive sensors are designed to detect changes in the dielectric constant of biofilter media.

Chapter 8 evaluates the capacitive sensing system and understand the limitations and drawbacks of the capacitive sensors.

Chapter 9 concludes the dissertation by stating the main achievement of objectives and recommendations for future work.

CHAPTER 2

LITERATURE AND METHODOLOGY OF BIOFILTER

Biofiltration has been used for more than 20 years as a method for reducing odours at composting operations, solid waste processing plants, and animal rendering plants (Williams and Miller, 1992). In fact, biofilters have been around as long as the nature itself, and it has become widespread due to the ever propelling of modern technologies. Biofilters rely on micro-organisms to break down and convert odorous air into by-product primarily consisting of carbon dioxide, water, mineral salts and microbial biomass. Hence, a biological process is an oxidation by micro-organisms, and can be written as Equation (2.1).

$$\text{Organic Pollutant} + \text{Oxygen} \rightarrow CO_2 + H_2O + \text{Heat} + \text{Biomass} \qquad (2.1)$$

(Source: Devinny, 2002)

In general, biofiltration performs as an air-cleaning technology that absorbs gases into a biofilm on the filter media where micro-organisms breakdown (i.e., oxidise) volatile organic compounds (VOCs) and oxidisable inorganic gases (MWPS-18, 2002). The odorous organic compounds in the air stream are accumulated on the surface or adsorbed into the biofilm layers where microbial community resides and oxidise them to less harmful products such as water, carbon dioxide and inorganic salts (Haug, 1993). In this way, biofilter effectively help to reduce odour, hydrogen sulphide and ammonia emission from mechanically ventilated livestock buildings and naturally ventilated, deep-pit buildings using pit exhaust. Furthermore, it has been proven by MWPS-18 (2002) that hydrogen sulphide and ammonia emissions from livestock and poultry facilities can be reduced by as much as 95% and 65% respectively.

2.1 Biofilter Design Methods

Biofilter designs are based on the volumetric flow rate of air to be treated, specific air contaminants and concentrations, media characteristics, biofilter size (area) constraints, maintenance and cost (Schmidt et al., 2004).

The four main steps recommended by MWPS-18 (2002) in designing a biofilter are:

1. The volume of media needed to treat the odorous air.
2. The area needed to place the biofilter.

3. The uniform airflow rate through the biofilter.

4. The total pressure drop through the biofilter.

The first two steps are used to determine the size the biofilter and the last two steps are used to estimate the operational characteristics of the biofilter, which are needed to select the proper fan size (MWPS-18, 2002).

2.1.1 Media Volume

The initial step to construct a biofilter is to determine the volume of media material that is needed to treat the odorous air. Media material volume can be determined by the maximum design airflow rate of the fan or fans being treated by the biofilter and a design component known as the Empty Bed Contact Time (EBCT) (MWPS-18, 2002). The EBCT is a retention time estimate or an estimate of the amount of time that ventilation air is in contact with the biofilter media material, Table 2-1 (MWPS-18, 2002).

The contact time defined by MWPS-18 (2002) is the required time to reduce odour and hydrogen sulphide emission by 90%, based on average gas concentrations from typical facilities. In addition, the contact times are based on 40% media porosity and are not dependent on media type.

Table 2-1. Recommended minimum Empty Bed Contact Times for various livestock.

Livestock system	**Empty Bed Contact Time, EBCT(seconds)**
Swine barn with deep pit manure storage	5
Poultry barns with dry litter	3
Covered manure storage units	10
Dairy heifer barn with deep pit manure storage	5

Based on Nicolai and Janni, 1999 and Zeisig, 1988.

Based on MPWS-18 (2002), EBCT is still a new concept whereby research is on-going. In fact, the actual contact time between the odorous air and the media is less than the EBCT listed in Table 2-1. Due to the fact that the actual contact time is difficult to measure, EBCT is used as an alternative to calculate the volume of media material needed to treat odorous air, Equation 2.2.

Media volume is defined as:

$$V_m = (Q) \times (EBCT) \div 60^1 \qquad (2.2)$$

(Source: MWPS-18, 2002)

Where:

V_m = media volume, cubic feet (ft^3)

Q = maximum design airflow rate through the media, cubic feet per minute (ft^3/min)

$EBCT$ = Empty Bed Contact Times, seconds (see Table 2-1)

[1] conversion, 60 seconds equals 1 minute

2.1.2 Biofilter Space Area

The second step is to determine the amount of space that the biofilter will occupy. Typically a design depth (D_m) is selected and should be from 10 to 18 inches (MWPS-18, 2002). MWPS-18 stated that if the depth is less than 10 inches it can lead to the filter drying out and this will reduce the efficiency of odour control. Depths greater than 18 inches will have a higher-pressure drop, resulting in increased equipment and operational costs. A typical biofilter will require 50 to 85 square feet of space per 1,000 cfm of airflow (MWPS-18, 2002). Equation 2.3 can be used to determine the area needed to set up the biofilter.

In some situations, when space is a constraint, there is a need to use a depth greater than 18 inches. In this case, determine the area available to place the biofilter, and use this value as A_m in Equation 2.3 to determine the media depth.

Biofilter space area is defined as:

$$A_m = \left(12^1 \times V_m\right) / D_m \quad (2.3)$$

(Source: MWPS-18, 2002)

Where:

A_m = biofilter space area, square feet (ft^2)

V_m = media volume, cubic feet (ft^3)

D_m = media depth, inches

[1] conversion, 12 inches equals 1 foot

2.1.3 Uniform Airflow Rate

The third step is to estimate the airflow rate through the media, known as the Uniform Airflow Rate (*UAR*). The *UAR* is calculated in cubic feet per minute per square foot of biofilter space area and shown in Equation 2.4. A typical biofilter will have a *UAR* in the range of 12 to 20 cfm per square foot (MWPS-18, 2002).

Uniform airflow rate is defined as:

$$UAR = Q / A_m \qquad (2.4)$$

(Source: MWPS-18, 2002)

Where:

UAR = uniform airflow rate (cfm/ft^2)

2.1.4 Biofilter Pressure Drop

The fourth step is to determine the pressure drop ($\Delta P_{biofilter}$) through the biofilter using the design media depth (D_m), *UAR*, and the estimated air void (n_a) (MWPS-18, 2002).

The biofilter media porosity or air voids should be between 40 and 60%. In order to achieve a lower static pressure drop at 60% voids, the mixture needs to be closer to 30-70 compost to wood chip ratio (MWPS-18, 2002). The procedure outlined in

Table 2-2 can be used to estimate media porosity. If the media is too porous, more compost or soil will be added. Otherwise more wood chips, shredded wood or straw will be added if the media needs more porosity.

During the useful life of the filter, the media material will settle and compact such that dust particles will accumulate in the media and reducing the void space. By applying Equation 2.6, the total pressure drop in inches of water through the biofilter can be estimated. And it takes into account of any settling or compaction that will occur during the life of the biofilter. It is important to note that a small change in air voids will have a large impact on pressure drop. For example the pressure drop for 45% air voids will be about 2.5 times higher than the pressure drop for 50% air voids at the same uniform airflow rate (MWPS-18, 2002).

Uniform pressure drop (the static pressure drop per foot of biofilter media depth) is defined as:

$$UPD = \left(8.82 \times 10^{11}\right)\left(n_a\right)^{-8.6}\left(UAR\right)^{1.27} \qquad (2.5)$$

(Source: MWPS-18, 2002)

Where:

n_a = percent voids

UPD = uniform pressure drop

Total biofilter pressure drop, inches of water is defined as:

$$\Delta P_{biofilter} = \left(D_m / 12^1\right) \times UPD \qquad (2.6)$$

(Source: MWPS-18, 2002)

Where:

$\Delta P_{biofilter}$ = total biofilter pressure drop

[1] conversion, 12 inches equals 1 foot

Table 2-2. Procedures for estimating voids in biofilter media.

Estimating percent voids in biofilter media
1. Start with two identical five-gallon buckets.
2. Fill one of the buckets one-third full with media. Drop the pail ten times from a height of six inches onto a concrete floor.
3. Add media to fill the same bucket two-thirds full and drop the pail ten times from a height of six inches on to a concrete floor.
4. Fill the bucket to the top with media and once again drop the pail from a height of six inches on to a concrete floor.
5. Fill the bucket once again to the top edge of the pail.
6. Take the second bucket and fill it to the top with clean water.
7. Slowly pour water from the second bucket into the first bucket containing media until the water reaches the top of the media-filled bucket.
8. Record both the total depth inside the second bucket, and the distance between the level of the remaining water and the top of the bucket.
9. Calculate the percent voids by dividing the distance from the water line to the top of the bucket by the total bucket depth and multiply by 100.

Reproduced from MWPS-18, 2002. Outdoor air quality. IA.

2.2 Biofilter Media

A biofilter media is simply a bed of organic material (medium), typically a mixture of compost and wood chips or shreds that support a microbial population and maintain a high porosity to allow air to flow easily. In order for biofilter to operate effectively, Leson and Winer (1991) concluded several requirements that the biofilter media must meet. First, the media should provide optimum environmental conditions for the resident microbial population to achieve and maintain high degradation rates. Second, the media particle size distribution and pore structure should provide large reactive surfaces and minimise in pressure drop. Third, compaction should be kept to a minimum, reducing the need for maintenance and replacement of the biofilter media.

2.2.1 Characteristics of Biofilter Media

A proven mixture for animal agriculture biofilters ranges from approximately 20:80 to 40:60 ratio by weight of compost and wood chips or wood shreds (Nicolai and Janni, 2001a). The wood provides the porosity and structure while the compost provides micro-organisms, nutrients, and moisture holding capacity. Media mixtures with more compost (less wood chips) will result in higher pressure drops but only slightly higher efficiencies (Schmidt et al., 2004).

In general, natural materials, such as peat, soil or compost, are generally chosen as biofilter media because they are relatively inexpensive and already have microbial populations. The critical properties of media material stated by Schmidt et al. (2004) include porosity, moisture holding capacity, nutrient content, and slow decomposition as shown in Table 2-3.

Table 2-3. Biofilter media characteristics.

Material	**Porosity**	**Moisture Capacity**	**Nutrient Capacity**	**Useful Life**	**Comments**
Peat	Average	Good	Good	Good	Good Sources of Micro-organisms
Soil (heavy loam)	Poor	Good	Good	Good	
Compost (yard waste)	Average	Good	Good	Good	
Wood chips	Good	Average	Average	Average	Good additions for porosity
Straw	Good	Average	Poor	Poor	

Based on Schmidt et al., 2004. University of Minnesota Extension Service

Porosity is the space between media particles that allows air to flow through the filter and is controlled through proper design and construction (MWPS-18, 2002). The higher the porosity the lower the pressure drops across the media. Moisture allows gas emissions and dust particles to adhere to the media and is controlled through management and maintenance (MWPS-18, 2002). Nutrient content allows micro-organisms to survive in the media and is controlled by media selection, management and maintenance (MWPS-18, 2002). Slow decomposition of the media is accomplished by selecting the proper material and by proper installation and maintenance.

In particular, compost derived from municipal waste, bark, tree trimmings, and leaves is widely used as a biofilter material (Sun et al., 2000). Typically, compost-based biofilter media will provide sufficient inorganic nutrients for micro-organisms (Leson and Winer, 1991). In addition, compost particles have large specific surface area, large air and water permeability, and good buffering and cation exchange capacities (Williams and Miller, 1992).

2.2.2 Biofilter Media Pressure and Flow Rate

For a biofilter, the relationship between air flow rate and static pressure depends on the type of media and media depth (Schmidt et al., 2004). Figure 2-1 shows the relation between Unit Airflow Rate and Unit Pressure Drop (the static pressure drop per foot of biofilter media depth) for a variety of materials tested in the lab by Schmidt et al. (2004).

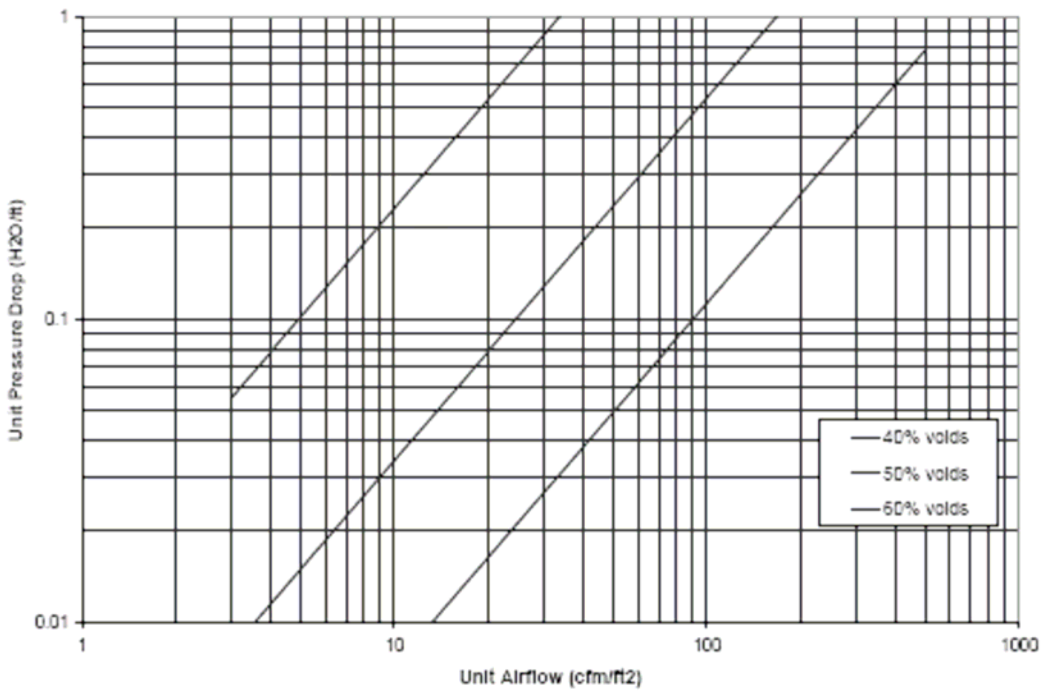

Figure 2-1. Media unit pressure drop and unit flow rate relations for different percent of media voids. (Schmidt et al., 2004. p5)

The different percent voids (measure of the amount of open pore space in the media) are represented by the lines shown in Figure 2-1 (Schmidt et al., 2004). It is shown that as the airflow rate increases the pressure drop through the media increases (i.e. as airflow increases it takes more pressure to push the air through the media). Likewise, when porosity increase the pressure drop will decrease.

This porosity is both a function of the original media, compaction of the media, and media moisture content (Schmidt et al., 2004). Porosity can also be affected by the age of the media. Over time the media decomposes and settles which reduces the pore space. Besides that, any activity that causes compaction, such as walking on the media, will reduce pore space.

2.2.3 Useful Lifespan of Media

The effective lifespan of the media is at least three years and likely five years or longer (Schmidt et al., 2004). Over time, the media will decompose and need to be replaced. An indication that the media may need to be replaced in a properly designed system is when the overall ventilation system performance is operating poorly. When the media decomposes, it will become denser which reduces the porosity (air space in the media) and increases the pressure needed to move the air through the biofilter media (Schmidt et al., 2004). As the airflow rate through the biofilter increases, the force needed to push the air through the media increases. This force is measured as the static pressure difference from the inlet side of the biofilter to the atmosphere. This static pressure can also be thought of as the resistance to air flow through the biofilter material. Resistance to air flow is fundamental to all ventilation systems and is typically reported in inches of water (Schmidt et al., 2004). Static pressure (pressure drop) between the inside and outside of a mechanically ventilated livestock building without a biofilter ranges between 0.04 and 0.10 inches of water (H_20) (Schmidt et al., 2004).

Also, a manometer can be used to check the pressure across the biofilter. Pressure drop over 50% of the design pressure drop at maximum ventilation rates indicate the need to replace the media (MWPS-18, 2002). Used media can be mixed with more wood chips and reused in the biofilter (MWPS-18, 2002).

2.2.4 Shortcoming of using Biofilter Media

One disadvantage of using natural biofilter media is that as the natural beds age, the media tends to settle and compact, resulting in increased pressure drop and channelling (Leson and Winer, 1991; Bohn, 1992). Another disadvantage is that natural media decomposes with time resulting in decreased particle size. Thus, physical properties related to airflow resistance are not stable. Biofilters that use high percentages of natural biodegradable materials therefore must be replaced over time (Williams and Miller, 1992).

2.3 Composition of a Biofilter

While simple in appearance, biofilters are rather complex biological systems that need to be designed and managed properly to perform well and prevent ventilation problems. Research is continuing to demonstrate their performance and to develop better design and management recommendations. Biofiltration works well in mechanically ventilated buildings at low airflow rates and provides some odour control in deep-pitted naturally ventilated buildings that use pit fans (MWPS-18, 2002). Some building design ventilation rates are shown in Table 2-4.

Table 2-4. Typical building ventilation rates.

	Ventilation requirements cubic feet per minutes (cfm) Per animal space		
Facility Type	Cold Weather	Mild Weather	Warm Weather
Nursery	3	15	35
Finishing	10	35	120
Gestation	12	40	150
Farrowing	20	80	500
Broiler/Layer (5 lb)	0.5	2.5	5
Turkey (40 lb)	3.2	14	32
Dairy (1400 lb)	50	170	470

Based on Schmidt et al., 2004. University of Minnesota Extension Service.

2.3.1 Ventilation Fan

Ventilation fans used in livestock facilities are usually selected based on a design airflow rate and a pressure drop ($\Delta P_{building}$) between 0.04 and 0.125 inches of water (MWPS-18, 2002). A biofilter requires fans that move air through both the buildings and the biofilter. The design airflow will remain the same, but the fan must overcome the increased pressure required to move air through the biofilter. For design purposes, the building pressure drop is usually estimated to be 0.125 inches of water (MWPS-18, 2002). A fan or series of fans in a ventilation system using a biofilter should be able to overcome a minimum pressure drop of 0.30

inches of water at the maximum design airflow rate (MWPS-18, 2002). Equation 2.7 can be used to determine the design static pressure (ΔP_{design}) for a ventilation system using a biofilter.

Design static pressure for a ventilation system using a biofilter is defined as:

$$\Delta P_{design} = \Delta P_{building} + \Delta P_{biofilter} \geq 0.30 \text{ inches of water} \qquad (2.7)$$

(Source: MWPS-18, 2002)

Because of the higher static pressures associated with a biofilter system, centrifugal fans may need to be used (MWPS-18, 2002). Typically, centrifugal fans are quieter and capable of providing higher airflows at higher pressures than axial fans. The disadvantage of centrifugal fans is that they provide less airflow at similar power requirements, which results in higher operational costs than axial fans.

It is advisable to select and use rated fans with known performance characteristics. Fans are constructed with fibreglass, stainless steel, and PVC materials instead of galvanised or carbon steel which are preferred in a corrosive environment (MWPS-18, 2002).

An existing facility that is adding a biofilter will probably need to either replace the existing fans with different fans that can achieve the design airflow at higher static pressures, or add a fan in series that can help provide the pressure necessary to push the air through the biofilter. When more than one fan is providing airflow to a biofilter, shutters may be needed so that the fans can cycle on and off to create circulating airflow. In this case, shutters will help to prevent back drafting through fans that are not operating.

2.3.2 Ductwork and Plenum

The ducting leading from the fan to the biofilter should not be overlooked and the design of the ducts and plenum should allow an air velocity from 800 to 1,000 feet per minute (MWPS-18, 2002). Due to the fact that dust will accumulate on fans, guards and shutters over time which will significantly reduce fan performance. There should be an access door to the ducts so that it will be convenient to maintain and inspect the fans. Furthermore, the materials that are used to construct both the ducting and plenum must be smooth and resistant to rotting or corrosion. If ducts are located below the eave, it should be designed to withstand the force of snow sliding from the roof and dropping to the ground. Constructing a completely ridged duct often leads to duct breakage. Instead, a ridged duct design with a flexible gasketed connection will resolve this problem.

2.3.3 Construction of Biofilter

Biofilter should be sited as close as possible to exhaust fans but far enough away from the building so as not to intercept roof runoff water (MWPS-18, 2002). If biofilters are located too close to a building, gutters may need to be installed to divert roof runoff water. Ideally, biofilter are situated on a sloped, well-drained area so water does not accumulate or pond on or near the filter boundary.

The major biofilter components are the biofilter structure (including foundation, walls, perforated floor, and primary and secondary plenum spaces), PVC ducting, blower fans, and biomass irrigation system (Green et al., 2005).

All ducting work should be done before the media is placed and no machinery or foot traffic should be allowed on the media. During construction, compaction of the biofilter media should be minimised. Access lanes could be constructed to allow for fan or duct maintenance. If there is a need to walk across the media, it is best to lay down planks and sheets of plywood to limit compaction (MWPS-18, 2002). MWPS-18 (2002) stated that plenums for filters have been constructed out of wood pallets. Pallets are covered with plastic netting, such as ¾-inch bird netting, to prevent media material from falling through the pallet slats. Media material can be placed onto slats with a TMR wagon to help prevent compaction during installation (MWPS-18, 2002). Media material can also be premixed and placed onto the slats using a front-end loader (MWPS-18, 2002).

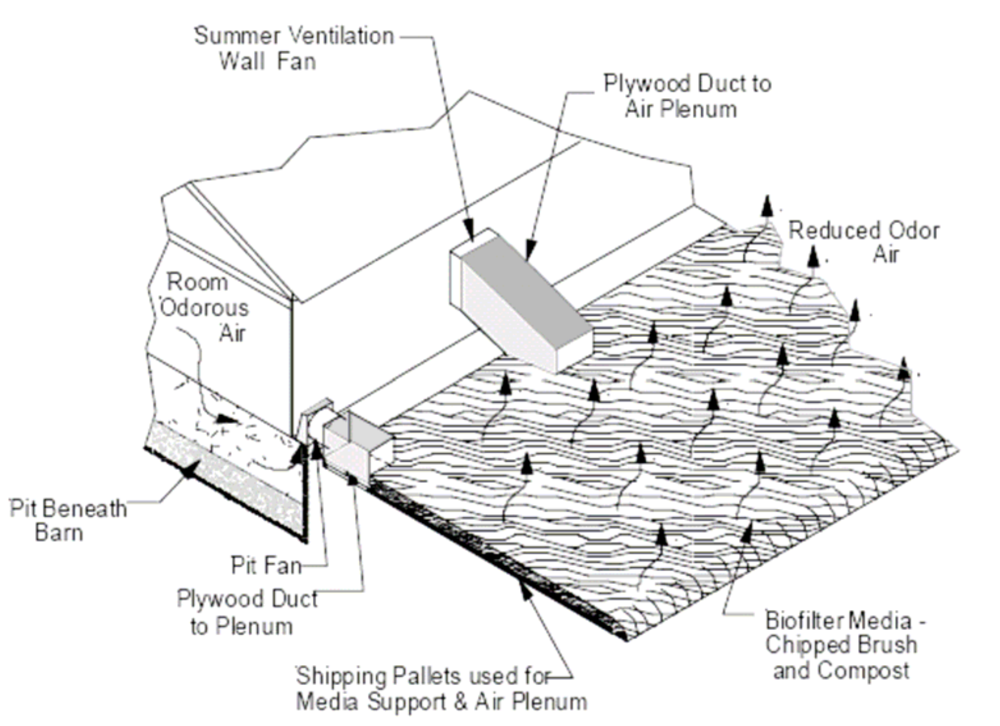

Figure 2-2. Biofilter construction. (Schmidt et al., 2004. p14)

Maintaining an even layer of media throughout the biofilter is critical. Air will follow the path of least resistance, which is often the thinnest region of the media (MWPS-18, 2002). Any channelling of air reduces the biofilter's effectiveness (MWPS-18, 2002). Odorous air may also escape from around the edges of the biofilter media or at the intersection of the ductwork and plenums. Therefore, efforts should be made to seal all duct and plenum joints with appropriate caulking or plastic sheeting (MWPS-18, 2002).

After the construction has completed, the micro-organisms will require approximately two weeks for it to adjust to the new conditions so as to achieve its operating efficiency (Boyette, 1998).

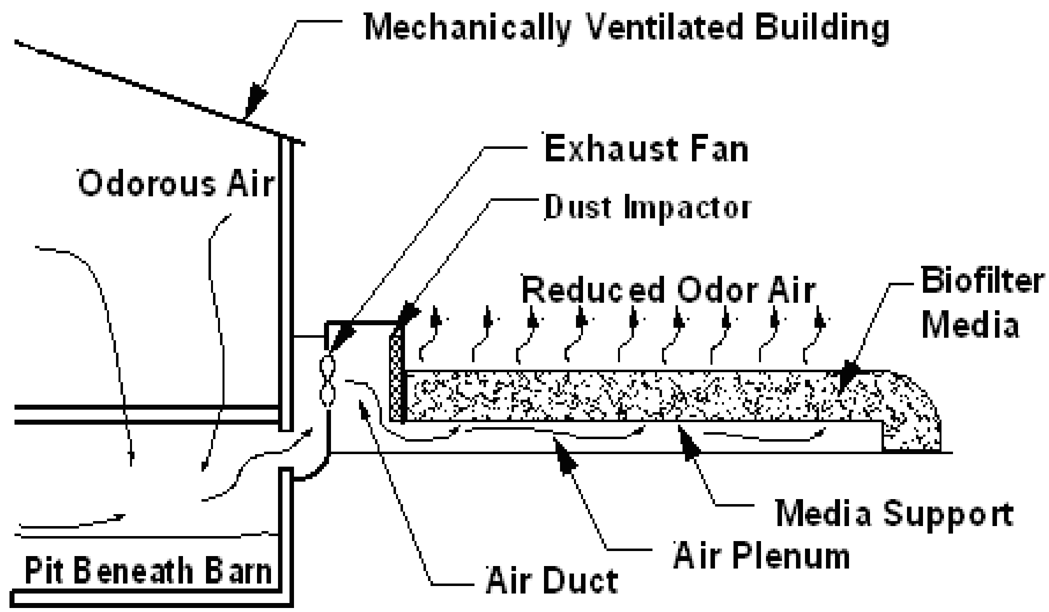

Figure 2-3. Schematic of a typical open bed biofilter. (Schmidt et al., 2004. p2.)

Open bed biofilters are typically built outdoors on the ground and are exposed to a variety of weather conditions, whereas the closed bed biofilters are mostly enclosed with a small exhaust port for venting of the cleaned air. In general, closed bed biofilter are use to treat smaller airflow, with deeper media (2-3 feet or more) to reduce the space needed to achieve the required treatment and are more expensive (Schmidt et al., 2004). Figure 2-3 illustrates the schematic of a typical open-bed biofilter.

2.3.4 Biofilter Cost Components

Open-bed biofilters are less costly with similar results to enclosed biofilters. The capital costs for constructing a biofilter are associated with the quantity of air to be treated, and larger biofilters are much costly primarily because of fan power requirements. The components that generate the largest capital costs are the fans, media, ductwork, plenum and irrigation system to maintain media moisture and labour (Nicolai et al., 2002). Typically for new construction on mechanically ventilated buildings will cost between $150 and $250 per 1000 cfm (Schmidt et al., 2004). Annual operation and maintenance of the biofilter is estimated to be $5-$15 per 1000 cfm (Schmidt et al., 2004). The operation and maintenance cost includes the increase in electrical costs to push the air through the biofilter and the cost of replacing the media after 5 years. Both capital costs and operation/maintenance costs are quite variable. In fact, the greatest operating cost is the operation of the fans/blowers, with media replacement being the second largest.

2.4 Health and Safety Concerns

Consider the air quality in the vicinity of your operation as well as inside the livestock buildings, wastes stored under slotted floors may be in the buildings long enough for bacterial action to produce gases and strong odours. Odours can be a nuisance to producers and cause complaints and even lawsuits by neighbours.

Noxious gases can irritate both livestock and operators such that it can be harmful and even lethal (MWPS-18, 1993). It is proven that ammonia (NH_3) and hydrogen sulphide (H_2S) at high concentrations has negative impacts on human health which may result in death if safety precaution is not taken (MWPS-18, 2002).

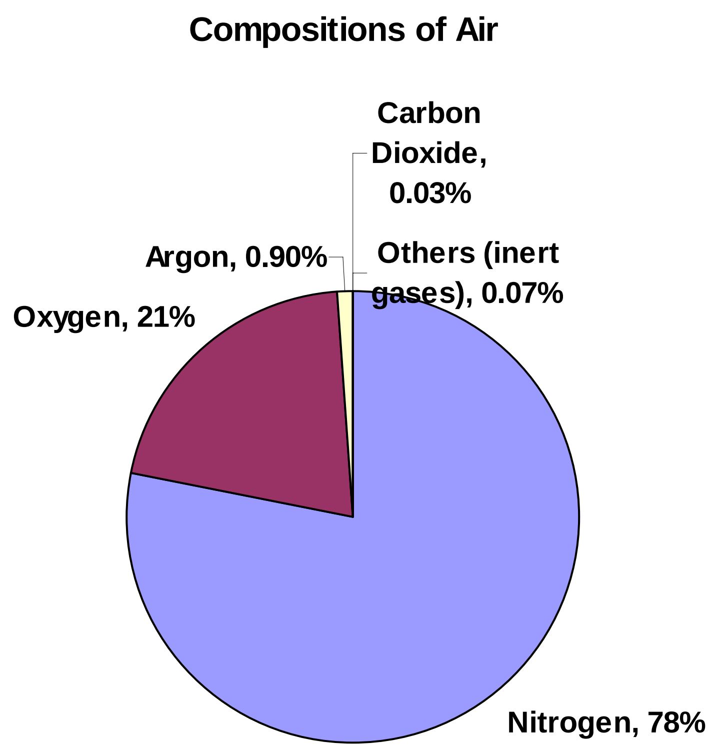

Figure 2-4. Compositions of atmospheric air.

Atmospheric air consists of 78% nitrogen, 21% oxygen, 0.9% argon, 0.03% carbon dioxide, and smaller amounts of inert gases, Figure 2-4. Air composition is changed in livestock buildings. Breathing requires oxygen and releases carbon dioxide. Oxygen content in the air of less than 10% is dangerous (MWPS-18, 1993). Odours are given off from animals' skins, urine, and manure. Anaerobic decomposition of manure in a pit releases additional noxious gases (MWPS-18, 1993). If ventilation is not adequate, concentrations of certain toxic gases within enclosed buildings can harm animals and operators.

Most gases generated in an enclosed animal building are carbon dioxide, ammonia, hydrogen sulphide and methane, all of which are colourless which are explained in Appendix C. Organic compounds from uncontrolled decomposition of waste include odorous gases such as amines, amides, mercaptans, sulphides, and disulphides (MWPS-18, 1993).

Odours and gases of concern inside animal buildings are different as compared to offsite. When it is offsite odours are primarily a nuisance, whereas onsite they may indicate potential health risks for workers and animals. Hydrogen sulphide, ammonia, carbon dioxide (CO_2), carbon monoxide (CO), and methane (CH_4) are primary inside gases emitted, Appendix B (Table B-1) (MWPS-18, 2002). The most dangerous is hydrogen sulphide, which can kill animals and people during the agitation of manure storage units, when the gas is released more quickly (MWPS-18, 2002).

In an environmentally controlled building, noxious gases usually do not reach lethal or even harmful concentrations except with ventilation failure or vigorous manure pit agitation (MWPS-18, 1993).

During the initial start-up, relatively a large numbers of spores were released but the number quickly diminished and stabilised (Schmidt et al., 2004). Dust and mould spore emissions during construction, maintenance, and removal may pose a potential health risk (Schmidt et al., 2004). Therefore, dust control and personal protection (dust filer masks) is used to minimise exposure. In general, the dust and bioaerosols from biofilters are not expected to be a problem during normal operation (Schmidt et al., 2004).

2.4.1 Potentially Lethal Situations

In the event of ventilation breakdown, when there is no natural draft to replenish the air it can cause death by asphyxiation from lack of oxygen and increased carbon dioxide, by heat prostration, by poisoning from other gases, or some combination (MWPS-18, 1993).

Agitation of liquid manure releases large quantities of noxious gases and creates dangerous and possible lethal conditions, even with maximum ventilation. MWPS-18 (1993) suggested that a mild day should be chosen to perform agitation of manure so as to allow maximum capacity for ventilation. Also, animals should be removed from the building before agitation to avoid any unnecessary ill effects.

When entering a storage pit it can be extremely dangerous and death can result from hydrogen sulphide or lack of oxygen. MWPS-18 (1993) emphasise that the right approach when entering the manure storage is only after it has been well ventilated. For safety precaution, personnel entering the manure storage need to wear self-contained breathing tanks and have an attached safety rope with at least two people standing by to observe if any symptom of dizziness is discovered.

According to MWPS-18 (1993), accumulation of methane in unvented covered pits will result in an explosive if a flame or spark is introduced. Therefore, as a preventive measure, it is advisable to ventilate the pit prior to any human activities within the boundary.

CHAPTER 3

VARIOUS MOISTURE MEASUREMENT TECHNIQUES

Most physical and chemical properties of soil vary with moisture content. Measurement of soil water content is needed in every type of soil study, like hydrology, agrology, plant science and civil engineering all require soil moisture data. Currently, extensive research has already been established to determine the moisture level of the soil content. Therefore, using the available technology and concept, it will be easier to co-relate biomedia with the soil content since they have relatively similar physical and chemical properties.

According to ICT International (2004) the choice of instrumentation for moisture determination will depend on the consideration of the following factors:

1. Physical limitations of different techniques.

2. The level of information required (either an absolute or relative moisture measurement).
3. The amount of data needed to objectively decide upon.
4. The reliability of the instrument and the collected data.
5. The ease of using the instrument in the field.

The method of measurement is simply a device allowing moisture determination in an objective fashion. It is important that measurements are made regularly and recorded systematically to allow enhanced moisture management. Currently, there are different methods using different tools to determine moisture content effectively. In this review, some of the more commonly used moisture measurement techniques are described.

3.1 Gravimetric Techniques

Gravimetric measurement of soil water content is based on removal of water from the sample, and thereafter the sample water is removed by evaporation, leaching or chemical reaction (AFMRC, 2004). Once the sample water is removed, the amount of water removed from the sample is determined and used to calculate the soil moisture content.

There are several methods that can be used to determine the water content and the simplest method to determine water content removed is by measuring the lost of weight of the sample. AFMRC (2004) stated that sample water content can also be determined by collection of the water through distillation or absorption in a desiccant. Extraction of substances which replace sample water and measurement of a physical or chemical property of the extracting material that is affected by water content is another method (AFMRC, 2004). Finally, sample water content can be determined by quantitative measurement of reaction products displaced from a sample (AFMRC, 2004). In each of these methods the water and soil are separated and the amount of water removed is measured or inferred.

3.1.1 Basic Principles of Gravimetric Techniques

Apparatus required for gravimetric water content measurements comes in many different forms and so exact specifications are not needed. Fedro and Xin (1994) stated that oven drying technique is probably the most widely used of all gravimetric methods for measuring soil moisture and is the standard for the calibration of all other soil moisture determination techniques. For the oven drying method, apparatus normally includes a soil sampling device such as an auger or sampling tube (AFMRC, 2004). In addition, soil containers with tight-fitting lids, an oven with means for controlling the temperature, desiccators with active desiccant and a balance for weighing samples are typical of the oven drying method

(AFMRC, 2004). Both convective and forced-draft ovens are used and for precise work a vacuum oven can be of benefit. Balances used range from analytical balances to rough platform scales and the balance used is dependent on the size of the sample used and the precision of measurement desired. If soil samples are taken under conditions where evaporation losses may affect the accuracy of measurement, it is advisable to weigh the sample immediately or use equipment that will minimise in evaporative loss.

3.1.2 Methodology of Gravimetric Techniques

For the oven drying method, moisture content is determined by measuring the weight of water removed. According to AFMRC (2004), drying the moist soil to a constant weight in a drying oven is controlled at 230° ± 9° F (110° ± 5° C). Temperature of the drying oven is checked frequently to ensure adequate temperature is maintained. The time necessary to reach constant weight will depend upon the type of oven used, the size or depth of the sample and the nature of the soil. Experiments conducted by AFMRC (2004) shown that if a forced draft oven is used, samples should be dried for at least 24 hours. Precautions should also be taken to avoid adding wet samples during the last half of the drying period and additional time should be added if the oven is loaded heavily. The weight of soil remaining after oven drying is used as the weight of soil solids, therefore moisture content expressed as a percent is equal to the weight of water divided by weight of soil solids multiply by 100.

Another alternative method introduced by AFMRC (2004) is radiation drying which can be used for soil water content measurements where low precision is adequate. Radiation drying uses an infrared or ordinary heat lamp, and due to the variable drying temperature, which makes it less accurate than those methods using closely controlled, constant temperature drying ovens (AFMRC, 2004). However, radiation drying method is rapid and requires only a few minutes to dry the soil which is desirable when time is a concern.

Moisture content is computed and shown in Equation 3.1.

$$Percent\ Moisture\ Content, Dry\ Basis = 100 \times \frac{W_t - W_s}{W_s} \qquad (3.1)$$

(Source: AFMRC, 2004)

Where:

W_t = weight of soil and water

W_s = Dry soil weight (weight of soil solids)

In some cases, water content for stony or gravely soils, both on a mass and volume basis, can be grossly misleading. Since rocks can occupy a large volume of a soil sample and contribute to the mass and not the water capacity of the soil, and errors may arise. For near surface soil moisture measurement, gravimetric techniques are unreliable, destructive and tedious. Rapid moisture changes imply frequent sampling and repeated interference with the surface and this can result in a severe drawback.

3.1.3 Evaluation of Gravimetric Techniques

The oven-drying technique is probably the most widely used of all gravimetric methods for measuring biofilter media moisture and is the standard for the calibration of all other media moisture determination techniques. This method involves removing a media sample from the biofilter and determining the mass of water content in relation to the mass of dry media. Although the use of this technique ensures accurate measurements, it also has a number of disadvantages: laboratory equipment, sampling tools, and 24 hours of drying time are required. In addition, it is a destructive test in that it requires sample removal. This makes it impossible to measure media moisture at exactly the same point at a later date. Eventually, measurements will become inaccurate because of variability from one point to another in a biofilter.

3.2 Resistive Sensor (OhmMapper Instrument)

Electromagnetic techniques include methods that depend upon the effect of moisture on the electrical properties of soil. Soil resistivity depends on moisture content and it is possible either to measure the resistivity between electrodes in a soil or to measure the resistivity of a material in equilibrium with the soil.

The OhmMapper is an instrument used for making rapid measurement of the soil moisture content. Studies done by Walker and Houser (2002) have shown that electrical resistance measurements may be used to infer soil moisture content under special circumstances.

3.2.1 Basic Principles of an OhmMapper

In conventional resistance surveys, four electrodes are inserted into the soil and a current injected into the ground by connecting a DC power source to two of the electrodes. The voltage is then measured at the remaining two electrodes and the resistance can be calculated by using Ohm's Law (Edwards, 1977). The resistance measured varies as a function of the distance and geometry between the probes, so it is normalised with geometric correction factor that converts the measurement to resistivity (Geometrics Inc., 1999).

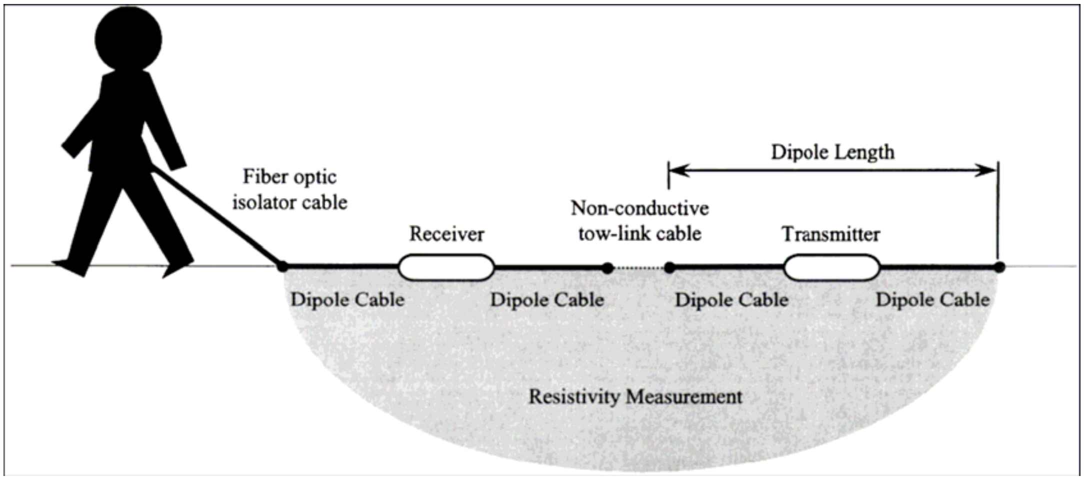

Figure 3-1. Schematic of the OhmMapper instrument. (Walker and Houser, 2002. p729.)

According to Geometrics Inc. (1999), an OhmMapper instrument is a capacitively-coupled resistivity system that measures the electrical properties of the ground without the galvanic electrodes used in traditional resistivity surveys. In this system, a coaxial-cable array with transmitter and receiver sections is pulled along the ground either by a single person or a small all-terrain vehicle (Figure 3-1). This provides the instrument with a potential to cover large areas in a comparatively short period of time.

Like some configurations of traditional galvanic resistivity, the OhmMapper uses a dipole-dipole array (i.e., injection of current following measurement of voltage as opposed to a nested measurement) to measure resistivity, except that contact is made with the ground capacitively. Loke (1999) stated that the dipole-dipole array is very sensitive to horizontal changes in resistivity but relatively insensitive to vertical changes, meaning that it is good in mapping vertical structures but relatively poor in mapping horizontal structures.

By increasing the dipole cable length and/or tow-link length, the distance between the midpoints of receiver and transmitter dipoles of a dipole-dipole array will increase, and hence depth of the resistivity measurement is increased.

3.2.2 Theory of OhmMapper

Hymer et al. (2000) have used a power relationship to correlate volumetric soil moisture content (θ) and resistance (*R*). Also, Walker and Houser (2002) stated that the OhmMapper apparent resistivity measurement is equivalent to the resistance value as derived in Equation (3.2).

$$\theta = a \times R^b \tag{3.2}$$

(Source: Hymer et al., 2000)

Where:

θ = moisture content

R = resistance

a and b = fitted parameters

A relationship of this form is compatible with Archie's Law (Archie, 1942), where *a* is the inverse of soil salinity and *b* is a soil texture parameter. Similar non-linear relationships have also been used by Seyfried (1993) and Amer et al. (1994).

3.2.3 Evaluation of OhmMapper

Electromagnetic techniques include methods that depend upon the effect of moisture on the electrical properties of biofilter media. Media resistivity depends on moisture content; hence it can serve as the basis for a sensor. It is possible either to measure the resistivity between electrodes in a media or to measure the resistivity of a material in equilibrium with the media. The difficulty with resistive sensors is that the absolute value of media resistivity depends on ion concentration as well as on moisture concentration. Therefore, careful calibration is required for these techniques.

3.3 Microwave Sensing Techniques

It was recognised more than 20 years ago that microwave measurements had the capability for providing a moisture measurement independent of bulk density (Kraszewski and Kulinski, 1976; Kraszewski et al., 1977).

3.3.1 Basic Principles of Microwave Sensing Techniques

Walker et al. (2004) stated that the fundamental basis of microwave sensing for soil moisture content is the contrast in dielectric properties of water and dry soil, and the relationship between the Fresnel reflection coefficient and dielectric constant. In use of the dielectric properties for determining moisture content, it has been learned that variables other than moisture content influence the dielectric properties (Nelson 1981, 1982). For land surface, the target consists of the interface between air and soil. As the dielectric constant of the air is a known value, the reflection coefficient provides a measurement of the dielectric constant of the soil medium (Jackson et al., 1996).

Since the scattering behaviour of a surface is governed by its geometrical and dielectric properties relative to the incident radiation, the variation in backscattering are influenced by soil moisture content (through the dielectric constant), surface roughness, observation frequency, wave polarisation and incident angle (Walker et al., 2004). A variation of relative dielectric constant between 3 and 30 (a shift in volumetric moisture content between approximately 2.5% and 50%, depending on frequency and soil texture) causes an 8 to 9 dB rise in backscatter coefficient for *vv* (vertical transmit vertical receive) polarisation (Hoeben et al., 1997). This change in backscattering is almost independent of other parameters, such as incidence angle, frequency and surface roughness, but the total amount of backscattering is affected (Walker et al., 2004). According to Walker et al. (2004), the relationship between backscattering coefficient and dielectric constant is non-linear, whereby having a higher sensitivity at low dielectric values.

3.3.2 Methodology of Microwave Sensing Techniques

Microwave techniques for the measurement of soil moisture content rely on the clear distinction between the dielectric properties of water and those of the soil particles. The dielectric properties are measured by the dielectric constant ε, which is a complex number representing the response of a material to an applied electric field, such as an electromagnetic wave (Schmugge, 1985). This property consists of both real and imaginary parts by the relationship $\varepsilon = \varepsilon' + i\varepsilon''$, and is usually measured relative to that of free space (i.e. $\varepsilon_r = \varepsilon / \varepsilon_o$, where $\varepsilon_o = 8.85 \times 10^{-12}$ farad m^{-1}) (Walker et al., 2004).

The real (in-phase) component of ε determines the propagation characteristics of the electromagnetic wave in the material (i.e. its velocity), and the complex (out of phase) component determines the energy losses or absorption as the electromagnetic wave travels through the material (Schmugge, 1985; D'Urso et al., 1994; Engman and Chauhan, 1995; Bolognani et al., 1996; Zegelin, 1996), and is often referred to as the dielectric loss factor (Zegelin, 1996). The energy losses result from vibration and/or rotation of the water molecules (Wuthrich, 1997).

For dry soil particles, the real part of the relative dielectric constant ε_r' varies from a value of 2 to 5 (depending on soil bulk density) independent of frequency (Dobson and Ulaby, 1986), with an imaginary part ε_r'' typically less than 0.05 (Ulaby et al., 1996). In contrast, for free water the relative dielectric constant at 1 GHz and room temperature is approximately 80 for the real component and 4 for the imaginary component (Ulaby et al., 1996). It is this large difference that makes the measurement of soil moisture content by the microwave techniques possible.

3.3.3 Evaluation of Microwave Sensing Techniques

The microwave sensing of biofilter media moisture depends on the measurement of electromagnetic energy that has either reflected or emitted from the media surface. The intensity of this radiation with media moisture may vary depending on dielectric properties, media temperature or some combination of both.

For active radar, the attenuation of microwave energy may be used to indicate the moisture content of porous media because of the effect of moisture content on the dielectric constant. Generally, thermal infrared wavelengths are commonly used for this measurement.

3.4 Neutron Scattering Techniques (Neutron Probe)

The neutron scattering method is an indirect way of determining soil moisture content which measures the slowdown of fast neutrons emitted into the soil resulting from collision with soil water molecular hydrogen. Thus, it measures the amount of total water in a volume of soil based on the rate of the neutron slowdown.

3.4.1 Basic Principles of Neutron Probe

The technique is based on the measurement of fast moving neutrons (generated from an Americium 241/Beryllium source) that are slowed (thermalised) in the soil by an elastic collision with existing hydrogen particles in the soil. (ICT International, 2004). Average energy loss or thermalisation is much greater when neutrons collide with atoms of low atomic weight than from collisions with heavier atoms. In soils, low atomic weight atoms are primarily hydrogen; as a result, hydrogen can decelerate fast neutrons much more effectively than any other element present in the soil or vapour state. Since water is the largest source of hydrogen atoms in soil, a relationship between water content and neutron thermalisation exists.

As stated by ICT International (2004), hydrogen (H^+) is present in the soil as a constituent of:

1. Soil organic matter.
2. Soil clay minerals.
3. Water.

Water is the only form of H^+ that will change from measurement to measurement. Therefore any change in the counts recorded by the neutron probe is due to a change in the moisture. When there is an increase in counts, it is relating to an increase in moisture content.

3.4.2 Methodology of Neutron Probe

According to AFMRC (2004), neutron moisture probes consist of a source of fast neutrons, a thermalised neutron detector and a protective shield and the probes may also contain a scaler for registration of counts or a meter for direct display of water content. In the field, aluminium tubes are inserted into the soil and readings are taken at depths down the profile (e.g. 20, 30, 40, 50, 60, 70, 80, 100 and 120 cm) with a sixteen second count. In order to minimise the effect of spatial variability, three aluminium tubes are used in measuring the moisture content of the soil (ICT International, 2004).

In general, the neutron probe allows a rapid, accurate, repeatable measurement of soil moisture content to be made at several depth and locations. But the use of radioactive material requiring a licensed and extensively trained operator, the very high equipment cost and extensive calibration required for each site.

3.4.3 Evaluation of Neutron Probe

Neutron scattering is widely used for estimating volumetric water content. With this method, fast neutrons emitted from a radioactive source are thermalised or slowed down by hydrogen atoms in the biofilter media. Since most hydrogen atoms in the media are components of water molecules, the proportion of thermalised neutrons is related to media water content.

This method offers the advantage of measuring a large media volume, and also the possibility of scanning at several depths to obtain a profile of moisture distribution. However, it also has a number of disadvantages: the high cost of the instrument, radiation hazard, insensitivity near the media surface, insensitivity to small variations in moisture content at different points within a 30 to 40 cm radius, and variation in readings due to media density variations.

3.5 Time-Domain Reflectometry (TDR)

In 1980, Topp et al. popularised Time-Domain Reflectometry (TDR) as a method to measure soil water content using soil Electromagnetic (EM) properties. Since that time, electronic methods of soil characterisation have seen much development (Veenstra et al., 2005b).

3.5.1 Methodology of Time-Domain Reflectometry

The TDR is a portable unit and it allowed point soil moisture measurements or linked to a multiplexer to measure an array of buried waveguides (Heimovaara et al., 1990). The TDR probes or sensors measure the difference in capacity of a non-conductor (soil) to transmit high-frequency EM waves or pulses, which is related through calibration to soil moisture content. Using this concept, the TDR measures the time it takes for an EM wave to travel through the soil between the probes. Thus, a delay time between transmitted and reflected pulses is then used to determine the velocity of the pulses.

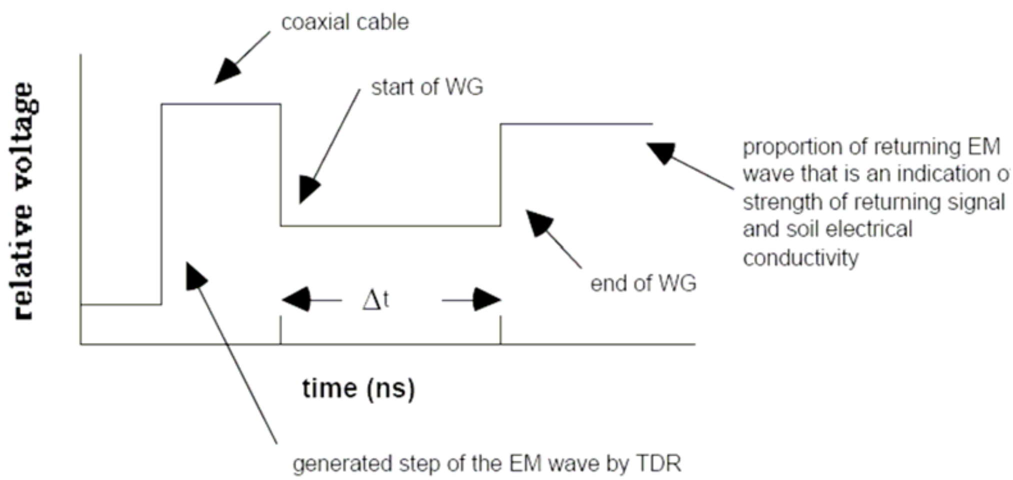

Figure 3-2. Schematic diagram of an EM wave generated by a step pulse TDR system at it travels along the coaxial cable and down the waveguides (WG) into the soil. (ICT International, 2004. p3.)

The technique is based on cable testing technology, with a broad-band EM step pulse generated and propagated along a coaxial cable (Figure 3-2). At the end of the cable, stainless steel rods (waveguides) are inserted into the ground. The time travel of the EM wave is determined by the apparent dielectric (Ka) of the medium (soil). Dobson and Ulaby (1986) also have proven that water has a relatively higher dielectric (Ka ≈ 80), as compared to soil (Ka ≈ 2 to 5) and air (Ka =1). Thus, if the soil is moisture the Ka will increase (due to the presence of increase water) and the travel time of the EM wave along the waveguides is long. If the soil is dry, the Ka will be low and the travel time along the waveguides is short.

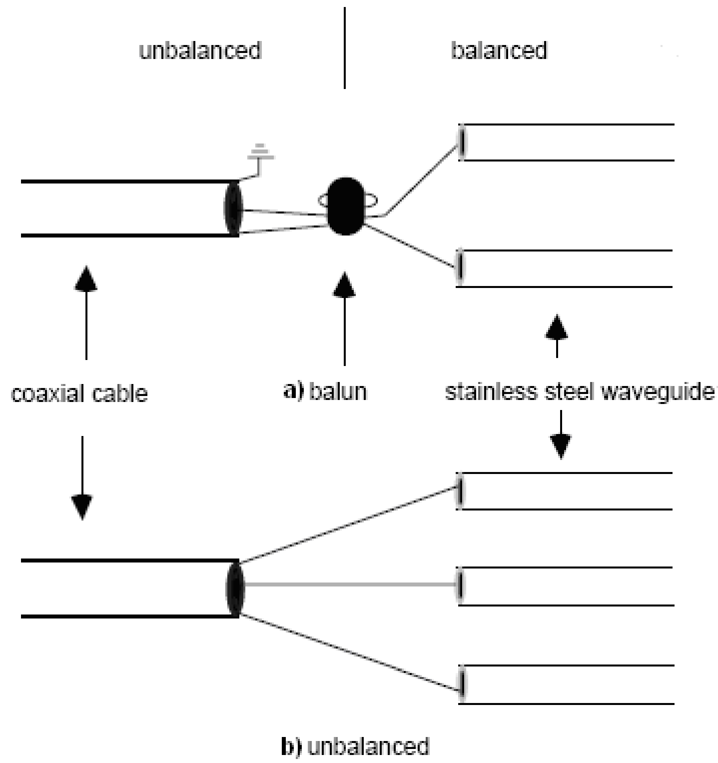

Figure 3-3. Schematic diagram illustrating the connection of the coaxial cable (unbalanced signal) to the stainless steel waveguides through, a) a balun for the two-wire system, and b) direct to the waveguides in the three-wire system. (ICT International, 2004. p4.)

In the field waveguides (stainless steel), it consists of either balanced (two-wire) or unbalanced (three-wire) as shown in Figure 3-3. Generally, two wire probes are used for portable measurement and the three wire probes for permanent placed waveguides (ICT International, 2004).

In general, the TDR equipment is relatively accurate and can provide direct readouts of volumetric, soil moisture percentages or continuous readings if used with a data logger. But the readings can be affected if good contact is not made with soil, and prongs can be damaged in hard or rocky soils.

3.5.2 Theory of Time-Domain Reflectometry

The relationship of Ka to travel time (*Δt*) is shown in Equation 3.3.

$$Ka = (c\,.\,\Delta t / 2L)^2 \tag{3.3}$$

(Source: Topp et al., 1980)

Where:

c = velocity of light (3 x 10^8 ms^{-1})

L = length of wave guide (m)

Δt = time travel

Topp et al. (1980) empirically related Ka to θ_v via third order polynomial and Equation 3.4 is the basis for soil moisture measurements at present.

$$\theta_v = \left(-5.3\times10^{-2}\right) + \left(2.92\times10^{-2}\,Ka\right) - \left(5.5\times10^{-4}\,Ka^2\right) + \left(4.3\times10^{-6}\,Ka^3\right) \tag{3.4}$$

3.5.3 Evaluation of Time-Domain Reflectometry

The TDR determinations involve measuring the propagation of EM waves or signals. Fedro and Xin (1994) stated that the propagation constants for EM waves in biofilter media, such as velocity and attenuation, depend on media properties, especially water content and electrical conductivity. The propagation of electrical signals in media is influenced by media water content and electrical conductivity.

Thus, the dielectric constant, measured by TDR, provides a good measurement of this media water content. Fedro and Xin (1994) have claimed that the water content determination is independent of media texture, temperature and salt content.

3.6 Tensiometric Techniques (Tensiometers)

The primary method for measuring the capillary or moisture potential is based upon the so-called suction force of the soil for water which involves the use of the tensiometer (AFMRC, 2004).

A tensiometer is an airtight, hollow tube filled with water. A porous ceramic cup is attached to the end of the tube inserted into the soil and a vacuum gauge is attached to the upper end. The tensiometer is used to measure soil moisture tension, an index of how tightly water is held in the soil.

3.6.1 Basic Principles of Tensiometers

AFMRC (2004) defined that the energy with which water is held by the soil is a common log of the height of a water column in centimetres equivalent to the soil moisture tension. The energy with which water is held by the soil can also be defined as suction (negative pressure) or a potential (energy per unit mass)

(AFMRC, 2004). AFMRC (2004) also commented that matric suction is the pressure difference across a boundary permeable only to water where the boundary solute separates bulk water and soil water in hydraulic, chemical and thermal equilibrium.

Hence, tensiometers are used to measure suction which consists of a liquid-filled porous ceramic cup connected by a continuous liquid column to a manometer of vacuum gage. The ceramic cup is porous to the water and solute but not to the air so when the soil water increases, it is held at lower tension. Hence, when the tensiometer reads zero, the soil is saturated and water tension is zero.

3.6.2 Methodology of Tensiometers

Based on ICT International (2004), portable and stationary tensiometers measure soil moisture content as a tension or pressure ranging from 0 to -100 kPa, (0 to -1 bar). Tensiometers fundamentally act in a similar fashion to a plant root, through measuring the force that plants have to exert to obtain moisture from the soil (ICT International, 2004). As the soil dries the water is lost from the tensiometer via a ceramic cup. According to ICT International (2004), the loss of water creates a vacuum in the tensiometer and is reported as a pressure reading and the drier the soil the higher the pressure reading, (noting -0.1 bar is considered field capacity and -1.5 bar wilting point).

In fact, tensiometers may be placed permanently in the soil giving an analogue or digital output. Logging of tensiometers is possible via transducers and a communication cable back to a computer or data logger. Furthermore, portable tensiometers allow greater freedom of sampling which give relatively quick readings of soil moisture tension. In order to operate accurately, tensiometers must be installed correctly and well maintained and the practical limit for reliable readings is around -800 kPa (-0.8 bar) (ICT International, 2004).

3.6.3 Evaluation of Tensiometers

The primary method for measuring matric potential (capillaric tension) in biofilter media involves the use of the tensiometer, which directly measures matric potential. Tensiometers are commercially available from several different sources and in numerous configurations. The main disadvantage of the tensiometer is that it functions only from zero to about -0.8 bar, which represents a small part of the entire range of available water. Therefore, the use of the tensiometer to determine the moisture content of biofilter media can cause over-watering; unless tensiometer readings are combined with information on media water content

3.7 Capacitive Sensor (Frequency Domain)

3.7.1 Basic Principles of Capacitive Sensor

The capacitance technique is similar to TDR in that the apparent (Ka) dielectric of the soil is measured and empirically related to the moisture content (θ_v). By using a high frequency transistor oscillator (≈150 MHz) and operates with the soil (dielectric) part of an ideal capacitor can be formed.

$$C = K\varepsilon_0 A / d \qquad (3.5)$$

Where:

C = capacitance

K = dielectric constant

A = total electrode area

d = spacing of the electrodes

ε_0 = permittivity (free space)

White and Zegelin (1994) emphasised that the dielectric (K) is related to the capacitance (C) via the relationship of the total electrode area (A) and spacing of the electrodes (d), noting that (ε_0) the permittivity of free space is constant.

In a field situation the design of the capacitance probe is not ideal with two annular rings (electrodes) placed in a plastic access tube in the soil (ICT International, 2004). The measured area is now removed from between the electrodes to outside the access tube as shown in Figure 3-4. Thus, in a field situation the measured capacitance (*C*) is determined as shown in Equation 3.6. The geometrical constant (*g*) depends upon the electrode spacing, area and orientation of the electrodes in the soil and ε_0 (White and Zegelin, 1994).

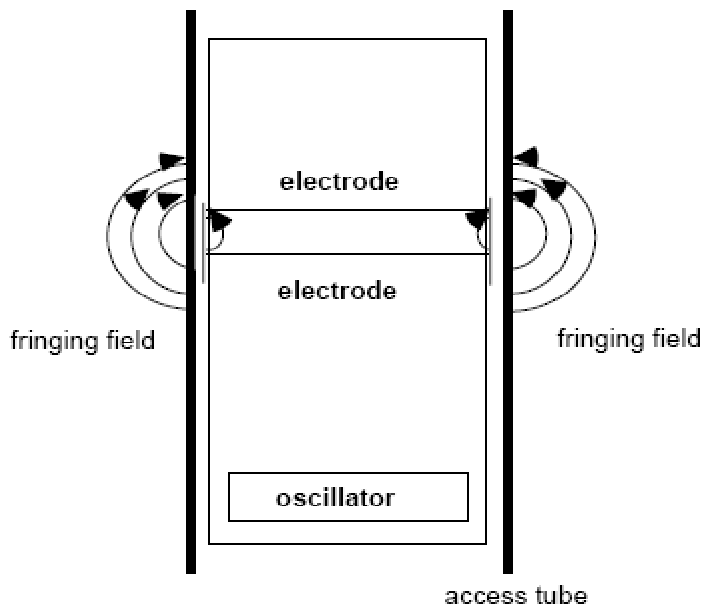

Figure 3-4. Schematic diagram of capacitance probe in an access tube (Source from White and Zegelin, 1994)

$$C = gK \qquad (3.6)$$

(Source: Whalley et al., 1992)

Bell et al. (1987) stated that the measurement is undertaken by either lowering a sensor into the access tube or placing an array of sensors into the access tubes and logging the output frequency. According to ICT International (2004), the measured (angular) frequency is related to the soil moisture content via a non-linear calibration. Thus, measurement of absolute moisture content is dependant on soil type and bulk density.

Whalley et al. (1992) commented that the potential for capacitance based soil moisture determination is good, however development is required to determine the actual measurement area of the probe and its spatial sensitivity to change in moisture content. Furthermore, the calibration of the technique *in situ* needs to be fully understood in order to allow universal usage (Whalley et al., 1992). Up to now, the effect of electrical conductivity, temperature and acidity of the soil of the measured frequency has not been fully studied.

3.7.2 Evaluation of Capacitive Sensor

Biofilter media moisture content may be determined via its effect on dielectric constant by measuring the capacitance between two electrodes implanted in the media. Since media moisture is predominantly in the form of free water, the dielectric constant is directly proportional to the moisture content.

The capacitive probes or sensors which based on frequency domain uses radio frequency waves to measure the difference in capacity of a non-conductor (media) to transmit high-frequency electromagnetic waves or pulses, is related through calibration to media moisture content. The probe is normally given a frequency excitation to permit measurement of the dielectric constant. The readout from the probe is not linear with water content and is influenced by media type and media temperature. Therefore, careful calibration is required and long-term stability of the calibration is questionable.

CHAPTER 4

FUNDAMENTAL THEORY OF CAPACITANCE

A capacitor consists of two conductive electrodes, or plates, separated by an insulator or dielectric. The capacitor's capacitance is a measure of the amount of charge stored on each plate for a given potential difference or voltage which appears between the plates. In SI units, a capacitor has a capacitance of one farad when one coulomb of charge causes a potential difference of one volt across the plates. Since the farad is a very large unit, values of capacitors are usually expressed in microfarads, nanofarads or picofarads.

The capacitance is proportional to the surface area of the conducting plate and inversely proportional to the distance between the plates. Also, it is proportional to the permittivity of the dielectric (non-conductor) substance that separates the plates.

Therefore, the value of capacitance depends not only on the geometry of the capacitor, but the dielectric as well.

4.1 The Basic Concept of Capacitance

A capacitor is a device for storing charge and is usually made up of two plates separated by a thin insulating material known as the dielectric. A capacitance of one farad results in a potential of one volt for one coulomb of charge. When a voltage is connected the plates take up the charge and are able to store a quantity of electricity. In fact, current only flows when the capacitor is actually charging or discharging and the charging current is quite high initially but it reduces gradually to zero as the voltage across the capacitor rises to equal the supply voltage.

Since the capacitance is a measure of the amount of electric charge stored (or separated) for a given electric potential, it can be expressed as Equation 4.1.

$$C = \frac{Q}{V} \tag{4.1}$$

(Source: Kraus and Fleisch, 1999)

The amount of electricity stored in a capacitor is measured in Coulombs and assuming no losses, this charge will remain in the capacitor after the supply voltage has been removed.

Or, according to Gauss' law, the capacitance can be expressed as the electric flux per volt as expressed in Equation 4.2.

$$C = \frac{\psi}{V} \quad (4.2)$$

(Source: Kraus and Fleisch, 1999)

Where:

C = capacitance, measured in farads, (F)

Q = electric charge, measured in coulombs, (C)

V = electric potential, measured in volts, (V)

ψ = electric flux associated with the charge Q in coulombs

According to Serway and Beichner (2000), capacitance exists between any two conductors insulated from one another and Equation 4.1 and 4.2 defining capacitance is valid if it is understood that the conductors have equal but opposite charge Q and the voltage V is the potential difference between the two conductors.

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \quad (4.3)$$

(Source: Kraus and Fleisch, 1999)

Where:

ε_0 = permittivity of free space, measured in farads per metre (F/m)

ε_r = dielectric constant or relative permittivity of the insulator used

A = area of each plane electrode, measured in square metres (m^2)

d = separation between the electrodes, measured in metres (m)

The capacitance can be calculated if the geometry of the conductors and the dielectric properties of the insulator between the conductors are known. Indeed, for ideal dielectrics, capacitance is strictly a function of the geometry of the system. For example, the capacitance of a parallel-plate capacitor consist of two identical plane electrodes of area A at constant spacing d is expressed as Equation 4.3.

4.1.1 Capacitance Energy

Serway and Beichner (2000) stated that the energy (measured in joules) stored in capacitance is equal to the work done to change it. Hence, consider a capacitance *C*, holding a charge +*q* on one plate and –*q* on the other, and moving a small element of charge *dq* from one plate to the other against the potential difference $V = q/C$ requires the work dW .

$$dW = \frac{q}{C} dq \qquad (4.4)$$

(Source: Kraus and Fleisch, 1999)

Where:

q = electric charge, measured in coulombs (C)

C = capacitance, measured in farads (F)

By integrating Equation 4.4, Serway and Beichner (2000) explained that the energy stored in a capacitance or work *W* required moving an uncharged capacitance from one plate to another plate is expressed in Equation 4.5.

$$E = W_{charging} = \int_0^Q \frac{q}{C}\,dq$$

$$= \frac{1}{2}\frac{Q^2}{C}$$

$$= \frac{1}{2}CV^2 \tag{4.5}$$

(Source: Kraus and Fleisch, 1999)

Equation 4.6 is obtained by combining Equation 4.5 with Equation 4.3.

$$E = \frac{1}{2}\varepsilon_0\varepsilon_r\frac{A}{d}V^2 \tag{4.6}$$

(Source: Kraus and Fleisch, 1999)

4.1.2 Self-capacitance

In electrical circuit, the term capacitance is usually a shorthand for the mutual capacitance between two adjacent conductors, such as the two plates of a capacitor. According to Serway and Beichner (2000), there also exists a property called self-capacitance, which is the amount of electrical charge that must be added to an isolated conductor to raise its electrical potential by one volt. The reference point for this potential is a theoretical hollow conducting sphere, of infinite radius, centred on the conductor (Serway and Beichner, 2000).

Using this method, the self-capacitance of a conducting sphere of radius R is expressed as Equation 4.7.

$$C = 4\pi\varepsilon_0 R \qquad (4.7)$$

(Source: Serway and Beichner, 2000)

4.1.3 Stray Capacitance

Any two adjacent conductors can be considered as a capacitor, although the capacitance will be small unless the conductors are close together or long. This (unwanted) effect is termed “stray capacitance”. Stray capacitance can allow signals to leak between circuits, and is a limiting factor for correct functioning of circuits at high frequency (Serway and Beichner, 2000).

Stray capacitance is often encountered in amplifier circuits in the form of “feed through” capacitance that interconnects the input and output nodes (both defined relative to a common ground) (Serway and Beichner, 2000). It is often convenient for analytical purpose to replace this capacitance with a combination of one input-to-ground capacitance and one output-to-ground capacitance.

4.1.4 Maxwell's Capacitor

Maxwell studied a capacitor built with two parallel plates of area A and two partially conducting dielectrics of thickness L, dielectric constant ε, and conductivity σ as illustrated in Figure 4-1

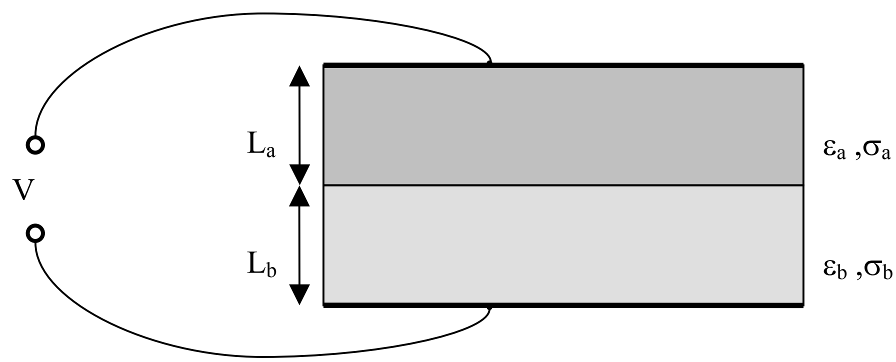

Figure 4-1. Maxwell's capacitor. (Baxter, 1997. p13)

The terminal behaviour and the electric fields can be analysed by application of Laplace's equation. By applying a voltage V at the terminal, it will produce an electric field which is initially divided between the two regions in proportion to the thickness L of the region and its dielectric constant ε, but due to the finite conductivity it will redivide over time in the ratio of the thickness and the conductivity σ (Baxter, 1997). After which the boundary between the dielectrics is an equipotential surface which can be replaced by a conductor, and that the single capacitor can then be dissected into two capacitors with capacitance $\varepsilon_a\ \varepsilon_0\ A/L_a$ and

$\varepsilon_b\ \varepsilon_0\ A/L_b$ (Baxter, 1997). The equivalent circuit is drawn as Figure 4-2, and can be solved by elementary circuit theory.

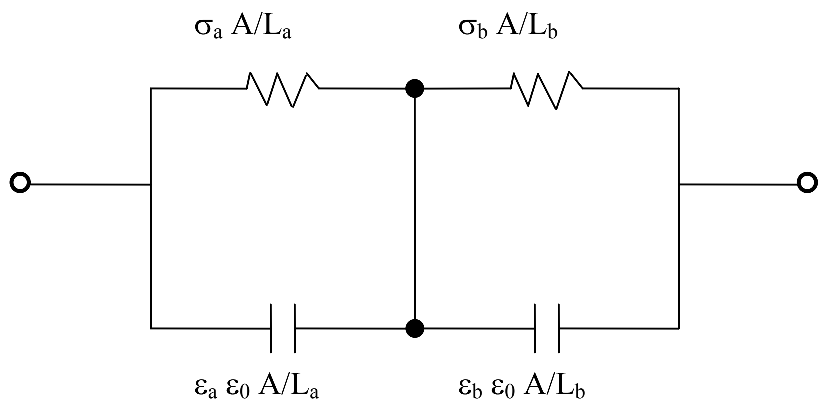

Figure 4-2. Maxwell's capacitor - equivalent circuit. (Baxter, 1997. p13)

4.1.5 Capacitors Connected in Parallel

The capacitance of a capacitor is proportional to the area of its plates and by increasing the area of the plates will increase the capacitance. Therefore, connecting two or more capacitors in parallel is equivalent to a single capacitor with larger plates. Hence, the resultant of capacitors connected in parallel is the sum of the individual capacitors.

4.1.6 Capacitors Connected in Series

When capacitors are connected in series it is the same as increasing the distance between the plates. Thus, when capacitors are connected in series, the total capacitance will be less than any of the individual capacitors. As a result, the capacitance of capacitors connected in series is the reciprocal sum.

4.1.7 Various Type of Capacitors

There are various type of capacitors currently used for different applications, and some of the more commonly used will be described here.

4.1.7.1 Paper Capacitors

These are made from a “sandwich” of strips of foil and wax impregnated paper. Due to the fact that a capacitor need two plates, therefore two such sandwiches are put on top of one another and then rolled up together. In this case, the foil forms the plates and the waxed paper is the dielectric.

4.1.7.2 Mica Capacitors

Mica stacked capacitors are made up of alternate layers of thin metal sheet and thin layers of mica. The odd metal sheets are connected together to form one plate and the even ones connected together to form the other.

4.1.7.3 Silvered Mica Capacitors

Similar to mica capacitor, silver is sprayed on the sheets of the mica to form the plates. Thus, it is possible to make these capacitors very accurately. In addition, the value of the capacitance changes very little with wide temperature changes which make this very suitable for the tuned circuits in oscillators.

4.1.7.4 Ceramic Capacitors

The ceramic capacitors consist of small pieces of ceramic that have a coating of silver on each side. These ceramic capacitors are suitable for de-coupling but should not be used in tuned circuits due to the large capacitance variations with changes of temperature.

4.1.7.5 Electrolytic Capacitors

Electrolytic capacitors can be manufactured with very high capacitance for their size. They consist of two aluminium foil strips interleaved with an absorbent paper strop and wound very tightly into a cylinder. The paper is impregnated with an electrolyte. A voltage is applied and a dielectric layer of aluminium oxide is formed on the foil that is connected to the positive supply.

Thus one capacitor plate is one of the foil strips and the other plate is the electrolyte itself with the oxide acting as the insulating dielectric. This is the clue to the high capacitance. Remember that the closer the plate the higher is the capacitance. The oxide film is extremely thin.

The second foil strip purely acts as a means of connecting to the electrolyte. It is very important to ensure that electrolytic capacitors are connected right way round in any circuit.

4.2 The Basic Concept of Dielectric Constant

Raymond and John (2003) have stated in their studies that the relative dielectric constant of a material under given conditions is a measure of the extent to which it concentrates electrostatic lines of flux. It is the ratio of the amount of electrical energy the material stores when a static electric field is imposed across it, relative to vacuum and it is also called relative permittivity.

The dielectric constant is represented as ε_r or sometimes K and is expressed in Equation 4.8.

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \tag{4.8}$$

Where:

ε = static permittivity, measured in farads per metre (F/m)

ε_0 = permittivity of vacuum, measured in farads per metre (F/m)

Vacuum permittivity (permittivity of free space) is derived from Maxwell's equations by relating the electric field intensity to the electric flux density 1 (Raymond and John, 2003). In vacuum (free space), the static permittivity ε is equivalent to ε_0, so the dielectric constant is.

The permittivity of vacuum, ε_0 is defined by μ_0 and c and is expressed in Equation 4.9.

$$\varepsilon_0 = \frac{1}{\mu_0 c^2}$$

$$\varepsilon_0 = 8.8541878 \times 10^{-12} \quad F/m \qquad (4.9)$$

Where:

μ_0 = magnetic permeability of vacuum ($4\pi \times 10^{-7}$ N/A^2)

c = speed of light in vacuum (299,792,458 m/s)

4.2.1 Dielectric Constant Measurement

The relative dielectric constant ε_r can be measured for static electric fields. First, the capacitance of a test capacitor C_{air} is measured with air ($\varepsilon_r \approx 1.00$) between its plates as shown in Figure 4-3. Then, using the same capacitor and distance between its plates the capacitance $C_{material}$ with a dielectric between the plates is measured as shown in Figure 4-4.

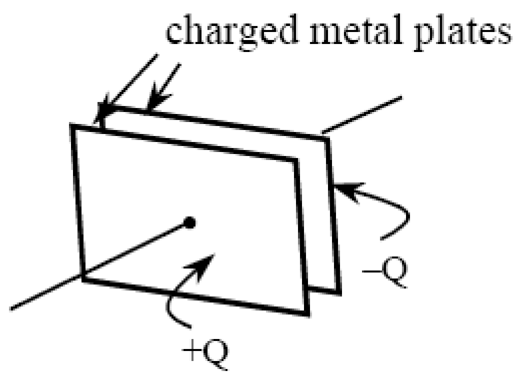

Figure 4-3. Air in the gap between the charged plates.

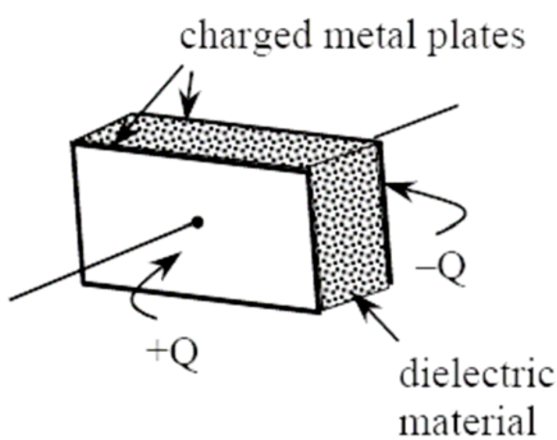

Figure 4-4. Dielectric material (insulator) between the charged plates.

The relative dielectric constant is expressed in Equation 4.10.

$$\varepsilon_r = \frac{C_{material}}{C_{air}} \qquad (4.10)$$

(Source: Ronald et al., 1998)

For time-varying electromagnetic fields, the dielectric constant of materials becomes frequency dependent and in general is called permittivity (Ronald et al., 1998)

The dielectric constant is an essential piece of information when designing capacitors and in other circumstances where a material might be expected to introduce capacitance into a circuit. According to Ronald et al. (1998), if a material with a high dielectric constant is placed in an electric field, the magnitude of that field will be measurably reduced within the volume of the dielectric. This fact is commonly used to increase the capacitance of a particular capacitor design.

4.3 Coulomb's Law

Two small charged conductors in a dielectric with charges of Q_1 and Q_2 coulombs, separated by r meters, exert a force in newtons is expressed in Equation 4.11.

$$F = \frac{Q_1 Q_2}{4\pi \varepsilon_0 \varepsilon_r r^2} \qquad (4.11)$$

(Source: Baxter, 1997)

The force is along the line connecting the charges and will try to bring the charges together if the sign of their charge is opposite (Baxter, 1997).

The coulomb is a large quantity of charge and the charge is equivalent to a 1A current travel in 1 second. Since an electron has a charge of 1.60206×10^{-19} C, therefore a coulomb is about 6×10^{18} electrons. Baxter (1997) has commented that the force between two 1 C charges spaced at 1 mm is 9×10^{15} N which is about 30 times the weight of the earth. In reality, electrostatic forces can often be ignored in practical systems, as the charge is usually very much smaller than a coulomb (Baxter, 1997).

With *V* volts applied to a parallel plate capacitor of plate area *A* square meters and spacing *d* meters, the energy stored in the capacitor (using Equation 4.5 and 4.6) can be determined. The force in newtons is then the partial derivative of energy and plate spacing and is expressed in Equation 4.12.

$$
\begin{aligned}
F &= \frac{\partial E}{\partial d} \\
&= \frac{1}{2}\frac{C}{d}V^2 \\
&= \frac{-\varepsilon_0\varepsilon_r}{2}\frac{A}{d^2}.V^2 \qquad (4.12)
\end{aligned}
$$

(Source: Baxter, 1997)

Transverse forces for simple plate geometries are small, and can be made insignificant with overlapped plates and for some interdigitated structures these forces may be significant and can be calculated using the partial derivative of energy with transverse motion (Baxter, 1997).

Baxter (1997) stated that for a large air-dielectric capacitor charged to 1 V DC and composed of two 1 m square plates at 1mm spacing, the force between the plates is attractive at 4.427×10^{-6} N. This force may be troublesome in some sensitive applications. In additional, Baxter (1997) also pointed out that AC operation does not offer a solution to unwanted electrostatic force as both positive and negative half cycles are attractive, but the small force does not affect most capacitive sensor geometry.

4.3.1 Electric Field

Two charged conducting plates illustrate in Figure 4-5 demonstrate the concept of electric field.

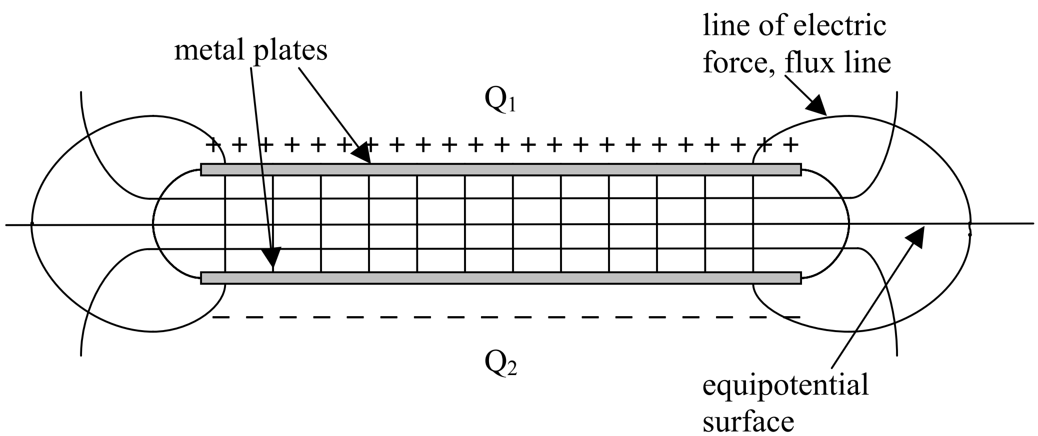

Figure 4-5. Electric field for parallel plates. (Baxter, 1997. p8)

4.3.2 Voltage Gradient

If the plates are arbitrarily assigned a voltage, then a scalar potential V between 0 and 1, can be assigned to the voltage at any point in space. Surfaces where the voltage is the same are equipotential surfaces (Baxter, 1997). The electric field *E*, a vector quantity, is the gradient of the voltage *V* and is defined as Equation 4.13.

$$E = -\frac{dV}{dn}$$

$$= -grad\ V$$

$$= -\nabla V\ .1\ V/m \qquad (4.13)$$

(Source: Baxter, 1997)

Where:

n = differential element perpendicular to the equipotential surface

In the sketch of parallel-plate fields as illustrated in Figure 4-5, surfaces of constant *V* are equipotential surfaces and lines in the direction of maximum electric field are lines of force (Baxter, 1997). The voltage along any path between two points *a* and *b* can be calculated as:

$$V_{ab} = \int_a^b -E\ .\ dn \quad V \qquad (4.14)$$

(Source: Baxter, 1997)

In the linear region near the centre of the parallel plates as illustrated in Figure 4-5, the electric field is constant and perpendicular to the plate.

4.4 Capacitor Hazards and Safety

Capacitors may retain a charge long after power is removed from a circuit and this charge can cause shocks (sometimes fatal) or damage to connected equipment. For example, even a seemingly innocuous device such as a disposable camera flash unit powered by a 1.5 volt AA battery contains a capacitor which may be charged to over 300 volts. This is easily capable of delivering an extremely painful and possibly lethal shock.

Many capacitors have low Equivalent Series Resistance (ESR), so can deliver large currents into short circuits and this can be dangerous. Therefore, care must be taken to ensure that any large or high-voltage capacitor is properly discharged before servicing the containing equipment. Therefore, for safety purposes, all large capacitors should be discharged before handling. Additionally, for board-level capacitors, this is done by placing a bleeder resistor across the terminals, whose resistance is large enough that the leakage current will not affect the circuit, but small enough to discharge the capacitor shortly after power is removed. High-voltage capacitors should be stored with the terminals shorted, since temporarily discharged capacitors can develop potentially dangerous voltages when the terminals are left open-circuited,

4.4.1 Hazards Associated with High-voltage Capacitors

Most of the time, hazards associated with working with high voltage, high energy circuits, there are a number of dangers that are specific to high voltage capacitors. High voltage capacitors may catastrophically fail when subjected to voltages or currents beyond their rating, or as they reach their normal end of life. Dielectric or metal interconnection failures may create arcing within oil-filled units that vaporises dielectric fluid, resulting in case bulging, rupture, or even an explosion that disperses flammable oil, starts fires and damages nearby equipment. Rigid cased cylindrical glass or plastic cases are more prone to explosive rupture than rectangular cases due to an inability to easily expand under pressure. Capacitors used in RF or sustained high current applications can overheat, especially in the centre of the capacitor rolls. The trapped heat may cause rapid interior heating and destruction, even though the outer case remains relatively cool. Capacitors used within high energy capacitor banks can violently explode when a fault in one capacitor causes sudden dumping of energy stored in the rest of the bank into the failing unit. And, high voltage vacuum capacitors can generate soft X-rays even during normal operation. Proper containment, fusing, and preventative maintenance can help to minimize these hazards.

CHAPTER 5

CAPACITIVE SENSOR BASICS

According to Baxter (1997), a circuit which convert the capacitance of a variable dielectric constant between the sensor plates into an output signal should have these characteristics:

1. Good linearity
2. Shield or guard to isolate the input from stray electric fields
3. Insensitivity to stray capacitance to ground on sensor electrodes
4. Low noise
5. Adequate signal bandwidth
6. Correct choice of carrier frequency and wave shape

This chapter discusses the basic circuit building blocks, while Chapter 7 covers these topics in more detail.

5.1 Linearity

Study done by Baxter (1997) on capacitive sensors is only based on either area variation or spacing variation. By looking again at the formulae for parallel-plate capacitance and calculate the capacitive impedance for the circuit.

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \tag{5.1}$$

$$X_C = \frac{1}{2\pi f C} \tag{5.2}$$

We see that with dielectric constant variation sensors, the capacitance is linear with the dielectric constant but the impedance is not, and Baxter (1997) stated that a correct circuit design will linearise in this type of sensor.

5.2 Measuring Capacitance

5.2.1 Circuit Comparison

The choice of a capacitive sensor circuit (Table 5-1) should consider the required system accuracy, the cost and space available and the noise environment. At one extreme, a few components only can handle capacitance measurement with the DC circuit, but at a cost of considerable noise sensitivity and drift. For applications needing more precision in a high noise environment, the synchronous bridge circuit is unsurpassed.

Table 5-1. Capacitance measurement circuit comparison: 0 is good, 5 is bad.

Circuit	**Function**	**Sensitive to stray capacity**	**Sensitive to noise**	**Needs ADC**	**Bandpass filter available**	**Size**	**Sensitive to shunt resistor**
DC	volt = 1/C	yes	5	no	no	0	5
RC oscillator or 1-shot	freq ≅ 1/RC period = RC	yes	5	no	no	1	5
IC oscillator (current-capacitance)	freq ≅ 1/RC period ≅ RC	yes	3	no	no	2	5
LC oscillator	$\text{freq} \cong \frac{1}{\sqrt{LC}}$	yes	2	no	yes	3	0
Sync., single ended	volt ≅ C1-C2 or C1/C2	no	1	yes	yes	4	1
Sync., bridge	volt ≅ C1-C2 or 1/(C1-C2)	no	0	yes	yes	5	0

Based on Baxter, 1997.

The different capacitance measurement circuits are rated by seven characteristics.

5.2.1.1 Function

For free-running *RC* oscillators, the output frequency in radian/second is proportional to *1/RC*. The output period is the reciprocal *RC* and with a one-shot *RC* oscillator the ON time varies directly as capacitance.

The two synchronous demodulator circuits can have different functions depending on how the input amplifier is connected; for single-ended circuits the output voltage is a function of a reference capacitor *C1* and the sense capacitor *C2* (Baxter, 1997).

For synchronous demodulators using a bridge, the output voltage is proportional to *C1–C2*. In any case, the appropriate function should be chosen to linearise the circuit for dielectric constant variation sensors.

5.2.1.2 Sensitivity to Stray Capacity

Sensor plates may have signal capacitances in the fractional picofarad range and connecting to these plates with 60 pF/m coax would totally obscure the signal. With correct guarding, however, the shield coax and any other stray capacitance can be almost completely nulled out. According to Baxter (1997), this guarding is simply a matter of adding a connection with synchronous demodulators, but it is more difficult to guard the oscillator circuits.

5.2.1.3 Sensitivity to Noise

The oscillator circuit is vulnerable as the frequency is changed whenever the capacitor picks up capacitively coupled crosstalk from nearby circuits. The sensitivity of an RC oscillator to a coupled narrow noise spike is low at the beginning of a timing cycle but high at the end of a cycle. This time variation of sensitivity leads to beats and aliasing where noise at frequencies which are integral multiples of the oscillator frequency is aliased down to a low frequency. This problem can usually be handled with shields, as shield effectiveness is high for electrostatic fields, and thorough power supply decoupling is also needed.

5.2.1.4 Requirement for an Analog-to-Digital Converter

Frequency is easily converted to a digital number by counting pulses for a fixed time interval, so no ADC may be needed in a typical microcomputer application with *RC* oscillator detectors. Also, period is similarly converted to digital by counting fixed clock pulses during the measurement interval.

As for synchronous demodulators, an ADC may be needed to convert the output voltage to digital which can be easily integrated.

5.2.1.5 Bandpass Filter Available

Wideband noise can be substantially reduced for the synchronous demodulators by adding a bandpass filter tuned to the excitation frequency, but no such option is available for the *RC* and IC oscillator solutions. This suggests that these oscillators are not the circuit of choice for very sensitive applications.

5.2.1.6 Circuit Size

The oscillators are much lower in component count than are the synchronous demodulators. This is a considerable advantage for conventional printed circuit board construction. For integrated circuits, however, switched capacitor methods easily integrate a synchronous demodulator in 1 or 2 mm^2 of area.

5.2.1.7 Sensitivity to Shunt Resistor

In an application where the circuit may be exposed to contaminants or excessive humidity, resistive paths on the surface of a printed circuit board can affect circuit operation. A very important characteristic of circuit design is sensitivity to resistive or conductive shunts. Correct guarding can handle these problems as well as cancelling the effect of stray capacitance, but it is not an available option with many oscillator and one-shot capacitance measurement circuits. In this case, *LC* oscillators and synchronous demodulators are insensitive to shunt resistance.

5.2.2 Direct DC Detection

The first entry in Table 5-1, direct DC, is the simplest detector circuit. With a very high impedance amplifier, capacitance changes can be measured as DC voltage differences, simply by charging the capacitor to be measured and connecting it to the amplifier input. According to Baxter (1997), as the charge is close to constant the capacitor voltage will vary as the reciprocal of capacitance by the relationship Q = CV. The time constant *RC* where *R* is the amplifier input resistance and *C* the capacitance being measured must be greater than the time measurement period so as not to introduce a low frequency loss; thus an electrometer-type amplifier with input currents in the femto-ampere region is often needed.

Baxter (1997) recommended that for direct DC circuits using an operational amplifier, an input resistor of very high value is needed, or a bootstrap circuit can be used to increase the AC input resistance, as shown in Figure 5-1.

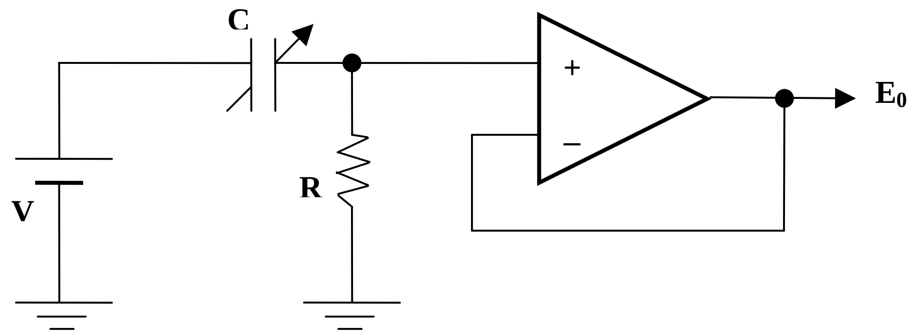

Figure 5-1. DC capacitance circuit.

When C varies at frequencies above *1/RC*, it is shown as Equation 5.3.

$$E_0 = \frac{Q}{C} = \frac{C_{avg}V}{C} \tag{5.3}$$

(Source: Baxter, 1997)

where Q is the charge on the capacitor C and C_{avg} is the capacitance of C with no displacement.

5.2.3 Oscillator

Based on Baxter's (1997) study, the direct DC measurement circuit above cannot handle very slow capacitance variations without a very high input impedance amplifier. With a 10 pF capacitor, measuring mV level signals at 1 Hz requires an amplifier with offset currents in the 0.01 pA range. Also, measurement at DC will admit other unwanted disturbances such as cable noise, thermo-couple voltages, power frequency crosstalk, semiconductor 1/f noise and slow variation of component parameters. Circuits which use a high frequency excitation are preferred; for example, the reactive impedance of the unknown capacitor can be measured by using it as the tuning element in an oscillator. Several different types of oscillator can be chosen with different advantages; with an *RC* oscillator, the frequency is proportional to *1/RC*, but with *LC* oscillators the frequency is proportional to $1/\sqrt{LC}$ and it is more difficult to linearise. A gyrator circuit as shown in Figure 6-2 which converts capacitance to inductance can be used to save an inductor and to change the output frequency to $1/\sqrt{C1C2}$; if *C1* and *C2* are both sense electrodes of equal value the response becomes *1/C*.

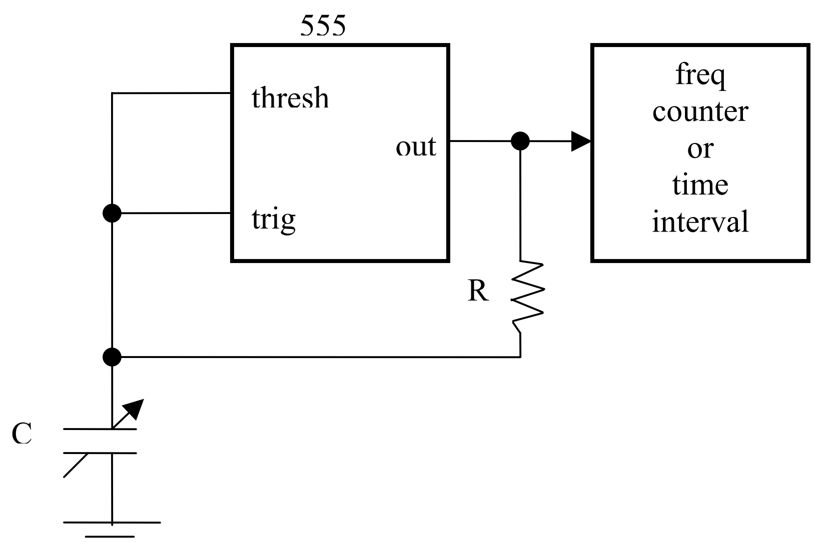

Figure 5-2. RC oscillator circuit.

Figure 5-2 is a little different from the usual 555 oscillator, but it saves parts, uses a grounded capacitor, produces a 50% duty cycle, and is more linear providing a CMOS-type integrated circuit like the 7555 is used. The normal 555 output does not swing to the power rails and is unstable with temperature in this circuit. The circuit operation is the classic Schmitt-trigger-with-RC-feedback, with the Schmitt trigger points accurately determined by the 555 as 1/3 and 2/3 of the power supply. As the output voltage with the CMOS part is accurately driven to the power rails provided that *R* is sufficiently large, the output frequency is unaffected by supply variation. Adding an analog switch allows the measurement capacitor to be switched between several measurement capacitances and a reference capacitor to compensate for changes in resistance and to establish a capacitance-ratio output for greater accuracy.

The output is converted to a digital value using either a frequency counter or a time interval counter with an accurate, usually crystal-controlled, timebase. In this case, a time interval measurement is correct for dielectric constant variation sensors.

5.2.3.1 Guarding the RC Oscillator

The unguarded *RC* oscillator may have problems with stray capacitance and leakage resistance at the sense capacitor node. The addition of a FET-input op amp as shown in Figure 5-3 produces a low-impedance guard voltage. Adding a guard to the amplifier's terminal will further reduce stray capacitance to a fraction of a picofarad.

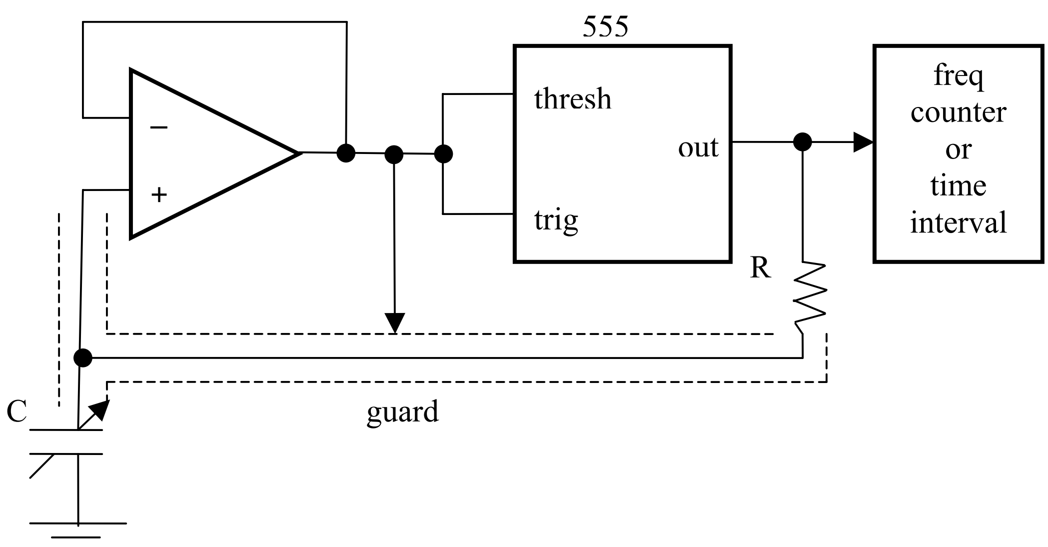

Figure 5-3. Guarded RC oscillator.

5.2.3.2 Bridge Circuit with RC Oscillator

The advantages of the bridge circuit include a more stable ratio-metric response if a matched pair of sense capacitances is used. The *RC* oscillator does not directly accept bridge inputs, but an *RC* oscillator can be configured for a ratio-metric response as shown in Figure 5-4.

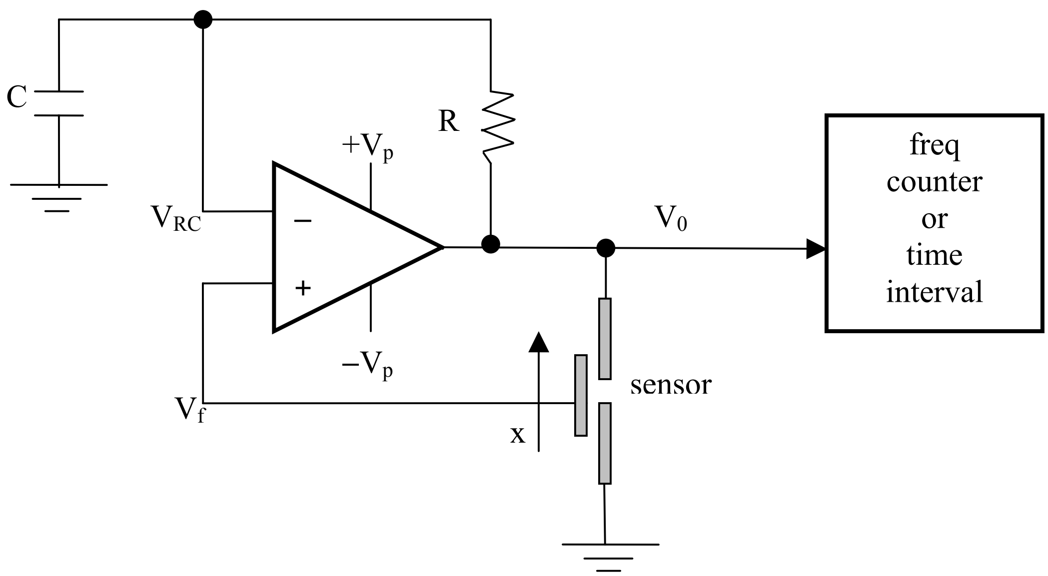

Figure 5-4. Bridge circuit with RC oscillator.

This circuit shows an *RC* oscillator with the usual output function reversed: frequency is proportional to *RC* instead of *1/RC*. The op amp output V_0 is multiplied by a constant *x* which varies linearly between 0 and 1 depending on the sensor plate position, and fed to the positive feedback input, so that $V_f = xV_0$. With the positive feedback, the op amp output will be either switched to the positive rail $+V_p$ or the negative rail $-V_p$. The op amp should be a rail-to-rail output type for good accuracy, and a large value resistor or a switch used on the positive op amp input to set the DC level at that point. The op amp negative input, then, oscillates from $+xV_p$ to $-xV_p$ with a time constant of *RC*, and the oscillation period *T* is shown in Equation 5.4.

$$T = 2RC \, . \, In\left(\frac{1+x}{1-x}\right) \qquad (5.4)$$

(Source: Baxter, 1997)

The circuit is reasonably linear for x <<1, and can be further linearised by replacing the resistor with a current source of I amperes; the equation then becomes linear with x and shown in Equation 5.5.

$$T = 2x \, . \, \frac{C V_p}{I} \qquad (5.5)$$

(Source: Baxter, 1997)

5.2.4 Synchronous Demodulator

The most flexible and accurate method of measuring capacitance is to first apply a high frequency signal in the 10 kHz – 1 MHz range through a known impedance to the capacitor under test, then amplify the signal and apply it to a synchronous demodulator. Several variations of the amplifier are available which can appropriately measure either capacitance, *C*, or impedance, proportional to *1/C*, to produce a linear output, and various input circuit configurations such as bridge or single-ended can be used. With high frequency excitation, electrometer-type very high input impedance amplifiers are not needed, as the capacitive impedance is much lower. Shielding and guarding are easier with a synchronous demodulator than with an oscillator circuit, and a bandpass filter is easily added to limit the noise bandwidth it needed.

The circuit in Figure 5-5 shows a full-wave demodulator, with both positive and negative half-cycles of signal contributing to the output DC level. It can linearise either capacitance- or impedance- variation sensors depending on the configuration of the amplifier.

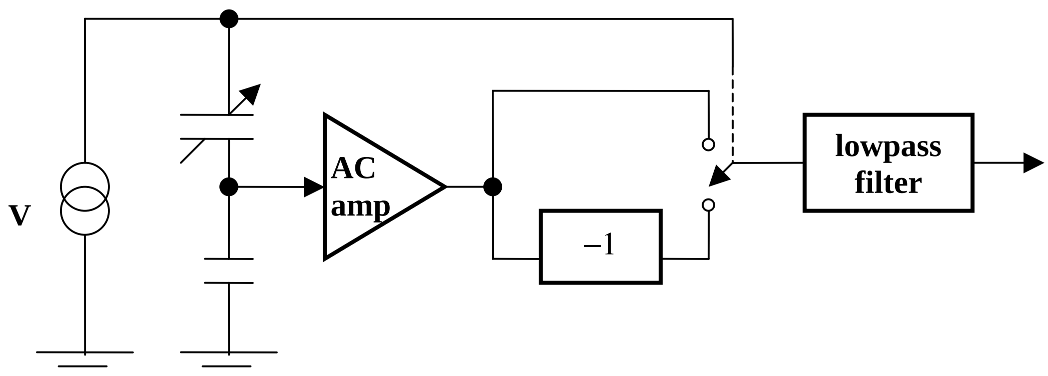

Figure 5-5. Synchronous demodulator circuit.

5.3 Amplifier

With the preferred synchronous demodulator, the amplifier circuit is chosen to produce a linear output for the given sensor configuration, to allow proper guarding and shielding, and to reduce the effect of stray capacitance. The different amplifier options for capacitive sensors are compared and shown in Table 5-2.

Table 5-2. Amplifier comparison.

	High-Z (Figure 5-6)	Low-Z (Figure 5-7)	Feedback (Figure 5-8)
Linearity	Good	Poor, 2% in centre 20 % of range	Good
Shield connect to:	Guard voltage	Ground	Ground
Noise	~ same	~ same	~ same
Parts count	middle	least	most

Based on Baxter, 1997.

The high-Z amplifier fixes most of the problems with the low-Z amplifier, but it adds the inconvenience of needing a shield which is not at ground potential, and the gage factor (the gain, or output voltage/input displacement) is affected by the stray input capacitance which often cannot made zero.

The feedback amplifier uses a grounded shield and the gage factor is sensitive only to amplifier input-to-output capacitance and a resistor ratio. Although a single operational amplifier will usually have an unusable high input-to-output capacitance for small sensors, a two-stage amplifier can be easily designed with negligible input-output capacitance. If the summing circuits are implemented with precision resistors, gage factor is accurate. This circuit is preferred for high precision uses.

5.3.1 High-Z Amplifier

The high input impedance amplifier uses a 1× non-inverting amplifier configuration as shown in Figure 5-6.

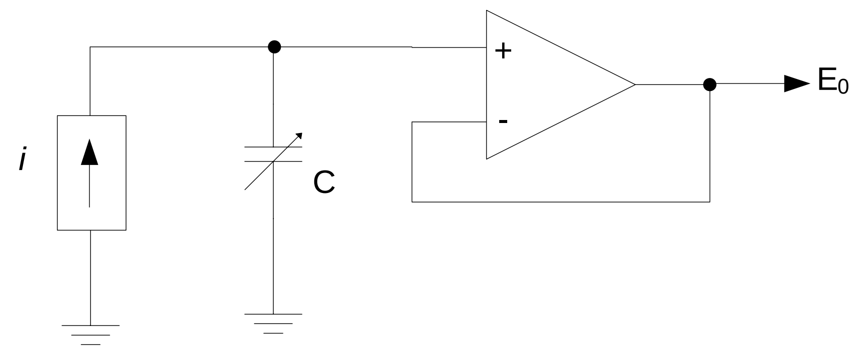

Figure 5-6. High-Z circuit.

With an AC current source, this circuit produces an output proportional to the impedance of sensor *C*, so it produce a linear output that is inversely proportional with dielectric constant variation sensors. The input is usually guarded by a shield connected to the output, without this guard, a stray capacitance of only a few picofarads will seriously attenuate the signal. This stray capacitance is almost completely nulled by a good guard.

5.3.2 Low-Z Amplifier

The low input impedance, or virtual ground amplifier (Figure 5-7), will have an input impedance inversely proportional to the gain of the amplifier times the feedback impedance. This connection has similar noise characteristics, better performance with low voltage rails because of its better common mode range, and it can be guarded by use of a grounded shield instead if a floating shield. The output is proportional to $C1/C2$ or Z_{C2}/Z_{C1} so it can be used to linearise the dielectric constant by using the sensor as *C1*.

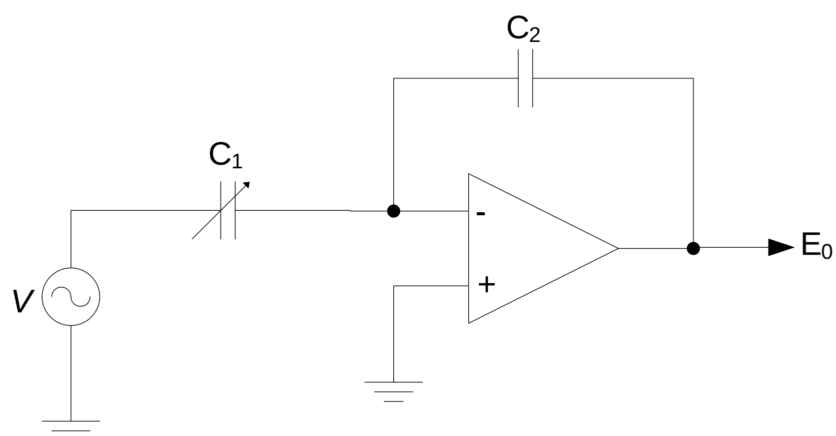

Figure 5-7. Low-Z circuit.

5.3.3 Feedback Amplifier

The feedback circuit of Figure 5-8 use summing circuits to avoid floating generators.

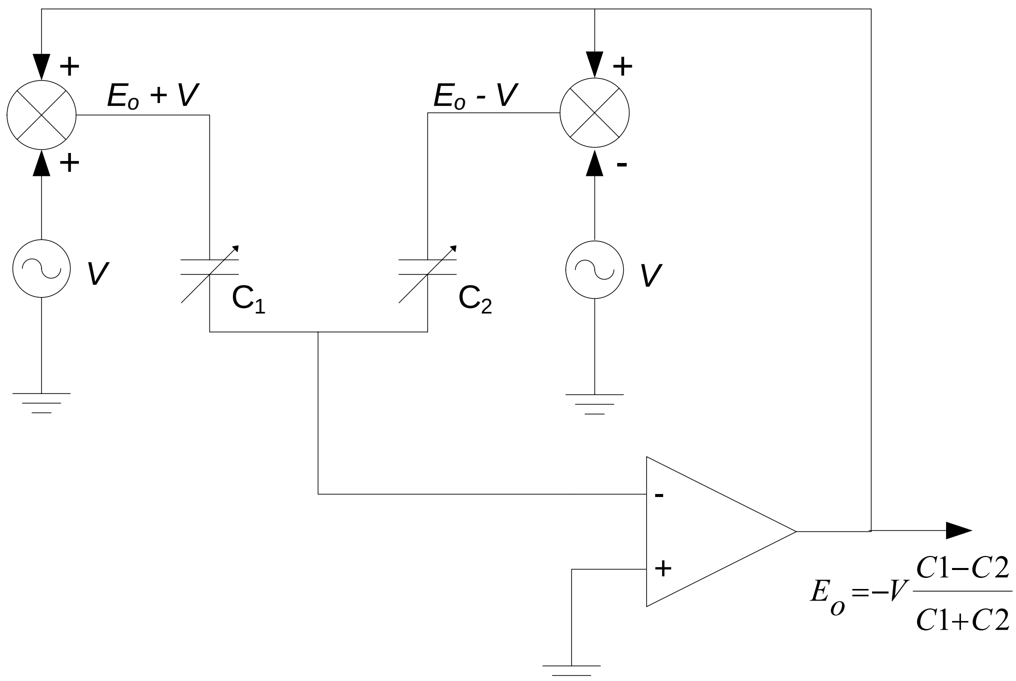

Figure 5-8. Feedback circuit

This circuit has an output proportional to *C1–C2* so it has a linear output with dielectric constant variation sensors. The input is guarded by ground. This amplifier is particularly good at eliminating the effects of stray capacitance.

According to Baxter (1997), the feedback circuit has two important advantages over other circuits:

1. Insensitivity to stray capacitance
2. Guard potential to ground

In addition, inverting amplifiers are more stable than followers, and amplifier input common mode range, which can be troublesome with followers, is less of a concern. Feedback amplifiers with synchronous demodulators have the best performance and are recommended for high precision applications (Baxter, 1997).

5.3.4 DC Restoration

The circuit of Figure 5-6 to Figure 5-8 will not work for very long, as the amplifier input bias current will cause the output to drift to a power supply rail. This problem can be handled with high-value impedance across the amplifier input, or across the feedback capacitor for inverting amplifiers, which bleeds off the charge. Some options recommended by Baxter (1997) are:

1. Very high value resistor, 100M or more
2. 1M resistor in T configuration
3. High impedance FET, or two back-to-back FETs (appropriately high impedance FETs are available only on integrated circuits, not as discrete devices)

4. FET switch, momentarily closed at a time when the measurement will not be affected

5.4 Capacitance Bridge Circuits

This type of bridge (Figure 5-9) relies on a balanced drive rather than on good common-mode rejection of the amplifier, and it is generally the preferred circuit. A centre-tapped transformer, an inverting amplifier, or a CMOS logic inverter can be used to supply the balanced drive.

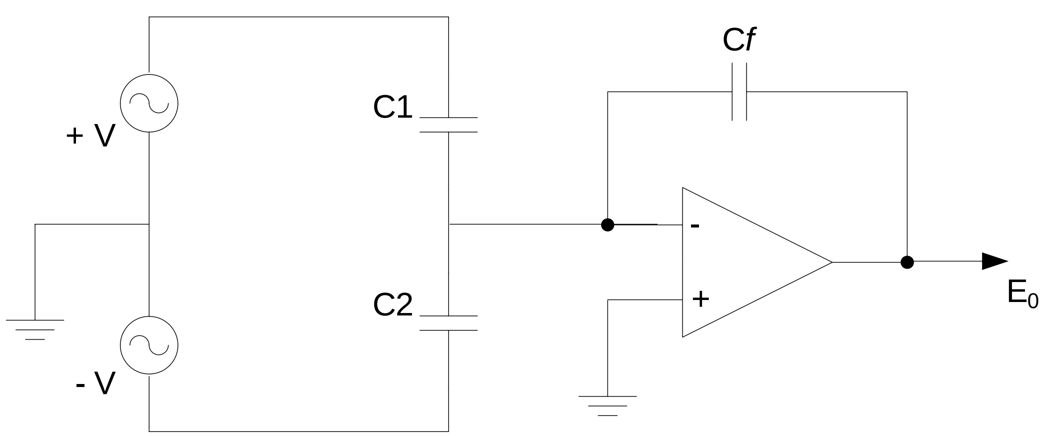

Figure 5-9. Capacitance bridge.

$$V_{out} = -V.\frac{C1 - C2}{Cf} \qquad (5.6)$$

(Source: Baxter, 1997)

The amplifier gain should be high for this equation to be accurate. Any stray capacitance to ground at the amplifier input does not affect the output voltage, but does cut down amplifier available gain at high frequencies, so it should be minimised. *C1* and *C2* should be of identical construction for the bridge balance to be stable. The gage factor, or the output voltage divided by input displacement, is a function of *Cf/C1* || *C2*, but the null accuracy is a function only of *C1/C2*. The ratio *C1/C2* can be made stable if the capacitors have identical construction.

5.5 Excitation

5.5.1 Sine Wave

Sine wave excitation is useful for systems needing high frequency (above 1 MHz) carriers, for example, systems which must measure very low capacitance. Since waves are also preferred for circuits which need high accuracy. Compared to square wave excitation, amplifier slew rate problems are lessened by a factor of 10 and lower frequency amplifiers can be used. Sine wave excitation is essential for high gain bridge circuits, as a good null is more easily achieved without the presence of harmonic energy. But accurate sine wave generation is difficult, and sine wave demodulation uses analog multipliers and other more expensive and less accurate parts compared to square wave circuits.

5.5.2 Square Wave

Square wave drives are available virtually free in any system using CMOS logic gates, as the CMOS rail-to-rail output voltage can be quite accurate. Square wave demodulation is generally done with CMOS switches and op amps, and it is easy to integrate for single-chip systems. It is also better suited to low gain systems, such as motion detectors with wide linear operation. For circuit using square wave modulation the designer must be careful to avoid the unstable and nonlinear effects which are produced when an amplifier runs into slew rate limiting, and amplifier bandwidth must be a factor of ten higher than for since wave circuits to retain good wave shape.

For both sine square wave amplifiers, some attention needs to be paid to the amplifier phase shift characteristics. Uncompensated phase shift will typically reduce the demodulator gain.

5.6 Bandpass Filter

A further improvement in rejecting noise can be made by inserting a bandpass filter before the amplifier. The amplifier, especially if is has high gain, can generate excessive spurious frequencies with out-of-band noise or slew rate limiting, or in extreme cases it can saturate. These effects are eased with a bandpass filter, centred on the carrier and sized as narrow as possible without affecting the signal bandwidth, preceding the amplifier. If a sharp cut-off bandpass filter is not used, single-pole highpass and lowpass filter will help.

CHAPTER 6

CAPACITIVE SENSOR DESIGN

Various capacitive sensors have been developed with varying degrees of accuracy during the last two decades for continuous monitoring of moisture status (Borhan and Parsons, 2004). Of all moisture sensors technologies in the market, those that measure moisture based on the dielectric constant, such as the ones based on Time Domain Reflectometry (TDR) and on capacitive sensors are most attractive for they can be automated and safely be left on the field without causing any environmental hazards (Silva et al., 2005).

Capacitive sensors are some of the commonly used electromagnetic type devices that relate dielectric constant of a biofilter media and its water content with reasonable accuracy (Fares and Alva, 2000; Paltineanu and Starr, 1997; Morgan et al., 1999). Capacitive sensors are particularly suitable for moisture monitoring because they provide output that can be registered by most data loggers. Furthermore, the electrodes (probes) can be inserted into the target profile at any depth without causing any disturbance to the material structure, and its high response time to a change in moisture makes it possible to obtain a precise monitoring of water content in the materials used (Silva et al., 2005).

Capacitance-based moisture measurement method uses the media as part of a capacitor in which the permanent dipoles of water in the dielectric medium are aligned by an electric field and become polarised (Paltineanu and Starr, 1997). Capacitive sensors are also useful for measuring biofilter media properties. Biofilter media have different values of dielectric constant as well as dielectric loss, and the values of both properties (particularly dielectric loss, or "loss tangent") change with temperature and frequency to give a material a characteristic signature which can be measured (Baxter, 1997). Measurement of the capacitance also yields the dielectric constant which can then be used to estimate the water content. These sensors or probes typically operate in the radio-frequency system from ten MHz up to several hundred MHz.

In this chapter, capacitive sensors are designed to detect changes in the dielectric constant of biofilter media. In general, the dielectric constant of pure water is about 80, and any dried media compounds vary from 3 to 9 and air is unity. This very high dielectric constant of water compared to the media explains the dominant effect of moisture on the dielectric property of a media (Sanchez et al., 2004). In this way, the water content of the media is directly related to its dielectric constant. Therefore, biofilter media moisture can be assessed by its effect in the variation of the dielectric constant of the complex, which can be estimated using two parallel electrodes or metal plates inserted into it (Zazueta and Xin, 1994).

6.1 Capacitance Plates Design

There are many different configurations of capacitance plates that are mentioned in Appendix E, and due to the large area of biofilter media, parallel plates design is adopted. The design requirements were for a probe that would be strong enough to withstand repeated insertions and extractions from the media in a biofilter measurement program and yet be sensitive enough to determine the moisture level of the media to within 5% by volume. In addition, the readout electronics need to design and measure the capacitance of the capacitance plates directly so that media moisture measurements could be made using battery-operated equipment.

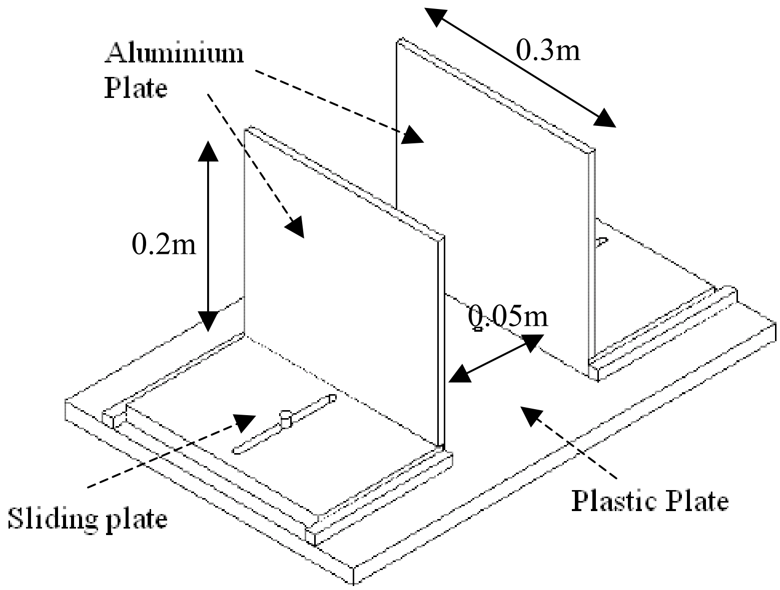

Figure 6-1. Parallel-plate setup. (Abdel et al., 2002. p4.)

The capacitance metal plate as described here is based on ideal theoretical approach without practical implementation and testing. The sensor itself is made up of two aluminium plates mounted onto a plastic plate. The gap between the two aluminium plates can be adjusted with the sliding plate (Figure 6-1), so as to allow flexibility in adjusting the capacitance values.

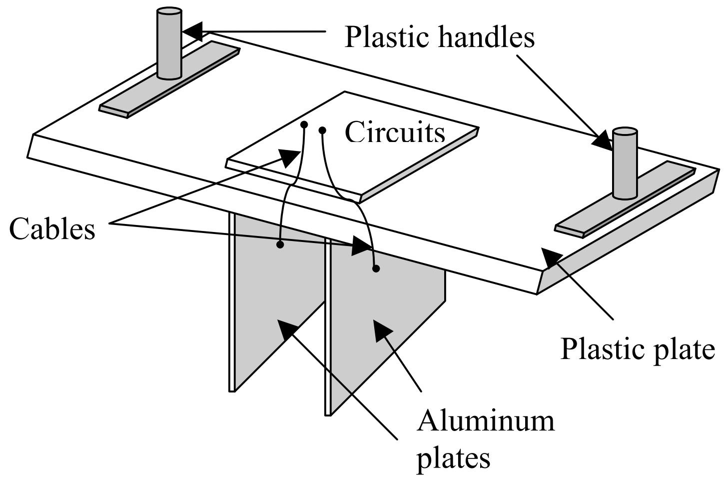

Figure 6-2. Parallel-plate configuration.

The circuit board is built at the back of the plastic plate as shown in Figure 6-2, with coaxial cables connected between the aluminium plates and the circuit. In addition, there are two handles attached at the plastic plate so that it will be easier to insert and extract from the media during and after moisture measurement and is illustrated in Figure 6-3.

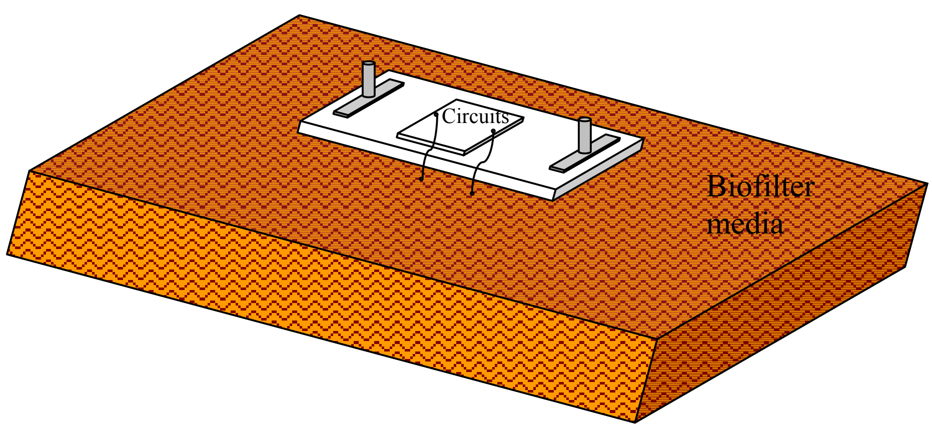

Figure 6-3. Capacitive sensor in a biofilter media.

6.2 Circuit Design

The accurate measurement of the dielectric parameters of a biofilter media, such as the dielectric constant and loss angle at low excitation voltage, is important in many aspects of instrumentation, such as low-voltage capacitor design. The dielectric constant and loss angle of a material may be measured from an accurate measurement of the capacitance of a capacitor of a particular shape, using the biofilter media as the dielectric. This change of capacitance is generally very small and may sometimes be comparable to the stray capacitance. Therefore, in all these applications, measurement of the capacitance of a capacitor is required to be made with high accuracy. There are different bridge techniques for measuring the capacitance, but the Schering bridge technique may, perhaps, be considered to be one of the most sensitive techniques for this measurement. One disadvantage of this technique may be the requirement for several repetitions of bridge balance for each observation.

6.2.1 Schering Bridges

The Schering bridge (Figure 6.4) is used for measuring capacitor and dielectric parameters of the biofilter media.

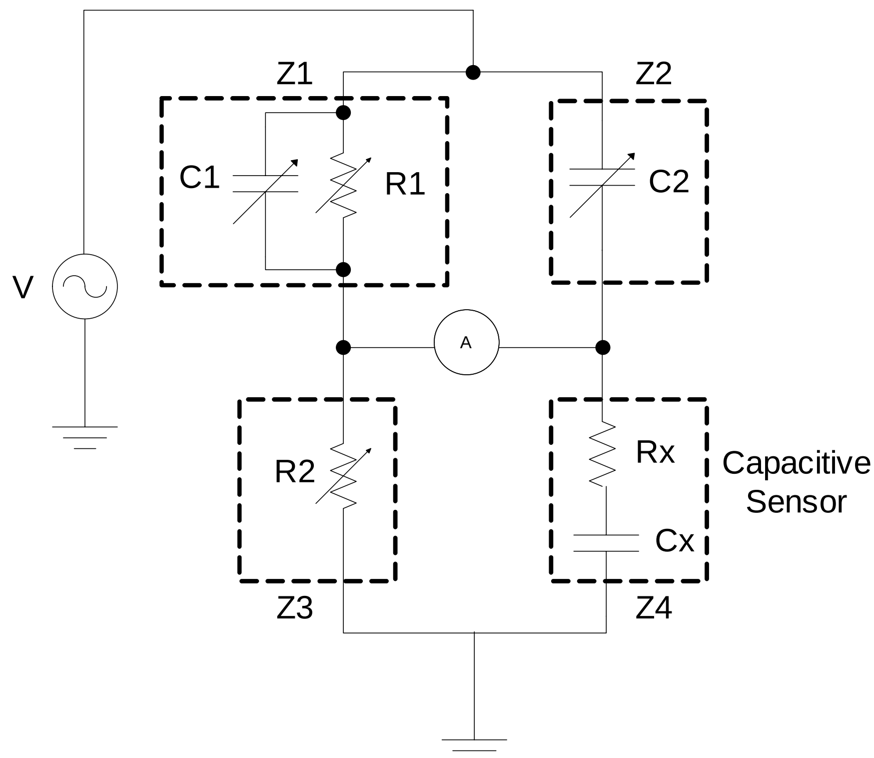

Figure 6-4. Schering bridge.

If the bridge is balanced:

Z1 Z4 = Z2 Z3

In this case,

$$\left(\frac{R1}{1+j\omega C1R1}\right)\left(Rx+\frac{1}{j\omega Cx}\right)=\frac{R2}{j\omega C2}$$

After multiplication:

The equation will be satisfied if both real and imaginary parts are equal.

(6.1)

and

(6.2)

In the Schering bridge circuit, only *Cx* and *Rx* are unknown and the best solution is to change *R1* and *C1* for fine-tuning, and *R2* and *C2* to set the measurement range. Most importantly, the balance condition of the bridges is independent of the frequency. With the ac signal applied to the bridge, *R1* and *C1* are varied until a zero reading is seen on the meter and zero deflection indicates that the bridge is balanced. In actual practice, the variables are adjusted for a minimum reading since the phase difference between the two legs will not allow a zero reading. Simply by input the values of the variables using Equation 6.1 and 6.2, the capacitance and resistance values for the aluminium plates within the biofilter media can be determined. Using the measured capacitance values, the dielectric constant of the biofilter media can be calculated and therefore the moisture level of the media can be predicted.

6.3 Media Moisture Measurements

The method for converting a capacitance measurement to a dielectric constant is summarised below:

1. Determine the capacitance of the plates in air (Equation 6.3)
2. Take the media measurement and calculate the capacitance (Equation 6.4)
3. Divide the media capacitance by the air capacitance; the resultant quotient is the dielectric constant of the media (Equation 6.5)

(6.3)

And,

(6.4)

So that,

Since ($\varepsilon_{air} \approx 1$),

(6.5)

Thus, the air capacitance for the plates needs to be determined so as to establish an accurate reading for the dielectric constant of the media.

6.3.1 Correlations of Dielectric Constant with Moisture Level

The most commonly used empirical equation to relate volumetric water content θ to the dielectric constant ε is proven by Topp et al. (1980) and expressed as:

(6.6)

Based on Topp et al. (1980) studies, Equation 6.6 is adopted as a method to determine the dielectric constant of the biofilter media (composition of both pine wood and compost) at different volumetric water content.

Table 6-1. Moisture level content vs. dielectric constant.

Moisture level content, θ	**Dielectric Constant, ε**	**Moisture level content, θ**	**Dielectric Constant, ε**
0%	3.03	55%	39.55
5%	3.85	60%	44.60
10%	5.34	65%	49.70
15%	7.45	70%	54.77
20%	10.12	75%	59.77
25%	13.28	80%	64.64
30%	16.89	85%	69.32
35%	20.88	90%	73.75
40%	25.20	95%	77.87
45%	29.79	100%	81.63
50%	34.59		

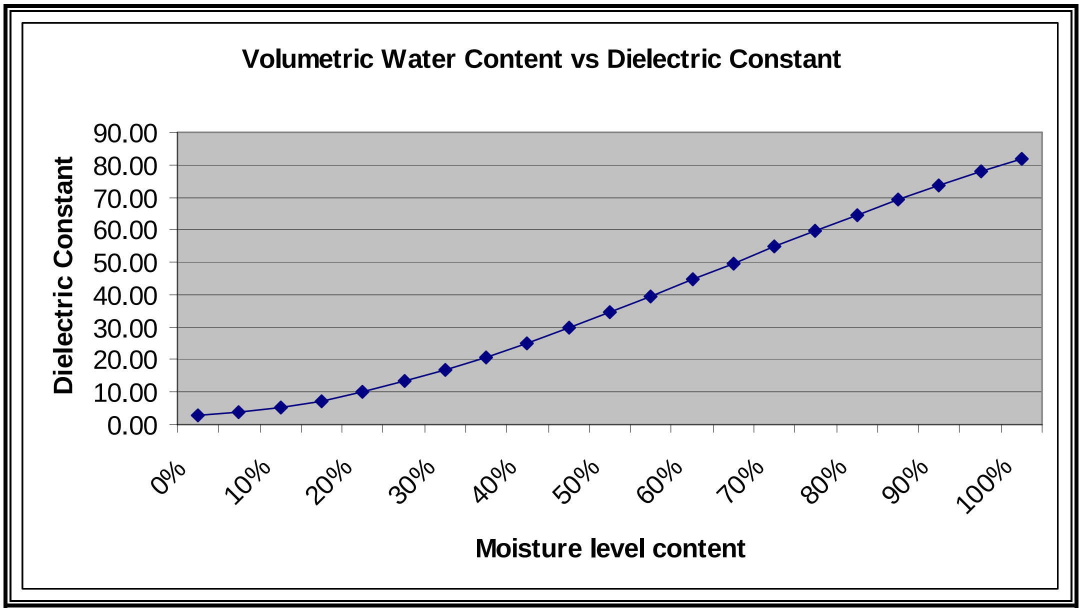

Figure 6-5. Volumetric water content vs. dielectric constant.

Using Equation 6.6 and substitute the volumetric water content, the dielectric constant can be derived at different moisture level content (Table 6-1 and Figure 6-5).

Using this as a starting point, a systematic way to control the moisture level content of a biofilter media is possible. When the dielectric constant drops below 30, the moisture level content is around 45% which is undesirable and water need to be added. Also, if the dielectric constant is above 60, the moisture level content will be more than 75% which also reduce the effectiveness of the biofilter. Using this concept, we can maintain the dielectric constant of the biofilter media between 30 and 60 so that the moisture level of the biofilter is maintained at 45% to 75%.

6.3.2 Correlations of Capacitance Values with Moisture Level

Using the information in Table 6-1 on dielectric constant, the values of capacitance and capacitive impedance can be calculated using Equation 6.7 and Equation 6.8, and tabulated as shown in Table 6-2.

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} = 8.854 \times 10^{-12} \times \frac{\varepsilon_r A}{d} \qquad (6.7)$$

Where:

A = 0.06 m^2, area of each aluminium plate, measured in square metres (m^2).

d = 0.05m, separation between the plates, measured in metres (m).

$$X_C = \frac{1}{2\pi f C} \qquad (6.8)$$

Where:

f = 10 MHz, oscillator frequency.

Table 6-2. Moisture level content vs. capacitance and capacitive reactance.

Moisture level content	Capacitance value, C	Capacitive reactance, X_c	Moisture level content	Capacitance value, C	Capacitive reactance, X_c
0%	32.19 pF	494.4 Ω	55%	420.2 pF	37.9 Ω
5%	40.91 pF	389.1 Ω	60%	473.9 pF	33.6 Ω
10%	56.74 pF	280.5 Ω	65%	528.1 pF	30.1 Ω
15%	79.15 pF	201.1 Ω	70%	581.9 pF	27.3 Ω
20%	107.5 pF	148.0 Ω	75%	635.0 pF	25.1 Ω
25%	141.1 pF	112.8 Ω	80%	686.8 pF	23.2 Ω
30%	179.5 pF	88.7 Ω	85%	736.5 pF	21.6 Ω
35%	221.8 pF	71.7 Ω	90%	783.6 pF	20.3 Ω
40%	267.7 pF	59.4 Ω	95%	827.4 pF	19.2 Ω
45%	316.5 pF	50.3 Ω	100%	867.3 pF	18.4 Ω
50%	367.5 pF	43.3 Ω			

From the illustration of Figure 6-6, the capacitance values increases (linearly) when the moisture level increases whereas the capacitive reactance decreases.

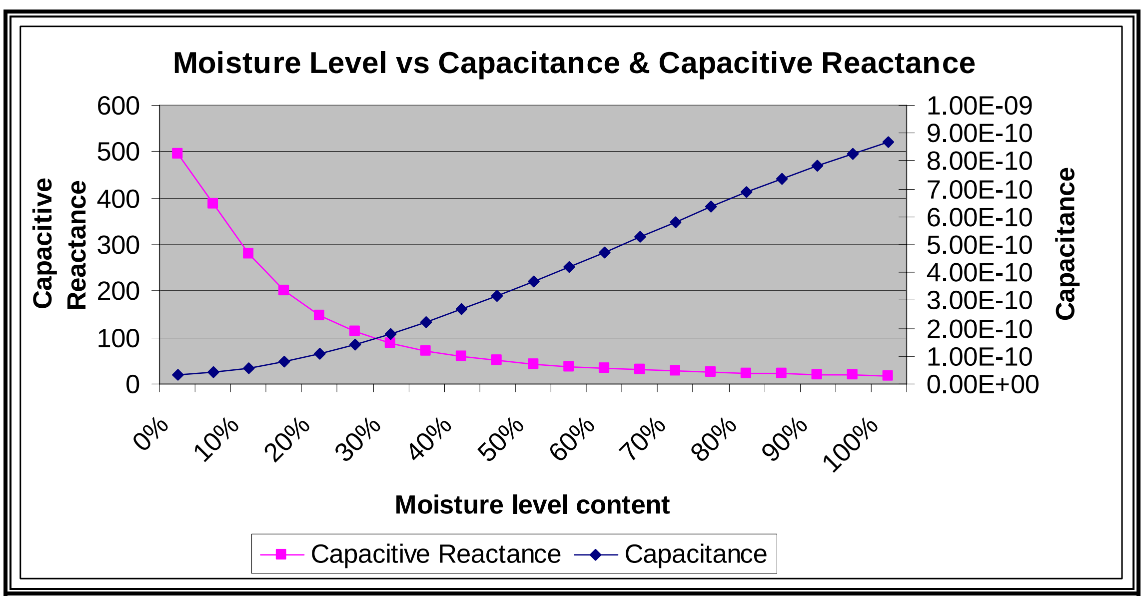

Figure 6-6. Moisture level content vs. capacitance and capacitive reactance.

6.4 Evaluation of Capacitive Sensor Design

Considerable research on capacitor dielectrics was done at the Laboratory for Insulation Research at MIT in the 1950s and 1960s, and it is reported in a number of publications. In 1954, von Hippel discusses macroscopic and molecular properties of dielectric parameters for many materials. This laboratory also has published research into the dielectric properties of biological materials, materials at high temperature and measurement techniques.

The IEEE Transactions on Dielectrics and Electrical Insulation reports on recent development in dielectric research.

6.4.1 Classical Dielectric Models

A lossy capacitor is classically modelled as a lossless capacitor with either a series or shunt resistor representing the loss term (Figure 6-7).

The series parasitic inductance L and the series resistance R_s can usually be ignored for our low current application, or R_s can be converted to R_p for a particular frequency using Equation 6.9

(6.9)

(Source: Baxter, 1997)

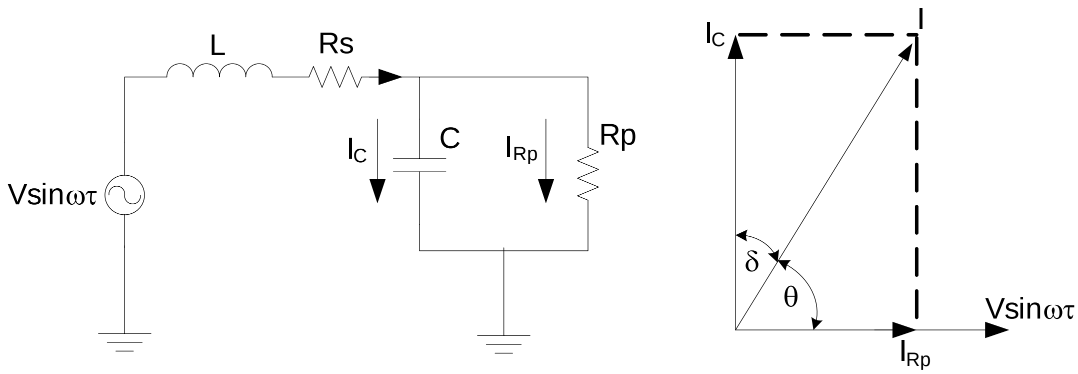

Figure 6-7. Lossy capacitor. (Baxter, 1997. p148.)

The phasor diagram above (with *Rs* and *L* ignored) shows the relationship of the applied AC voltage to the in-phase current through the resistance and the 90° current through the capacitor. The capacitor dissipation factor *D*, also called loss tangent, tan δ, is the ratio of capacitive reactance X_C to resistance defined as

(6.10)

(Source: Baxter, 1997)

As frequency increases, I_C increases while I_{Rp} remains constant, so *D* decreases with increasing frequency if *Rp* is constant.

A similar dimensionless figure of merit is the power factor, defined as Equation 6.11.

(6.11)

(Source: Baxter, 1997)

For $Q > 10$, *PF* is close to *D*.

The value of the equivalent lossless capacitor *C* is usually relatively independent of frequency over a wide range, but the behaviour of the loss component *Rp* is not as simple. Various mechanisms contribute to loss, including actual conductivity due to migrating charge carriers and friction associated with the reorientation of polar molecules (Baxter, 1997). According to Baxter (1997), most commonly used dielectrics have a loss tangent which is relatively independent of frequency, implying that *Rp* decreases directly with an increase in ω. According to von Hippel (1954), the loss tangent remains relatively and remarkably constant through 16 frequency decades, 10^{-4} Hz to 10^{12} Hz, for common capacitor dielectrics.

6.4.2 Loss Tangent

In contrast with the stable loss tangent of capacitor dielectric materials, the loss tangent of water is especially active, which is also responsible for the large change in loss tangent of biofilter media where moisture level fluctuated. The relative dielectric constant of water is very high at about 80 and shows large changes with temperature. In Figure 6-8, water is shown with an expanded frequency range (note the nonlinear x axis). Measurement of water below 100 kHz is difficult because the angle of the loss tangent is nearly 90°. At 100 kHz, the loss tangent of 4 means that the impedance has an angle of 76°; the resistive component has much lower impedance than the reactive component.

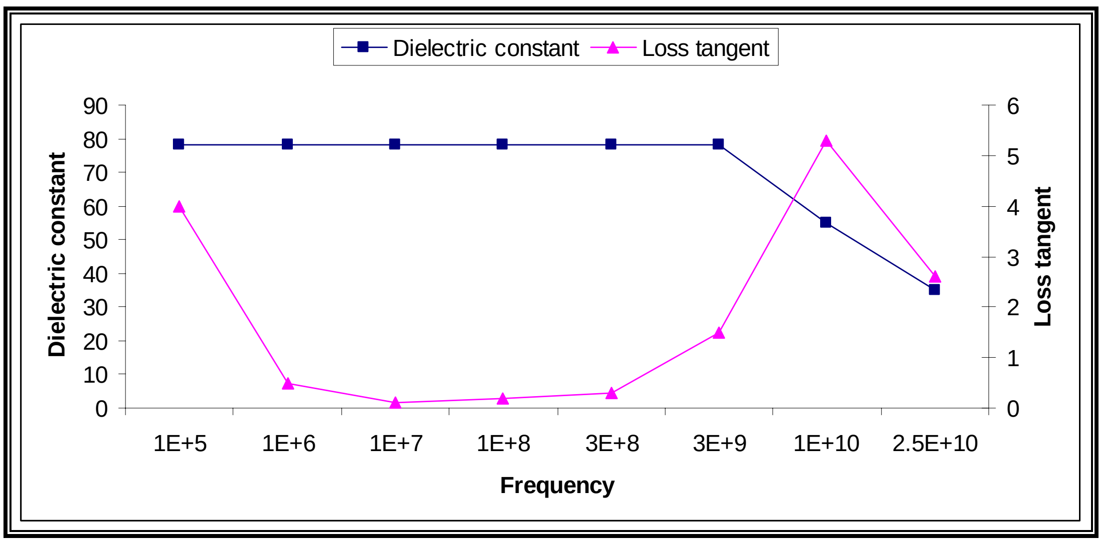

Figure 6-8. Dielectric constant and loss tangent of water vs. frequency at 25°C. (von Hippel, 1954).

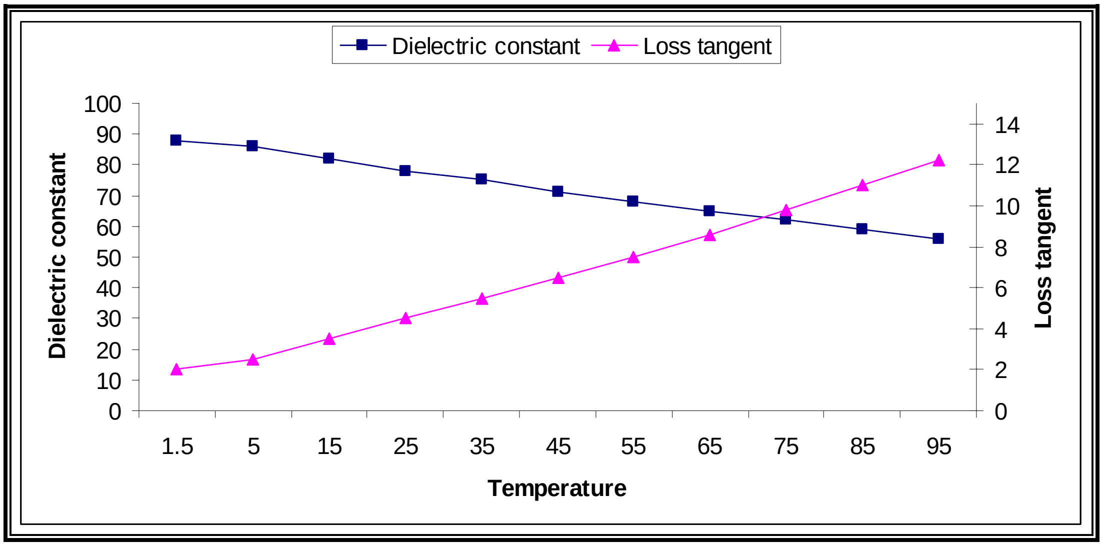

Figure 6-9. Dielectric constant and loss tangent of water vs. temperature at 1 MHz. (von Hippel, 1954).

Generally, the loss tangent is a more sensitive indicator than dielectric constant. Studies done by von Hippel (1954) on polar molecules such as water often produce a temperature sensitive peak in loss tangent, caused by a molecular resonance effect. As temperature is increased, the peak frequency will increase. The change of loss tangent may also be accompanied by a change in dielectric constant.

6.4.3 Dielectric Constant varies with Water Temperature

Study based on Ronald et al. (1998) has shown that increase in water temperature will result in decreasing dielectric constant. The temperatures in Australia range from 5°C to 35°C, and based on Table 6-3, the dielectric constant of water will fluctuate from 86.40 to 75.00. Taking this into consideration, we need to predict the variation of dielectric constant for the different temperature in a biofilter media.

Table 6-3. Dielectric constant of water.

T (°C)	K	T (°C)	K
0	88.00	40	73.28
5	86.40	45	71.59
10	84.11	50	69.94
15	82.22	60	66.74
20	80.36	70	63.68
25	78.54	80	60.78
30	76.75	90	57.98
35	75.00	100	55.33

Based on Ronald et al., 1998

Table 6-4. Volumetric water content vs. dielectric constant (temperature from 5°C to 35°C).

Moisture level content	0%	5%	10%	15%	20%	25%	30%	35%	40%	45%
Dielectric Constant(5°C)	3.03	3.85	5.35	7.47	10.15	13.36	17.02	21.09	25.51	30.23
Dielectric Constant(10°C)	3.03	3.85	5.35	7.46	10.14	13.32	16.96	20.99	25.36	30.02
Dielectric Constant(15°C)	3.03	3.85	5.34	7.45	10.12	13.29	16.91	20.91	25.24	29.84
Dielectric Constant(20°C)	3.03	3.85	5.34	7.45	10.11	13.26	16.85	20.83	25.12	29.67
Dielectric Constant(25°C)	3.03	3.85	5.34	7.44	10.09	13.23	16.81	20.75	25.00	29.51
Dielectric Constant(30°C)	3.03	3.85	5.34	7.43	10.08	13.21	16.76	20.67	24.89	29.35
Dielectric Constant(35°C)	3.03	3.85	5.34	7.43	10.06	13.18	16.71	20.60	24.78	29.19
Standard Deviation	0.00	0.00	0.00	0.01	0.03	0.06	0.11	0.17	0.26	0.37

Moisture level content	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%	100%
Dielectric Constant(5°C)	35.19	40.34	45.63	51.01	56.41	61.78	67.08	72.25	77.22	81.96	86.40
Dielectric Constant(10°C)	34.90	39.96	45.14	50.38	55.62	60.82	65.91	70.84	75.55	80.00	84.11
Dielectric Constant(15°C)	34.67	39.65	44.73	49.86	54.97	60.02	64.94	69.68	74.18	78.38	82.22
Dielectric Constant(20°C)	34.43	39.34	44.33	49.35	54.34	59.24	63.99	68.54	72.82	76.78	80.36
Dielectric Constant(25°C)	34.21	39.03	43.94	48.85	53.71	58.47	63.06	67.42	71.49	75.22	78.54
Dielectric Constant(30°C)	33.98	38.74	43.55	48.36	53.10	57.71	62.14	66.32	70.19	73.69	76.75
Dielectric Constant(35°C)	33.76	38.45	43.17	47.88	52.50	56.98	61.25	65.24	68.91	72.18	75.00
Standard Deviation	0.51	0.68	0.88	1.12	1.39	1.71	2.08	2.49	2.96	3.48	4.06

Table 6-4 is tabulated based on Equation 6-6, where different temperature of the water component is taken into consideration. From the results of Table 6-4, it can be deduce that when moisture level content is 45% the standard deviation of dielectric constant is 0.37. This will only result in a difference of 0.4% in the moisture level content that is due to temperature variation and is rather insignificant.

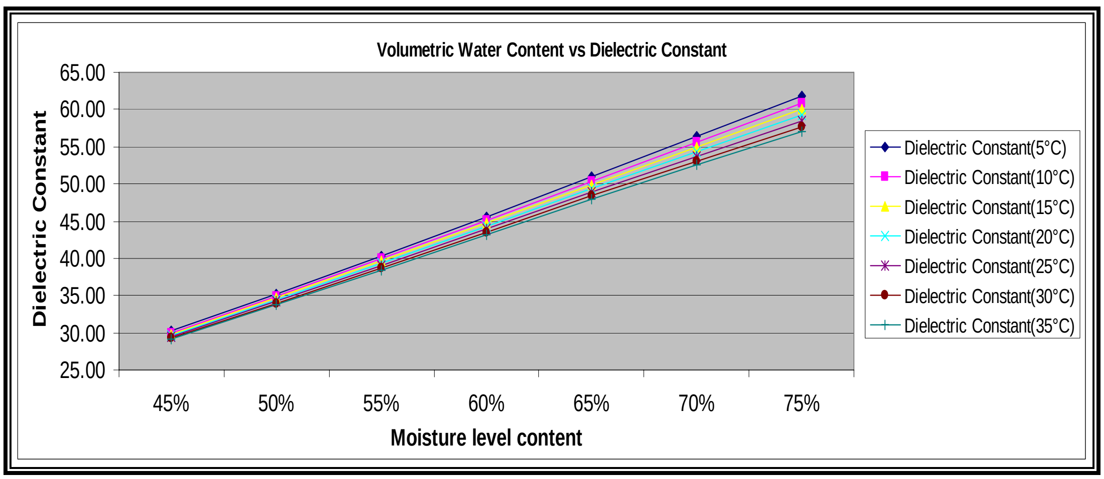

Figure 6-10. Volumetric water content vs. dielectric constant (temperature from 5°C to 35°C)

When moisture level content is 75%, the standard deviation of the dielectric constant is around 1.71. This will translate to about 1.8% difference in moisture level content. Therefore, the variation of dielectric constant due to temperature difference will not contribute to any adverse impact in determining the moisture level of the biofilter media.

CHAPTER 7

EVALUATE THE PERFORMANCE OF CAPACITIVE SENSING SYSTEM

Capacitive sensor performance is limited by circuit noise from various sources, by mechanical stability and by environmental factors. If these limits are understood and handled correctly, capacitive sensor designs can have exceptionally stable and low noise performance.

7.1 Capacitive Measurement System

The ideal media moisture measurement system would have the following characteristics:

- Accuracy

- Good long-term stability
- Reliability
- Easy read using untrained observers
- Low cost
- Easily adapted to data loggers
- Easily calibrated
- Easily installed
- Ruggedness
- Resistance to environmental parameters such as temperature and humidity

A detailed, serious review of the media moisture literature will reveal that there is no presently available method that can be considered to meet the ideal characteristics (Campbell, 1988). In fact, most methods have serious failings in several of these areas.

The plate geometry, sensing area size and mechanical construction will have an effect on the range, accuracy and stability on the measurement (Lion Precision, 2004).

7.2 Limitation of a Capacitive Sensor

The capacitive sensor has the advantages of low cost and very fast response. However, additional tests conducted by Andrade et al. (2001) indicated that this moisture sensor not only responded to media moisture but also to salinity, media texture, and temperature. Rhoades et al. (1989) also obtained similar results. Accounting for the effects of temperature is relatively easy since its linear effect on capacitance can easily be compensated by measuring temperature. If a media texture map of a biofilter is available, then the effect of media texture on the dielectric measurement can be estimated due to the static property. Once the temperature and texture effects have been accounted for, two factors (moisture content and salinity) are responsible for the capacitance and resistance of the media (Andrade et al., 2004). Salts in the media solution can affect the dielectric constant of the media and the response of the capacitive sensor. The effects of salts amplify the frequencies which are lowers than 30 MHz (Silva et al., 2005).

Another drawback of the capacitance plates as a moisture sensor is its small area of influence, defined by the volume of media that influences the reading on the parallel-plates (Silva et al., 2005). The size of that area depends mostly on the size of the plates and according to Chanzy et al. (1998) it is limited to a few centimetres between the plates. In addition, Dean et al. (1987) and Chanzy et al. (1998) have demonstrated that the heterogeneity of the media between the plates can affect largely the response of the sensor to the volumetric moisture content.

The cables used in the capacitance plates can induce to a preferential flux of water in the media (Ruth, 1999). These cables can affect the capacitance of the sensor and, therefore, the sensor must be designed to minimise the use of cables.

In fact, the performance of capacitance sensors in the media has not shown consistent results mainly due to variability of media factors such as texture and structure, and type of media compositions, which in turn affect the ion exchange capacity. Research with biofilter media under static conditions (Gaudu et al., 1993; Eller and Denoth, 1996; Gardner et al., 1998; Nadler and Lapid, 1996) has so far been unable to produce a constitutive relationship between electrical energy input and the response of the media mass.

CHAPTER 8

CONCLUSIONS

This chapter gives final conclusions with respect to the overall project, discussing the achievement of objectives and the potential for further work in a number of areas. Undertaking this project, although difficult at times, has been a very rewarding and educational process. Many of the topics covered and skills learnt are useful over a wide range of applications.

8.1 Main Achievements of Objectives

The aims and objectives set out in the Project Specification at the beginning of the project were:

1. Research literature of the biofilter and biofilter control methods.
2. Evaluate on the various possible moisture measurement techniques that are uses in biofilters.
3. Research on how capacitance-based moisture measurement technique works and alternatives for implementing capacitance-based moisture measurement.
4. Design a measurement system using a capacitance-based sensing to determine the moisture level deep within the biofilter.
5. Analyses on how well the proposed moisture sensing system (or alternative systems) are likely to work.

Chapter 2 has covered the literature which discusses on the design methods, understanding of biofilter media, composition of a biofilter and biofilter control methodology.

Chapter 3 has covered the various moisture measurement techniques and how each technique can be implemented in a biofilter.

Chapter 4 to 6 have covered on the aspects of how capacitance-based moisture measurement technique works and alternatives for implementing capacitance-based moisture measurement.

Chapter 7 has covered on the methodology in designing a hardware and circuit for the capacitive sensor to determine the moisture level of the biofilter media.

Chapter 8 evaluates the performance of the proposed capacitive sensing system and identify the limitation.

The completion of this project has demonstrated the advantages of using the capacitive sensor as the basis for the design and proved the feasibility of the capacitive sensing system in determining the moisture content of the biofilter media.

8.2 Recommendations for Future Work

This project presents many opportunities for further work. The most obvious being the full construction of a capacitive sensor to be tested on a biofilter. This would be a large task, and involves a large amount of testing and careful design to be done at Toowoomba (Qld Dept of Primary Industries & Fisheries). The end result, however, would be a very useful design which could be used in determining the moisture content of the biofilter media.

During the course of the project many areas with potential for further investigation also became apparent. Most notably these include:

1. It is possible to use insulated aluminium plates (on the outer side of the plate) to make accurate media moisture measurements, but a careful calibration program is required.
2. Select a measurement circuit and null it for the selected cable length.
3. Derive the calibration equations for the volumetric media moisture contents and use them to solve for the media moisture at the field site.
4. Identify and implement a moisture sensor suitable for incorporation in a system built to automatically control the moisture level of a biofilter.

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APPENDIX A – PROJECT SPECIFICATION

University of Southern Queensland
Faculty of Engineering and Surveying

ENG4111/2 Research Project
Project Specification

FOR: **Lee Boon Chong, Jeff**

TOPIC: Measuring moisture content of biofilter media using capacitance

SUPERVISORS: Dr. Nigel Hancock, Mark Dunlop and Les Zeller

ENROLMENT: ENG4111 – S1, X, 2006;
ENG4112 – S2, X, 2006

SPONSORSHIP: Qld Dept of Primary Industries & Fisheries, Toowoomba

PROJECT AIM: This project will firstly review the literature on biofilter and biofilter control methods; and also on capacitance-based and other possible moisture measurement techniques. Based on this research designs will then be developed for the measurement of the moisture content of selected biofilter media such as wood chips and soil.

PROGRAMME: Issue A, 27 Mar 2006

1. Research literature of the biofilter and biofilter control methods.

2. Evaluate on the various possible moisture measurement techniques that are uses in biofilters.

3. Research on how capacitance-based moisture measurement technique works and alternatives for implementing capacitance-based moisture measurement.

4. Design a measurement system using a capacitance-based sensing to determine the moisture level deep within the biofilter.

5. Analyses on how well the proposed moisture sensing system (or alternative systems) are likely to work.

As time permits

6. Identify and implement a moisture sensor suitable for incorporation in a system built to automatically control the moisture level of a biofilter.

AGREED:

______________ (Student) ______________, ______________, ______________, (Supervisor)

(Dated) _____ / _____/ _____

APPENDIX B – PROPERTIES AND EFFECTS OF NOXIOUS GASES

This table is based on adult humans. The effects of two or more gases tend to be additive.

Table B-1. Properties, limits and effects of noxious gases. (Reproduced from MWPS-18, 2002. Iowa State University)

Gas	Odour	Odour Threshold[a] (ppm)	Threshold Limit Value (TLV)		Concentration Effects		
			Time-weighted average (TMA)[b] (ppm)	Short-term exposure limit (STEL)[c] (ppm)	Level[d] (ppm)	Exposure period[e] (minutes)	Physiological effects[f]
Carbon dioxide (CO_2) (asphyxiant)							
	None	-	5,000	30,000	20,000	-	Safe
					30,000	-	Increased breathing
					40,000	-	Drowsiness headaches
					60,000	30	Laboured breathing, asphyxiating
					300,000	30	Could be fatal
Ammonia (NH_3) (irritant)							
	Sharp, pungent	5	25	35	400	-	Throat irritant
					700	-	Eye irritant
					1,700	-	Coughing and frothing
					3,000	30	Asphyxiating
					5,000	40	Could be fatal
Hydrogen Sulfide (H_2S) (poison)							
	Rotten egg smell, nausea	0.7	10	15	100	Several hours	Eye and nose irritant
					200	60	Headaches, dizziness
					500	30	Nausea, excitement, insomnia
					1,000	-	Unconsciousness, death

Methane (CH4) (asphyxiant)							
	None	-	-	30,000	500,000	-	Headache, non-toxic
Carbon monoxide (CO) (poison)							
	None	-	25	-	500 1,000 2,000 4,000	60 60 60 60+	No effect Unpleasant, but not dangerous Dangerous Fatal

[a] About the lowest concentration at which odour is detected.

[b] Threshold limit value (TLV) for time-weighted average (TWA) exposure concentration for a conventional 8-hour workday and a 40-hour workweek, to which it is believed that nearly all workers may be repeatedly exposed, day after day, without adverse effect. (Source: 1999 Guide to Occupational Exposure Values, American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio.)

[c] Short term exposure limit: 15-minute TWA exposure which should not be exceeded at any time during a workday even if the 8-hour TWA is within the TLV-TWA. Exposure above the TLV-TWA up to the STEL should not be longer than 15 minutes and should not occur more than four times per day. There should be at least 60 minutes between successive exposure in this range. (Source: 1999 Guide to Occupational Exposure Values, American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio.)

[d] Parts of pure gas per million parts of atmospheric air. Divide by 10,000 for % volume. Example: 20,000 ppm ÷ 10,000 = 2 % by volume.

[e] The time until immediate reaction to the gas.

[f] Value is based on air with 18% oxygen and 3% methane. This value for methane was **not** obtained from the American Conference of Governmental Industrial Hygienists. Methane is explosive at concentrations of 5%-15%.

APPENDIX C - DESCRIPTIONS OF COMMON GASES EMISSION FROM LIVESTOCK

(based on MidWest Plan Service, 1993)

Carbon Dioxide (CO_2)

General description

Carbon dioxide is highly soluble in water. It is released from manure decomposition and animal respiration. Most of the gas bubbling up from liquid manure lagoons is CO_2.

Human Responses

Carbon dioxide is not highly toxic in itself, but it contributes to oxygen deficiency or asphyxiation. Small increases above normal seem harmless, but a 10% concentration (by volume) causes violent panting, and above this is narcotic even if there is adequate oxygen. At a 25% concentration, death occurs after a few hours.

Animal Responses

At a 4% concentration, CO_2 increases the depth and rate of respiration; a 7%-9% concentration can be tolerated, but with considerable discomfort. Concentrations above 10% may produce dizziness and even unconsciousness.

The average CO_2 concentration in a normally ventilated hog confinement unit may be 0.06%-0.07% about twice the normal atmospheric level. Without ventilation, the level can rise to over 0.4% in 6 hr.

Ammonia (NH_3)

General description

Ammonia is also highly soluble in water. It does not burn readily, but mixtures of over 16% with air are explosive. Ammonia is released from fresh manure and during anaerobic decomposition. Its solubility in water is lowered when the pH is raised, as by the addition of lime. Ammonia can be controlled somewhat in liquid manure systems, because much of it dissolves in the water. High water solubility explains the greater ammonia odours in units with litter or solid floors (such as in scraper systems) than in liquid manure units. Heated floors also promote ammonia production and release.

Odour from as little as 1 ppm (0.0001%) can be detected and identified. Dimethylamine has the characteristic pungent odour of ammonia and irritates mucous membrane and respiratory tract.

Human Responses

Low concentrations irritate eyes and the respiratory tract; more may cause suffocation; a 0.5% concentration is a dangerous level. Ammonia begins to burn eyes at 25 to 30 ppm (0.0025%-0.0030%).

Animal Responses

Ammonia is an irritant, and at concentrations up to 0.02%, induces sneezing, salivation and appetite loss, but no loss of feed efficiency. Above 50 ppm (0.005%), eye inflammation develops in chickens. Prolonged exposure may increase respiratory diseases and pneumonia.

Ammonia can condense and subsequently oxidise to nitrite or nitrate. These compounds may accumulate on the floor and cause poisoning if ingested.

Hydrogen Sulphide (H_2S)

General description

Hydrogen sulphide is the most toxic gas associated with liquid manure storage. It is soluble in water, so it can be controlled somewhat by high dilution of manure. The gas burns with a bluish flame and, in a mixture with oxygen, can explode violently. It smells like rotten eggs.

Hydrogen sulphide is produced by anaerobic decomposition of organic wastes. High concentrations can be released by agitation and pumping of liquid wastes.

Paper impregnated with lead acetate solution turns black in hydrogen sulphide and indicates its presence. Hydrogen sulphide forms black copper sulphide on copper, white zinc sulphide on galvanised steel and black discoloration of lead-pigmented white paint.

Human Responses

It is both an irritant and an asphyxiant. Low concentrations severely irritate eyes and respiratory tract in an hour. Concentrations of 0.1% cause immediate unconsciousness, and death through respiratory paralysis occurs unless artificial respiration is immediate.

The sense of smell can be rapidly fatigued by H_2S. Higher concentrations do not proportionately increase odour, so odour is not always an adequate warning.

Animal Responses

High concentrations during agitation can cause death. Hydrogen sulfide concentrations as high as 0.08% have been reported in confinement hog houses during agitation and for several minutes thereafter.

Animals living continuously at levels of about 20 ppm (0.002%) develop fear of light, nervousness and appetite loss that decreases daily gain. Symptoms at 50 to 200 ppm (0.005%-0.02%) include vomiting, nausea and diarrhoea. With normal ventilation, the levels of hydrogen sulphide can be maintained well below 20 ppm (0.002%) except, perhaps, during pit agitation.

Methane (CH_4)

General description

Methane is not very soluble in water, is highly flammable and burns with a blue flame. It is most hazardous in a highly explosive mixture with air in concentrations as low as 5%.

Ruminant animals exhale a minute amount of methane, but most comes from manure decomposition.

Being lighter than air, methane tends to rise and accumulate near the top of stagnant corners of tightly enclosed manure storage pits. Methane dissipates fairly rapidly with some ventilation.

Human and Animal Responses

Methane normally is not considered a toxic gas. Accumulations in stagnant areas of buildings or manure storage pits can be asphyxiating, but explosions are a more serious concern.

Carbon Monoxide (CO)

CO is a colourless and odourless gas about the same weight as air. It is exhausted from gas engines and from gas, oil and coal heaters. Vent engines to the outside to prevent toxic carbon monoxide accumulations. Provide adequate ventilation with unvented heaters to prevent toxic concentrations.

APPENDIX D - BIOFILTER OPERATING PARAMETERS

Table D-1. Operating parameters and performance for biofilters from literature. (Reproduced from Sun et al., 2000)

Reference	Dimension of Media	Type of Media	Moisture Content (% wb)	Flow Rate (m^3/h)	Surface Loading Rate ($m^3/m^2.h$)	Retention Time (s)	Target Pollutant	Inlet Concentration (ppm)	Removal Rate (%)	Notes
Rands et al., 1981	Ht: 10.2cm 38.7cm 69.2cm Dia: 21.5cm	Compost	29	1.2	33	11 41 73	H_2S	69-212 45-212 77-263	97.4-99.8 97.6-99.8 99.3-99.6	Pilot scale
Furusawa et al., 1984	Ht: 50cm Dia: 15cm	Fibrous peat	65	22.5-225 L/h	-	-	H_2S	60	≈100	Lab experiment, temperature 15-19°C
Langenhove et al., 1986	Ht: 0.9m 0.3m × 0.3m	Wood bark	-	5.85	65	36.9	H_2S	10	96-100	Lab experiment
Ottengraf, 1987	Depth: 0.5-1.0m	Compost	25-50, biofilter optimum: 30-60	-	10-100	30-60	Odour	-	-	Review paper
Beerli, 1989	Ht: 1m Surface Area: $5.8m^2$	Peat	-	540 710	93 122	38.7 29.4	NH_3	0.04 mg/L	86.1 86.8	Case study, swine building
Scholtens, 1991	Ht: 0.5m Surface Area: $0.33m^2$/pig $0.23m^2$/pig	Peat/heather, compost/bark	-	-	300 450	-	NH_3, Odour	-	>85 >75	Field study, swine building
Clark and Wnorowski, 1992	Ht: 0.39m Dia: 0.2m	Compost, sewage sludge	-	0.78	25	56.5	H_2S	20-23	>90	Lab scale, temperature 18°C, pH 6.9
Pearson et al., 1992	Ht: 1.5m 4m × 4m	Mature heather	-	3600	225	20	NH_3, Odour	2-30	50 72	Field study, broiler chicken house
Yang and Allen, 1994	Ht: 1.0m-1.1m Dia: 0.15m	Compost, yard trash, sewage sludge	35-65	-	-	>15	H_2S	5-2650	95	Temperature 25-50°C, compost pH >3.0
Schafer and Prokop, 1995	Ht: 2.8m	Compost	-	16920	148	45	H_2S	5-70	>98	Case study, emission from primary

	8.5m × 13.4m									equalisation tank at WWTP
Wolstenholme and Finger, 1995	Dia: 30cm Ht: 90cm	Bark, top soil, compost, different combinations	-	122	-	40-60	H_2S VOC	1.1-24 0.017-0.123	97 97	Long-term pilot test, wastewater foul air streams
Mora and Manrique, 1997	Ht: 35cm 70cm Dia: 19.5cm	Compost	10-20 20-30 30-40	-	10.02	-	H_2S	0-600 600-900	100 99.3	Lab experiment, temperature 28°C
Nicolai and Janni, 1997	Ht: 0.3m 6.4m × 6.4m	Compost, dark red kidney bean straw	-	3600	122	8.8	NH_3, H_2S, Odour	5-19 0.32-1.2	28-100 39-98	Field study, swine building
Young et al., 1997	Ht: 0.5m Dia: 0.6m	Yard waste compost, wood chips	62-67	28.8	102	17.7	Odour intensity	-	56-63	Field study, swine building

Ht: height.
Dia: diameter.

APPENDIX E - CAPACITANCE PLATES CONFIGURATIONS

E.1 Parallel Plates

When two parallel plates are connected across a battery, the plates become charged and an electric field is established between them. Therefore to calculate the capacitance, Gauss's law can be applied to a surface surrounding one of the parallel plates in Figure E-1. If the surface is correctly chosen and the fringing flux lines at the edge of the plates are ignored, the total charge inside the surface is equal to the total displacement flux *d* times the area of the surface *A* which is expressed in Equation E.1.

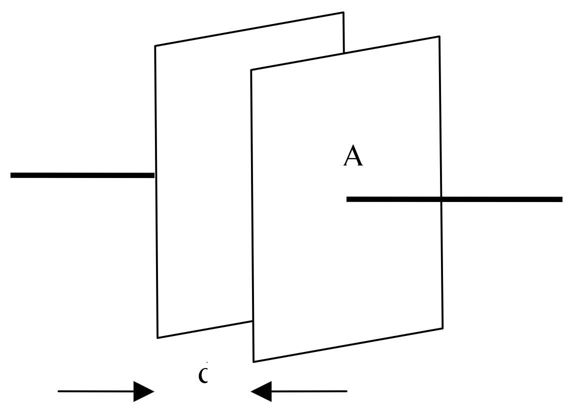

Figure E-1. Two parallel plates.

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} = 8.854 \times 10^{-12} \times \frac{\varepsilon_r A}{d} \qquad \text{(E.1)}$$

(Source: Baxter, 1997)

Where:

C = capacitance, measured in farads (F)

ε_0 = permittivity of free space, measured in farads per metre (F/m)

(8.854×10^{-12})

ε_r = dielectric constant or relative permittivity of the insulator used

A = area of each plane electrode, measured in square metres (m^2)

d = separation between the electrodes, measured in metres (m)

E.2 Disk/Sphere

The simplest configuration is a single thin plate or a sphere with a diameter of d meters. This has a well-defined capacitance to a ground at infinity which is shown in Figure E-2 and the capacitance is calculated using Equation E.2 and Equation E.3.

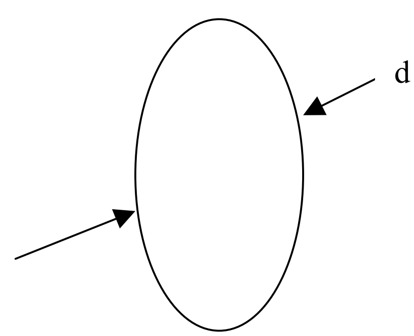

Figure E-2. A single disk/sphere.

(E.2)

(Source: Baxter, 1997)

(E.3)

(Source: Baxter, 1997)

E.3 Two Spheres

The capacitance in farads between two spheres of radius *a* and *b* meters and separation *c* is approximately derived in Equation E.4 and shown in Figure E-3.

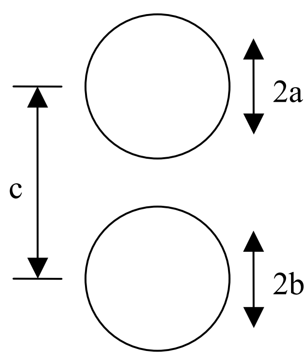

Figure E-3. Two spheres.

(E.4)

(Source: Walker, 1990)

According to Walker (1990), the approximation is good if *a* and *b* are much less than *2c*. With this geometry and the single disk above, capacitance scales directly with the length and is independent of the cross-section size.

E.4 Concentric Cylinders

Another geometry which results in a flux distribution which can be easily evaluated is two concentric cylinders (Baxter, 1997). The capacitance (farads) between two concentric cylinders of length *L* and radius *a* and *b* meters is illustrated in Figure E-4 with the Equation E.5.

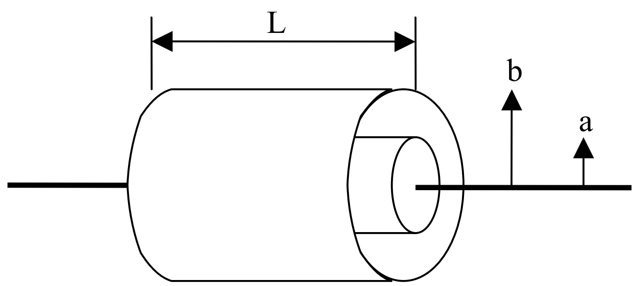

Figure E-4. Concentric cylinders.

(E.5)

(Source: Baxter, 1997)

E.5 Parallel Cylinders

For cylinders if length *L* meters and radius *a* meters separated by *b* meters, the capacitance in farads is illustrated in Figure E-5 with both equation E.6 and E.7.

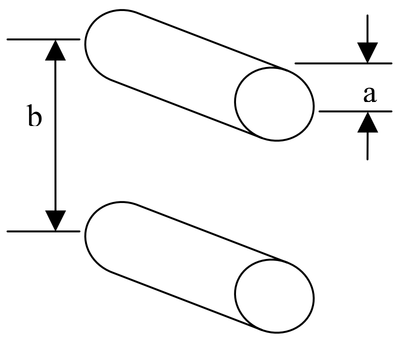

Figure E-5. Parallel cylinders.

(E.6)

(Source: Baxter, 1997)

If $b >> a$, Equation E.7 will be applicable.

(E.7)

(Source: Baxter, 1997)

E.6 Cylinder and Plane

A cylinder with length *L* and radius a located *b* meters above an infinite plane is illustrated in Figure E-6 with the Equation E.8.

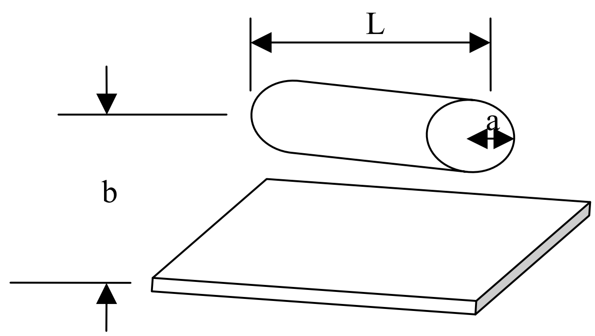

Figure E-6. Cylinder and plane

(E.8)

(Source: Hayt, 1958)

E.7 Two Cylinders and Plane

The mutual capacitance (farads) between two cylinders of length *L* and radius *a* meters is reduced by the proximity of a ground plane as illustrated in Figure E-7 (Walker, 1990).

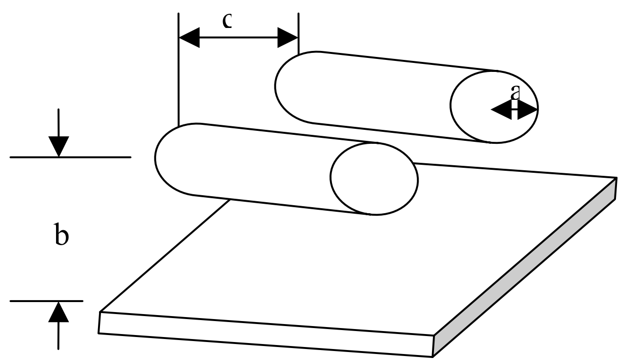

Figure E-7. Two cylinders and plane

The approximation is good if *2b* >> *a*, and Equation E.9 is applicable.

(E.9)

(Source: Walker, 1990)