

A Parallel-plate Capacitor Has Plates With Area 2.30102 m^2 Separated By 1.10 mm Of Teflon. Calculate

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When exploring the fascinating world of capacitors in physics and electrical engineering, understanding the fundamental parameters that determine their behavior is essential. In this article, we focus on a specific example: a parallel-plate capacitor with plates measuring 2.30102 square meters, separated by a 1.10 millimeter thick sheet of Teflon. Our goal is to calculate key electrical properties such as capacitance, electric field, and potential difference. This detailed analysis will help demystify the principles behind capacitor operation and provide practical insights applicable in various electronic applications.

Understanding the Basics of a Parallel-plate Capacitor

A parallel-plate capacitor is a simple yet effective component used to store electrical energy. It consists of two conductive plates positioned parallel to each other, separated by an insulating material called a dielectric. The capacity of the capacitor to store charge depends on the physical dimensions of the plates, the dielectric material's properties, and the distance between the plates.

Key Parameters in Capacitor Calculations

To perform accurate calculations, we need to understand the following parameters:

- **Plate Area (A):** The surface area of each conductive plate, which in this case is 2.30102 m^2 .
- **Separation Distance (d):** The distance between the plates, given as 1.10 mm .
- **Dielectric Material:** Teflon, characterized by its dielectric constant (relative permittivity).

Calculating the Capacitance of the Teflon-Insulated Capacitor

The primary feature of interest is the capacitance, which quantifies the capacitor's ability to store charge. The formula for the capacitance of a parallel-plate capacitor with a dielectric is:

Capacitance Formula

$$C = \frac{\epsilon_0 \times \epsilon_r \times A}{d}$$

where:

- C is the capacitance in farads (F),
- ϵ_0 is the vacuum permittivity (8.854×10^{-12} F/m),
- ϵ_r is the dielectric constant of Teflon (approximately 2.1),
- A is the area of the plates in square meters,
- d is the separation between the plates in meters.

Step-by-step Calculation

Given data:

- $A = 2.30102$ m²,
- $d = 1.10$ mm = 1.10×10^{-3} m,
- $\epsilon_r = 2.1$,
- $\epsilon_0 = 8.854 \times 10^{-12}$ F/m.

Plugging these into the formula:

$$C = \frac{8.854 \times 10^{-12} \times 2.1 \times 2.30102}{1.10 \times 10^{-3}}$$

Calculating numerator:

$$8.854 \times 10^{-12} \times 2.1 \times 2.30102 \approx 8.854 \times 10^{-12} \times 4.833162 \approx 4.278 \times 10^{-11}$$

Now, dividing by d :

$$C \approx \frac{4.278 \times 10^{-11}}{1.10 \times 10^{-3}} \approx 3.89$$

$\times 10^{-8} \text{ F}$

Expressed in picofarads (pF):

$C \approx 38.9 \text{ pF}$

Thus, the capacitance of this parallel-plate capacitor is approximately 38.9 picofarads.

Electric Field and Potential Difference in the Capacitor

Understanding the electric field and potential difference is crucial for analyzing the capacitor's behavior under voltage.

Electric Field Between the Plates

The electric field (E) in a parallel-plate capacitor with a dielectric is uniform and given by:

$$E = \frac{V}{d}$$

where (V) is the potential difference across the plates. But first, we calculate the maximum electric field the dielectric can withstand before breakdown, which for Teflon is approximately (60 MV/m) .

Calculating the maximum voltage before dielectric breakdown:

$$V_{\text{max}} = E_{\text{breakdown}} \times d = 60 \times 10^6 \text{ V/m} \times 1.10 \times 10^{-3} \text{ m} = 66,000 \text{ V}$$

This indicates Teflon can withstand a maximum voltage of about 66 kV across the plates without breakdown.

Potential Difference for a Given Charge

If a certain charge (Q) is stored, the potential difference across the

plates is:

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

Suppose we charge the capacitor with 1 nanocoulomb ($1 \times 10^{-9} \text{ C}$):

$$V = \frac{1 \times 10^{-9}}{38.9 \times 10^{-12}} \approx 25.7 \text{ V}$$

This illustrates that a modest charge results in a potential difference well below the breakdown voltage, ensuring safe operation.

Practical Applications and Considerations

Understanding these calculations helps in designing capacitors for various electronic systems, including:

- Energy storage devices
- Filtering and tuning circuits
- Sensor applications
- High-voltage insulation systems

However, real-world applications must also consider factors such as dielectric losses, temperature effects, and manufacturing tolerances, which can influence the actual performance.

Summary of Key Calculations

- **Capacitance:** Approximately 38.9 pF
- **Maximum Voltage Before Breakdown:** About 66 kV
- **Electric Field at Breakdown:** 60 MV/m
- **Potential Difference for 1 nC Charge:** Approximately 25.7 V

Conclusion

By analyzing a parallel-plate capacitor with specified dimensions and dielectric material, we have calculated its capacitance, electric field, and maximum voltage before dielectric breakdown. Such detailed calculations are essential for designing reliable electronic components and understanding their operating limits. Whether used in energy storage, signal processing, or insulation, capacitors like these serve as fundamental building blocks in modern electronics.

Understanding these principles empowers engineers and students alike to optimize capacitor performance, ensuring safety, efficiency, and durability in various technological applications.

Frequently Asked Questions

What is the capacitance of a parallel-plate capacitor with plates of area 2.30 m^2 separated by 1.10 mm of Teflon?

The capacitance can be calculated using $C = \epsilon_0 \epsilon_r A / d$. With $\epsilon_0 \approx 8.85 \times 10^{-12} \text{ F/m}$, ϵ_r for Teflon ≈ 2.1 , $A = 2.30 \text{ m}^2$, and $d = 1.10 \text{ mm} = 1.10 \times 10^{-3} \text{ m}$, the capacitance is approximately $3.91 \text{ }\mu\text{F}$.

How does the dielectric constant of Teflon affect the capacitance of the parallel-plate capacitor?

The dielectric constant ($\epsilon_r \approx 2.1$ for Teflon) increases the capacitance compared to a vacuum or air, as C is directly proportional to ϵ_r . Using Teflon as a dielectric roughly doubles the capacitance compared to air.

What is the electric field between the plates of this capacitor?

The electric field E is given by $E = V/d$, but without the voltage V , we cannot determine E directly. If V is known, $E = V/1.10 \times 10^{-3} \text{ m}$.

How much charge is stored on the plates of this capacitor when a voltage of 100 V is applied?

Using $Q = C \times V$, with $C \approx 3.91 \text{ }\mu\text{F}$ and $V = 100 \text{ V}$, the charge stored is approximately $391 \text{ }\mu\text{C}$.

What is the energy stored in the capacitor when charged to 100 V?

The energy stored is $U = (1/2) C V^2$. Substituting $C \approx 3.91 \mu\text{F}$ and $V = 100 \text{ V}$, $U \approx 19.55 \mu\text{J}$.

How does increasing the plate area affect the capacitance?

Capacitance is directly proportional to the plate area; increasing the area increases the capacitance proportionally.

What would happen to the capacitance if the separation distance between plates is doubled?

The capacitance is inversely proportional to the separation distance; doubling the distance halves the capacitance.

Additional Resources

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Introduction

Parallel-plate capacitors are fundamental components in electrical engineering and physics, serving as essential elements in circuits, energy storage systems, sensors, and various electronic devices. Their simplicity and well-understood behavior make them ideal for both practical applications and theoretical explorations. This article delves into a specific scenario involving a parallel-plate capacitor with given dimensions and dielectric material, aiming to compute its capacitance, stored energy, and related parameters.

Understanding how the physical characteristics—plate area, separation distance, and dielectric material—affect a capacitor's behavior is crucial in designing efficient electronic systems. In the case at hand, the capacitor comprises plates with an area of 2.30 square meters, separated by a 1.10 millimeter layer of Teflon, a common dielectric material renowned for its high dielectric strength and low permittivity.

This comprehensive review will analyze the problem step-by-step, providing insights into the underlying physics, relevant formulas, and practical implications.

Physical Principles Governing Parallel-Plate Capacitors

Basic Structure and Operation

A parallel-plate capacitor consists of two conductive plates positioned parallel to each other, separated by a dielectric material. When a voltage is applied across the plates, an electric field develops, storing energy in the electrostatic field.

Key Parameters

- Plate Area (A): The surface area of each plate, determining the amount of charge the capacitor can hold.
- Separation Distance (d): The distance between the plates influences the electric field strength and capacitance.
- Dielectric Material: An insulating substance placed between the plates, characterized by its relative permittivity (ϵ_r), which enhances the capacitance compared to a vacuum.

Fundamental Equations and Concepts

Capacitance of a Parallel-Plate Capacitor

The capacitance (C) indicates how much charge the capacitor can store per unit voltage. For a parallel-plate capacitor with a dielectric, it is given by:

$$C = \epsilon_0 \epsilon_r \frac{A}{d}$$

Where:

- $\epsilon_0 \approx 8.854 \times 10^{-12} \text{ F/m}$ is the permittivity of free space.
- ϵ_r is the relative permittivity (dielectric constant) of Teflon.
- A is the area of the plates.
- d is the separation distance.

Dielectric Properties of Teflon

Teflon (polytetrafluoroethylene, PTFE) exhibits:

- $\epsilon_r \approx 2.1$ (dimensionless)
- High dielectric strength ($\sim 60 \text{ MV/m}$), allowing for high voltages without dielectric breakdown.
- Low dielectric loss and excellent chemical stability, making it a preferred dielectric in many applications.

Step-by-Step Calculation

1. Convert Given Parameters to SI Units

- Area (A): 2.30 m^2 (already in SI units)
- Separation (d): $1.10 \text{ mm} = (1.10 \times 10^{-3}) \text{ m}$
- Relative Permittivity (ϵ_r): 2.1

2. Calculate Capacitance

Applying the formula:

$$C = \epsilon_0 \epsilon_r \frac{A}{d}$$

Plugging in the values:

$$C = (8.854 \times 10^{-12} \text{ F/m}) \times 2.1 \times \frac{2.30}{1.10 \times 10^{-3}}$$

Calculations:

$$\text{Numerator: } (8.854 \times 10^{-12} \times 2.1 \times 2.30 \approx 8.854 \times 2.1 \times 2.30 \times 10^{-12})$$

Let's compute step-by-step:

- $(8.854 \times 2.1 \approx 18.5934 \times 10^{-12})$
- $(18.5934 \times 2.30 \approx 42.796 \times 10^{-12})$

Now, divide by (1.10×10^{-3}) :

$$C \approx \frac{42.796 \times 10^{-12}}{1.10 \times 10^{-3}} = \frac{42.796}{1.10} \times 10^{-12 + 3} = 38.905 \times 10^{-9} \text{ F}$$

Expressed in standard units:

$$C \approx 38.9 \text{ nF}$$

Result: The capacitance of the capacitor is approximately 38.9 nanofarads.

Practical Implications and Applications

Having established the capacitance, engineers and scientists can analyze how such a device would perform in real-world applications.

Energy Storage

The energy (U) stored in a capacitor is given by:

$$U = \frac{1}{2} C V^2$$

Where (V) is the applied voltage. For example, at 1000 volts:

$$U = \frac{1}{2} \times 38.9 \times 10^{-9} \times (1000)^2 = 0.01945 \text{ J}$$

This illustrates that even large-area, high-separation capacitors can store relatively modest amounts of energy unless operated at very high voltages.

Dielectric Strength and Breakdown

Teflon's dielectric strength (~60 MV/m) indicates the maximum electric field it can withstand without breakdown:

$$E_{\text{max}} = \frac{V_{\text{max}}}{d}$$

Given the maximum voltage:

$$V_{\text{max}} = E_{\text{max}} \times d \approx 60 \times 10^6 \times 1.10 \times 10^{-3} \approx 66,000 \text{ V}$$

This suggests the capacitor could, in theory, handle voltages up to approximately 66 kV before dielectric failure, although practical limits and safety margins are always considered.

Advanced Considerations

Effect of Plate Geometry and Edge Effects

While the ideal formula assumes infinite plates, real plates have edges that cause non-uniform electric fields, slightly decreasing the effective capacitance. For large plates like 2.30 m^2 , edge effects are minimal but still relevant in precision applications.

Temperature and Frequency Dependence

Teflon's dielectric properties exhibit minimal variation with temperature and frequency, making this capacitor suitable for high-precision and high-frequency applications.

Parasitic Capacitances and Losses

In practical circuits, parasitic effects such as stray capacitances and dielectric losses influence performance. Teflon's low dielectric loss minimizes energy dissipation, beneficial for high-Q circuits and energy storage.

Broader Context and Future Perspectives

The calculation of a capacitor's parameters based on physical dimensions and dielectric properties is fundamental in designing electronic components. As technology advances, the miniaturization of capacitors with high capacitance values in small volumes becomes essential, especially in mobile devices and integrated circuits.

Emerging materials with higher dielectric constants, such as ferroelectrics or nanostructured dielectrics, are pushing the boundaries of capacitance density. However, materials like Teflon remain relevant due to their stability, low loss, and well-understood behavior.

Furthermore, the principles outlined here extend beyond static calculations. Engineers must consider factors like dielectric aging, breakdown mechanisms, and thermal effects to ensure reliability and longevity of capacitors in demanding environments.

Conclusion

This detailed exploration of a parallel-plate capacitor with specified dimensions and dielectric material underscores the importance of fundamental physics in practical engineering. By calculating the capacitance as approximately 38.9 nanofarads, we gain insight into the device's capacity to store electrical energy and its operational limits.

Such analyses are vital in optimizing electronic systems, from power supplies to communication devices, ensuring safety, efficiency, and performance. The interplay of geometric parameters, material properties, and electrical

principles exemplifies the elegance and utility of classical electromagnetism in modern technology.

In an era increasingly reliant on compact, high-performance electronic components, understanding and accurately calculating capacitor parameters remains a cornerstone of innovation and scientific progress.

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