Determination of Dielectric Constant of different materials

Objectives:

1. To establish the relation between charge Q and voltage U_c using a parallel plate capacitor separated by air gap and to determine dielectric constant of air.
2. Variation of charge on a plate capacitor as a function of the distance between the plates, under constant voltage (with air as a dielectric).
3. To establish the relation between charge Q and voltage U_c using a plate capacitor with different dielectric materials and to determine dielectric constants of different materials.

Theory:

Electrostatic processes in vacuum are described by the following integral form of Maxwell's equations:

$$\oiint \boldsymbol{E}.\boldsymbol{dA} = \frac{Q}{\varepsilon_0} \qquad (1)$$

$$\oint \boldsymbol{E}.\boldsymbol{dS} = 0 \qquad (2)$$

where **E** is the electric field intensity, Q the charge enclosed by the closed surface A, ε_0 is the permittivity of free space and s a closed path. If a voltage U_c is applied between two capacitor plates, an electric field **E** (Fig. 1) will prevail between the plates, which is defined by:

$$U_c = \int_1^2 \boldsymbol{E}.\boldsymbol{dr} \qquad (3)$$

Due to the electric field, equal amount of electrostatic charges with opposite sign are drawn towards the surfaces of the capacitor. Assuming the field lines of the electric field always to be perpendicular to the capacitor surface, for small distances d between the capacitor plates, Eq. 1 and 3 give

$$\frac{Q}{\varepsilon_0} = \frac{U_C.A}{d} \qquad (4)$$

The charge Q on the capacitor is thus proportional to voltage the proportionality constant C is called the capacitance of the plate capacitor.

$$Q = CU_c = \varepsilon_0 \frac{A}{d} U_C \quad (5)$$

The linear relation between charge Q and voltage U_c applied to the otherwise unchanged capacitor is represented in fig. 4. Eq. 5 further shows that the capacitance C of the capacitor is inversely proportional to the distance d between the plates and directly proportional to the area A of the plates:

$$C = \varepsilon_0 \frac{A}{d} \qquad (6)$$

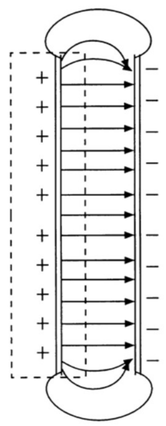

Fig. 1: Electric field lines between capacitor plates

Equations (4), (5) and (6) are valid only approximately, due to the assumption that field lines are parallel. With increasing distances between the capacitor plates, capacitance increases, which in turn systematically yields a too large electric constant from equation (6). This is why the value of dielectric constant should be determined for a small and constant distance between the plates (Fig. 1).

Once an insulating material (dielectrics) is inserted between the plates the above equations are modified. Dielectrics have no free moving charge carriers, as metals have, but they do have positive nuclei and negative electrons. These may be arranged along the lines of an applied electric field $\mathbf{E_0}$. Formerly non-polar molecules get polarized and thus behave as locally stationary dipoles. As can be seen in Fig. 2, the effects of the single dipoles cancel each other macroscopically inside the dielectric. However, no partners with opposite charges are present on the surfaces; these thus have a stationary charge, called a free charge. The free charges in turn weaken the effective electric field $\mathbf{E}$ as given below

$$\boldsymbol{E} = \frac{\boldsymbol{E_0}}{\varepsilon_r} \qquad (7)$$

Here ε_r is the dielectric constant (relative permittivity) of the medium which is a dimensionless, material specific constant.(ε_r= 1 in vacuum). If $\mathbf{P}$ is the polarization vector, the induced electric field $\mathbf{E_P}$ due to these charges will be in opposite direction to applied electric filed:

$$\boldsymbol{E_P} = \boldsymbol{E_0} - \boldsymbol{E} = \frac{\varepsilon_r - 1}{\varepsilon_r}\boldsymbol{E_0} = \frac{\boldsymbol{P}}{\varepsilon_0} \qquad (8)$$

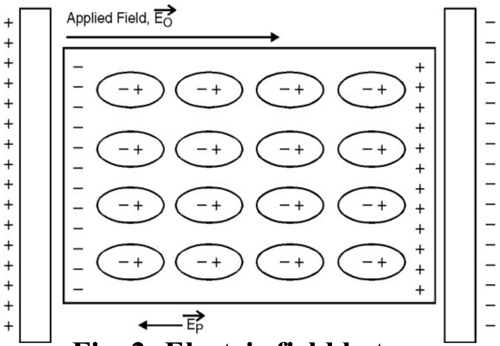

Fig. 2: Electric field between capacitor plates with a dielectric

The electric displacement vector for an isotropic medium is defined as

$$\boldsymbol{D} = \boldsymbol{\varepsilon E} = \varepsilon_0\varepsilon_r\boldsymbol{E} == \varepsilon_0\boldsymbol{E} + \boldsymbol{P} \qquad (9)$$

where ε is the electrical permittivity of the dielectric medium. When a dielectric is inserted between the capacitor plates, according to Eq. (3), voltage U_c between the plates is reduced by the dielectric constant, ε_r, as compared to voltage in vacuum (or to a good approximation, in air). Since the real charge stored is constant, the capacitance will increase by a factor ε_r:

$$C_{dielectric} = \varepsilon_r\varepsilon_0\frac{A}{d} \qquad (10)$$

Thus the general form of Eq. 5 is

$$Q = \varepsilon_r\varepsilon_0\frac{A}{d}U_c \qquad (11)$$

Knowing all the parameters, one can determine the dielectric constant of the medium using the following equation:

$$\boldsymbol{\varepsilon_r} = \frac{\boldsymbol{1}}{\boldsymbol{\varepsilon_0}}\frac{\boldsymbol{d}}{\boldsymbol{A}}\cdot\frac{\boldsymbol{Q}}{\boldsymbol{U_c}} \qquad (12)$$

Apparatus:

1. Set of parallel plate capacitors (Diameter = 26 cm)
2. High voltage power supply (0-10kV)
3. A 10 MΩ resistor
4. Reference capacitor (220nF)
5. Universal measuring amplifier
6. Voltmeter
7. Dielectric materials (Plastic and glass plates)
8. Connecting cables, adapters, T-connectors

Experimental set up:

The actual experimental set up and a schematic of the same are shown in Fig. 3. In this experiment the plate capacitors are charged using a high voltage supply. The charge stored on it is transferred to a known capacitor C_{ref} (220nF) by discharging the plate capacitor. The voltage across C_{ref} is fed to an electrometer amplifier and then measured using a voltmeter as V_0. From the reference capacitance C_{ref}, the total charge, Q, stored on the capacitor is obtained using the following equation and subsequently values of ε_r for different media are determined using Eqns. 12 and 13.

$$\mathbf{Q = V_o.C_{ref}} \qquad (13)$$

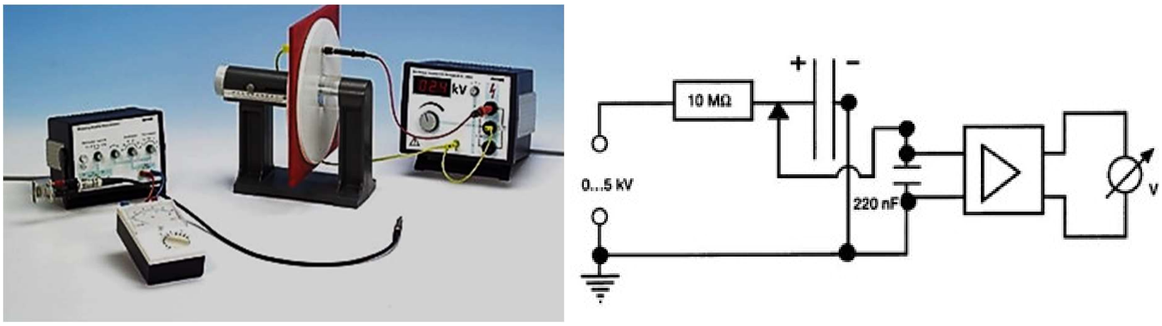

Fig. 3: Experimental set up and its schematic

Procedure:

1. To start with, the surface area of the capacitor plates is determined using their given radius.

2. For this experiment, we will be needing 0-5kV from the power supply. So select the range of the power supply accordingly. The middle terminal will act as "0" for 0 – 5kV range. **Please switch off the supply when not in use and be extremely careful while handling this high voltage source.**

3. For charging the capacitor plates, connect the highly insulated capacitor plate connected to the positive terminal of the high voltage power supply through the 10 MΩ protective resistor. The other plate is connected to the middle terminal of the power supply and grounded (see Fig. 1).

4. Similarly, for discharging the plate capacitor, remove the high voltage probe and switch off the power supply. Connect the BNC cable to the insulated plate. The other end of the BNC is connected to the 220nF through a T-connector.
5. The voltage appearing across 220nF is fed to the amplifier and the output of the amplifier is read out on a voltmeter. The amplifier should be set to: i) high input resistance, ii) amplification factor at 1 and iii) time constant at 0.
6. **Be sure not to be near the capacitor during measurements, as otherwise the electric field of the capacitor might be distorted.**
7. **You may need to use a drier to get rid of moisture from the plate surfaces if the humidity is very high. Do this when your data becomes irreproducible.**

A. Measurement of charge Q for different supply voltage U_C with air as a dielectric medium:

1. Set the air gap between the two plates to be around 2 mm using the vernier attached to the capacitor plate.
2. Check that output voltage on voltmeter is 0 by doing "zero adjustment" (to be done once just at the beginning of the experiment) and then using "reset to zero" button (to ensure the C_{ref} is completely discharged) before taking every measurement.
3. Set the voltage on the power supply, U_C, at 0.5kV.
4. Charge the capacitor plate as mentioned in step 2 of previous section. Once charged completely, remove the high voltage probe and switch off the power supply.
5. Now to transfer the charge on plate capacitor to C_{ref} follow steps 3 and 4 of the previous section. Note down the maximum voltage reading on the voltmeter, V_0.
6. Vary the voltage from 0.5kV to 4kV in steps of 0.5kV and note down corresponding values of V_0. Calculate Q in each case.
7. Plot a graph of Q ~ U_C and fit it with a straight line. Determine ε_r for air.

B. Measurement of charge Q for different distances d:

1. Arrange the set up with an air gap of 1mm (set the gap using the scales on the rail) and U_C = 1.5 kV (say).
2. Follow steps 2-4 of part A and determine Q.
3. Vary the distance from 1 – 4mm in steps of 0.5 mm using the vernier attached to the plate capacitor. Measure Q.
4. Plot Q ~ 1/d. Check if it fits with a straight line.

C. Measurement of charge Q for different supply voltage U_C with a dielectric (plastic/glass):

1. Place the dielectric (plastic/glass) sheet between the capacitor plates and make sure that the surfaces of plates touch the sheet completely without any air gap. Secure the sheet using the vernier attached to the plate capacitor. Be extremely careful while placing and securing the dielectric between the capacitor plates.
2. Vary U_C between 0.5 – 4 kV in steps of 0.5kV. Note the value of V_0 in each case using the same procedure described above and determine Q.
3. Plot Q ~ U_C. Determine capacitance and the dielectric constant of glass/polystyrene.

Observations:

Table-1: Q ~ U_C **C_{ref}= 220 nf , d (air) = 2 mm**

U_C (kV)	A=…….	
	V_0 (V)	Q (in nAs) = $V_o.C_{ref}$
0.5		
..		
..		

Table-2: Q ~ 1/d

A=…., C_{ref} = 220nF, U_c = … kV

d (mm)	V_0 (kV)	Q (in nAs) = $V_o.C_{ref}$
1		
..		
..		

Table 3: Q ~ U_C (with dielectrics)   A=…, C_{ref} = 220nF

U_C (kV)	Plastic		Glass	
	V_0 (V)	Q = $V_o.C_{ref}$ nA/s	V_0 (V)	Q = $V_o.C_{ref}$ nA/s
0.5				
..				
..				

Typical values of ε_r for air: 1.0006
Plastic ~ 3.
Glass ~ 3.8 – 14.5

Precautions:

1. Take extreme care while operating with the high voltage supply.
2. Avoid touching of the plates while connected to high voltage supply.
3. Avoid synthetic clothing and maintain distance from the set up while performing the experiment.
4. Use short cables as much as possible. Avoid loose connections.