Pressure of liquid metal droplets in tokamak plasmas

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Abstract

The pressures of molten metallic droplets in fusion tokamaks are investigated by using the modified Laplace equation (MLE). Based on this, we can determine the region of plasma parameter space in which equilibrium droplets can exist. As a metallic droplet submerged in a plasma with low plasma temperature evaporates, it can reach a very high liquid pressure before the equilibrium breaks down due to electrostatic effects.

1 Introduction

It has been known for some time that solid macroparticles ("dust grains") are produced by plasma-surface interactions in tokamaks. The increasing use of metal for plasma-facing surfaces, as exemplified by JET with ITER-like walls and ITER [1], implies that metallic dust grains will be present in future tokamaks. Under fusion conditions, such dust grains can rapidly melt. In the TEXTOR-94 tokamak [2], metallic dust grains were collected, a significant number of which were spherical. This implied that they have been melted at some stage. We therefore need to consider the physics of misty plasmas [3], i.e., plasmas containing small liquid droplets.

2 Misty Plasma Physics

In misty plasmas [3], the pressures acting at the surface of a droplet are: a total external material pressure (TEMP); a pressure due to a surface tension (P_{ST}); and an electrostatic pressure (P_{ES}). The TEMP is the sum of ion (P_i) and electron (P_e) pressures and an effective pressure due to a neutral recombination (P_r). For small droplets ($r_d \leq \lambda_D$), where r_d is the radius of a droplet and λ_D is a Debye length, for which electron emissions can be neglected as a charging mechanism, the OML theory [4] can be used to find the droplet potential (ϕ_d) and the relevant pressures namely:

$$P_i = \frac{1}{2} n_i k_B T_i \left[2\left(\frac{2}{3}\hat{V}+1\right)\sqrt{\frac{\hat{V}}{\pi}} + \exp(\hat{V})\operatorname{erfc}\left(\sqrt{\hat{V}}\right)\right] \tag{1}$$

$$P_e = \frac{1}{2} n_e k_B T_e \exp(-V) \tag{2}$$

$$P_r = \frac{2}{\pi} n_e k_B (T_e T_d)^{1/2} \exp(-V) \left(\frac{m_i}{m_e}\right)^{1/2} \tag{3}$$

where $V = \frac{e|\phi_d|}{k_B T_e}$, $\hat{V} = V\frac{T_e}{T_i}$, n_e and n_i are electron and ion number densities, T_e and T_i are electron and ion temeratures, m_e and m_i are electron and ion masses and T_d is a droplet temperature. The pressure due to a surface tension is

$$P_{ST} = \frac{2\gamma}{r_d} \tag{4}$$

where γ is a surface tension. The electrostatic pressure is

$$P_{ES} = \frac{\varepsilon_0 \phi_d^2}{2r_d^2} \tag{5}$$

Unlike the other pressures, this pressure acts in an outward direction. From this, we can establish the *modified Laplace equation (MLE)* for the liquid pressure of a droplet, which is

$$P_{liq} = P_i + P_e + P_r + P_{ST} - P_{ES} \tag{6}$$

3 Droplet Equilibrium

With regard to the MLE, no equilibrium is possible beyond the limit of $P_{liq} \to 0$ because P_{liq} must be non-negative. In this work, we consider tungsten (W) droplets, as this is the main material used in the divertors of ITER and JET with ITER-like walls [1]. The droplets are submerged in a hydrogen plasma. We assume a constant value of a surface tension for tungsten (W), $\gamma = 2.5\,\mathrm{N\,m^{-1}}$ [5]. By varying the plasma number density ($n_e = n_i = n$), the electron temperature ($T_e = T_i$) and the radius of a droplet (r_d), we can establish the region of $\mathrm{n - T_e - r_d}$ parameter space, in which an equilibrium droplet can exist. We refer to this as the *droplet equilibrium diagram*, and it is shown for W droplets in a hydrogen plasma in figure 1. Figure 2 is a cross-section of this diagram at $r_d = 10^{-6}\,\mathrm{m}$.

As can be seen on figure 1 and 2, we can distinguish three regions: region 1, in which an equilibrium is dominated by a surface tension; region 2, in which an equilibrium is dominated by an ion pressure; and region 3, in which no equilibrium is possible. The boundaries between these region are also important. At the boundary between region 1 and 2, both P_{ST} and P_i are significant. The boundary between region 1 and 3 represents the Rayleigh limit for an electrostatic breakup [6]. The boundary between region 2 and 3 represents the breakdown of the equilibrium due to the electrostatic effects, the details of which have not been studied. From figure 2, it is noticeable that for 1-μm droplets, most SOL plasma parameters occupy region 1. However, for smaller droplets, the SOL moves into region 3. This implies that W droplets whose size is in the order of $10^{-6}\,\mathrm{m}$ should be mostly discovered because it is not easily to encounter the rapid disintegration caused by electrostatic effects.

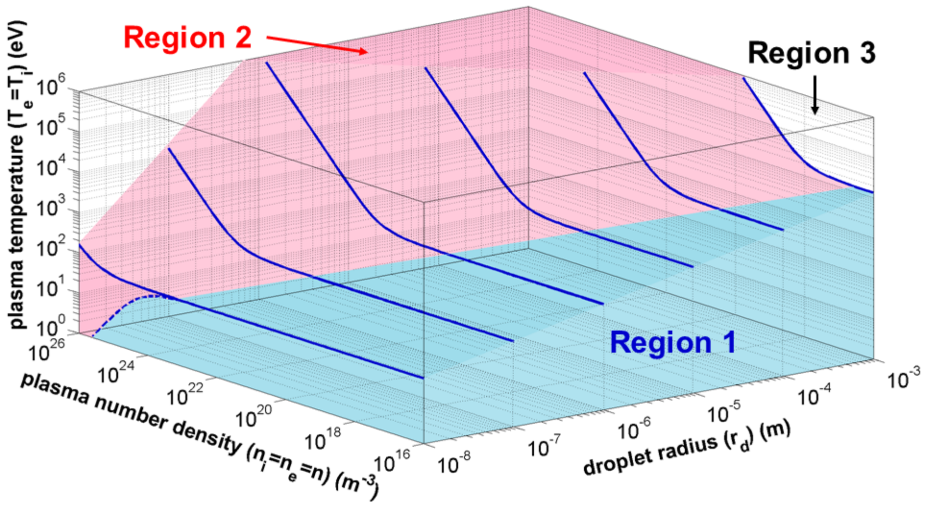

Figure 1: Three-dimensional droplet equilibrium diagram for W droplets.

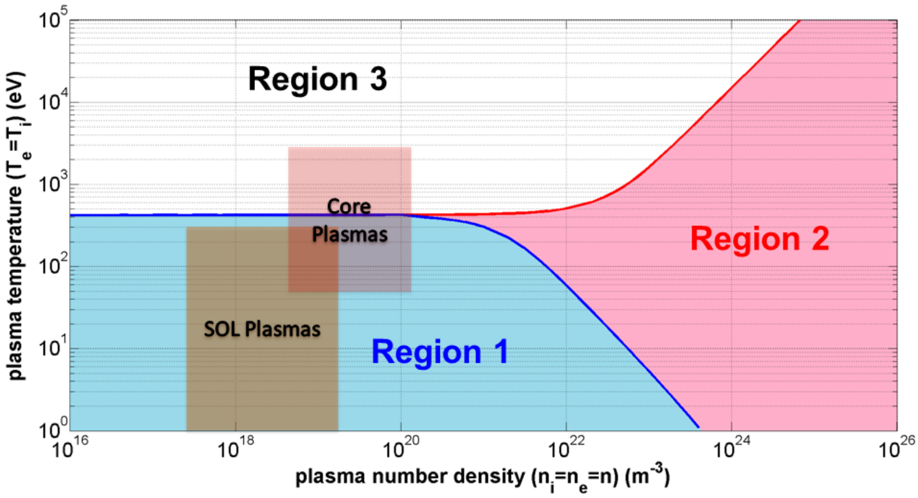

Figure 2: Cross-section of the droplet equilibrium diagram (figure 1) for $r_d = 10^{-6}$ m.

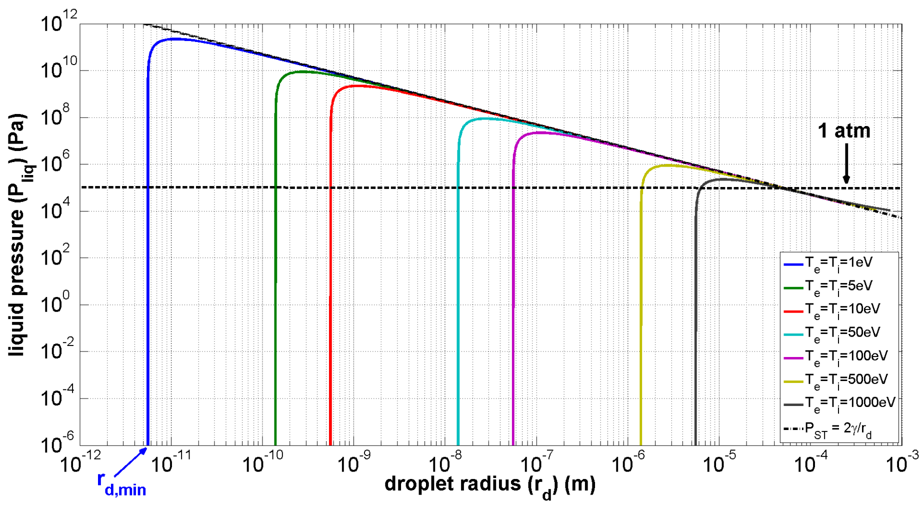

Figure 3: P_{liq} against r_d for W droplets with $n_e = n_i = n = 10^{19} m^{-3}$ and various T_e.

4 Liquid Pressure of a droplet

As the droplets evaporate, r_d falls. From the MLE, we can plot P_{liq} against r_d for various $T_e (= T_i)$ which correspond to fusion conditions (see figure 3). From figure 3, we see that the liquid pressure can greatly exceed 1 atm especially for the SOL plasma parameters (Te $<$ 100eV). This means that the thermodynamic properties of the droplet material, e.g. a boiling temperature, may well be modified. This issue should be considered during the modelling of a metallic dust grains in tokamaks.

5 Conclusions

The liquid pressure of an equilibrium droplet in a misty plasma is given by the modified Laplace equation (MLE). For small droplets for which electron emission is negligible, OML theory can be used to calculate an ion pressure, an electron pressure, an effective pressure due to a neutral recombination and a floating potential, which is used to calculated the electrostatic pressure. By using the MLE, we can establish the $\mathrm{n - T_e - r_d}$ parameter space, the *droplet equilibrium diagram*. It is noticeable that there is a region of $\mathrm{n - T_e - r_d}$ parameter space in which no equilibrium is possible, and droplets which cross the boundary of the forbidden region are destroyed by electrostatic effects. In addition, as a droplet evaporates, its radius falls and its pressure rises to a maximum value due to surface tension. In the SOL, the liquid pressure can reach a very large ($\gg$ 1 atm) value. Soon after that, the equilibrium breaks down due to electrostatic effects at the minimum allowed radius ($r_{d,min}$).

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