FROM CASIMIR TO TRIBOELECTRIC EFFECT

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Abstract. The present work proposes to establish a connection between Casimir and triboelectric effects, as a response whether Casimir effect can be one of the causes of the appearance of triboelectric charges. The Casimir effect consists in a force arising in the microscopic world between two uncharged bodies as a result of radiation pressure of vacuum fluctuations, due to modification of the zero-point energy associated with the electromagnetic modes in the space between them. On a submicrometre scale, this force becomes so strong that it becomes the dominant force. The triboelectric effect consists in the appearance of electric charges with opposite signs at the contact of two surfaces belonging to dissimilar materials. Contact electrification can occur at solid-solid, liquid-liquid or solid-liquid interfaces. The study addresses the triboelectric charging as an interfacial phenomenon of interacting insulating surfaces, taking into account that water absorption influences the charging mechanism and the role of Casimir forces as dominant at sub-micron distances.

Keywords: Casimir effect, triboelectric effect, ionic dissociation, triboelectric charges, interfacial.

1. Introduction

The triboelectric effect consists in the appearance of electric charges with opposite signs at the contact of two surfaces belonging to dissimilar materials. Contact electrification can occur at solid-solid, liquid-liquid or solid-liquid interfaces. When rubbed against each other, two insulating materials acquire a net electric charge, with one becoming negative and the other positive. This method of charging usually referred to as triboelectrification or frictional charging [6, 7]. The charges transferred between two solid bodies put into contact are in most case electrons, but in some situations, an ion transfer appears [8].

Based on the results obtained from electrostatic separation experiments performed on mixtures containing different types of polymers, the authors validate an original physical model for the tribocharging of two insulating surfaces in the presence of a thin water film. This model is consistent with the observation that tribocharging between two insulating surfaces first increases with the increase of the relative humidity of the ambient air, achieves a maximum, and then decreases. The authors observed that the maximum charge transfer occurs at a 1 nm thickness of the interposed water layer between the contacting surfaces.
The Casimir effect describes the interaction between two parallel surfaces, in which each experiences a small attractive force towards the other in the absence of particle exchange. It was originally predicted by Hendrick Casimir in 1948 while investigating van der Waals forces in colloidal liquids for Phillips Research Labs. In his treatment of the phenomenon, Casimir attributed the attractive force between two parallel plates to small fluctuations around the expectation value of the ground state vacuum energy in the electromagnetic field. The force then experienced by the plates is proportional to area, but inversely proportional to the quadratic distance between the conductors.

\[ F_c = \frac{\pi^2 \hbar c}{240 A r^2} \]  

FIGURE 1. Allowed normal modes inside the cavity and net force on the parallel conductors due to radiation pressure.

The force between uncharged conducting surfaces, the so-called ‘Casimir force’, was described by Schwinger as one of the least intuitive consequences of quantum electrodynamics. For conducting parallel flat plates separated by a distance \( r \), this force per unit area has the magnitude [1, 2]:

This relationship can be derived by consideration of the electromagnetic mode structure between the two plates, as compared with free space, and by assigning a zero-point energy of \( \frac{1}{2} \hbar \omega \) to each electromagnetic mode. The change in total energy density between the plates due to modification of the mode structure compared with free space, as a function of the separation, \( r \), leads to the force of attraction. Because the strength of the force falls off rapidly with distance, it is only measurable when the distance between the objects is extremely small. On a submicrometre scale, this force becomes so strong that it becomes the dominant force between uncharged conductors. In fact, at separations of 10 nm—about 100 times the typical size of an atom—the Casimir effect produces the equivalent of 1 atmosphere of pressure.
(101.3 kPa), the precise value depending on surface geometry and other factors. The only fundamental constants that enter equation are $h$ and $c$, the Plank constant and light velocity; the electron charge, $e$, is absent, implying that the electromagnetic field is not coupling to matter in the usual sense. The term ‘Casimir effect’ is applied to a number of long-range interactions, such as those between atoms or molecules (retarded van der Waals interaction) and an atom and a material surface (Casimir–Polder interaction) and the attraction between bulk material bodies.

For real materials, equation (1) must break down when the separation, $r$, is so small that the mode frequencies are higher than the plasma frequency (for a metal) or higher than the absorption resonances (for a dielectric) of the material used to make the plates. In analogy with the attractive forces between atoms, the force in this range is sometimes referred to as the London–van der Waals attraction, while the $1/d^4$ range is referred to as the retarded van der Waals (Casimir) interaction. For the Casimir force, the crossover distance between the regimes is $d \sim 100$ nm, much larger than the atomic spacing in the materials, and so it still makes sense to describe the materials by their bulk properties. Therefore the crossover between the two regimes appears to be of physically different origin compared with the case of the attractive forces between isolated atoms.

2. Theoretical considerations

Triboelectric charging is an interfacial phenomenon, depending by two fundamental mechanisms [4, 5]:

1. The electron transfer between two contacting insulator surfaces.

2. The presence of ionic species on the surfaces, case in which the charge exchange takes place as a flux and exchange of oppositely charged ions.

Charging experiments made in ambient air of higher humidity show that water is able to control the charging behavior, by means of ionic species.

Water absorption influences the charge mechanism; a water layer covers most surfaces in air with a thickness that varies from a monolayer to a microscopic thin film. Therefore, the sign and magnitude of the charge depends on the material type and on the relative humidity of the atmosphere in which the process takes place.

Whenever a continuous film is formed, the water provides a medium for dissociation of ions. The usual hypothesis is that the ionic species arise from a self-ionization process of adsorbed water on the surface: $\text{H}_2\text{O} \leftrightarrow \text{H}^+ + \text{OH}^-$. Water dissociates at the interface: ions of opposite polarity to the interfacial charge (counter ions) provided by the dissociation of water at the
interface, are attracted to it while ions of the same polarity are repelled. One polarity of charge will be held, relatively tightly bound at the interface, with ions of the other polarity attracted to the bound charge, to form a diffuse double layer extended into the liquid at a distance \(d\) (Fig. 2). As a result, on the interface appear counter ions (ions on the interface). Some of these electrons neutralize a part of the counter ions and the released recombination energy determines the extraction of supplementary electrons, determining the appearance of an interfacial double layer, which extends in the particle on the distance [8]:

\[
I = \left( \frac{2eV_c}{\epsilon N_d} \right)^{1/2}
\]  

where \(V_c\) is the contact potential at the water-insulator interface, \(\epsilon\) the dielectric constant of the interface, \(e\) the electronic charge and \(N_d\) the concentration of the localized states of the electrons in the conduction band.

The surface potential relates to the surface charge density \(\sigma_s\) as [6,8]:

\[
V_c = (\sigma_s / \epsilon) / l
\]  

A first conclusion is that at water-insulator interface, there will be an immediate flow of electrons from the insulator surface states to the surface.

During the collision between two insulated particles intermediated by a thin water layer a charge transfer in the contact layer (formed by superposition of the diffuse layers) appears due to the negative and positive charges being in excess on each particle. Ions of opposite polarity moves under the action of the contact field (the contact layer field), a part of they recombines with the electrons from the interfaces, but, due to the grater mobility of the electrons, only a part of they recombines, determining in this way a supplementary ionic
charging of the particles. After the impact, the particles move away one from another and the surfaces of insulators become bipolar charged in the transfer region.

To put in evidence the Casimir effect on triboelectrification begin with the interaction between two dielectric plane parallel surfaces, separated by a distance $r$ across a medium “$m$”, which can be an aqueous medium. Each of the bodies is semi-infinite, filling the space to the left or the right of the surface, as in Fig. 3.

![FIGURE 3: Dielectric plane parallel surfaces, separated by an aqueous medium](image)

While each of these bodies is electrically neutral, it is composed of moving charges so that at any given instant there is can be a net positive or negative charge at any given location, an instantaneous configuration of charges throughout the space occupied by the bodies and a corresponding electromagnetic field throughout those bodies and the space around them. When “A” and “B” are far apart the behavior of their charges and field will depend only on their own material properties and that of the surrounding space. When they come to a finite separation, the electrodynamic work, or free energy to bring bodies A and B to separation $r$ from an infinite separation in medium $m$ depends on there being a difference in the dielectric permittivity $(\varepsilon_A - \varepsilon_m)$ and $(\varepsilon_B - \varepsilon_m)$ of each of the bodies and the medium [6].

In this case the surface density of Casimir force becomes [3, 6]:

$$f_c = \frac{\pi^2 \hbar c}{240 r^2} \Delta_A \Delta_B \Delta \Delta R_n$$

(4)

Where: $\Delta_A = \frac{\varepsilon_A - \varepsilon_m}{\varepsilon_A + \varepsilon_m}$, $\Delta_B = \frac{\varepsilon_B - \varepsilon_m}{\varepsilon_B + \varepsilon_m}$ and $R_n$ the relativistic screening function. For small distances (< 10 nm) $R_n \to 1$ and for large distances $R_n \sim 1/r \to 0$

To simplify the analysis, the geometry is reduced to a model as shown in Fig. 4. The particles are approximated by two dielectric planes between exists an interposed water layer.
Thus the only degree of freedom of the system is the gap $r$ between the dielectric plates. Taking into account the little oscillations of the surfaces during collision, due to the elasticity of the interposed water layer, the equilibrium condition of the plates by Casimir, electrostatic and elastostatic forces: $f(r) = f_e + f_{elec} + f_{elast} = 0$, yields:

$$\frac{\pi^2 h c}{240 r^2} \Delta \Delta + \frac{\varepsilon_m V^2}{2r^2} - K(L - r) = 0$$  \hspace{1cm} (5)

With $V$ the potential difference between surfaces, determined by their triboelectrocharging, $L$ the thickness of adsorbed water layer at the particle’s surfaces and $r$ the equilibrium distance during collision. $K$ is the effective spring constant of the system particle A-water-particle B.

![FIGURE 4: One-dimensional model](image)

The equilibrium is stable with: $\frac{\partial f(r)}{\partial r} < 0$. By using the critical condition $\frac{\partial f(r)}{\partial r} = 0$ and defining solution by $r_i$ we get the surface charge density of the surfaces after impact:

$$\sigma_s = \varepsilon_m \frac{V(r_c)}{r_c} = \sqrt{2 \varepsilon_m \left[ K(L - r_c) + \frac{\pi^2 h c}{240 r_c^2} \Delta \Delta \right]}$$  \hspace{1cm} (6)

As can see, in this approximation, the surface tribocharge density strongly depends on the physical properties of the system, reflected mainly by Casimir force.

### 3. Conclusions

The triboelectric charging is an interfacial phenomenon of interacting insulating surfaces, depending on electron and ion transfer.
Water absorption influences the charge mechanism, the sign and magnitude of the charge depends on the material type and on the relative humidity of the atmosphere in which the process takes place, by thickness of interposed water layer.

Considering the role of Casimir forces as dominant at sub-micron distances, the surface tribocharge density can strongly depend on that.

References