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Disruption Simulation Experiments and Extrapolation to Reactor Conditions

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Laboratory experiments to simulate plasma disruptions have contributed significantly in many aspects to the understanding of the physical processes occurring during high-energy deposition on target material surfaces due to plasma instabilities. Laser light, electron beams, and plasma guns have been used worldwide to study disruption effects and erosion damage of candidate divertor materials. The differences among these simulation experiments are examined. The net power flux reaching the originally exposed surface depends on many parameters, such as type of energy deposited, target material, pulse duration, and geometrical factors. Experimental results have been evaluated and compared with theoretical predictions, and the overall relevance of simulation experiments to reactor conditions has been critically examined.

1. INTRODUCTION

In current tokamak machines, the heat loads and disruption conditions expected in future devices are not achievable. Therefore, the expected conditions during a plasma disruption in future devices must be simulated in laboratory experiments. Laser light, electron beam, and plasma gun devices have all been used worldwide to study disruption effects and erosion damage in candidate plasma-facing materials (PFMs). The majority of these experiments have near-reactor-relevant disruption parameters (i.e., heat loads of 10-20 MJ/m^2 and deposition time of <1 ms).

It is well known that during the early stage of an intense energy deposition, a vapor-cloud from the target debris will form above the bombarded surface in many applications. This shielding layer, if well confined, significantly reduces the net energy flux to the originally exposed surface to only a few percent of the initial value, therefore substantially reducing the surface vaporization rate [1]. The shielding efficiency of this cloud, however, depends on many parameters such as type of energy deposited, target material, pulse duration, and geometrical factors. The net power flux reaching the target surface will determine the net erosion and therefore the lifetime of plasma-facing components (PFCs). Net erosion damage to PFMs due to plasma instabilities includes surface vaporization loss, erosion damage to nearby components from intense vapor radiation, and macroscopic erosion from liquid-metal splashing and brittle destruction of carbon-based materials (CBMs).

Surface erosion from vaporization will depend on the magnitude of the vapor-shielding efficiency and vapor-cloud magnetohydrodynamic (MHD) instabilities. During a typical reactor disruption, an energy density of ≈10-200 MJ/m^2 is deposited within 0.1-5.0 ms. A well-confined vapor cloud can reduce surface vaporization loss by one to two orders of magnitude compared to the loss with no shielding effect. However a well-confined vapor cloud will quickly and intensely radiate most of the deposited plasma kinetic energy to other nearby locations. Secondary erosion damage of these locations will depend on design configuration, as well as on MHD instabilities developed in the vapor cloud. A closed divertor configuration, although desirable for better core-plasma operation, can result in severe damage to components near the original disruption location [2]. Loss of vapor-cloud confinement by the reactor magnetic field will also cause the hot diffusing vapor to deposit its energy on nearby components. Macroscopic erosion of liquid layers and CBMs depends mainly on the net power flux reaching the disruption area and can significantly exceed surface vaporization loss. The lifetime of metallic and carbon-based materials will be determined largely by macroscopic erosion mechanisms that exist during disruptions.

2. SIMULATION DEVICES

Laser beams have been used extensively to simulate the effects of high heat loads on target surfaces for many applications. Laser simulation, however, usually produces higher erosion rates from surface vaporization, mainly because vapor shielding is less effective. Because the beam size is very small (≤2-4 mm), it penetrates the rapidly and freely expanding cloud of vaporized material with little attenuation. Therefore, a larger fraction of the incident power reaches the original surface and causes additional vaporization.

Electron beam devices such as those at the JUDITH, JEBIS, and SOM facilities have also been used to simulate disruption effects on candidate target materials [3]. Because of the high electron kinetic energy in these devices (100-150 keV), the electrons have a much longer range in both target material and vapor zone than in laser or plasma gun devices. Two effects can result from the energetic electrons. First, more energy is deposited in the condensed target. Second, the deposited energy density in the developed vapor cloud is relatively low because of the long range of the electrons. Therefore, the vapor cloud is heated to lower temperatures than in plasma gun experiments. As a result, no significant vapor radiation is expected. Surface vaporization from energetic electron beams is usually higher than that from plasma gun devices under conditions expected during disruptions. The numerical results of the A*THERMAL-S code (part of the HEIGHTS simulation package [4]) agree well with electron beam experiments and measured vapor interferometry data [3].

Plasma gun devices, however, when used with proper parameters and when the results are carefully interpreted, can more closely simulate tokamak plasma disruptions than can either laser or electron beam devices. One of the main concerns in the use of current plasma guns is the low kinetic energy of the incident plasma (0.1-1 keV), which is much lower than in reactor conditions (<<10-20 keV). This may cause a significant fraction of the incident particles and energy to be reflected at the surface and intercept its own incoming plasma particles, i.e., this is a self-shielding effect rather than a vapor-shielding effect! This phenomenon can result in significant underestimation of the resulting damage compared to real reactor conditions.

Among plasma-gun devices currently used to simulate disruptions are those at the VIKA, QSPA, and 2MK-200UG facilities [5]. The plasma-gun device that is most relevant to simulate reactor disruption conditions is that at the 2MK-200UG facility, which can produce deuterium plasma (in a magnetic field strength of up to 3 T) with total energy of up to 50 kJ and particle kinetic energy of nearly 1 keV. Power density can be as high as 10 MW/cm^2, but with a maximum pulse duration of only ≤40 μs. Because of this limitation, 2MK-200UG can be most useful in studying the physics of early stages of a tokamak disruption. Measured erosion over the duration of the pulse is very small and should not be extrapolated to conditions expected during a reactor disruption.

Optical interferometry was used to determine the spatial distribution of plasma electron density and temperature in the evolving target vapor. The self-consistent model, which takes into account the multispecies mixture, implemented in the A*THERMAL-S code was used to simulate a recent disruption experiment at the 2MK-200UG facility. In the first 1 to 2 μs, a dense carbon vapor cloud formed above the surface, and this is in good agreement with the experimental data [3]. Because of the low kinetic energy of the ions in plasma gun simulation experiments, the density of the incident plasma particles is of the same order as, or higher than, that of the vaporized target material. Therefore, it was necessary to account for the influence of incident plasma particles on the evolved vapor hydrodynamics and on radiation transport. Initially, the deuteron plasma ions deposit their energy in the target material and then in the target vapor. Soon after, the density of the stopped plasma particles becomes comparable to and can exceed that of the target vapor. After a few microseconds, almost pure deuteron plasma particles exist at the front region of the vapor cloud. Most of the incoming energy is further deposited and stored as thermal energy in the plasma particles. Part of this energy is transferred to the target vapor behind the mixture region, via electron heat conduction. Under reactor conditions, the situation is different: the density of the incoming plasma particles is much lower than that of the target vapor and only a small fraction of the energy is stored as thermal energy. Most of the deposited energy is quickly radiated from the target vapor to the divertor surface and nearby components, which can cause more erosion than expected in plasma gun experiments having the same initial disruption energy and deposition time.

The reduced power to the target surface as a result of the vapor-cloud shielding is high enough, however, to cause significant erosion from melt-layer splashing and from explosive erosion of CBMs. The net power flux reaching the target surface in a typical disruption is estimated to be several hundred kW/cm^2, with slight dependence on the initial incident power and target material. In addition, the intense radiation emitted from the heated vapor-cloud is proven to cause damage to nearby locations other than the originally exposed area.

Among the various mechanisms that can cause melt-layer erosion during plasma instabilities, two have been demonstrated experimentally and studied in detail theoretically [5]. First is melt splashing due to the formation, growth, and bursting of bubbles inside the liquid layer. This is due to the continuous heating and overheating of the liquid layer during energy deposition. The amount and rate of melt-layer erosion depend on many parameters, such as degree of liquid overheating, impurity and gas content, material properties, and disrupting plasma parameters. The second mechanism is the development and growth of hydrodynamic instabilities due to various forces acting on the free surface of the liquid layer. These forces include electromagnetic, gravitational, inertial, and those from plasma impact momentum (plasma wind) at the liquid surface. During the disruption, part of the incident plasma momentum is deposited in a thin surface layer; this will accelerate the liquid metal in this layer to very high velocities. As a result, hydrodynamic instabilities such as the Kelvin-Helmholtz (K-H) instability will cause formation of liquid droplets that will be carried away by the plasma wind.

The models of melt-layer erosion mechanisms implemented in the SPLASH code (also part of the HEIGHTS simulation package) are generally in good agreement with experimental data but slightly underestimate the average eroded depth at the higher energy densities. This may suggest additional erosion mechanisms such as those due to nonuniform incident plasma dynamic pressure and to Rayleigh-Taylor hydrodynamic instability caused by inertial forces from acceleration of the melt front at the solid/liquid interface [6]. Melt-layer erosion of heavier materials such as copper, for example, is usually lower than lighter-material erosion under similar irradiation conditions in gun facilities. This is explained by the modeling simulation as having two main causes. The first is the required higher energy to remove the volume bubbles and the associated heavier liquid droplets. The second is the lower splashing velocity from K-H instability, again because of the higher density effect that requires more energy to liberate the liquid droplets. Melt-layer erosion of much heavier materials such as tungsten, however, was shown to be very low in plasma gun experiments [5]. This may have several causes, such as the much higher fraction of the incident plasma energy reflected from the heavier target surface due to the very low kinetic energy of the incident plasma particles.

In modeling melt-layer erosion in the SPLASH code, three different behaviors were observed over time. Initially, most of incoming plasma energy is directly deposited at the target surface, causing overheating and the start of a splashing wave. A shielding layer then develops and the power flux to the surface is significantly reduced, causing less splashing from bubble explosion. Splashing due to hydrodynamic instabilities is also reduced due to partial absorption of the incident plasma momentum by the shielding layer. After that, the liquid-layer temperature will start to rise again due to a decrease in heat conduction near the surface area. Splashing will then start again with a somewhat constant velocity up to the end of disruption. Splashing erosion has been found to depend on two main parameters: net power flux to surface and disruption time. The net power flux, through a well-confined vapor cloud, to the surface is usually ≈300-600 kW/cm^2 (over a wide range of disruption conditions), with slight dependence on initial power flux and target material. For a beryllium PFC and typical disruption conditions with a net power flux to surface ≈ 300 kW/cm^2 and a disruption time of $\tau_d \approx 1$ ms, the calculated erosion thickness is ≈200 µm. A sacrificial beryllium coating thickness of ≈5 mm will survive only about 25 disruptions! This is significantly fewer than the expected total number of several hundred disruptions during the reactor lifetime.

Strong erosion with considerable mass losses exceeding that from surface vaporization is also observed in nonmelting materials such as graphite and CBMs. Showers of macroscopic particles were seen ejected from samples of CBMs during electron beam irradiation and plasma devices [4]. In most facilities, the measured mass loss of graphite materials was much higher than predicted from surface vaporization, and the emitted particles had a more macroscopic nature than that due to monoatomic surface vaporization. Models were also developed and implemented in the SPLASH code to predict the erosion of CBMs due to different macroscopic destruction mechanisms [4].

From simulation experiments, the energy required for brittle destruction of a graphite similar to the MPG-9 graphite is estimated to be ≈10 kJ/g, or 20 kJ/cm^3. Therefore, for a net power flux to the material surface during the disruption of ≈300 kW/cm^2, the deposited energy for time $\tau_d \approx 1$ ms is ≈0.3 kJ/cm^2, which results in a net erosion thickness of 150 µm. This value is extremely high for reactor candidate graphite materials compared to that predicted from pure surface vaporization of ≈10 µm per disruption. A sacrificial coating thickness of 1 cm could survive less than 70 disruptions. This is also far fewer than the current expectations of several hundred disruptions during reactor lifetime.

Therefore, additional relevant experimental data and more detailed modeling are needed to evaluate the macroscopic erosion of metallic and CBMs, particularly in a strong oblique magnetic field.

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