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Thermal Shock in Powder Targets

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Thermal Shock in Powder Targets

1. Introduction

Consider a free jet of tungsten powder travelling at a speed of 10-20 m/s. If an intense pulsed proton beam hits the jet on its axis with the same beam diameter as the jet, the powder will absorb some of the beam energy and heat up. With a 10 GeV beam of 1 MW pulsed at a repetition rate of 50 Hz, the powder will heat up approximately 150°C per pulse. The beam pulse is assumed to be 3 ns long.

If every particle of the powder is separated from all other particles, the thermal expansion of the particles will have no affect on the motion of other particles or the jet. However, the free particles will be able to vibrate in various modes. Love [1] gives two types of vibration:

<u>1.1.Vibrations of the First Class.</u>

There are no radial motions only rotary vibrations - which are waves of distortion (equivoluminal). The wave velocity is,

$$c_1 = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{E}{2(1+\nu)\rho}}$$

where μ is the shear modulus, E is the elastic modulus, ν is Poisson's ratio and ρ is the density of the particle. Putting in values for tungsten, E = 411 GPa, ν = 0.28 and ρ = 19254 kg m^{-3} gives c_1 = 2626 m s^{-1}.

The ratios of the time taken for the wave to travel across a diameter to the period of oscillations are given by: 1.8346, 2.8950, 3.9225, 5.9489, …. , for the fundamental frequency and the first few harmonics.

1.2. <u>Vibrations of the Second Class.</u>

1.2.1. Radial

Here the vibrations are radial and are waves of dilation (irrotational). The wave velocity is,

$$c_2 = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{(1-\nu)E}{(1+\nu)(1-2\nu)\rho}}$$

Putting in values as before, gives c_2 = 4751 m s^{-1}. The ratios of the time taken for the wave to cross the sphere to the periodic time of the oscillations are, 0.816, 2.9359, 3.9658, … , for the fundamental and the first few harmonics. The fundamental frequency for a sphere of 100 μm radius, a = 0.0001 m is,

$$f = 0.816\frac{c_2}{2a} = 19.39 \text{ MHz.}$$

1.2.2. Spheroidal

In addition to the radial vibrations, there are ellipsoidal vibrations. The frequency of the fundamental vibration is given by,

$$f_e = \frac{0.84}{2a}\sqrt{\frac{E}{2(1+\nu)\rho}} = 11 \text{ MHz}$$

2. Two Particles Touching Each Other – The Long Pulse Case.

Now consider two particles in the powder which are in contact near the surface of the jet, see Figure 1. Each particle, assumed to be a sphere of radius a = 100 μm (= 0.1 mm), will expand by,

$$da = \alpha \cdot a \cdot dT$$

where α is the coefficient of thermal expansion of the particle and dT is the temperature rise. The surface velocity of the particle relative to its centre is,

$$u = \frac{da}{\tau}$$

where τ is the length of the beam pulse. If the beam pulse is long compared to the period of oscillation (see Section 1) then we can treat the motion quasistatically. The velocity of the centre of each particle along the line joining their centres is u in equal and opposite directions. Putting in values gives, u = 22.5 m/s.

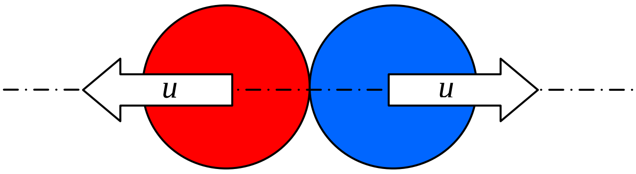

Figure 1. Two touching powder particles.

The powder jet is not completely densely packed but approaches 50% of the solid density. Hence most of the particles will be touching another particle and some will have their centre lines directed not far from radial to the jet axis. This will produce energetic particles escaping from the jet and hitting the enclosure with velocities of up to 20 m/s.

In the case where there are a number of coalescing particles, the velocities can be higher. Consider a clump of many particles of dimension 2A, see Figure 2. A particle at the surface will experience a velocity of,

$$U = \frac{\alpha \cdot A \cdot dT}{\tau}$$

Assuming that A = 1 mm, gives a velocity of U = 225 m/s and if A = 5 mm, U = 1125 m/s. Clearly clumps are best avoided and every effort needs to be made to keep all the particles separate and the particle size small.

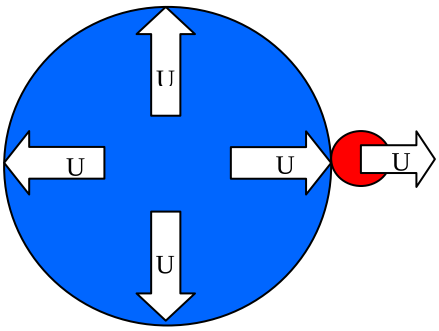

Figure 2. A particle (red sphere) at the edge of a large clump of particles (blue sphere).

3. Two Particles Touching Each Other – The Short Pulse Case.

Take the previous case, but assume that the beam pulse is short (3 ns) compared to the natural radial period of oscillation of the sphere. Thermal shock can be expected when the length of the beam pulse is less than one half of the period of oscillation. In Section 1, the radial frequency of a 100 μm radius sphere of tungsten was shown to be 19 MHz. The periodic time is 52 ns, considerably longer than the duration of the beam pulse; hence there will be the possibility of thermal shock being produced in the particles of the powder. The particles would need to have a radius of ≤ 2 μm to avoid the possibility of thermal shock. For ellipsoidal oscillations, the periodic time is 91 ns, again considerably longer than the beam pulse length, so shock is quite possible in the powder particles.

The maximum radial excursion will be,

$$A = 2\alpha \cdot a \cdot dT$$

and this will occur in half a period of the oscillation. The radial excursion is given by an equation of the form,

$$a(t) = A\cos(2\pi ft + \theta)$$

where A is the amplitude of the vibration, f is the frequency of vibration and θ is a phase term. Differentiating the amplitude term with respect to time gives the velocity equation of the form,

$$u(t) = 2\pi fA\sin(2\pi ft + \theta)$$

The maximum surface velocity of a free particle is $2\pi fA$ and occurs immediately after the beam pulse. Assuming two particles of equal mass are initially touching each other, then the point of touching will remain stationary and the centre of the particles will achieve a velocity of one half of the free surface velocity after one half of the oscillation cycle. After this time the radial oscillation reverses and thus the two particles are no longer in contact; they fly apart each with a velocity πfA. The velocity will be of the order of 100 m s^{-1}. Larger velocities can be expected when clumps of powder occur.

This is a somewhat idealised view of the motion of the two particles. In many cases the particles will be of different masses, not be spherical and deform under the stress particularly at the point of contact. Intuitively, one imagines the particles may vibrate spheroidally. Also, this assumes that the outer radius of the powder jet receives the maximum power, whereas it is only the particles near the axis that will heat to 150°C and they will have less chance of escaping from the jet. Clearly the motion is complicated.

4. Conclusions

1. The powder particles will suffer some degree of thermal shock.
2. There is a possibility that some particles could receive large transverse velocities which could damage the surrounding enclosure.
3. Further calculations are required to evaluate these possible problems.

References

[1] A. E. H. Love, A Treatise on the Mathematical Theory of Elasticity, Cambridge University Press. 2nd Edition, 1906.