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October 1990

UWFDM-844

Presented at the 9th Topical Meeting on the Technology of Fusion Energy, 7–11 October 1990, Oak Brook IL.

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EXPERIMENTAL STUDY OF CONDENSATION IN EXPANDING METAL VAPORS AND IMPLICATIONS FOR ICF TARGET CHAMBERS

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ABSTRACT

Condensation within rapidly expanding metal vapors has been experimentally investigated by exploding wires in a test chamber filled with helium or argon at various pressures (10 millitorr to 760 torr). Lead and silver wires were vaporized using a 5.0 kV, 15.4 - 500 μF capacitor discharge system. It was observed that the metal vapor prefers to condense as droplets with a resulting fog or aerosol cloud as opposed to surface condensation. The debris analysis showed that the resulting aerosol particles were spherical and the size ranged from 0.02 to 0.2 microns, suggesting the vapor condensed by homogeneous nucleation. The time-dependent conditions of the expanding vapor were simulated using a 1-D hydrodynamics code. The calculations indicate that the vapor quickly becomes supersaturated due to expansion cooling. The implications of our results for nucleate condensation in ICF target chambers are also discussed.

INTRODUCTION

Many of the conceptual Inertial Confinement Fusion (ICF) designs utilize the vaporization and condensation of liquid metals for protection of the first wall of the ICF reaction chamber and/or for heat transport and power conversion. The condensation of liquid metal vapor from the reaction chamber atmosphere, in particular, has been estimated to be one of the constraining factors limiting the allowable repetition rate in reactor applications[1].

One of the conceptual designs of the first wall protection is the INPORT concept[2] (Inhibited Flow-Porous Tube). The INPORT unit is a woven SiC tube, acting as the first structure facing the fusion products. It is flexible, sufficiently strong, compatible with $Li_{17}Pb_{83}$, and porous enough to allow some of the liquid metal to leak out and wet the outside of the tube. The thickness of the film ($\sim$1 mm) is enough to absorb the x-rays and debris from the target explosion in order to reduce the heat load of the outside structure. After absorbing this energy, the liquid film is evaporated and produces a dense gas inside the reactor chamber. The evaporated Li and Pb vapor expands into the chamber, cools down as it expands, and would eventually condense back onto the cold surfaces. The repetition rate of the target explosion is determined by the time required to reduce the cavity pressure in this evaporation-condensation sequence. It has been shown that the hydrodynamic motion during evaporation is negligible because the time of evaporation is short compared to the time of recovery after each event. Consequently the design study has been focused on the condensation process, and several detailed models have been developed using the concept of molecular transport[1,3]. However, the most important point to note is that these liquid metal condensation models have yet to be verified experimentally.

This paper reports experimental observations of the condensation process in expanding metal vapors. The rapid vaporization was simulated by exploding a metal wire using a capacitor discharge system. The exploding conductor phenomena has been widely investigated in the past and abundant literature can be obtained from the bibliographies of Chase and Moore[4]. However, little information is found in this literature on the condensation process of the metal vapor from the exploding wire.

The present experimental study was, in its early stage, intended to investigate the condensation mass flux on the chamber wall. However, the preliminary wire explosion tests consistently showed a dense smoke that persisted for a long time (tens of seconds) before settling out. Therefore, the rest of the study has been focused on the investigation of the droplet condensation process and the resulting particle sizes in various chamber pressures.

EXPERIMENTAL

The experimental apparatus was constructed in three sections: the electronic circuitry, the test chamber, and the instrumentation of shock pressure measurement and laser scattering. The circuit consisted primarily of a low inductance energy storage capacitor bank (15.4 - 500 μF, 5 kV), 0 - 5 kV charging supply, a triggered ignitron switch, a pair of copper electrodes, and a knife switch between the capacitor and the charging supply. The circuit leads were short and the ignitron was directly coupled to the capacitor to minimize inductance and resistance. The current was measured using a Rogowski coil and a voltage divider was used to measure the voltage drop across the two electrodes. The current and voltage traces were used to estimate the energy input to the exploding wire.

The test chamber was constructed from a Pyrex glass cross member measuring 150 mm in inside diameter and 450 mm in length. The three closure flanges containing the various fittings and penetrations were machined from aluminum and one was a clear Lexan plate to allow undistorted visual access. A vacuum pump was connected to the test chamber to vary the initial pressure with an inert gas. A Granvill-Philips Convectron vacuum gauge was used to determine the initial chamber pressure. A schematic of the test chamber is shown in Figure 1.

A laser scattering system was constructed as one of the pri-

mary experimental diagnostics. It consisted primarily of a 15 mW HeNe laser, an avalanche photodiode detector, and a photomultiplier tube. The scattered light was collected at a 90 degree angle. Although it was originally intended to measure the metal vapor density by Rayleigh scattering, it was actually used to qualitatively observe the condensed droplet density. Two piezoelectric pressure transducers were placed in the test chamber to measure the shock pressure traces of expanding metal vapor. This pressure measurement was intended to supply the expansion rate of the high pressure metal vapor for comparison with a numerical simulation. As the distance between the transducers and the exploding wire was reduced to observe the near-wire expansion rate (28 mm and 53 mm typically), the pressure transducer signal became spurious due to the high electromagnetic field near the wire. This problem was resolved by using an optoelectric isolation circuit between the capacitor discharge circuit and the transducer charge amplifier.

The powdered debris were collected and analyzed using a scanning electron microscope. The sample debris was collected either on the chamber base or on the two hanging aluminum-foil coupons with the collecting surface facing down toward the wire. In the latter case the distances between the wire and the coupons were 10 mm and 30 mm. It was believed that the debris collection with the latter configuration could eliminate sedimentation of particles and reveal some evidence on the timing of the onset of nucleation in expanding vapor. For better resolution a small amount of gold was sputtered onto the debris sample.

Lead wires of better than 99.99 per cent purity were exploded throughout this study. Wires were 100 mm long and 0.25, 0.5, or 1.0 mm in diameter so that the mass exploded ranged from 55 mg to 880 mg. In a few tests 0.05 mm diameter silver wires were used to attempt to increase the initial vapor temperature by reducing the wire mass.

RESULTS AND DISCUSSION

Initial efforts to generate a lead vapor using an exploding wire were made at low chamber pressure. These pressures were at relatively mild vacuums of 0.01 to 0.4 torr. Helium was normally the background gas and was introduced via a repeated purging procedure. The capacitor voltage ranged from 1.0 to 4.5 kV and the capacitance was 500 μF. Problems with the exploding wire in vacuum immediately became evident. Following each shot, macroscopic balls of lead ranging from tenths of a millimeter to a few millimeters were found on the base of the chamber. Substantial quantities of molten lead had been splattered onto surfaces as well. The appearance and the large size of the debris indicated that a substantial fraction of the mass of the wire had not vaporized and had been blown off in molten droplets. The weighing of the large debris collected indicated that less than 20 per cent of the wire mass was vaporized.

The estimation of the input energy to the wire seemed to be inaccurate due to the high frequency spurious noise of the voltage signal measured by a voltage divider. With this uncertainty the specific input energy ranged from 300 J/g to 600 J/g. Considering that the required energy for vaporization of lead ranges from 1083 J/g[5] to 1188 J/g, the measured input energy also indicated the incompleteness of wire vaporization. The incompleteness of the wire vaporization was thought to be due to breakdown in the gas surrounding the wire under the high imposed electric field. According to the Paschen curve[6], the breakdown voltage in helium increases as the gas pressure increases. It corresponds to several hundred volts in the current cases. When the background gas breaks down, most of the electrical current passes through this arching plasma. If this occurs before the substantial fraction of the required energy for the wire vaporization is deposited into the wire, incompleteness of the wire vaporization can result, as was observed in the current cases. Further efforts to produce complete vaporization were made by using wires smaller in diameter to reduce the wire mass or by replacing helium with argon. However, these did not show significant improvement.

In view of the repeated failure to consistently vaporize a large fraction of the wire mass in the low chamber pressure, it was suggested that an increase in chamber pressure would be necessary in order to suppress the gas breakdown[4]. The tests with increased chamber pressures (10 to 100 torr) showed an appearance which was quite different from the low-pressure tests. The entire test chamber was instantly filled with a thick, black fog which required several tens of seconds to settle out. The tests with three different chamber gases (He, Ar, or air) generally showed complete vaporization of the lead wires when the chamber pressure was greater than 20 torr. The energy measurements also showed significant increases in the wire explosion energy, ranging from 820 to 1160 J/g, although the data bears the uncertainty mentioned earlier.

The observations of the fogging in the high-pressure tests immediately led us to suspect that the lead vapor produced might be rapidly condensing by aerosol fog formation (homogeneous nucleation in bulk) into tiny droplets. The laser scattering diagnostics was one method that was employed in investigating the condensation behavior. It was initially hoped that direct measurement in the vicinity of the wire would provide strong evidence that the wire had completely vaporized. Computations had indicated that the vapor would have to expand to several times the initial wire radius before it cooled enough to reach a supersaturation state. It was therefore desirable to locate the measuring volume within a few millimeters of the wire. The laser scattering diagnostics were first complicated by a brilliant flash which dominated any scattering signal despite a laser line filter on the photomultiplier detector. This flashing was reduced in its intensity by crowbarring the capacitor discharge circuit in a preset time (typically a half millisecond) so that it was only a small peak on the scattering signal. In a number of tests no evidence of droplets in close proximity to the wire was observed by the scattering signals between the discharge circuit triggering and the flashing peak, indicating that the wire had completely vaporized.

In an effort to further clarify the origin of the fog, the powdered debris was collected and analyzed using a scanning electron microscope. The debris appeared quite spherical and ranged in size from about 0.02 to 0.2 μm in diameter. This range of the particle size agreed well with the past experimental data collected by Phalen[7], 0.01 - 0.11 μm. Figure 2 shows an

SEM photograph of the lead debris. Two high-magnification photos were analyzed to investigate the particle size distributions, which are shown in Figure 3. The most probable particle diameter was 0.025 μm and the count median diameter was 0.038 μm. The past experimental data of copper[7] showed a similar mean diameter of 0.035 μm.

The high-pressure tests showed that the metal vapor prefers to condense as droplets with a resulting fog or aerosol cloud as opposed to surface condensation. However, since these high chamber pressures were too high for the initial conditions of an ICF event, it was necessary to check if this fog formation persisted at lower pressures near vacuum conditions (~0.01 torr). Based on the earlier observations of the gas breakdown effect on the incomplete wire vaporization in the lower chamber pressures, it was thought that the electrical current rise time should be as short as possible compared to the time at which breakdown occurs. Considering that the current rise time is proportional to $\sqrt{LC}$ where L is the circuit inductance and C is the capacitance, the capacitor bank was replaced with a single, low inductance, 15.4 μF capacitor. With this change the current rise time was reduced to a few microseconds from a half millisecond.

With the modified capacitor discharge system a number of tests were conducted in lower pressures. While the breakdown effects still persisted even with the reduced current rise time, a significant improvement was observed in the vaporized fraction of the wire mass. The SEM analysis of the debris samples collected on the two aluminum foil coupons at the distances of 10 mm and 30 mm each from the wire showed similar particle sizes regardless of the collecting distance, and that the particle sizes were also within the same range observed in the high-pressure tests. Figure 4 shows the electrical current traces at three chamber pressures with helium. In this figure the times at which breakdown occurred are seen clearly by the points at which the oscillating current begins. The time of breakdown was reduced substantially as the chamber pressure was lowered. The rapid breakdown in lower pressure could be the explanation of the incomplete vaporization of the wire. The period of near-zero current in the high pressure case is called "dwell time"[4]. The dwell time was not observed in lower pressure tests because of the lower breakdown voltage.

In this series of tests the shock pressure of the expanding metal vapor was measured at the two locations of 28 mm and 53 mm from the wire in order to further study the hydrodynamics of expanding vapor with condensation. However, problems were observed in acquiring reliable pressure traces in lower pressures or helium chamber gas. In both cases the pressure signals contained large peaks immediately following the wire vaporization so that the arrival times at the two locations seemed to be ambiguous. The cause of the large peaks in these lower pressure tests could be the thermal radiation from the gas breakdown. However, the cause of the ambiguity with helium even in high chamber pressure was not clear, but one notes the lighter molecular mass of helium compared to argon or nitrogen in which reliable data were acquired.

Typical pressure traces in high-pressure tests with argon are shown in Figure 5. In this figure, comparisons with a numerical simulation using a Lagrangian hydrodynamics code, CONRAD[8], is also shown. In the simulation it was assumed that the wire was vaporized instantaneously and that the initial vapor temperature was 2000 K, which is about the boiling temperature of lead. The code was not capable of modeling droplet condensation. The results indicated that the vapor expanded faster in the simulation than in the real case, although the pressure shapes were qualitatively similar. Since the boiling temperature was chosen as the initial vapor temperature in the simulation, which is the possible lower bound, the vapor temperature may not be a cause of the difference. There may be two competing effects of condensation on the expansion rate: latent heat release which would reheat the vapor and strengthen the shock, and the vapor depletion due to the droplet growth which would weaken the shock.

For a given condensation mass rate, $\dot{m}_c$, the time derivative of pressure can be written as follows if the vapor is assumed to behave as an ideal gas in a constant volume:

$$\frac{dP}{dt} = \frac{mR}{V}\frac{\partial T}{\partial t} + \frac{RT}{V}\frac{\partial m}{\partial t}. \tag{1}$$

The expressions for the vapor depletion and the reheat by latent heat are

$$\frac{\partial m}{\partial t} = -\dot{m}_c \tag{2}$$

$$\frac{\partial T}{\partial t} = \frac{h_{fg}}{mc_v}\dot{m}_c \tag{3}$$

where h_{fg} is vaporization heat and c_v is specific heat of vapor. The resulting expression for the pressure change is

$$\frac{dP}{dt} = \frac{R\dot{m}_c}{V}[\frac{h_{fg}}{c_v} - T]. \tag{4}$$

Since the ratio of vaporization heat to vapor specific heat of lead is about 5000 K and the vapor temperature is less than 2000 K, the above equation indicates that the condensation process during vapor expansion should strengthen the shock, which is in contrast to the comparisons in Figure 5. However, one possible explanation which could support the current observations is that the time scale of the latent heat transport into the bulk vapor would be longer (> millisecond) than the expansion time scale so that the vapor depletion can be dominant over the reheating. One also notes that in the above analysis thermal equilibrium was assumed.

The CONRAD simulations of exploding wires shown various hydrodynamic characteristics of expanding metal vapor which would support the occurrence of homogeneous nucleation. The calculation showed that the vapor temperature decreases very rapidly regardless of the background pressure; within a few microseconds after the expansion begins the temperature near the center of the vapor has fallen to roughly 100 K from the initial 3000 K. Within one microsecond the vapor becomes supersaturated with a temperature of 100 - 1000 K and a density of 10^{20} - 10^{21} cm^{-3}. For these conditions, the homogeneous nucleation rate should be very high according to the classical homogeneous nucleation theory[9].

CONCLUSIONS

Condensation in rapidly expanding metal vapors has been experimentally investigated by exploding wires using a capacitive discharge system. The exploding wire technique has

showed several limitations in the vaporization and the diagnostics: (1) in vacuum the vaporization of wire was incomplete due to gas breakdown effect, (2) flashing from the exploding wire as well as arching blinded the critical time window for laser scattering diagnostics. Despite the above limitations the observations and analysis of the condensation process indicated that homogeneous droplet condensation occurred with a resulting fog or aerosol cloud. The debris analysis showed that the resulting aerosol particles were spherical and very small in size (0.038 μm). The computer simulations showed that the vapor temperature becomes quickly supersaturated which may support the occurrence of the droplet condensation process.

We feel that studying nucleate condensation with wire explosion experiments may provide valuable data relevant to ICF target chambers. The presence of homogeneous droplet condensation in target chambers might have important consequences. The creation of a fog would cause obvious repetition rate problems. Although the initial specific energy in the vaporized wall material in ICF target chambers can be significantly higher than the vaporization energy, the vapor will quickly cool due to expansion[9]. For example, under adiabatic expansion, the temperature decreases as

$$\frac{T}{T_o} = (\frac{n}{n_o})^{\gamma-1} = (\frac{\ell_o}{\ell})^{\gamma-1}_{planar} \qquad (5)$$

where n is vapor density, ℓ is length, and γ is a constant specific heat ratio. Therefore, if the initial temperature in the vaporized wall material ($\sim$10 μm thick) is 100 times the supersaturation temperature, by the time the vapor has expanded 1000 times (to $\sim$1 cm), the vapor has become supersaturated.

The further study of the droplet condensation phenomena is also limited by the vaporization physics and the diagnostics. While the exploding wire technique has shown several limitations in studying the condensation process, one would consider a thermal decomposition method in a shock tube for the fundamental study of homogeneous nucleation and its growth rate.

ACKNOWLEDGEMENTS

The financial support for this work was initially provided by Lawrence Livermore National Laboratory. Computing support was provided by the National Science Foundation through the San Diego Supercomputing Center.

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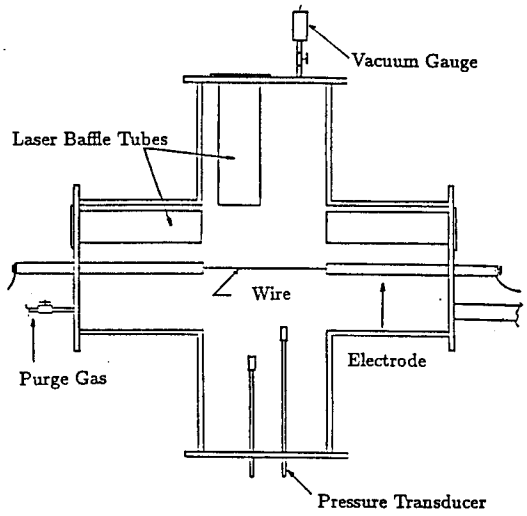

Figure 1. Schematic of test chamber.

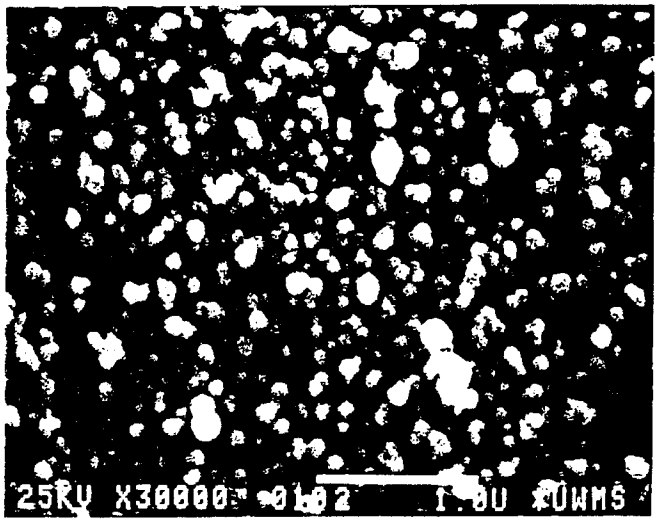

Figure 2. Electron microscope photograph of the debris from Pb wire exploded in helium.

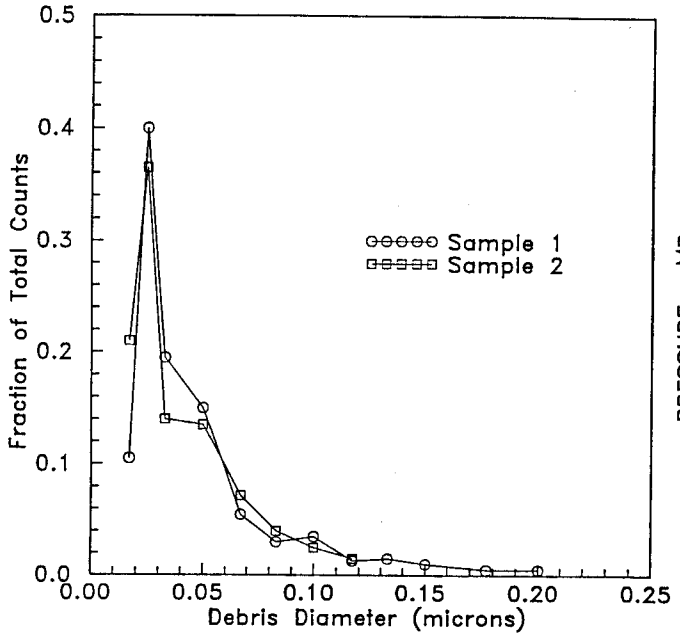

Figure 3. Size distribution of the debris from Pb wire exploded in helium.

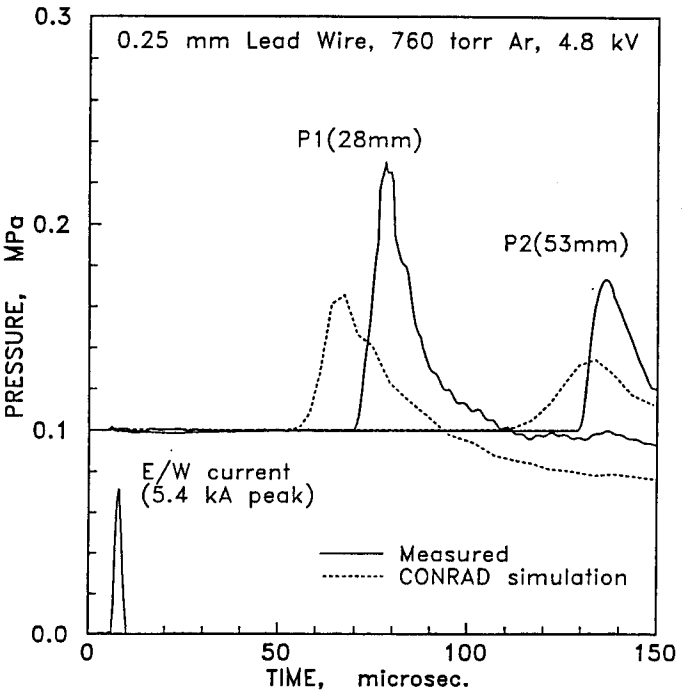

Figure 5. Measured and computed pressure traces for lead wire exploded in argon.

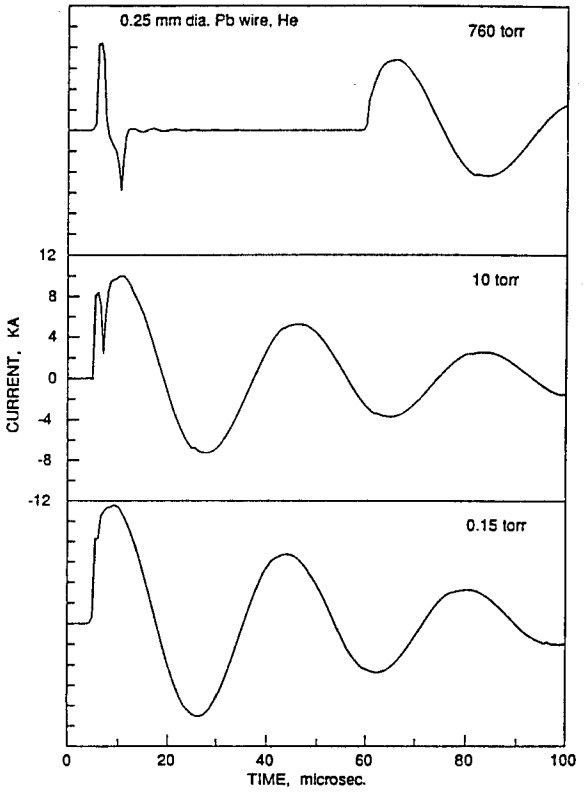

Figure 4. Current traces for lead wires exploded under three different chamber pressures.