ASSESSMENT OF A PARTICLE BED BASED BEAM STOP

N. Simos[*], H. Ludewig, P. Montanez, M. Todosow
Brookhaven National Laboratory, Upton, New York, USA 11973

Abstract

Accelerator target/beam stop concepts able to withstand the thermal shock induced by intense, undiluted beams are being assessed in this study. Such conditions normally push target materials beyond their limits leading to limited useful life. A number of ingenious options have been attempted to help reduce the level of stress generated. Attention is paid to a very promising option that calls for a target consisting of a cooled particle bed. In such configuration the ability of the particle bed structure to diffuse and attenuate the generated thermal shock waves is being explored by performing comprehensive dynamic analyses that incorporate anticipated energy depositions, thermal diffusion, and wave propagation and attenuation. Further, options of coolant liquid filling the porous structure of the particle bed, including concerns of pressure drop and heat transfer, are evaluated for maximizing particle yield.

1. INTRODUCTION

High performance accelerator targets able to withstand the thermal shock induced by intense, undiluted beams are being assessed by various groups interested in a variety of accelerator applications. Such conditions normally push target materials beyond their limits leading to limited useful life. A number of ingenious options have been attempted to help reduce the level of thermal stress generated by such fast, high intensity beams. A very promising option has been the one that calls for a target or a beam stop consisting of a cooled particle bed. In such configuration the ability of the particle bed structure to diffuse and attenuate the generated thermal shock waves is being utilized. In this study, the survivability potential of such particle-bed like scheme is explored by performing a comprehensive dynamic analysis that incorporates energy deposition estimates, thermal diffusion and wave propagation and attenuation. Specifically, attention is focused on the response of a single sphere interacting through surface contact with the surrounding particle bed and subsequently on the overall response of the particle bed resembling a porous structure. Of interest in the study is how stress waves emanate from the beam-intercepting region and subsequently attenuate as they travel through the particle bed. Pressure drop and heat transfer in a particle bed are addressed on the basis of particle size. The particle size, along with the beam profile and beam time-structure are key elements in the optimization procedure which is necessary for the selection of the right packed bed configuration.

2. PARTICLE BED ANALYSIS

2.1 Pressure Drop and Heat Transfer

In determining the parameters of a particle bed the particle size and coolant velocity are primary values from which the bed pressure drop and surface film temperature drop can be determined for a given coolant type. It is important to minimize the pressure drop (to reduce the forces, and the implied loads on the structural components), and simultaneously to minimize the film drop in order to avoid coolant boiling at the particle surfaces and particle over-heating. Boiling can be suppressed by operating at elevated pressures. However, this option is not very desirable, since pressure vessels would require thicker walls in this case, which implies added radiation heat deposition, and increased thermal stresses. The coolant velocity is determined by the requirement to remove the heat generated in the volume. Assuming inlet and desired outlet conditions the enthalpy rise per unit mass of coolant can be determined and given the total power the mass flow rate and the velocity follow. In the case of gas cooling an elevated pressure is desirable to increase the coolant density.

The pressure drop correlation for randomly packed spheres is given by:

$$\Delta p = \frac{X\rho V_o^{\,2}(1-\varepsilon)}{d_p\varepsilon^3} f(1-\varepsilon)$$

Where, f is a friction factor (1.75 + [150/Re_p]), X is the particle bed length in the flow direction, ρ is density, V_o is the approach velocity, d_p is the particle diameter, ε is the bed porosity , ν is kinematic viscosity and Re_p is the modified Reynolds number

$$\mathrm{R}e_p = \frac{V_o d_p}{\nu(1-\varepsilon)}$$

The Nusselt number correlation, used to determine the heat transfer coefficient is given by,

$$Nu = [0.631(1\text{-}\varepsilon)/\varepsilon]\{0.622(\mathrm{R}e_p)^{2.32} + 6.34\mathrm{x}10^{-4}\,(\mathrm{R}e_p)^3\}^{0.25}\{\mathrm{Pr}/0.71\}^{0.333}$$

[*] simos@bnl.gov
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where, Nu is the Nusselt number hd_p/k, h is the heat transfer coefficient, k is the thermal conductivity and Pr is the Prandtl number.

The film temerature drop can be estimated from the following relationship,

$$\Delta T = P_o/hA$$

Where, P_o is the power per unit volume of bed, A is the heat transfer area per unit volume of the packed bed ($A = 6(1- \varepsilon)/d_p$ for spheres). Based on the above relationships it can be shown that for a bed of randomly packed particles the pressure drop and film temperature drop vary approximately in the following ways, as functions of particle diameter and velocity only,

$$\Delta p \sim V^2/d_p \quad ; \quad \Delta T \sim d_p^{5/4}/V^{3/4}$$

where, Δp is the pressure drop across the packed bed, and ΔT is the film temperature drop between coolant and particle surface. The above relationships indicate that it is not possible to simultaneously minimize both the pressure drop and film temperature drop, and thus a compromise is required. In the case of gas cooled targets the ambient pressure is generally increased in order to increase the coolant density, which in turn implies a reduction in the coolant velocity for a given power extraction requirement and thus a reduction in the bed pressure drop. The compromise in this case must thus be extended to include the ambient pressure. In the case of water-cooling the avoidance of boiling in the bed is the primary criterion, and thus the particle surface temperature must be below the saturation temperature at all points within the bed. This comment also applies to other liquid coolants. However, in the case of liquid metals the probability of boiling is much lower, and pressure is generally not of concern. Thus an appropriate particle diameter must be chosen to result in an acceptable film drop and particle surface temperature. Finally, in the case of liquid metal coolants the pressure (both ambient and pressure drop) and film drop are not of primary concern, but the mixed mean outlet temperature will be. It is desirable to keep this temperature within practical limits in order to guarantee that the target will have a reasonably long life, while operating in the implied radiation environment. In addition, the entire outlet duct network will have to operate at the elevated temperature.

2.2 Thermal Shock Considerations

In combination with the thermal considerations discussed above, the promise of a packed particle scheme in absorbing and diffusing an undiluted beam is explored. What the particle bed promises is the attenuation of stress wave generated in the "heated" zone and propagating outward. Borrowing the concept from the study of the dynamic response of saturated porous media where, in bulk terms, stress waves attenuate more due to sharing of energy between the solid and fluid phases as well as frictional effects between the particles making up the solid skeleton, it is anticipated that the thermal stresses experienced by the packed bed outside the heated zone are reduced significantly when compared to a solid volume. While the benefit of the packed bed can be realized in the larger scale, the survivability of the bed particles intercepting the incoming beam will depend almost entirely on three parameters, namely, the particle diameter, the beam spot size relative to the diameter and the pulse structure.

The relation between the pulse length and the particle diameter has been dicussed in length in [1]. It is analytically shown that the ratio t_{pulse}/t_{travel}, where t_{pulse} is the pulse length and t_{travel} is the time it takes the sound to traverse the particle diameter, controls the level of dynamic stress in the particle that follows the initial thermal stress of same magnitude within the heated zone. Thus, if the deposition of energy in the particle is "slower" than the sound propagation, the dynamic stress is reduced. Thus, a choice of particle size can be made based on the pulse length while considering the effects of the previous section regarding the heat transfer requirements.

This study also investigated the relationship between the beam spot size and the diameter of the particle. Specifically, for the applicable case in which the beam spot radius is smaller than that of the diameter, the ability of the particle to dynamically relax from the initial quasi-static thermal stress state depends on the ratio of the two radii.

Figure 1 depicts an idealized arrangement of packed bed particles with the central element intercepting the beam. Shown in Figure 2 are the radial stresses in the central particle for two ratios of beam spot radius to particle radius while the particle is not in contact with the surrounding bed. Based on the stress amplitudes which indicate that the center of the particle experiences the same stress at the end of the pulse, the subsequent stress wave field is quite different. Indeed, the particle sees less stress as a result of the stress wave propagation and reflection.

Figure 3 depicts various times of the thermal stress propagation in the particle arrangement of Fig. 1 by considering the non-linear surface contact between the particles but ignoring the possible contribution of the fluid in the "porous" structure. The latter is expected to be of significance when a liquid metal playing the role of coolant. In such case, the liquid will absorb a potion of the beam, heat-up and induce its own pressure waves plus, due to its high acoustic impedance, will allow for stress waves to propagate outward through its interface with the particles and not just through the contact points alone.

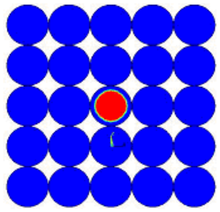

Figure 1: Packed bed arrangement used in study

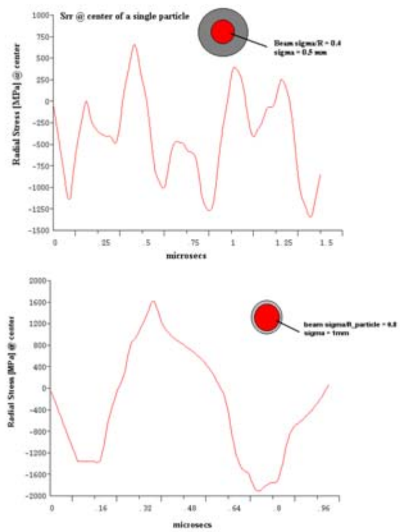

Figure 2: Radial stress at the center of a particle for different ratios of particle diameter and beam spot size

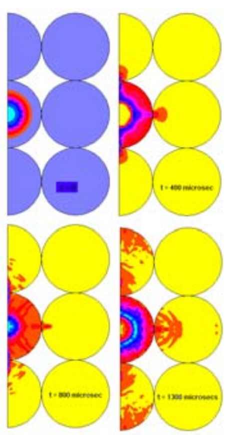

Figure 3: Stress wave propagation snop-shots in a packed particle arrangements

Figure 4 is a comparison of the stress experienced by the central particle with and without interaction with the rest of the particles in the bed. Clearly, the interface conditions, for the shown ratio of beam spot to particle radii, do not help reduce the stress levels in the heated particle. Of importance, however, are the results shown in Figure 5 where the stress in the neighboring particle has been reduced dramatically.

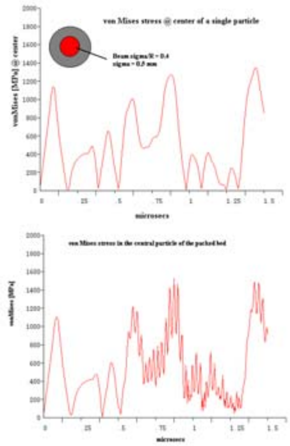

Figure 4: von Mises stress observed in central particle of packed bed for: (a) no interface with surrounding bed and (b) interface conditions shown in Fig. 3

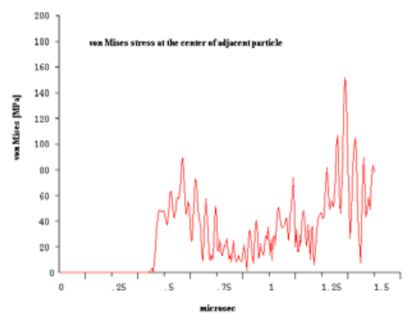

Figure 5: von Mises stress in the particle adjacent to the one intercepting the beam

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