Shatter Thresholds and Fragment Size Distributions of Deuterium-Neon Mixture Cryogenic Pellets for Tokamak Thermal Mitigation

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Abstract – **Reliable mitigation is necessary to eliminate the detrimental effects of a disruption event in large high-current tokamaks such as ITER. To avoid serious damage to plasma facing components during the thermal quench phase of a disruption, material is injected to radiate the plasma energy over the inner surface of the machine. The most promising method of material injection is a process known as shattered pellet injection (SPI). SPI utilizes cryogenic cooling to desublimate gas into the barrel of a pipe gun to form a solid pellet. High pressure gas or a mechanical punch is used to dislodge the pellet and accelerate it into a bent tube to intentionally fracture it. Pellets made of a mixture of deuterium and neon are likely candidates for thermal mitigation. The survivability of these pellets throughout their flight path, before striking the shatter tube, is essential for reliable SPI operation. Experiments were conducted to determine intact speed limits for various mixtures. This paper outlines the details of brittle fracture theory and compares a theory-based model to experimental results from various mixtures of deuterium and neon pellets.**

Index Terms—Cryogenic Pellets, Mixed Gas Pellets, Disruption Mitigation, Shattered Pellet Injection, Brittle Fracture Mechanics

I. Introduction

ITER selected shattered pellet injection as the baseline disruption mitigation system (DMS) on ITER. Experiments on DIII-D have shown that SPI is more effective at radiating the thermal energy of the plasma than massive gas injection (MGI) [1]. The current design for the ITER DMS utilizes pellets of various sizes and compositions for different roles in the mitigation process. Figure 1 in Ref. 2 shows the temporal evolution of a disruption mitigated using the SPI technique. Thermal mitigation using SPI will utilize deuterium-neon mixture pellets that contain a small (~20% by molar fraction) amount of neon. This will provide an effective radiator of plasma kinetic energy. The pellet injected for thermal mitigation greatly increases the density, which, in theory if dense enough will suppress the production of runaway electrons. Runaway electron dissipation, if needed, will be provided by very large high-Z (argon) pellets to collisionally dissipate the runaway electrons; so they do not impact the wall as a coherent beam.

As the pellets transverse the guide tubes, gate valves, and pumping gaps in the flight path between the barrel and shatter tube, there is a possibility of small angle impacts with the wall or funnels used to collimate the pellets as they make jumps across gaps in the flight tubes. Previously, we published results on the survivability of pure single species deuterium, neon, and argon pellets as a function of normal impact velocity [3]. This paper presented and applied a brittle fracture model on experimental data of the post-shatter fragment sizes in the shatter plume. The model, based on a theory of explosive fragmentation, showed good agreement with the experimental data. Understanding the normal impact limitations and fragment size distributions as a function of deuterium-neon mixture levels is important for optimizing the effectiveness of the pellets used for thermal mitigation and suppression of runaway electron formation. The following sections of this paper will discuss experimental and theoretical mixture pellet survivability limits and post-shatter fragment size distributions of deuterium-neon mixture pellets of various ratios.

II. Mixed Gas Pellet Fracture Thresholds

The model for pellet fracture thresholds, outlined in Ref. 3, hypothesizes that to shatter a cryogenic pellet, a fraction of the total cohesive strength of the pellet must be achieved in the kinetic energy of the impact. This fraction is dependent on the crystal structure of the material. Since the pellets are formed in low-pressure (< 100 mbar) environments, the resulting crystal structure of the pellet will have many voids and imperfections resulting in a weak pellet structure. The fraction, X, of energy required to initiate fracture in a pellet is defined by;

$$X = \frac{\sigma_{th}}{\sigma_{coh}} = \frac{\frac{1}{2}mv_{perp}^2}{V\sigma_{coh}} \tag{1}$$

where σ_{th} and σ_{coh} are the fracture threshold strength that needs to be exceeded to initiate fracture and the cohesive strength of the crystal lattice of the pellet, m is the mass of the pellet, v_{perp} is the component of the velocity perpendicular to the plate, and V is the volume of the pellet. Simplifying and substituting the perpendicular impact threshold velocity, v_{th}, for v_{perp}, the threshold strength can be expressed as;

$$\sigma_{th} = \frac{1}{2}\rho v_{th}^2 \tag{2}$$

where ρ is the density of the pellet material and v_{th} is the perpendicular impact threshold velocity in which pellets traveling below that speed have a 100% survival rate. This survivability limit is defined as the highest velocity in which the pellets do not chip or crack when impacting a surface. Previous research has shown that deuterium has a normal impact threshold velocity of 20 m/s and that this speed limit is independent of pellet size [4]. This model is dependent on knowing the properties and crystal structure of the pellet material. Almost no data are available on the strength or physical properties of solid deuterium-neon mixtures. Studies of deuterium-neon mixtures that are desublimated onto a cold (~6 K) surface have a unique crystal structure, which is dependent on temperature and mole percentage of neon in the mixture [5]. The crystal structures of pure neon and deuterium are stable FCC and HCP and are well understood. When temperatures are low, relative to the triple point of deuterium, the crystal structure of the mixtures contains a metastable HCP lattice comprised of both deuterium and neon. Above 50 mole-% neon, pure FCC neon appears along with the metastable HCP D_2-Ne phase. The unknown interatomic distances of the metastable HCP lattice make the theoretical ratio, X, difficult to calculate because interatomic distances are needed to calculate the cohesive strength of the material. The normal impact velocity is measured, and the density is inferred from the data presented in Ref. 5. Densities of pellets that are 26%, 59% and 77% neon by mole-% were calculated using data from Ref. 5 and found to be 0.61, 1.11, and 1.34 g/cm^3. Densities of pure solid deuterium and neon are 0.2 and 1.44 g/cm^3, respectively. These density values assume that large voids do not exist in the pellet structure.

Experiments were conducted using a mechanical punch [6] to dislodge and accelerate 12.5 mm pellets of these mixtures into an angled plate downstream. The angle of the plate can be adjusted to vary the normal impact velocity. It was found that solid mixtures of deuterium and neon exhibit a mass dependency on the impact fracturing threshold velocity. Using pellets that are 26%, 59% and 77% neon by molar fraction, a threshold velocity as a function of molar fraction was found. Figure 1 shows the result of the effect of molar percent of neon on the impact fracturing threshold velocity of the pellet. As molar percentage of neon increases, the threshold velocity drops at a rate proportional to the mass percent of neon in the pellet until the neon limit is reached. As mixtures approach 77% neon by molar fraction the pellets tend to start acting like pure neon with respect to strength and shattering thresholds, rapidly approaching the 8 m/s speed limit. At a molar fraction of 77% the mass fraction of neon in the pellet is ~0.94.

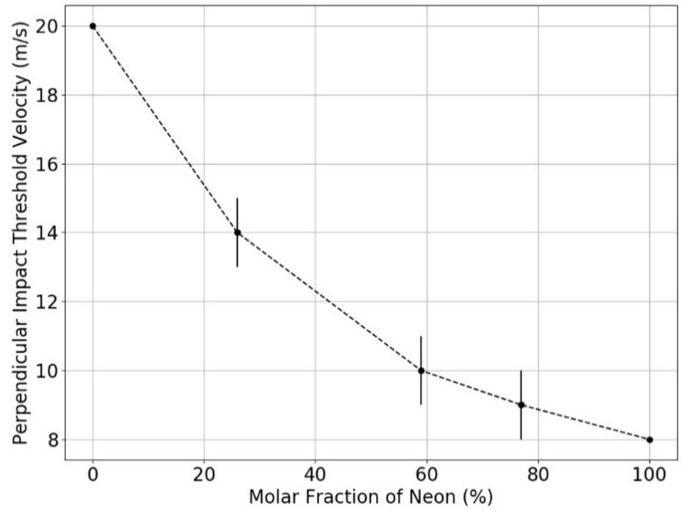

Figure 1. A plot showing the effect of molar percent of neon in mixed gas pellets to the fracture threshold velocity.

III. Mixed Gas Pellet Fragmentation Model

The pellet fragmentation model is derived from a statistical solution of wave propagation through a brittle material with a cylindrical geometry. The theory behind this model and its implementation is outlined in Ref. 3, where it is applied to pure deuterium, neon, and argon pellets. Equation 3 shows the expression for the relative probability distribution function of fragment sizes. It is expressed as;

$$f(d) = \alpha d K_o(\beta d) \tag{3}$$

where d is the characteristic shard diameter, in cm, α and β are explained below and have units of cm^{-1}. K_o is a modified Bessel function of the second kind that is used to account for the propagation of energy through the pellet's cylindrical geometry. The constants α and β can be expressed as;

$$\alpha = X_R/D \tag{4a}$$

$$\beta = \frac{X_R}{L * C} \tag{4b}$$

where X_R is the ratio of normal impact kinetic energy to threshold kinetic energy. The threshold kinetic energy is defined by the normal threshold velocity experimentally measured in the first part of this paper. X_R can be simplified to be expressed as v_{perp}^2/v_{th}^2 for the specific material in question. This ratio is essentially the excess energy beyond initial pellet fracture that is available for cascade breakdown of the crystal structure of the pellet. D, L, and C are the pellet diameter, length (both expressed in cm), and pellet material constant. The constant is assumed to be linear with respect to the neon mass fraction, ω_{Ne}, in the pellet. The constant parameter we use, explained in Ref. 3, is given by;

$$C = 2.5(1.5 + \omega_{Ne}) \tag{5}$$

Experimental agreement with this model was found by the impact studies using 12.5 mm deuterium-neon mixture pellets. The pellets were fired with a mechanical punch for slow speeds, and a high-pressure fast-gas valve for fast pellets. The pellets struck down-stream shatter tubes with a 10, 20, or 30-degree miter bend. Figure 2 shows two images of shattered pellet plumes exiting the shatter tube with the 20-degree miter bend. Both pellets in this image are 26% neon by molar fraction. The pellet in the top image had a normal impact velocity of 140.2 m/s, which corresponds to an X_R ratio of 100.3. The pellet in the bottom image has a normal impact velocity of 259.9 m/s and an X_R ratio of 344.7. The difference in the resulting fragment sizes is obvious in this side-by-side comparison. In Fig. 3 we plot the model's theoretical relative probability of resulting particle size, shown in Eqn. 3, for the two cases shown in Fig. 2 along with two cases using pellets that are 59% neon by molar fraction. The shot parameters are labeled on the plot. The 77% neon by molar fraction pellets are not shown on this plot because they have a distribution that is very similar to the 100% neon pellets (seen in [2]). This is likely because they are ~94% neon by mass. The amplitudes of the theoretical curves shown in Fig. 3 are relative values. The amplitudes of the curves with respect to each other are irrelevant. To compare theory to experiments, Fig. 4 shows a plot of the actual measured particle size distribution (Eqn. 3) for the same cases shown in Fig. 3.

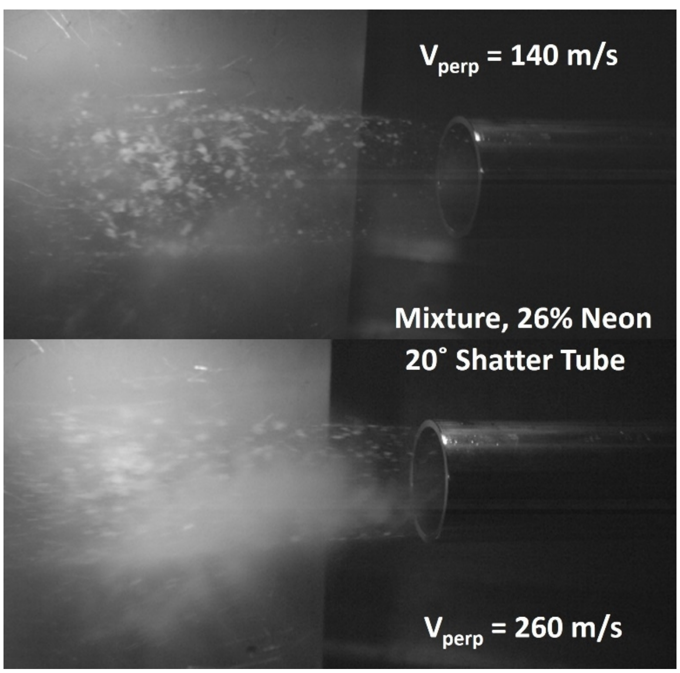

Figure 2. An image showing the resulting shatter plume of two different speed deuterium-neon mixture pellets that are 26% neon by molar fraction. These pellets have impacted the same 20-degree shatter tube. The initial velocities of these pellets were 410 m/s (top) and 760 m/s (bottom).

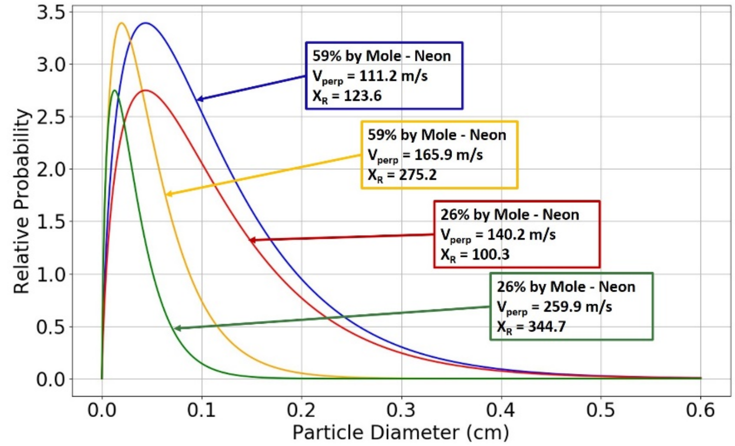

Figure 3. Model theoretical relative probability of shard size for the multiple deuterium-neon mixed gas pellet cases.

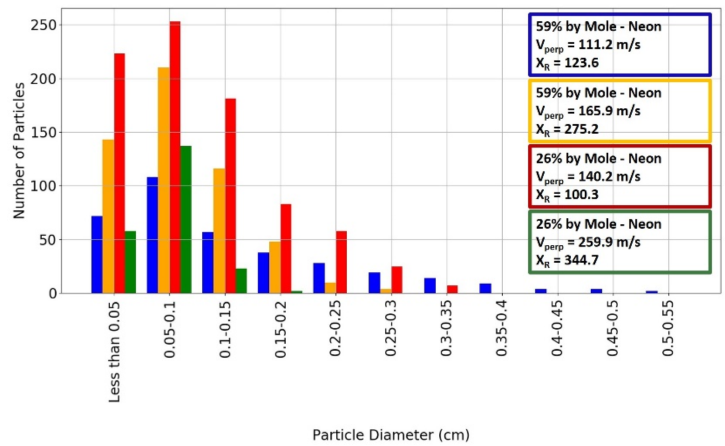

Figure 4. A plot showing the experimentally measured shard size distribution for multiple deuterium-neon mixed gas pellet cases.

As discussed in Ref. 3, the fragmentation process converts some of the solid mass to gas due to heating and compression at the fracture boundaries. The percent of solid mass conversion is compared to the ratio, X_R, in Fig. 5 for pure deuterium and neon, and deuterium-neon mixtures containing 26% and 59% neon by mole. The amount of post-shatter solid mass accounted for, versus X_R, is proportional to the mole percentage of neon in the pellet. The fragment size bins, shown in Fig. 4, were assigned average diameters, which were used to calculate the total mass in the shatter plume based on the number of fragments in each bin and assuming a homogeneous mixture (uniform density) throughout each fragment.

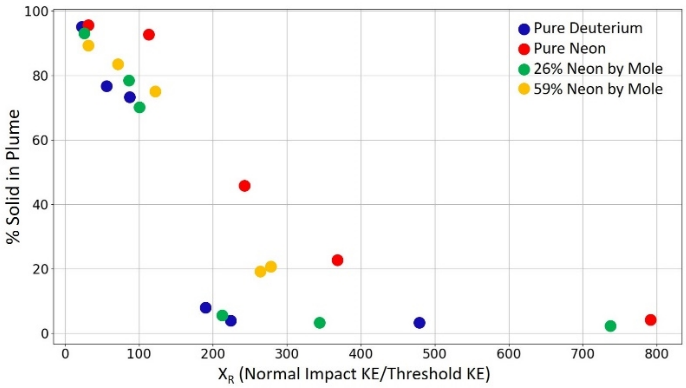

Figure 5. The percent of solid mass acounted for, with respect to the initial pellet, in the shatter plume versus X_R for pure deuterium and neon, and deuterium-neon mixtures containing 26% and 59% neon by mole.

IV. Discussion and Conclusions

The data presented in this paper show that the deuterium-neon mixture pellet SPI parameters of threshold impact velocity, the fraction of solid mass in the shattered plume, and the fragment size distribution, all follow a linear trend between those of pure deuterium and pure neon based on the molar percent or mass fraction of neon in the pellet. The optimal fragment size distribution for SPI thermal mitigation as a function of plasma parameters has yet to be determined experimentally but is a topic of current research. These results are intended to provide a design basis for future experiments and a working model for disruption mitigation simulations.

Acknowledgments

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