PRELIMINARY ASSESSMENT AND ANALYSIS OF CO_2 CLEANING FOR AN INERTIAL FUSION DEVICE

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ABSTRACT

The mechanisms of cleaning with carbon dioxide ice (CO_2) for the National Ignition Facility (NIF) application are discussed and analyzed. The compatibility between this cleaning process and the materials proposed for energy-relevant liquid-interaction experiments is examined. The cleaning mechanisms include kinetic shear stress, sublimation followed by thermophoresis, and solvent action. The study shows that the debris size could determine the efficiency of this cleaning technique. Furthermore, if the condensed vapor particulate becomes flattened and embedded inside the abscissa while hitting the surface, a large kinetic shear would be needed for debris removal which might damage the surface.

INTRODUCTION

One possible method of cleaning the NIF chamber wall, debris shields, and beam dump between shots is to use a solid CO_2 cleaning technique[1]. This cleaning technique involving either a snowflake or a hard pellet of solid dry ice CO_2 was developed as a tool to penetrate the boundary layer and physically transfer energy to the contaminant, thus knocking it off the surface. It was initially proposed for precision cleaning applications and later used on component surfaces of instruments ranging from telescopes to vacuum systems[2-4]. It has been shown to be particularly effective for removing small particles/debris on component surfaces. Recently, the use of the CO_2 pellet blasting technique has been successfully demonstrated as a method of decontaminating the JET (Join European Tokamak) vacuum vessel[5]. Debris analysis from the collected samples shows that the particle diameters lie in the range of 1 to 22 microns.

To produce CO_2 snowflakes, liquid carbon dioxide is released to atmospheric pressure through a nozzle. Spray-cleaning surface with this CO_2 snow has been shown to be an effective method for removing particles and debris. CO_2 snow can also be compressed into hard pellets which are propelled toward a surface with a high-pressure gas as a carrier. In this form, the pellets are blasted at subsonic or supersonic speeds to remove surface contaminants. As an example, dry ice pellets' operating condition uses compressed air ranging from 50 to 250 psig in which pellet velocities can be adjusted from 75 ft/sec to 1000 ft/sec[6]. In applying this technique for NIF chamber cleanup, the kinetic shear force of the pellets must overcome particle-to-surface adhesion yet not to damage the plasma-sprayed aluminum chamber.

The objectives of this study are to identify possible cleaning mechanisms by which CO_2 cleaning removes contaminants, along with associated ranges of operating parameters to be compatible with the NIF environment. These parameters which influence the cleaning effectiveness include contaminant particle characteristics of size, particle-to-surface adhesion forces, temperature gradients, and dislodging shear forces. Material compatibility with the CO_2 cleanup system is examined to ensure that the model materials used for IFE chamber technology testing will not damage the surface.

CLEANUP COMPATIBILITY WITH REGARD TO IFE LIQUID INTERACTION EXPERIMENTS IN NIF

Water, silicone oil, lead eutectic and molten salts (without fluorine or beryllium) are proposed as model materials for experiments in the NIF concerning IFE liquid interactions with debris, x-rays and neutrons[7]. The major concern associated with these IFE technology liquid interaction experiments relates to the management of significant quantities of liquids and their condensable vapors which may be released into the NIF chamber, target debris and beam dumps. A constraint on the chosen model wall (experimental) material would be that any vaporized or droplet material escaping through the model chamber holes should be able to be removed by the NIF Vacuum Recovery System, in this case a CO_2-pellet/snow cleaning system. [Further cleaning involves

Conservation of energy and momentum implies that in an elastic, head-on collision [$\theta \approx 0$] with a CO$_2$ pellet a debris particle will inherit a velocity V given by

$$V = \frac{2v_i}{\left[\frac{M}{m} + 1\right]} \tag{5}$$

where m is the CO$_2$ pellet mass, M the debris particle mass, and v_i is the CO$_2$ particle velocity. For lead particulate diameters of less than 100 microns, V approaches to 2 v_i because a typical m is much greater than M. Obviously, some of the kinetic energy would be lost during the bounce process, and a lower velocity would be expected. Before estimating the required kinetic shear forces for knocking the particles off the surface, the magnitudes of particle-surface adhesion forces are examined.

PARTICLE ADHESION FORCES

One must know the strength of the adhesion force holding the particle before removing a particle from a surface. The adhesion strength is a combination of physical and chemical forces, and mechanical strains and stresses, all at and around that adhesion interface. Adhesion must also be normally approximated geometrically such as by a sphere on a flat surface. For dry, uncharged particles, the main components of the adhesion force are the van der Waals force and the electrical double layer force[17]. Other adhesion forces could result from the establishment of the interfacial reactions such as capillary effect. The bonding between the solidified liquid droplets and the chamber wall could be enhanced by capillary adhesion.

The van der Waals adhesion force between a spherical particle and a flat surface is given by:

$$F_{vdW} = \frac{\hbar\,\omega\, d}{16\,\pi\, z^2} \tag{6}$$

where d is the particle diameter and z the atomic separation distance (typically 4 angstroms). This formula treats the force of adhesion as the force necessary to remove the particle, and as such is a maximum force under ideal conditions for a perfectly spherical particle on a flat surface. The constant $\hbar\omega$ ranges from about 0.6 to 9 eV[18], depending on materials combination. Particle deformation produces an additional van der Waals force as a function of the increased contact area given as:

$$F_{vdW\,/\,def} = \frac{\hbar\omega\gamma^2}{8\pi z^3} \tag{7}$$

where γ is the radius of the adhesion surface area. The total van der Waals force is then:

$$F_{vdW\,/\,total} = F_{vdW} + F_{vdW\,/\,def} \tag{8}$$

Electrical double layer forces are caused by electrostatic contact potentials due to differences in local energy states and electron work functions between two materials, it is given by the equation:

$$F_{el} = \frac{\pi\varepsilon_o(\Delta\phi)^2 d}{2z} \tag{9}$$

where z and d are defined in Eq. 6, $\Delta\phi$ = work function difference, ~ 1V, ε_o = permittivity = 8.9 pF/m[17]. Figure 4 shows van der Waals adhesion and electrical double layer forces versus particle diameter for material combinations of 0.6 and 9 eV and of the effect of particle deformations (which translates a point contact to a surface contact). The gravitational attraction forces calculated for lead particles are also shown in the same graph. These calculations show that deformation due to particle flattening can add tremendously to the total force of adhesion. The results also show that for a particle size less than 100 µm diameter, the adhesion force greatly exceeds the force due to gravity. It also shows that the van der Waals forces could dominate over the electric double layer forces.

CALCULATION RESULTS

The calculated minimum velocities required to shear off the particulate as a function of particulate size are shown in Figure 5 for the lower and upper value of van der Waals adhesion constants. A static friction coefficient of 1.0 is used in the calculations. The calculations indicate that the forces of adhesion are strong enough that extremely high velocities are needed to shear off submicron size particles. Clearly the cleanup involving only kinetic shear forces would be less effective for these sizes of particles. Although not presented in the figure, the calculations indicate that a 100% increase of adhesion force due to the flattening deformation requires a 60% increase of the shearing velocity in order to knock off the particle. At micron sized particle removal, the velocity cannot be below 100 m/s (for $\hbar\omega$=5 eV) or the particle's speed will be reduced to zero before it moves a significant distance.

the assistance of proper chemical scrubbing agents, which is beyond the scope of this paper.]

CO_2 cleaning has been shown to be able to dissolve thin organic layers of oils[2]. This solvent action is due to a thin layer of liquid CO_2 that forms at the collision interface between a dry ice particle and surface. This liquid is generated at the moment of impact when the dry ice particle is deformed. Surface pressure on the dry ice particle rises above the triple point pressure of 75 psia. At this pressure, all three phases : solid, vapor and liquid of CO_2 are present. Liquid CO_2 is an excellent solvent for organics. The liquid film at the interface dissolves the organic film contaminants, which are then carried away in the following flow of CO_2 pellet and vapor. On the other hand, this cleaning technique has failed to remove molecular contaminants[8] and paint-type coating from aircraft surfaces[9]. Thus, based on the results obtained from the aforementioned tests, CO_2 cleaning technique appears feasible for removing silicone oil, however it might be impractical for water molecule removal.

Of particular concern related to metal debris cleanup (such as lead eutectic) is the debris size and structure of the condensed vapor. Condensation within rapidly expanding metal vapors has shown that the metal vapor prefers to condense as droplets as opposed to surface condensation[11]. These experiments were performed using lead and silver exploding wires in a test chamber filled with helium or argon at various pressures (10 millitorr to 760 torr). Although the initial specific energy in the vaporized material is significantly higher than the vaporization energy, the vapor quickly cools due to expansion. The debris analyses from the condensation experiments showed that the aerosol particles were spherical, with sizes ranging from 0.02 to 0.2 microns[11]. Similar particle size distributions were experimentally observed for copper vapor condensation[12]. As shown in Figure 1, cleanup of this range of particle size becomes very difficult with noncontact methods (such as blowing) because the boundary layer associated with the hydrodynamic flow is thicker than the particle sizes. Although CO_2 pellets can easily penetrate the non-turbulent layer immediately adjacent to the surface and dislodge contaminants, the efficiency of removing particle size less than 0.1 micron remains to be studied.

If the vapor condenses in flight [or liquid droplets of stainless steel tube shrapnel], the subsequent molten droplet generally spreads radically to form a thin disc when impacting on a cold surface. The difficulty involved with the subsequent cleanup process is the force required to overcome the adhesion force resulting from the increase of the surface contact area. The final terminal thickness of the flattened disc is controlled by the consumption of droplet kinetic energy against surface and viscous energies during flattening and is also affected by the solidification of the droplet which may occur simultaneously with flattening. The thickness of the flattened particle has been experimentally studied and is expressed as[13]:

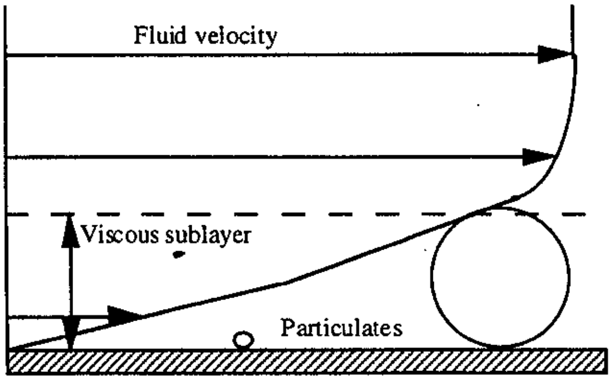

Figure 1. Viscous sublayer near a wall region in a turbulent flow stream

$$\frac{d}{\delta} = \left(\frac{8\rho v d}{\mu}\right)^{0.25} \tag{1}$$

where d = droplet diameter [Hydrodynamic analysis is required in order to determine the pressure history and subsequent condensed droplet diameter], v= velocity, δ = thickness of flattened particle, ρ = density of droplet, μ = viscosity of liquid droplet. Figure 2 shows the thickness of the flattened particle as a function of droplet diameter and subsequent increase in adhesion force due to the increase of surface contact area. The calculation shows that a 1 micron size lead droplet can form an about 0.1 micron thick disk splatter on the surface and lead to a ten thousand times increase in the adhesion force. It becomes clear later that a large increase in the kinetic shear force is required to remove the deformed particle.

CONTAMINANT CHARACTERISTICS OF NIF DEBRIS SHIELDS AND BEAM DUMPS

The object of cleaning the NIF debris shields and beam dumps is to remove the accumulation of shrapnel materials which are produced from structures not vaporized by the laser or ignition yield energy in the vicinity of the target[1]. The primary sources are the target support stalk for non-cryogenic targets and the stainless steel cooling

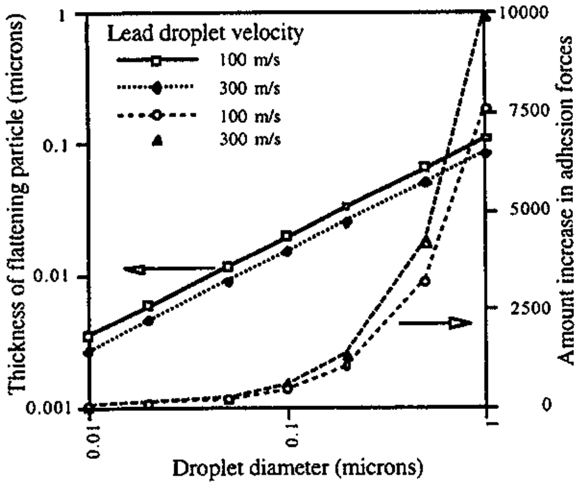

Figure 2. The effect of particle flattening on flattened thickness and increased adhesion force as a function of droplet diameter for different droplet velocities.

tubes for the cryogenic targets. These structures are heated and broken up by neutrons, x rays, and target debris. Both solid fragments and liquid droplets will be propelled radially at velocities of 300 to 3000 m/s. Previous analysis has shown that the anticipated fragment size distribution for stainless steel tube shrapnel gives a range from four hundred 50-μm diameter particles, to ten million 4-μm particles[10]. The fragment size distribution appears to be compatible with CO$_2$ cleaning technique. However the particle sizes must first be confirmed as a NIF development activity.

KINETIC ENERGY TRANSFER AS A CO$_2$ CLEANING MECHANISM

The solid particles such as CO$_2$ pellets have an advantage over the air or liquid cleaning systems in that they can penetrate right to the surface itself- there is no boundary layer effect. As shown in Figure 1, with any hydrodynamic flow, there will be a boundary layer where the velocity is far less than that at some distances from the surface. At the surface itself, the flow velocity must be zero, these effects reduce the chance that small particles will be removed from the surface by fluid flows.

A debris particle adhering to a surface will be dislodged when the removal force provided by the drag and lift of the fluid stream on the particle exceeds the force of particle adhesion. Bhattacharya and Mittal have shown that the force of removal is a function of angle of the applied force[14]. This can be seen with aid of the diagram shown in Figure 3.

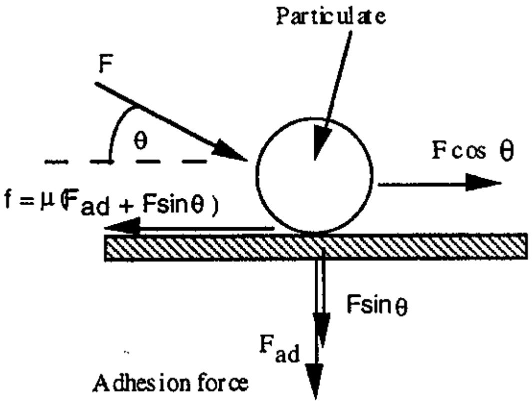

Figure 3. Forces required to remove a particulate

Here F is the force applied to remove the particulate, F_{ad} is the force of adhesion and theta is the angle of the applied force. As can be seen, forces tangential to the chamber wall will be the most effective, and forces normal to the surface will produce a shaking effect. At equilibrium, the force necessary to shear off the particle is thus:

$$F = \frac{\mu F_{ad}}{\cos\theta - \mu \sin\theta} \qquad (2)$$

where μ is the coefficient of static friction. The coefficient of static friction μ found at the interface between an aluminum particulate and an aluminum surface in air is about 1.9[15]. If θ is equal to zero, the minimum operating condition for the particulate to shear off is:

$$F \approx \mu F_{ad} \qquad (3)$$

By assuming that drag is the only removal force acting on a particle residing on a surface, and that the drag can be calculated as though the particle were completely surrounded by the fluid, the force required is:

$$F = F_D = \frac{C_d \rho V^2 A_p}{2} \qquad (4)$$

where C_d is the drag coefficient, ρ is the fluid density, V is the velocity of debris particle in the static stream, and A_p is the particle projected area. Typical results for C_d as a function of the Reynolds number N_{Re} can be found in Ref. 16.

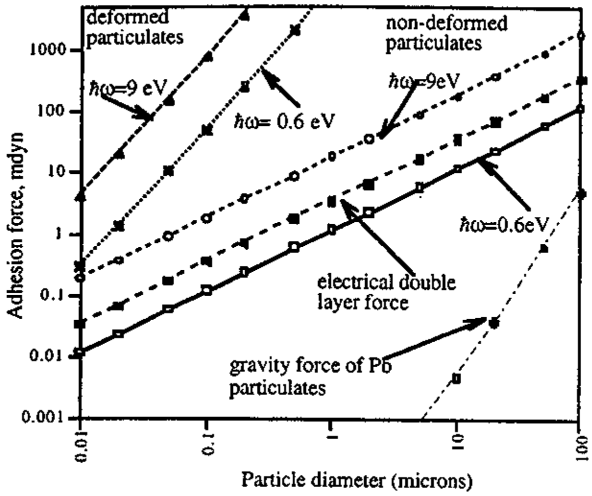

Figure 4. Summary of adhesion forces as a function of particle sizes for van der Wallas adhesion constants of 0.6 and 9 eV.

The calculated minimum required CO$_2$ velocities for removing lead particulates are also shown in the same figure. [The results can be applied to any lighter particulate.] The calculated range of velocity is consistent with the operational condition applied for the decontamination of the JET vacuum vessel where the removed particulate diameters lie in the range of 1 to 22 microns. Example CO$_2$ pellet operating velocities shown in the figure signify its capability for removing stainless steel shrapnel from NIF debris shields and/or beam dumps.

ADDITIONAL CO$_2$ CLEANING MECHANISMS

Aside from mechanical transfer of kinetic energy by physical contact of the CO$_2$ pellet with the particles, there are several other cleaning mechanisms involved in using CO$_2$ cleaning techniques. For example, spray cleaning surfaces with soft flake CO$_2$ snow has been shown to remove particles and other debris without damage to the cleaned surfaces[4]. In this case, the speed with which the CO$_2$ ice moves is of little or no importance. Even a fall by gravity alone is great enough to remove dust particles. One theory as to why the very soft flakes can be effective on removing particles is that when a snow flake comes in contact with a stuck particle, it sits on top of it until it sublimates. This explosive sublimation can be quantitatively understood in terms of the Arrhenius relation. The number N of CO$_2$ molecules capable of sublimation at temperature T out of a total of N$_0$ molecules is given by:

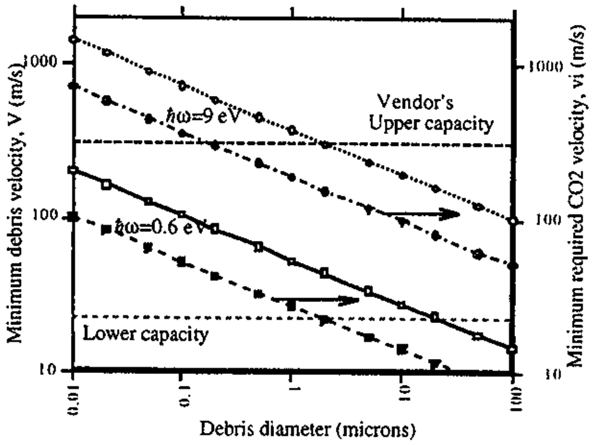

Figure 5. Summary of minimum required velocities to shear off the particulates for different van der Waals' constants

$$N = N_0 \, e^{-E_s/kT} \tag{10}$$

where E_s is the energy of sublimation (= 72 cal/g) and k is Boltzmann's constant. This indicates that about 0.47% of molecules sublimed at the room temperature. Upon sublimation there is a micro explosion as the solid changes to gas. This micro explosion imparts a shock to the stuck particles, providing the force necessary to dislodge the particle.

Once the particulate is dislodged, it must be contained so it is not redeposited on the cleaned surface or another clean area. Most frequently, precision cleaning is done under a laminar flow hood with adequate filtering of the air. As the particles are freed from the surface, they are picked up in the air (or carrier gas) stream and filtered out. However, small particles are attracted and held to the CO$_2$ snow flake by thermophoretic forces. Thermophoresis refers to the force on a particle due to a temperature gradient. It offers the opportunity to protect surface against the re-deposition of the particles. Experimental results indicate that if there is a 50 degree Kelvin per centimeter temperature gradient near a heated surface, the upward velocity of a one micrometer particle of unit density will be 0.15 cm/sec[19]. In contrast, the gravitational settling velocity of a particle of this type will be 0.003 cm/sec. Clearly the particle will never arrive at the surface. With CO$_2$ cleaning, there is approximately 100°C difference in temperature over the distance of a few microns or less[3]. The small particles that are freed become caught in the chimney and are whisked away from the clean surface.

TECHNICAL CONCERNS

I. THERMAL SHOCK

Because the CO$_2$ dry ice has a temperature of - 78.5°C, a sudden drop in surface temperature might occur during the cleaning process and lead to a thermal shock. The temperature excursion necessary to produce cracking in a coating film such as the plasma-sprayed boron (or low-Z high melting material) film in NIF chamber can be estimated by calculating the thermal strain developed in the coating film due to differential expansion. One may then assume that for cracking to occur, the stress induced by the strain has to be equal or greater than the tensile strength of the substrate. This gives[20]:

$$\Delta T = \frac{\sigma}{kY(\alpha_{Al} - \alpha_{Bcoating})} \qquad (11)$$

where σ is the tensile strength of the aluminum, k is the stress concentration factor, αs are thermal expansion coefficients of the aluminum and the low-Z coating (such as boron or alumna), and Y is the Young's modules for the aluminum. The calculated temperature difference is about 90 °C for a k value of 2. Tests have shown that thermal shock is rarely a problem because the time required for the cleaning action is not long enough to drop the surface temperature significantly. Temperature drops of 0.2 to 2.0 °C during normal operations have been estimated for cleaning aluminum plate bombarded by CO$_2$ snowflakes[20]. Such temperature changes are about at least 50 times too small to produce cracking of a boron coating.

II. HIGH PRESSURE OPERATION

The dry ice pellet is powered by a high pressure unit (such as 825 psi), which causes concerns of high pressure destroying critical pieces of equipment. Tests have shown that at the moment of impact, a pressure distribution exists across the particle-surface interface. When the local pressure exceeds the yield stress of the dry ice, the dry ice will yield. The yield stress point is equal to the triple point pressure of 75 psia. At pressure above the triple point pressure, a liquid phase will form which causes it to yield, resulting in an increased impact area. Spreading the impact force over a larger area limits the stress and permits thorough cleaning without destructive forces.

CONCLUSIONS

CO$_2$ snow/pellet blast cleaning method has been shown to be viable for removing a wide range of micron sizes particulate materials off component surfaces ranging from telescopes to vacuum chambers. The cleaning mechanisms include kinetic shear stress, sublimation followed by thermophoresis and solvent action. The sublimation produces a cushion of cold gas on the surface which protects the surface from damage unless the kinetic shear force of the pellet exceeds the plasma-sprayed bond strength (simple calculation shows that this could occur for a 0.5 cm diameter of ice pellet flying at velocity of 181 m/s hitting a plasma-sprayed surface with a typical bonding strength of 35 N/mm^2).

The debris size could determine the efficiency of this cleaning technique. If the particle size falls to submicron ranges, cleanup of these debris (less than 0.1 µm) could become a challenging task for NIF. Experimental studies are needed to determine the debris size distribution with regard to rapid vapor condensation. One of the difficulties encountered during the decontamination process of the JET vacuum vessel was the prevention of the dislodged particles flying around and then adhering to other parts of the chamber. An effective debris collector design becomes essential in order to come up with an efficient NIF CO$_2$ cleaning system.

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