Development of High Quality Plastic Fuel Shells for Laser Fusion Energy

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Abstract. An overview of the emulsion process to make fuel capsules for a laser fusion power plant is presented, emphasizing the fact that high quality shells, of which sphericity is close to the extrapolated NIF standard, were successfully fabricated. A simulation model for the centering process, by which uniformly thick shells were formed, was compared with the experiment, and showed good agreement. It was indicated that the water core approaches the center by repeated instantaneous deformations.

1. Introduction

In a future laser fusion reactor, it is necessary to make millions of fuel capsules with a 5-mm diameter and several hundred-μm wall-thickness in a day with acceptable cost. The thickness uniformity and the sphericity of the capsule must be better than 99%. The demonstration of mass production of the capsule is very important in order to proceed with the laser fusion research.

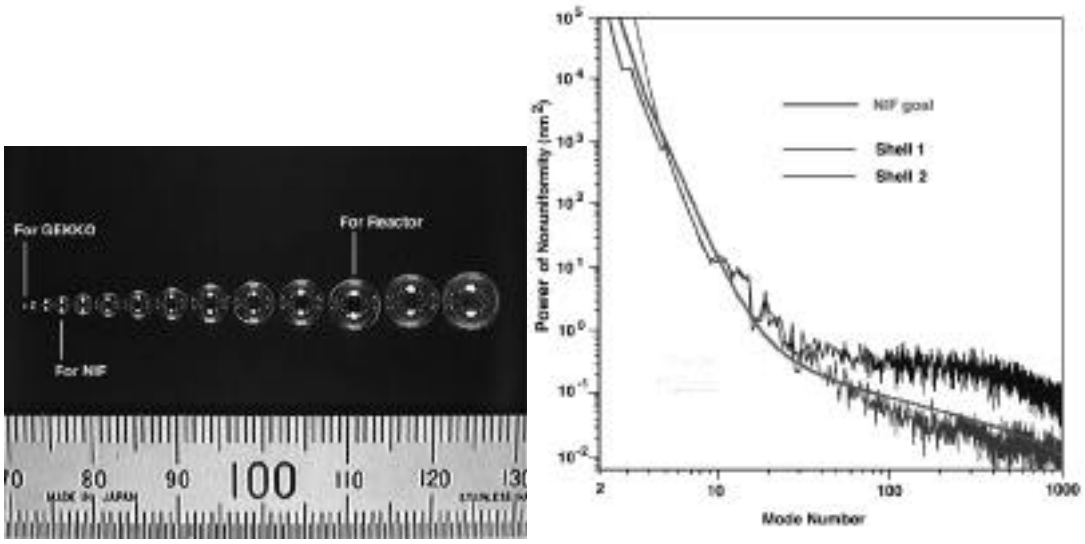
At ILE, Osaka University, polystyrene shells ranging from 0.5- to 7-mm diameter have already been fabricated by an emulsion process using a droplet generator.[1] A sphericity>99% is constantly achieved and the thickness uniformity ranged from 95% to >99% depending on the experimental conditions.[2] In this research, polystyrene was dissolved in oil, and the oil was pushed out from a double nozzle into a bath to make water (W_1)/oil (O)/water (W_2) emulsions. Polystyrene shells containing water inside were harvested after the oil in the emulsion was evaporated through W_2. The W_1 in the shell was dried in air at room temperature.

Based on our understanding, the thickness uniformity is improved by repeating the instantaneous deformations of the emulsion. On the other hand, deformations after the loss of the fluidity of O leave a permanent non-sphericity on the outer surface. When to change the curing process from the centering mode to the relaxation mode is our current objective.

Construction of a model for the centering and monitoring of the curing process is the key to making high quality shells. The research for the modeling of this process has been continued in order to eliminate the dispersion in the thickness uniformity mentioned above. In a previous report, modeling for the motion of the water core in an emulsion with known deformation was described.[3,4] The model was compared with the experimental results in this report. It was indicated that the water core approaches the center by repeated instantaneous deformations.

2. Recent Fabrication Results

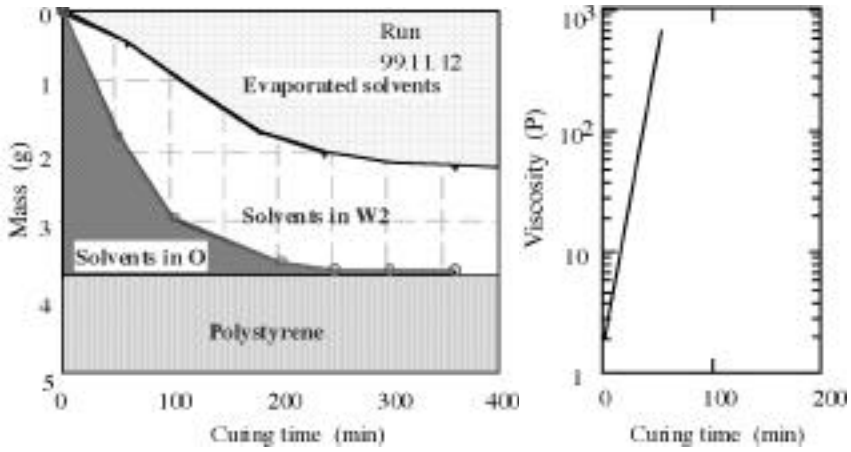
The basic fabrication process was the same as previously. With precise control of the process, we successfully fabricated high quality polystyrene shells with a sphericity that is close to the extrapolated NIF standard assuming that the growth rate of the RT instabilities is in the linear phase. (Fig. 1) In our latest experiment, we used a rotary drum in the curing process instead of a conventional bath stirred with propellers. The results showed that this method could also fabricate 5- to 7-mm diameter polystyrene shells with 30 to 250 μm walls. Typical sphericity measured by a laser displacement meter was 99.9% and the uniformity measured by x-ray radiography was >99% which is close to the resolution limit of the x-ray radiography.



(a) (b)

Fig. 1 Polystyrene shells fabricated by emulsion process with a stirred bath. The diameters ranged from 0.5 to 7 mm,(a); Non-sphericity of shells fabricated by emulsion method(b). The vertical axis is the amplitude for the out-of-roundness and the horizontal axis is the mode number in the tangential direction. This measurement was carried out by LLNL.

To understand the curing process of the emulsion, the evaporation rate of the solvents in the O-phase was monitored by trapping them with a glass tube cooled at 77 K. The concentration of the solvents in the distillate was analyzed by gas chromatography. The result is shown in Fig. 2 where the estimated viscosity of the O-phase is also shown. Because of the different solubility in water, the solvents in W_2 were 80% dichloroethane and 20% benzene although the initial solvents in the O-phase were an equivalent mixture of dichloroethane and benzene. They were chosen to adjust the density of the O-phase because they had similar boiling points. However, this result indicates that solvents must be chosen based on their solubilities in water.



(a) (b)

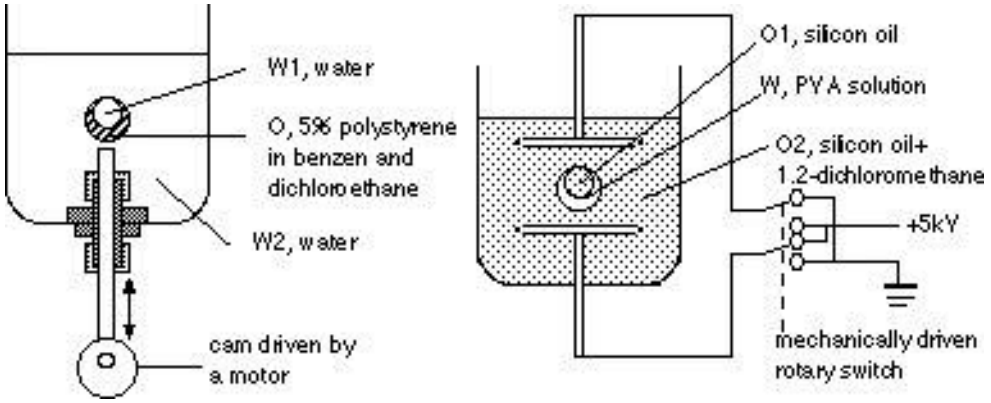
Fig. 2 Flow of solvents during curing process (a) and estimated viscosity of the O-phase (b).

3. Comparison of Model with Experiment

3.1 Experimental Equipment

We used two sets of equipment; one is a mechanical driving system for the $W_1/O/W_2$ emulsion and the other is an electric driving system for the $O_1/W/O_2$ emulsion. They are illustrated in Fig. 3. The mechanical driving system was employed because one can use the same materials to make the plastic shells. The electrical driving system, however, could not stimulate a sufficient amplitude of oscillation on the $W_1/O/W_2$ emulsion due to the higher conductivity in W_2.

In the mechanical driving system, the top surface of a 4-mm-diameter driving rod was coated with a paint that is wettable with the oil phase to fix the emulsion at the top. The diameter of the rod was chosen to be 60 % of that of the emulsion to prevent higher mode oscillations. The stroke of the rod was fixed at 0.5 mm and only the driving frequency was adjusted depending on the size of the emulsion. The primary mode of this system was a sloshing mode where W_1 and O oscillate in a counter phase. In the electrical driving system, the water phase was a 3% PVA solution and the oil phase was silicon oil whose viscosity and density were 10 cP and 0.934 g/cc, respectively. A small amount of 1,2-dichloroethane was slowly added in O_2 to make a density gradient to fix the water globule at the middle of the electrodes. The primary mode of this system was a bubble mode where W_1 and O oscillate in the same phase.



(a) (b)

Fig.3 (a) Mechanical driving system for a W/O/W emulsion. (b) Electrical driving system for an O/W/O emulsion.

3.2 Experimental Results

3.2.1 Sloshing mode experiment with W/O/W emulsion

To determine the drag coefficient, the emulsion was periodically deformed by the rod to fix W_1 at the center of the compound emulsion. After stopping the deformation, W_1 moved upward because of insufficient density matching ($\delta\rho$=0.018 g/cc that was obtained before making the emulsion. The viscosity of O was 0.1 P (+/- 15%).). The floating velocity was calculated from the VTR image. Unexpectedly, the resultant floating velocity was less than the theoretical value. The experimental result indicated that the density difference between W_1 and O was less than 0.01 g/cc and there was some friction between W_1 and O. The density difference may be changed after formation of the emulsion due to the diffusion of water and oil.

Although our model assumed a bubble mode, our model calculations could explain the experimental results as shown in Fig. 4. More details are available in a reference.[5]

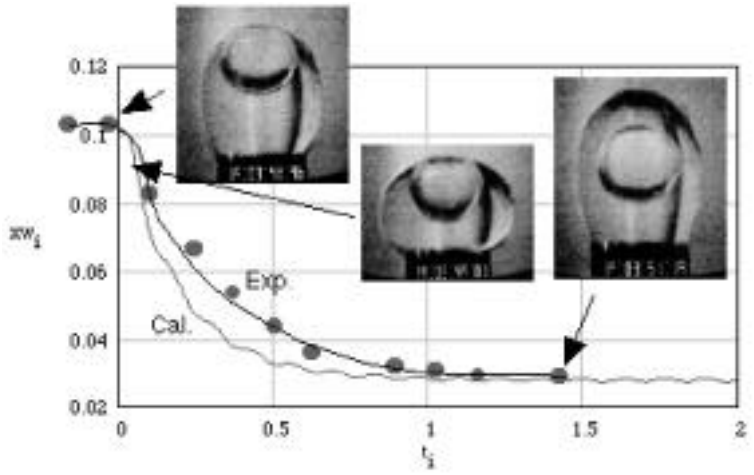


Fig. 4 Motion of a compound emulsion after starting the oscillation. The vertical axis is the position of the core in cm. Time origins for the experiment and simulation are arbitrary.

3.2.2 Bubble mode experiment with O/W/O emulsion

The densities of O_1 and W measured before making the compound emulsion were 0.934 and 0.998 g/cc, respectively. To fix the compound emulsion at the middle of the electrodes, a small amount of dichloroethane was added to O_2. Since the 1.2-dichloroethane diffuses into the W and O_1, and their densities changed during the experiment, we estimated the difference of the density from the floating velocity. The change in the viscosity of W can be ignored after the diffusion of dichloroethane into W. From the floating speed, we estimated that the density difference between O_1 and W is 6.88 mg/cc assuming that the viscosity of W is the same as that of pure water (0.009 P).

Comparison of the centering process of O_1 in the compound emulsion with the simulation is shown in Fig. 5. In this experiment, the resonance frequency for the bubble mode 2 oscillation was 19.9 Hz. The amplitude of oscillation and the interfacial tension were 8% of Ro and 9.12 dyn/cm, respectively. In the simulation, we used Happel's K [6], the density difference of 6.88 mg/cc, and the amplitude ratio of 1. Here, the amplitude ratio is defined as the ratio of the amplitude of oscillation of the core with the existence of the interfacial tension to that without the interfacial tension. Since our model does not include the wall effect for an offset core, the discrepancy in the initial phase is understood. However, the final balancing position agrees with the experimental results.

4. Simulation for Curing Process with a Rotary Drum

In our recent experiment, a rotary drum was employed instead of a conventional bath with stirring propellers to minimize the deformation induced by collisions of the emulsions with the propeller. The thickness uniformity for shells harvested with the rotary drum ranged from 95% to >99% depending on batch.

Using the scaling law obtained by our centering model[7], we calculated the thickness uniformity for shells obtained by the rotary drum method. We assumed that deformations in the emulsions were induced by waves that were stimulated in W_2 by the rotation of the nonconcentric drum. The simulation results are shown in Fig. 6. In this calculation, the emulsion was assumed to be deformed every 0.7-sec by the amplitude of 5% of the O radius. The temporal change in the viscosity of O shown in Fig. 2 (b) was used in the calculation. The final thickness uniformity is 98% that is similar to the experimental result. Because the centering force is proportional to the square of the amplitude of deformation, the final thickness uniformity was only 80% if the amplitude of deformation was 3% of the O radius. Although it takes 5 hours to dry the O-phase, the thickness uniformity of the shell is almost

fixed in the first 20 minutes as shown in Fig. 6.

4. Conclusions

We could fabricate 5- to 7-mm diameter polystyrene shells with 30 to 250 μm thick walls with a high sphericity and thickness uniformity close to the reactor goal. Our model for the centering of a core in a compound emulsion could explain the experimental results and indicated that the thickness uniformity is fixed within the first 20 minute of the curing process.

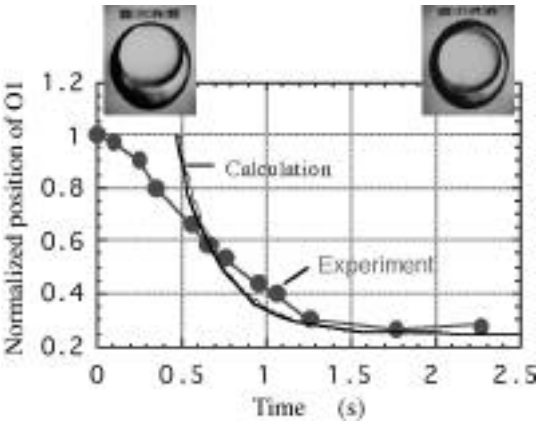


Fig. 5 Comparison of centering process of an O/W/O emulsion with simulation.

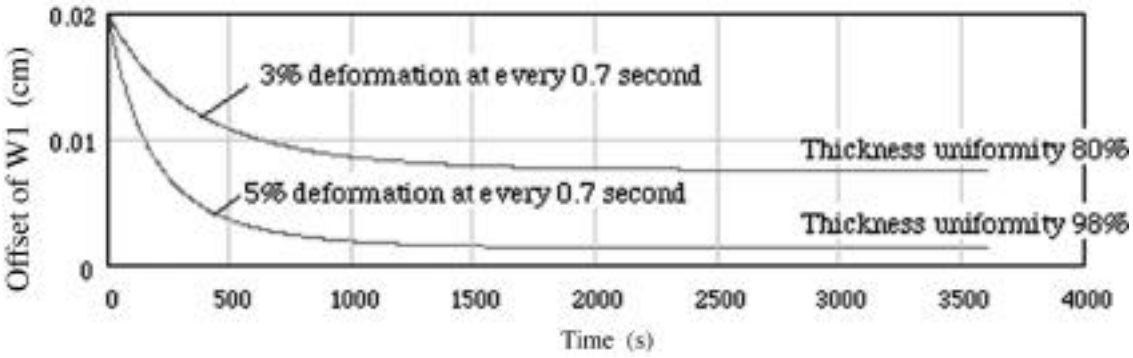


Fig. 6 Centering of W_1 in O deformed by 5% of the radius of O at a repetition rate of 1.3 Hz. Final thickness uniformity was calculated to be 98%

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