Lithium pellet production (LiPP): A device for the production of small spheres of lithium

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Lithium pellet production (LiPP): A device for the production of small spheres of lithium

P. Fiflis,[1,a)] D. Andrucyzk,[1,b)] A. L. Roquemore,[2] M. McGuire,[1,c)] D. Curreli,[1] and D. N. Ruzic[1]
[1]*Center for Plasma Material Interactions, Department of Nuclear, Plasma, and Radiological Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*
[2]*Princeton Plasma Physics Laboratory, Princeton, New Jersey 08540, USA*

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With lithium as a fusion material gaining popularity, a method for producing lithium pellets relatively quickly has been developed for NSTX. The Lithium Pellet Production device is based on an injector with a sub-millimeter diameter orifice and relies on a jet of liquid lithium breaking apart into small spheres via the Plateau-Rayleigh instability. A prototype device is presented in this paper and for a pressure difference of $\Delta P = 5$ Torr, spheres with diameters between $0.91 < D < 1.37$ mm have been produced with an average diameter of $D = 1.14$ mm, which agrees with the developed theory. Successive tests performed at Princeton Plasma Physics Laboratory with Wood's metal have confirmed the dependence of sphere diameter on pressure difference as predicted.
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INTRODUCTION

One of the most significant problems in magnetic confinement fusion devices is controlling the recycling of hydrogen from the walls of the vacuum vessel which limits the performance of the plasma. It is known that lithium is a powerful getter of hydrogen and by depositing lithium in specific regions of a fusion device, most notably the divertor,[1,2] higher energy confinement times, reduction in the amplitude of Edge Localized Modes (ELMs), higher edge temperatures and densities have been achieved.[3] At Princeton Plasma Physics Laboratory (PPPL) the National Spherical Torus eXperiment (NSTX) is a leader in lithium research for fusion and its primary method for depositing lithium is via a lithium evaporation (LITER) system[4] or a lithium aerosol.[5]

Recently, a granular injector has been developed at PPPL and tested on EAST in China and RFX in Italy.[6] The granular injector uses spheres of lithium that are released from a dropper[5] and then impacted with a rotating impeller that injects these spherical pellets into the plasma and is able to trigger an ELM in a controlled fashion. The supply of pellets at the correct size is important and pellets up to 1 mm diameter are predicted for proper ELM control. Having a method for producing regularly sized pellets would be of great benefit for a device like the granular injector. This paper presents a Lithium Pellet Production (LiPP) device that has been developed at the Center for Plasma Material Interactions (CPMI) at the University of Illinois Urbana-Champaign (UIUC). LiPP is intended to produce small lithium pellets in the range of 1 mm diameter for use with the granular injector and lithium particle dropper at PPPL. The method is based on the disruption of a jet of liquid metal into small droplets and can be extended to any metal with sufficiently low melting point.

The result is a very simple and relatively inexpensive tool that can create hundreds of small spheres of lithium with a very tight size distribution in a matter of tens of seconds.

SPHERE PRODUCTION

Figure 1 shows a schematic and photo of the injector that was developed to produce spheres of a uniform size. The injector consists of three sections; the first is a pressure chamber, the second is a 1/2″ heated stainless steel tube, and the third is the nozzle which is also made from stainless steel. The most important section is the nozzle which has the orifice that the lithium is forced through. Several nozzles have been manufactured, each one having a different size orifice: $R_0 = 0.15$ mm, 0.5 mm, and 1.0 mm. The nozzle can be screwed on or off the end of the 1/2″ stainless steel tube to change the orifice size as needed. The tube and the nozzle are heated with a coil of nichrome wire with an insulating layer of Kapton tape in between the wire and the tube surface. The nozzle has its own separate heating coil since the nozzle is immersed in mineral oil. The nozzle is immersed in mineral oil to cool the spheres upon ejection and to coat the surface of the sphere to slow oxidation.

To produce the spheres, argon gas is flowed through the injector while a rod of lithium fitting the inner diameter of the stainless steel tube is inserted. The lithium is heated to its melting temperature, 181 °C, while argon gas is flowed. Once the lithium melts it makes a seal and the argon stops flowing, which can be monitored by observing bubbles of argon exiting the nozzle. A ball valve between the tube and a small ballast chamber is closed to allow pressure to build in the ballast chamber. The lithium further heated to 220 °C, ensuring the whole volume of lithium is melted. The valve is then opened and the pressure in the ballast chamber forces the liquid lithium to exit as a jet, shown in Figure 2. This jet

a)Author to whom correspondence should be addressed. Electronic mail: fiflis1@illinois.edu.
b)Present address: Princeton Plasma Physics Laboratory, Princeton, New Jersey 08540, USA.
c)Present address: Exelon Corporation, Clinton, Illinois 61727, USA.

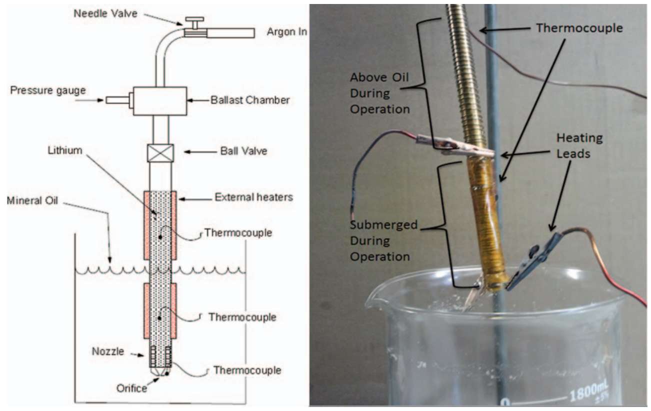

FIG. 1. LiPP schematic and device photo.

then breaks into droplets or "pinches-off" due to the Plateau-Rayleigh instability.[7] Plateau-Rayleigh theory begins with a sinusoidal perturbation to the radius of the jet, and follows the evolution of this disturbance over a falling column of liquid. To first order, the dispersion relation for the instability is given by

$$\omega^2 = \frac{\gamma}{\rho R_0^3} k R_0 \frac{I_1(kR_0)}{I_0(kR_0)} (1 - (kR_0)^2). \tag{1}$$

The fastest growth rate in these instabilities occurs at $kR_0 = 0.697$, or $\lambda_{max} = 9.02R_0$, where R_0 is the nozzle radius. This is this mode which determines the size of the droplets. Let the height of a column of liquid, h_{liq}, expelled in one cycle of the growth rate be

$$h_{liq} = \frac{v_{liq}}{\omega}, \tag{2}$$

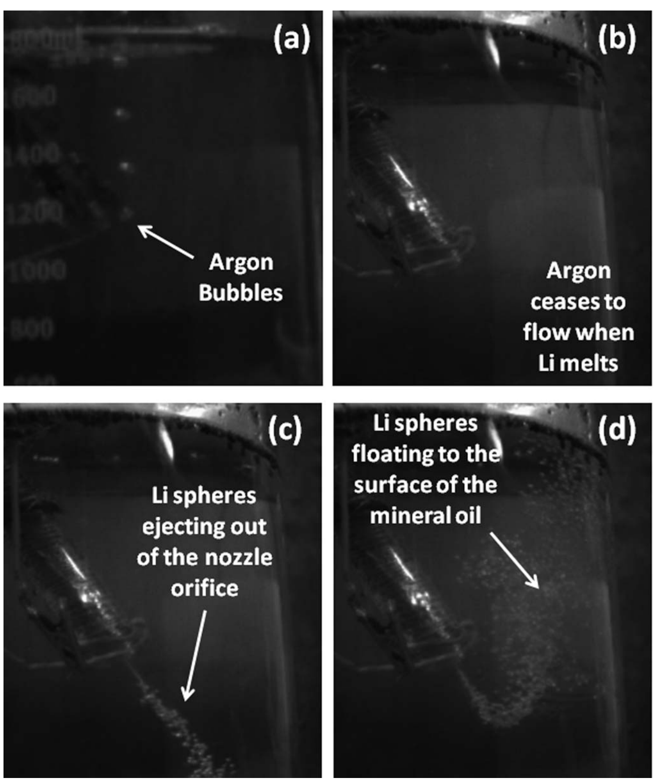

FIG. 2. Photos illustrating various stages of process.

where v_{liq} is the velocity of the column of liquid exiting the orifice. Using the Young-Laplace equation for pressure, ΔP, across a capillary surface, and the dispersion relation for the Plateau-Rayleigh instability, substitution yields a droplet volume of the form

$$V_{droplet} = 9.2338 \frac{v_{liq} R_0^3}{\sqrt{\frac{\Delta P}{\rho}}}. \tag{3}$$

The diameter of a sphere is then calculated to be

$$D_{sphere} = 2.603 \left(\frac{v_{liq} R_0^3}{\sqrt{\frac{\Delta P}{\rho}}} \right)^{\frac{1}{3}}. \tag{4}$$

INJECTOR FABRICATION

The injector is a stainless steel tube with a nozzle attached to one end and an argon line attached to the other. The nozzle is manufactured by machining a short cylinder of stainless steel that is the same diameter as the tube. The upper part of the nozzle and the inside of the tube are threaded, so that the nozzle may be screwed into the tube. A tapered hole was pre-drilled through the center of the nozzle. At the top of the nozzle, the hole is as wide as may be machined without compromising the threading, in this case, 5 mm in diameter. The hole then tapers down to the desired orifice diameter on the bottom. The injector tube must also be heated beyond the melting point of the sphere material. This was accomplished via a nichrome heating wire electrically insulated from the tube with a layer of Kapton tape. The nozzle and part of the tube was then submerged in mineral oil. The oil serves two purposes, one is to cool the droplets, the second is to coat the lithium produced in a protective layer of oil to slow the process of impurity growth.

Since the mineral oil degrades the adhesive coating of the Kapton tape, each end of the heater coil was crimped to the previous loop to ensure that the coil stayed in place. The mineral oil is also thermally conductive so it was necessary to use two heating coils, one for the submerged portion of the injector and the other for the remainder of the injector tube that is not submerged. In this manner, the power to the submerged portion of the injector could be controlled independently. Three type-K thermocouples were used to monitor the temperature on the outside of the injector tube.

EXPERIMENTAL RESULTS (SIZE DISTRIBUTION)

Experiments were performed with the injector where sphere diameter and quality were monitored. The nozzle used for these experiments had an orifice of $R = 0.15$ mm in radius and the pressure difference $\Delta P = 5$ Torr. Using Eq. (4), the predicted droplet diameter is 1.04 mm. Experimentally, the distribution has been measured and agrees with the theoretical plot and over 80% of the pellets fall within a sphere diameter $0.91 < D < 1.37$ mm.

When the 0.15 mm nozzle was replaced with a nozzle of 0.5 mm in radius, the mean diameter of the spheres

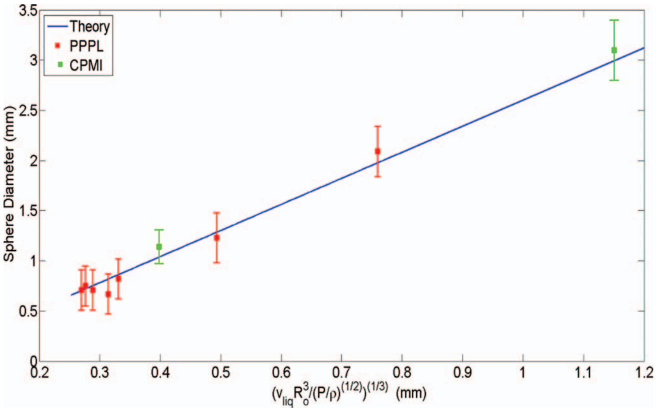

FIG. 3. Sphere diameter vs $(v_{liq}R_0^3/(P/\rho)^{1/2})^{1/3}$ theoretical and experimental sphere diameters as a function of nozzle size and argon pressure.

was approximately 3.1 mm in size, also in agreement with theory. Experiments were attempted to confirm the relationship between sphere size and backing pressure, however, equipment constraints limited both accurate pressure control and pressure measurement. However, experiments performed at PPPL verified the dependence predicted by Eq. (4). The setup for these tests consisted of a heated pool of Wood's metal ejected through a 0.15 mm radius nozzle by a backing pressure of argon. Wood's metal was used because its surface tension is comparable to that of lithium, and it therefore should also produce spheres of similar diameter predicted by Eq. (4). Figure 3 illustrates the relationship of the drop diameter on pressure, plotting sphere diameter against the parameter $(v_{liq}R_0^3/(P/\rho)^{1/2})^{1/3}$. As can be seen from the graph, the experimental points fit along a line with the slope 2.6, as can be calculated from Eq. (4).

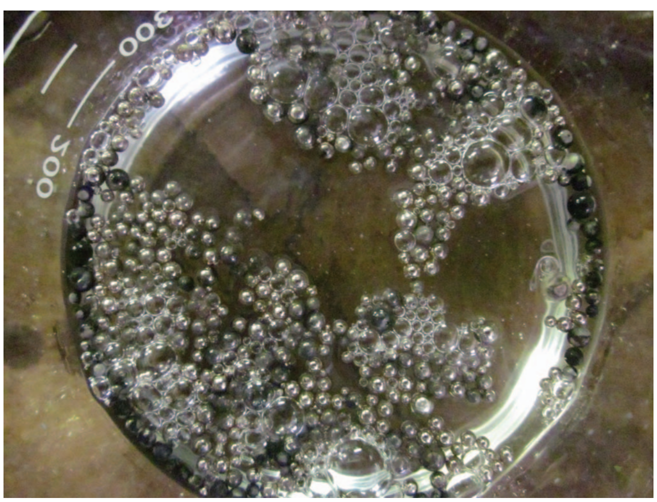

FIG. 4. Lithium pellets post production floating in Multi-Therm PG-1 mineral oil.

EXPERIMENTAL RESULTS (QUALITY)

To ensure the quality of the spheres, they were checked for voids and deformation. Several larger spheres were sectioned and found to contain no voids. Deformation was observed for droplets that were still molten when impacting the surface. To combat such deformations, droplets were produced at a greater depth within the oil to ensure that they had more time to solidify before reaching the surface. Figure 4 shows the spherical pellets produced by LiPP.

CONCLUSION

A method for producing small diameter spheres of low melting point, malleable metals were created at the University of Illinois. This device has been used to produce spheres of lithium in mineral oil, whose size distribution centered on approximately $D = 1.1$ mm and agrees with theory. This process is adaptable, and by adjusting the nozzle's orifice diameter and pressure, the different size spheres have been produced in agreement with theory. The size of the spheres is determined by the Plateau-Rayleigh instability as described in the Sphere Production section of this paper. It is also important to ensure that the lithium droplets are solidified before they impact the surface of the mineral oil where they are produced inside to minimize deformation. Additional experiments performed at PPPL with Wood's metal confirmed theoretical predictions for droplet diameter verses pressure. In short, the device can be used to produce spheres of variable diameter either by altering the nozzle radius or the backing pressure behind the fluid.

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