*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, O-1.07 (2004)*

Dust grain temperature in a tokamak plasma

J.D. Martin[1], M. Coppins[1], G.F. Counsell[2]

1. Imperial College, Blackett Laboratory, Prince Consort Road, London, SW7 2BZ, UK

2. EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon OX14 3DB, UK

1. Introduction

In tokamaks, large quantities of dust can be produced during a shot by power flux to the divertor. This has efficiency and safety implications, including erosion of plasma-facing components, impurities introduced by dust evaporating near the core plasma, and tritium retention in dust [1]. Evaporation due to arcing during disruptions is thought to produce most of the dust. In a tokamak, surfaces are generally made of carbon fibre composite (CFC), although tungsten will be used in ITER. This paper continues work done by Annaratone *et al* [2] in finding dust grain steady-state temperatures in an isotropic plasma.

The following notation is used: Γ is flux, I is energy flux (intensity). Other symbols have their usual meanings. The subscripts i, e, and d denote ions, electrons and the dust grain respectively, and the subscript 0 denotes a property of the bulk plasma.

2. Dust grain floating potential

For a spherical dust grain in an isotropic plasma, the potential (ϕ) can be estimated by the (cold ion) radial motion (ABR) [3] or the orbital motion limited (OML) approach [4]. Fusion considers ions at high temperatures, making OML preferable. The effect of secondary electron emission will be added to the OML model.

If the ion and electron collection areas are the same, then for singly charged ions, the fluxes balance. A fraction (δ) of the incoming electrons will induce secondary electron emission, reducing the flux to $(1-\delta)\Gamma_e$. Equating ion and electron fluxes gives an expression for the floating potential

$$(1-\delta)\exp(-V) = \left(\frac{m_e\beta}{m_i}\right)^{\frac{1}{2}}\left(1+\frac{V}{\beta}\right) \tag{1}$$

where $V = -e\phi/(k_B T_e)$ and $\beta = T_i/T_e$. The dust grain reaches the floating potential within a few ion plasma periods, much quicker than the heating time.

If the secondary electron yield exceeds 1, this theory will break down (this happens for tungsten, but not carbon). The electron current will be negative and the dust grain will charge positively, until the secondaries are trapped in a confining potential. As the majority of secondaries are at about 3eV, we assume a potential of 3V. We take ions to be Maxwellian all the way to the grain, and take $\Gamma_i = \Gamma_e$ in this case.

3. Heating and Cooling Mechanisms

Incoming particles add thermal energy to the dust grain material through collisions. Ions gain energy as they are accelerated through the sheath. The total energy for ions will be the one-way flux at the presheath edge ($2k_B T_i \Gamma_i$) plus the energy gained in the potential (assuming no collisions). The ion and electron energy fluxes at the grain are therefore

$$\begin{aligned} I_i &= (2k_B T_i + V k_B T_e)\Gamma_i \\ I_e &= (2k_B T_e)\Gamma_e \end{aligned} . \qquad (2)$$

Conversely, for a positively charged grain, electrons are accelerated and ions are assumed to be Maxwellian. The effect of neutrals will be ignored.

Incoming plasma particles with enough energy are able to dislodge electrons from the material. The dominant component comes from electron bombardment. The secondary electron emission coefficient (δ) for an electron beam has an analytic expression [5]. For a Maxwellian electron distribution, one can integrate numerically to find δ as a function of T_e. If we assume an average energy loss per electron of 3eV, the energy flux is $-3e\delta\Gamma_e$.

Backscattered particles take away a fraction of the incoming bombardment energy. The fraction of energy backscattered (R_E) is well described by empirical laws [6]. Only backscattering of ions is significant. In the case of negatively charged dust we assume that the ion distribution at the grain surface retains the shape that it has in the plasma, but each individual ion gains an energy $|e\phi|$. One integrates over the OML ion energies to find R_{Eav}. The energy flux lost is then $R_{Eav} I_i$. For a positively charged grain, a Maxwellian distribution can be used for the integration.

Energy is liberated by recombination of electrons and ions, the energy per reaction being 13.5eV for hydrogen. It is safe to assume all ions incident on the grain will recombine due to large electrostatic forces. If we assume all photons are absorbed, the energy flux gained is $13.5e\Gamma_i$. Similarly, two hydrogen neutrals may form a molecule, releasing 2.2eV. We assume that all neutrals are released as molecules. There is a factor of a half introduced: two neutrals to one molecule, so the energy flux is $1.1e\Gamma_i$. These molecules thermalise with the grain and are released. Each has energy $2k_BT_d$, resulting in an energy flux loss of $k_BT_d\Gamma_e$.

The particle will cool as dictated by Stefan's law. The energy flux lost is $\alpha\sigma T_d^4$ where α is material dependent, and σ is Stefan's constant. This becomes the dominant cooling mechanism at larger grain temperatures.

4. Steady-State Temperatures

At steady-state, the net power flux is equal to zero. The balance is independent of the dust grain radius, but does depend on the material. The particle can survive indefinitely if the predicted steady-state temperature is less than the evaporation/sublimation temperature. Graphite sublimes at 3925K, but tungsten will not evaporate until it reaches 5930K. We assume that tungsten particles stay intact in the liquid phase.

Figure 1 shows predicted steady state temperatures for a graphite and tungsten dust grain with a range of electron temperatures. For typical MAST densities (10^{18}m^{-3}) graphite dust reaches a steady state for $T_e \leq 70$eV. In contrast, for JET/ITER densities (10^{19}m^{-3}) graphite dust will only reach steady state in temperatures below 15eV. Tungsten shows interesting behaviour as the dust grain charge flips sign at around 112eV changing the particle bombardment terms. At temperatures above this the steady-state temperature drops significantly. It appears discontinuous, but this is probably due to the fact that both suggested charging models break down around this temperature. When the grain is charged positively, the flux of ions and electrons is determined by the Maxwellian ion flux, and due to the average ion velocity being much lower than the average electron velocity, this lowers the fluxes, and therefore the temperatures significantly. According to these results, tungsten dust in MAST only evaporates in a band of temperatures just below 112eV, otherwise it is stable. In JET/ITER, it can survive below 50eV, and from 112-180eV.

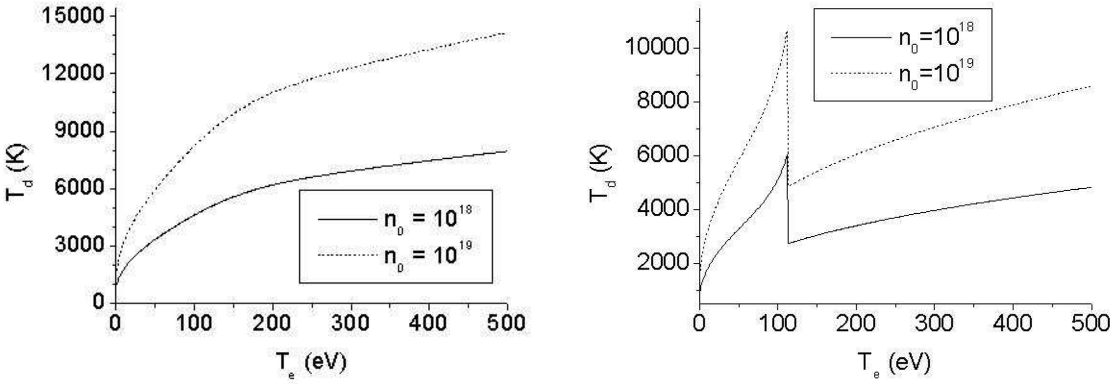

Figure 1. Steady state temperatures with $T_i = T_e$ for a graphite dust grain (left), and a tungsten dust grain (right) for typical densities in m^{-3}.

5. Conclusions

It has been shown that dust can survive in plasmas of high temperature. More work needs to be done on positively charged grains in order to check the behaviour of tungsten. The model will be used with a plasma background from a code in order to make predictions about the survivability of dust.

Acknowledgements This work was jointly funded by the United Kingdom Engineering and Physical Sciences Research Council and EURATOM.

Bibliography

[1] J. Winter, Phys. Plas., 7 (2000), 3862

[2] B. M. Annaratone, J. E. Allen, S. N. Karderinis, D. A. Law, W. H. Steel, E. B. Tomme, Report, UKAEA Fusion

[3] J. E. Allen, R. L. F. Boyd, P. Reynolds, Proc. Phys. Soc., 52 (1957), 297

[4] H. Mott-Smith, I. Langmuir, Phys. Rev., 28 (1926), 756

[5] E. W. Thomas, J. Nucl. Fus. Supplement, 1 (1991), 79

[6] E. W. Thomas, R. K. Janev, J. Smith, J. Nucl. Inst. Methods Phys. Res., B69 (1992), 427