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The critical droplet size in a misty plasma

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Abstract

A misty plasma is defined as a plasma containing small liquid droplets. An expression for the minimum droplet radius, below which condensation cannot occur, is derived from the Rayleigh charge limit condition.

1 Introduction

It is customary to consider the dust in a dusty plasma to be solid particles, but, in fact, there are many situations in which plasmas contain macroscopic liquid droplets. These include: thermal spraying, which frequently uses liquid droplets injected into a plasma jet [1]; fusion plasmas in which small pieces of wall material can become detached and melt in the plasma [2,3]; and particle growth in discharges, in which condensation to the liquid state often takes place [1]. With regard to the last of these, condensation of water vapour has even been observed in processing discharges [4]. In these situations it would seem more appropriate to use the term "misty plasma".

Many aspects of the physics of such systems are identical to those of conventional dusty plasmas. However, the particles are now deformable and subject to a surface tension force, and this gives rise to some interesting new effects. In this paper we combine the well known predisposition of macroscopic objects in plasmas to acquire charge with the equally well known Rayleigh limiting charge, to find a minimum droplet size in a misty plasma.

2 Timescales

There are three important timescales for misty plasma droplets: (1) *charging*, i.e., the timescale on which the steady state charge of the droplet changes, given by $\tau_{ch} = \omega_{pi}^{-1}$ (where $\omega_{pi} = (n_0 e^2/m_i \epsilon_0)^{1/2}$ is the ion plasma frequency, and n_0 is the background plasma electron number density), (2) *hydrodynamic*, i.e., the timescale on which fluid deformations occur, given by $\tau_{hyd} = a/c_{sd}$ (where a is the droplet radius and c_{sd} is the sound speed in the liquid, and (3) *vaporization*, i.e., the timescale for the droplet to evaporate, given by $\tau_{vap} = Lm_d/\Gamma_E A$ (where L is the latent heat of vaporization, m_d is the droplet mass, Γ_E is the energy flux onto the droplet, and $A = 4\pi a^2$ is the droplet surface area. To evaluate τ_{vap} we note that the energy flux associated with neutrals in the discharge is usually negligible, and in steady state the ion and electron particle fluxes onto the droplet surface are equal.

For water droplets in an Argon plasma ($n_0 = 10^{16}$ m^{-3}, $T_e = 5$ eV) we obtain the following estimates for these timescales: $\tau_{ch} \simeq 4.8 \times 10^{-8}$ s; $\tau_{hyd} \simeq 7.1a$ s, and $\tau_{vap} \simeq 8.5 \times 10^3 a$ s (where a is the droplet radius in metres). We notice that $\tau_{vap} >> \tau_{hyd}$ and $\tau_{vap} >> \tau_{ch}$. Thus, for the phenomenon of interest here, involving electrostatic deformations of the droplet, we can neglect evaporation. Furthermore, for all but the very smallest (nanometre) droplets $\tau_{hyd} >> \tau_{ch}$, and we can use the instantaneous steady state charge, as given by conventional dusty plasma considerations (see below). For very small droplets the charge can still change faster than τ_{hyd} since the electron response is at ω_{pe}^{-1} ($\simeq 1.8 \times 10^{-10}$ s for the above conditions), even if the steady state charge is not attained.

3 The Rayleigh limit

Plasma immersed macroscopic objects acquire a charge. For most plasmas of interest the Debye length, λ_D, is much greater than the size of the "dust grains". For instance, a plasma with $n_0 = 10^{16}$ m^{-3} and $T_e = 5$ eV has $\lambda_D = 166$ μm, whereas most dust grains or droplets are micron or sub-micron size. In this situation the charge on a dust grain/droplet, of radius a can be written $Q_d = 4\pi\epsilon_0 a\phi_d$, where ϕ_d is the potential of the dust grain/droplet.

The charge on a liquid drop in vacuum is limited by the Rayleigh condition [5]. This is obtained by considering the linear stability of a spherical drop. In equilibrium the charge, Q, is uniformly distributed over the spherical surface, and the outward electrostatic and liquid pressure forces are balanced by the inward surface tension. A small perturbation will modify these forces and, assuming that the total charge on the drop is constant, the condition for stability is $|Q| < Q_R$, where

$$Q_R = 8\pi(\epsilon_0 \gamma a^3)^{1/2} \tag{1}$$

and γ is the surface tension of the liquid involved. If $|Q| > Q_R$ the electrostatic force will tear the drop apart. This process has recently been observed experimentally [6].

If we simply apply this condition to a misty plasma, i.e., impose $|Q_d| < Q_R$, we find that the droplet radius, a, must exceed a critical value

$$a_{crit} = \frac{1}{4}\epsilon_0 \frac{\phi_d^2}{\gamma} \ . \tag{2}$$

Interestingly, this minimum droplet size, below which condensation will not occur, is proportional to γ^{-1}. This is in contrast to the usual situation for uncharged droplets, in which the minimum radius, found from Kelvin's equation (for the equilibrium saturation ratio) [7], is proportional to γ.

In order to evaluate a_{crit} we need to specify ϕ_d and γ. The most basic charging mechanism is by collection of ions and electrons from the plasma. This produces a particle potential which is traditionally calculated from orbit-motion limited (OML) theory [8,9]. In this case $\phi_d = -\Lambda(kT_e/e)$, where Λ is a weak (logarithmic) function of m_i/m_e and T_i/T_e with a value of order unity. Thus, in OML, ϕ_d depends only on the properties of the background plasma, and is independent of the properties of the droplet itself.

For most liquids the surface tension falls nearly linearly with temperature. In low temperature discharges we can assume that the droplets are in approximate thermal equilibrium with the neutral gas. Thus we conclude that a_{crit} increases with both the electron temperature (through ϕ_d) and the neutral gas temperature (through γ).

For an Argon plasma with an electron temperature of 5 eV, and a neutral temperature of 350 K we find for water $a_{crit} \simeq 4.3$ nm. This is the lengthscale at which the transition from molecular cluster to droplet occurs. It is therefore difficult to quantify the extent to which droplet growth in plasma is electrostatically impaired using the simple theory described here.

4 Generalising the Rayleigh limit

Clearly, a more refined theory is required, and there are several obvious directions in which the refinements might be sought. Firstly, the Rayleigh condition itself needs to be rederived for misty plasmas. Here, the droplet is subject to extra inward forces due to electron pressure and ion bombardment. Furthermore, the assumption of constant charge in the stability analysis is not appropriate, since hydrodynamic effects are always slower than the timescale for charge adjustment. However, in order to take account of charge variations we need a convincing charging theory. The choice of such a theory is the second, and much harder, part of building an improved model.

There is reason to believe that the ABR radial motion theory [10] is more valid than OML. Even without a modified Rayleigh condition this is an important issue, since in ABR the droplet potential, ϕ_d, is not independent of a and the scaling of a_{crit} would therefore be different. Other processes should also be included (e.g., secondary electron emission).

Once an appropriate charging model has been established, other modifications could be explored. Two possibilities here are charging in strong plasma flows, e.g., in the sheath of a discharge, and deformations due to inter-droplet forces.

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