High-Pressure Colloidal Hydrogen Aphrons (CHAs): A Study on Generation, Storage, Stability, and Release

ABSTRACT

Hydrogen has been widely acknowledged as a highly promising energy source due to its exceptional energy density and environmentally friendly combustion characteristics. Hydrogen can be utilized as a fuel in various applications, including transportation and power generation.

In 1971, Felix Sebba proposed a method to produce a 'microfoam' referred to as Colloidal Gas Aphrons (CGA). These CGAs are different from conventional foam in their structure and fluid mechanical properties.

This thesis investigates the application of CGAs in safe hydrogen storage, focusing on their distinctive characteristics to mitigate safety concerns and to enhance hydrogen's viability as a widely acceptable energy source. The study addresses key challenges posed by conventional hydrogen storage methods by introducing an innovative colloidal system that encapsulates hydrogen within stable microbubbles suspended in aqueous surfactant solutions.

The experimental methodology involved the preparation of CGAs under closed conditions. The CGAs thus prepared under hydrogen pressure have been named colloidal hydrogen aphrons (CHAs). The experimental setup was equipped with features for optical observation, magnetic stirring, and safety systems. The study investigated various aspects, including the generation of CHAs, hydrogen release mechanisms, drainage behavior, stability enhancement, and morphological characterization.

The results indicated that CHAs have excellent hydrogen storage capabilities, reaching storage capacities of up to 5.8 wt% at 90 bar pressure. Morphological analysis showed that CHAs size distribution varies significantly with pressure; mean diameters decreased from 125.2 µm at 10 bar to 31.7 µm at 90 bar, with increased size uniformity at higher pressures.

A significant advancement was the development of the Interfacial Gas-Disengagement Element (I.G.D.E.), made of three stainless steel sieves paired with double-layer 0.5 mm Teflon sheets. This innovative device allowed for hydrogen extraction while completely preventing the outflow of surfactant solutions.

Hydrogen safety tests confirmed that CHAs released hydrogen in a controlled manner; any accidental spillage led to localized, manageable ignition instead of catastrophic failure.

Drainage kinetics studies revealed a distinctive three-phase drainage pattern under gravity, with

complete drainage taking about 140,000 s. By applying centrifugal acceleration, however, drainage times were reduced to as low as 1800 s at 8000 RPM, achieving a 77-fold acceleration. The drainage behavior remained consistent in its three-stage pattern, indicating strong structural resilience under various drainage conditions.

Investigations into stability enhancement revealed significant improvements through modifying viscosity. While adding glycerol increased stability from 39 hours in the base case to 288 hours at 98% concentration, carboxymethyl cellulose (CMC) emerged as the most effective stabilizer, extending CHAs longevity to 25 days at concentrations of 1.5%-3%. CMC demonstrated excellent rheological properties, including shear-thinning behavior, long-term stability against microbial degradation, and cost-effectiveness compared to other viscosifiers.

The morphological study provided valuable insights into individual CHA behavior through systematic microscopic observation. Experiments on the dissolution of single aphrons with diameters ranging from 44.86 μm to 74.97 μm validated a diffusion-limited dissolution model, $R(t) = (R_i^2 - 2K_e D_a t)^{\frac{1}{2}}$, showing a strong correlation between experimental data and theoretical predictions, thus confirming the proposed mass transfer mechanisms. Innovative resistance analysis also led to the first experimental validation of Felix Sebba's hypothesis about surfactant layer structure, confirming the presence of a single bilayer (about two surfactant layers) in CHAs.

This research positions CHAs as a promising hydrogen storage technology, offering significant advantages over traditional methods. The distributed storage within discrete microbubbles reduces the risk of catastrophic failures, while the aqueous medium adds inherent fire suppression capabilities. The system operates effectively at moderate pressures, eliminating the need for extreme pressurization while still achieving competitive storage densities.

This research contributes significantly to the field of hydrogen storage technology by introducing a fundamentally new approach that addresses safety, efficiency, and practical implementation challenges. The findings establish a crucial foundation for scaling CHAs technology for different applications, especially in sectors prioritizing enhanced safety measures. Future work may focus on optimizing surfactant formulations, exploring alternative viscosifiers, and examining long-term storage performance under various environmental conditions.

Keywords: Colloidal gas aphrons; Hydrogen storage; Drainage kinetics; Morphological characterization; Clean energy; Hydrogen safety.