Synthesis of Temperature-Responsive Hydrogel Particles for Hydraulic Control of Cooled Short Circuits

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Primary CNF Tools Used: Heidelberg DWL2000, ABM Mask Aligner, AMST MVD100, PDMS Station

Abstract:

Enhanced geothermal systems (EGS) offer a promising pathway for harvesting subsurface heat from previously unsuitable regions of the planet. Their operational efficiency, however, is often compromised by the occurrence of "short circuits", which arise from uneven permeability distributions within rock fracture networks. These short circuits can lead to preferential fluid flow through highly permeable regions, resulting in localized heat depletion, lower energy production efficiency, and even possible system failure. To mitigate this issue, temperature-responsive poly(N-isopropylacrylamide) (pNIPAM)-based hydrogel particles are designed to mitigate the issue by reducing the local permeability of "short circuit" regions. A parallel step emulsifier device is fabricated at CNF to produce particles with a narrow size distribution, and fundamental rheology tests will be conducted on the produced particles to understand their jamming behavior.

Summary of Research:

The "short circuit" issue arising from uneven permeability distributions within fracture systems is one of the major challenges in Enhanced Geothermal Systems (EGS). When a fluid gets injected underground, it preferably flows through highly permeable paths. As a result, these regions are rapidly drained of heat, leading to a premature thermal breakthrough and system failure [1]. To alleviate this problem, we designed temperature-responsive nanocomposite poly(N-isopropylacrylamide) (pNIPAM)-based microgel particles. As one of the most studied thermosensitive hydrogels, pNIPAM exhibits a reversible entropy-driven volume phase transition, leading to particle expansion at low temperatures and particle contraction at high temperatures [2]. With careful design, these pNIPAM-based particles can expand to up to several hundred times their original volume when the temperature of their local environment falls below a threshold. This could effectively diminish short circuits by decreasing local channel permeability.

To produce thermo-responsive microgels with a narrow size distribution, a parallel step emulsifier was fabricated and optimized at the Cornell Nanoscale Science and Technology Facility (CNF). As of the last reporting period, we started the fabrication of the emulsifier device. Specifically, an emulsifier device adapted from Stolovicki et al. was produced at CNF (Figure 1) [3]. Photolithography was used to make the device master mold. The mold was subsequently used to pattern the final poly(dimethylsiloxane) (PDMS) based device. This device was expected to produce pre-gel droplets with a target size of around 30 μm. The droplets will then be polymerized under a UV source to form the final crosslinked polymer particles.

During this reporting period, our efforts have been focused on further optimizing the device fabrication and droplet production process. A key challenge we encountered in the previous fabrication attempts was the inconsistent bonding of nozzles to glass slides. As illustrated in Figure 2a, the previous bonding process involved first cutting the PDMS into the desired shape and then bonding it to the glass slides. The major issue with this method is that the PDMS is extremely deformable, and therefore even small deformations of the PDMS material can result in insufficient bonding of the channel to the glass substrate, which leads to polydisperse droplet production (Figure 3a).

To address this problem, a new bonding process has been developed. Here, instead of cutting the PDMS into its final shape and directly bonding it to the glass slides, we first cut and bond the whole molded PDMS slab with another plain PDMS slab. Then, we cut the assembled

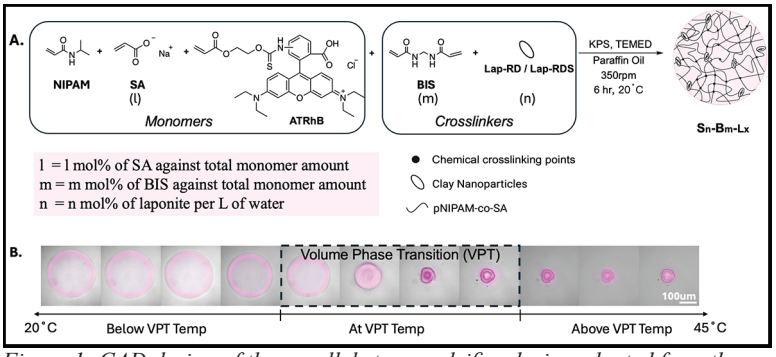

Figure 1: CAD design of the parallel step emulsifier device adapted from the Weitz group [1]. (A) Layer 1; (B) Layer 2; (C) merged images.

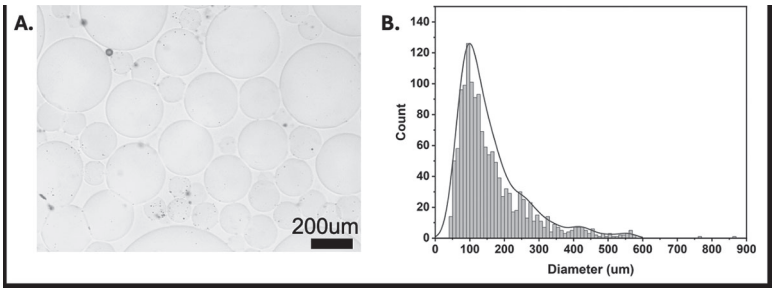

Figure 2: (A) Original PDMS device fabrication process (from the last reporting period) compared to optimized PDMS device fabrication process shown in (B).

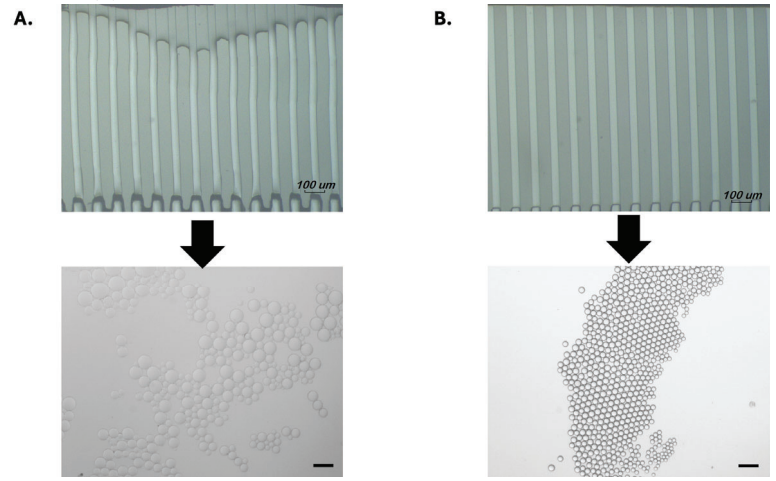

Figure 3: Typical optical images of the device nozzle areas (top) and resulting droplets (bottom) when using (A) the original PDMS device fabrication process (from the last reporting period) versus (B) the optimized PDMS device fabrication process. (Scale bar=100 μm)

PDMS slabs into the final shape of the device and bond it to the glass slides (Figure 2b). This method significantly improves the nozzle bonding quality and allows better production of monodisperse droplets. As shown in Figure 3b, the produced particles exhibit significantly reduced size variation, indicating improved monodispersity.

Conclusions and Future Steps:

In conclusion, we have successfully fabricated a microfluidic device to produce temperature-response polymeric particles for geothermal applications. With further optimization in the PDMS binding process, we were able to produce droplets with narrow size distributions. In the next step, particles with varying compositions will be produced using this device and studied for their rheological behaviors.

References:

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