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Measurements of Wall Slip during Rise of a Physically Blown Foam

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Abstract. Polymeric foam systems are widely used in industrial applications due to their low weight and abilities to thermally insulate and isolate vibration. However, processing of these foams is still not well understood at a fundamental level. The precursor foam of interest starts off as a liquid phase emulsion of blowing agent in a thermosetting polymer. As the material is heated either by an external oven or by the exothermic reaction from internal polymerization of the suspending fluid, the blowing agent boils to produce gas bubbles and a foamy material. A series of experiments have been performed to allow observation of the foaming process and the collection of temperature, rise rate, and microstructural data. Microfocus video is used in conjunction with particle image velocimetry (PIV) to elucidate the boundary condition at the wall. These data provide input to a continuum level finite element model of the blowing process. PIV is used to measure the slip velocity of foams with a volume fraction range of 0.50 to 0.71. These results are in agreement with theoretical predictions which suggest that at high volume fractions the bubbles would exhibit jamming behavior and slip at the wall. At these volume fractions, the slip velocity profile has a shear profile shape near the side walls and a plug flow shape at the center. The shape of the velocity profile is in agreement with previous experimental work investigating different foam systems. As time increases, the available blowing agent decreases, the volume fraction increases, the viscosity increases, and the average slip velocity decreases, but the slip velocity profile maintains the plug-shear shape.

Keywords: Foam, Particle Image Velocimetry, Wall Slip
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INTRODUCTION

The most common uses of foams are for thermal, shock and vibration isolation. The two main categories of foam are chemically blown foam and physically blown foam. Chemically blown foam expands due to gas producing reactions that occur during the polymerization. Polyurethanes are an example of a chemically blown system. Physically blown foams incorporate a blowing agent that boils at an elevated temperature or reduced pressure. For our experiments, we consider a physically blown system that uses Fluorinert™ (3M) as the blowing agent. Initially, the reactants exist in an emulsion of curing agent, monomer and blowing agent. This mixture is then injected into a heated mold where the blowing agent boils and polymerization occurs. The characteristics of the cured foam depend on polymerization, Fluorinert concentration, temperature, pressure, Fluorinert nucleation and heat transfer. The goal of this work is to measure the slip velocity of the foam during under isothermal and isobaric conditions and relate that slip to the foam density and viscosity as foaming and curing progress. The slip velocity will be measured using particle image velocimetry (PIV) to track the motion of the bubbles in the foam [1, 2]. The results of this work will provide insight into the physical process and information regarding the appropriate boundary conditions for modeling efforts.

EXPERIMENTS

Experiments were performed at constant pressure in a vertical, rectangular mold with a single transparent wall. Curing epoxy foam with a Fluorinert (boiling point of 53°C at laboratory conditions) blowing agent was used. The

foam precursor liquid was a two-part epoxy with the blowing agent blended into the curative. Each part of the epoxy was preheated separately to near, but below, the boiling temperature. Time was measured from the mixing of the two parts, so that the velocity measurements could be correlated with the extent of reaction and the viscosity of the continuous phase, as determined in separate experiments. The mold was preheated to temperature, which varied from 53°C to 65°C, and then the foam liquid precursor was injected.

Particle image velocimetry (PIV) was used to measure the slip velocity profile of the foam adjacent to the transparent wall. Tracer particles were not necessary since the foam bubbles themselves could be used for data analysis. Images were taken at 1 second intervals with a CoolSnap EZ CCD camera using standard optics. PIV was performed using DaVis visualization software to cross-correlate successive images. Figure 1a illustrates a typical foam experiment at three separate time points. Each image includes a close-up of the foam on the left and a larger image of the entire mold on the right. Figure 1b shows a close-up of a rising foam interface with superimposed velocity vectors results from PIV. As the foam fills the mold, the interface flow profile is fountain-like. However, it should be noted that there is a small gap between the transparent wall and the rest of the mold which contributes to the interface flow profile. Figure 1c illustrates the bulk foam motion within the mold. At this time point, the volume fraction of the foam is ~60% and the PIV results illustrate the slip velocity along the mold wall. The velocity profile consists of three separate regions. There is a shear velocity profile near both side walls and a plug flow velocity profile near the center. From this image, it is also possible to see the gradient in the vertical velocity along the direction of flow.

Figure 2 shows the foam velocity profile for four distinct time points. The arrow points in the direction of increasing time. As time increases, the available blowing agent decreases, the viscosity increases and the volume fraction increases resulting in a decrease in the average slip velocity, but the profile maintains the three flow regions. Figure 3 illustrates the foam viscosity and density over the course of the experiment. Although, the continuous phase viscosity increases with time as the polymerization takes place, the foam viscosity increases primarily from the increase in the gas volume fraction, ϕ. In separate experiments it was found that the expression for the apparent relative viscosity of the foam, $\eta/\eta_c = \exp(\phi/1-\phi)$, matched the low-shear-rate viscosity measured in a conventional shear rheometer [3,4]. During the experiment the volume fraction of gas is determined from the height of the sample and the known quantity of liquid injected. The unblown foam has density of ~1.1g/mL and a final density ~0.3 g/mL which corresponds to a final volume fraction of ~0.73.

CONCLUSIONS

The PIV results from this work show that our free rise foam has a slip velocity over a volume fraction range of 0.50 – 0.71. The presence of a slip velocity for foams within this volume fraction range agrees with theoretical predictions. The slip velocity profile consists of shear profiles near the perpendicular walls and plug flow profiles along the center. The shape of the slip velocity profile is consistent with non-curing foam systems [5-7]. The decrease of the average slip velocity is the result of a decreased availability of the blowing agent and the increase in viscosity due to polymerization and increasing gas volume fraction. These data, in addition to the rise rate, density, and viscosity measurements will provide needed input to a finite-element-based computational model of free rise foaming being developed to aid in process optimization.

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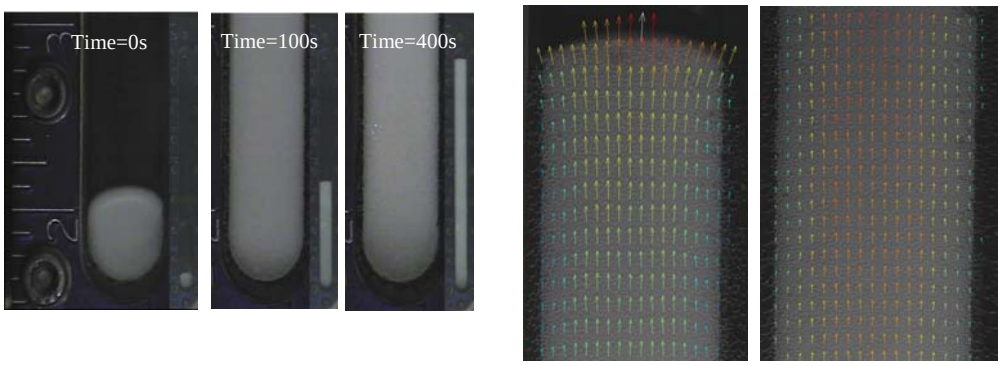

FIGURE 1. Images of free rise foam growth. (a) Three partial frames from a video of foam growth. Close-up shot on left and larger field shot on right of each frame. (b) Particle image velocimetry of a rising foam interface. (c) Particle image velocimetry of bulk foam motion. The velocity profile consists of three separate regions perpendicular to the direction of flow. The velocity profile is shear-like near both side walls and exhibits a plug flow behavior near the center.

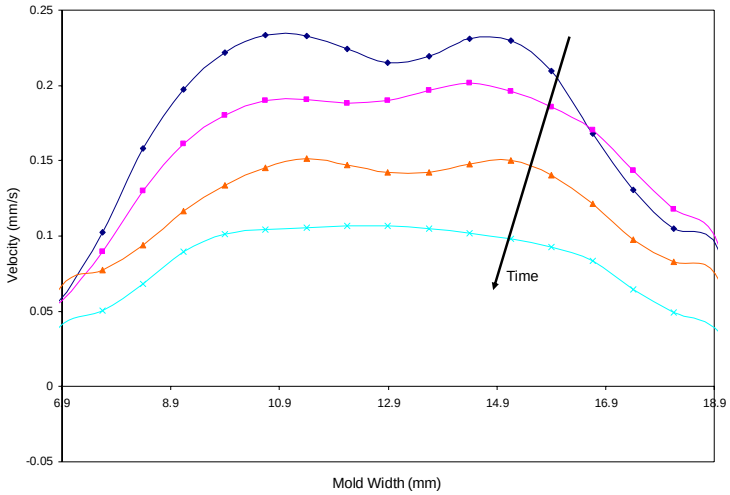

FIGURE 2. Free rise slip velocity versus mold width for four distinct time points. The arrow points in the direction of increasing time.

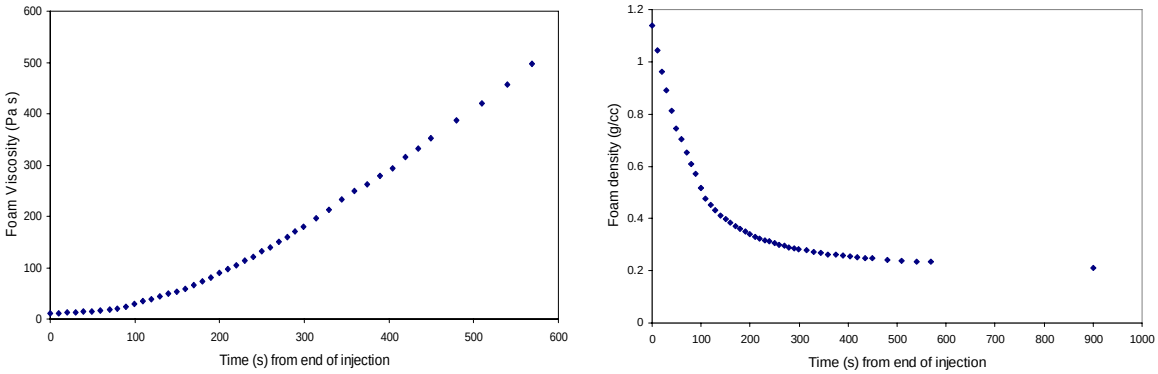

FIGURE 3. Plot of foam viscosity and density versus time for the physically blown foam system.