Capacitance

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I. INTRODUCTION

We demonstrated that a voltmeter was incapable of determining the initial voltage of a capactior with typical capacitance ratings because the internal impedance was too small. An electrometer with $10^6\times$ greater impedance was more suitable. We then demonstrated that shielding a capacitor results in a stable charge buildup. It virtually eliminated electric fields from the environment.

Plotting calculated capacitance vs plate separation confirmed the theoretical equation for capacitance. We used this equation to calculate the capcitance of an dielectricless capacitor of some thickenss, then compared this value to a calculated capacitance of a dielectric capacitor. We used our results to determine κ for various materials. The calculated κ values were very close to their corresponding known values.

II. MATERIALS AND METHODS

A. Using a Voltmeter to Measure Voltage across a Capacitor

We made the circuit shown in figure 1 using the wires provided and omitting the breadboard. Two capacitors were connected in series. One of the capacitors was known to be 1μF and came in an "electronic component" form. The other capacitor was a Pasco Adjustable Air Capcitor. This is a pair of parallel plates of 10cm radius with one plate on sliding rails. The plates were separated 1cm apart with no dieletric between them. We will refer to the parallel plate capacitor as the unknown capacitor. Power was supplied using a Raytheon QRS30-1 power supply set to 10V. A voltmeter was used to measure the initial potential across the unknown capacitor when the switch was closed. We used the following equation

$$C_{ukn} = C_{known}\Big(\frac{V_{PowerSupply}}{V} - 1\Big)$$

and compared the result to the theoretical capacitance using

$$C = \kappa\epsilon_0\frac{A}{d}.$$

B. Stability of a Shielded vs Unshielded Capacitor

The rest of our experiments involved only the Pasco adjustable capacitor as our capacitor. We also switch from using a power supply and voltmeter to just using an electrometer. The electrometer on hand was a Keithley model 617. This unit functioned as a power supply and charge measurement device. It's input impedance is 200TΩ, 10x greater than a typical voltmeter. The electrometer was engaged using the following procedure:

1. Set output voltage
2. Set to charge measuring mode
3. Enable zero check
4. Enable zero correct
5. Disable zero check
6. Press Operate

We assembled the circuit shown in figure 3 using a 1MΩ resistor and the Pasco Capacitor. The Pasco Capacitor plates were separated 1cm apart with no dielectric between the plates ($\kappa = 1$). The output voltage was set to 10.00V. This set up was not shielded by a metal cage. We recorded four charge readings, each 5 seconds apart, starting at 0 seconds. After the last reading, we placed our hands near one of the plates to see how it effected the charge reading.

We repeated the same procedure with a metal cage around the capacitor. The cage was connected to ground.

C. Air Capacitor Measurements as a Function of Plate Spacing

This experiment is schematically the same as the Shielded Capacitor experiment above. We took nineteen charge readings for different plate separation lengths. We started at the maximum separation length of 10cm and ended at 1mm.

A wooden stick was used to push the plates through a hole slot in the shielding cage. Between 10cm and 1cm, we took data at 1cm increments. Between 1cm to 1mm, we took data at 1mm increments.

To prevent overloading the electrometer, we calculated the maximum voltage to be applied using 20nC as the maximum charge input. The maximum charge occurs when the plate separation is minimum (note V is constant):

$$\begin{aligned} V &= \frac{Qd}{\epsilon_0 A} \\ \Rightarrow V_{max} &= \frac{Q_{max} \cdot d_{min}}{\epsilon_0 A} \\ \Rightarrow V_{max} &= \frac{20nC \times 1mm}{8.85 \times 10^{-12} \cdot \pi(10cm)^2} \\ &= 71.94V \end{aligned}$$

We choose the source voltage to be 65.00V. The data recorded was then processed using the relationship

$$\begin{aligned} C &= \frac{Q}{V} \\ &= \frac{\epsilon_0 A}{d} \end{aligned}$$

to plot $\frac{Q}{V} vs \frac{1}{d}$. I've taken into consideration the error for measurements taken between 1mm and 1cm to be $\pm.5mm$. The error bars were calculated by multiplying the relative error shown in the first table by the $\frac{1}{d}$ value of the second table.

D. Capacitance Measurements with Dielectric Materials

We sandwiched the following materials between the plates:

1. Gray PVC
2. Stycast
3. Stycast 2
4. Teflon

Each dielectric thickness was measured. There was a 1mm thick tab that separated the adjustable plate with the dielectric material. So the circuit was equivalent to two series capacitors, one with and one without a dielectric. The following relationship was used to calculate the dielectric capacitance:

$$\begin{aligned} \frac{1}{C_d} &= \frac{1}{C_s} - \frac{1}{C_a} \\ &= \Big\{\frac{V_{powersupply}}{Q_{read}} - \frac{1}{2.78 \times 10^{-10}}\Big\} F^{-1} \\ &= \Big\{\frac{V_{powersupply}}{Q_{read}} - 3.59 \times 10^{9}\Big\} F^{-1} \end{aligned}$$

Note that I used the theoretical capacitance in calculating C_a.

III. DATA

A. Using a Voltmeter to Measure Voltage across a Capacitor

The inital voltage was found to be 6.6V when the switched closed.

$$\begin{aligned} C_{ukn} &= C_{known}\Big(\frac{V_{PowerSupply}}{V} - 1\Big) \\ &= (1\mu F)\Big(\frac{10}{6.6} - 1\Big) \\ &\boxed{= .515\mu F} \end{aligned}$$

The theoretical capacitance was calculated to be

$$\begin{aligned} C_{ukn} &\approx (8.85 \times 10^{-12})\frac{F}{m} \cdot \frac{\pi(10 \times 10^{-2})^2 m^2}{10^{-2} m} \\ &\boxed{= 27.8pF} \end{aligned}$$

B. Stability of a Shielded vs Unshielded Capacitor

Below are the charge measurements t seconds after a source voltage is applied to the unshielded capacitor

Time [s]	Charge [nC]
0	.2888
5	.2882
10	.2904
15	.2917

The charge reading increased to .3125nC when a hand was placed near one of the plates.

The shielded capacitor data is:

Time [s]	Charge [nC]
0	.2849
5	.2849
10	.2848
15	.2847

The charge reading did not change when our hands were placed near the cage.

C. Air Capacitor Measurements as a Function of Plate Spacing

Here is the data recorded for this experiment:

Plate Separation [cm]	Charge[nC]
10	0.1623
9	0.1906
8	0.2225
7	0.2636
6	0.3175
5	0.3903
4	0.4933
3	0.6586
2	0.9739
1 ±5%	1.9070
0.9 ±5%	2.1200
0.8 ±6%	2.3780
0.7 ±7%	2.6380
0.6 ±8%	3.0250
0.5 ±10%	3.5800
0.4 ±13%	4.5190
0.3 ±17%	5.8060
0.2 ±25%	8.3550
0.1 ±50%	14.6430

The data was calculated and tabulated below:

$\frac{1}{d}[m]^{-1}$	error $[m]^{-1}$	Charge [C]
10.00	-	2.49692E-12
11.11	-	2.93231E-12
12.50	-	3.42308E-12
14.29	-	4.05538E-12
16.67	-	4.88462E-12
20.00	-	6.00462E-12
25.00	-	7.58923E-12
33.33	-	1.01323E-11
50.00	-	1.49831E-11
100.00	5.0000	2.93385E-11
111.11	6.1728	3.26154E-11
125.00	7.8125	3.65846E-11
142.86	10.2041	4.05846E-11
166.67	13.8889	4.65385E-11
200.00	20.0000	5.50769E-11
250.00	31.2500	6.95231E-11
333.33	55.5556	8.93231E-11
500.00	125.0000	1.28538E-10
1000.00	500.0000	2.25277E-10

The plot with error bars is shown on the last page. The slope of this plot was found to be $2 \times 10^{-13}\,\frac{F}{m}$. The calculated slope $\epsilon_0 \times \pi(10cm)^2 = 2.78 \times 10^{-13}\frac{F}{m}$.

D. Capacitance Measurements with Dielectric Materials

We use the following equations to calculate the Dielectric capacitance:

$$C_d^{-1} = \left\{\frac{V_{powersupply}}{Q_{read}} - 3.59 \times 10^9\right\}F^{-1}$$

Air Capacitance of Dielectric Thickness:

$$C_a = \left\{(\frac{.2}{d} + 5) \times 10^{-12}\right\}F$$

Relative Dielectric Constant:

$$\kappa = \frac{C_d}{C_{air}}$$

1. Gray PVC

- Thickness = 6.42mm
- Charge Measured = 6.216nC
- Known $\kappa = 3.19$
- **Calculated Capcitance =** $.146nF$
- **Air Capcitance of same thickness =** $.0361nF$
- κ **calculated = 4.03**

2. Stycast 1

- Thickness = 6.50mm
- Charge Measured = 11.4630nC
- Known $\kappa = 12$
- **Calculated Capcitance =** $.481nF$
- **Air Capcitance of same thickness =** $.0358nF$
- κ **calculated = 13.44**

3. Stycast 2

- Thickness = 6.60mm
- Charge Measured = 8.840nC
- Known $\kappa = 6$
- **Calculated Capcitance =** $.266nF$
- **Air Capcitance of same thickness =** $.0353nF$
- κ **calculated = 7.54**

4. *Teflon*

- Thickness = 12.65mm
- Charge Measured = 2.680nC
- Known $\kappa = 2.1$
- **Calculated Capcitance =** $.0484nF$
- **Air Capcitance of same thickness =** $.0208nF$
- κ **calculated = 2.33**

IV. DISCUSSION

We initially thought that the charge reading fluctuations for the unshielded capacitor was due to noise since we were dealing with small quantities. The shielding demonstrated that the plate's charge buildup is affected by the environment. When I placed *my* hand next to one of the plates, the reading was virtually unchanged. But when my partner put his hand near it, we saw a considerable change from $\approx .2800nC$ to $\approx .3100nC$. My hands were too dry.

The plot of different plate spacing confirmed the theoretical equation of capacitance. Error was considerable for the small increments between 1mm and 1cm. To my surprise, best fit line fell into the error bars. Usually, there's atleast one error bar interval that is completely disjoint from the best fit line for past labs.

I chose to use the theoretical air capacitance for the equivalent dielectric thickness because the theoretical equation of capacitance was confirmed by our plot and is more accurate than the best fit line extrapolation. Our κ values were still off though. I think this was due to charge leaking through the contact points of the 1mm tab and errors on measuring thickness.