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Effect of Hydrodynamic Cavitation on Powder Detergent Dissolution Using Venturi Reactors

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Abstract **-** Hydrodynamic cavitation (HC) was explored in this study as an energy-efficient method to accelerate the dissolution of laundry detergents, and the performance of the approach was evaluated via UV–Vis absorbance measurements. For this, a custom Venturi-type HC reactor was used to dissolve standard detergent formulations at various operating pressures of 30 psi to 150 psi and the results were compared to conventional mixing benchmarking cases. UV–visible spectroscopy (measuring peak absorbance at characteristic wavelengths) provided a quantitative comparison of dissolved detergent concentrations. Accordingly, the HC treatment significantly enhanced the dissolution rate of detergent by up to 105%, achieving higher solution concentrations in shorter times as little as 35 s, compared to mixing which required 2 minutes and yielded a lower dissolution rate. Notably, the cavitation flow led to physical deagglomeration of detergent particles, as evidenced by reduced particle size distributions, which in turn improved mass transfer. These findings demonstrate that Venturi-induced hydrodynamic cavitation can greatly improve both the duration and efficiency of detergent dissolution. The results suggest a strong potential of HC-based processes in washing applications to reduce time and increase dissolution rate.

Keywords**:** Hydrodynamic cavitation, detergent dissolution, venturi

1. INTRODUCTION

Hydrodynamic cavitation (HC) is triggered via a flow constriction, such as an orifice or Venturi, so that rapid pressure drops generate vapor bubbles that collapse violently and produce shock waves, microjets, localized heating, and reactive radicals [1]. Unlike acoustic cavitation, HC is readily scalable and energy-efficient for industrial applications covering wastewater treatment and chemical synthesis. The extreme turbulence and shear forces originating from collapsing bubbles also accelerate the solid dissolution by breaking apart particles and enhancing mass transfer. As an exampl, Dvorsky et al. [2] reported markedly improved silicon microparticle fragmentation in a water-jet HC device.

Efficient powder detergent dissolution is critical in laundry yet often demands longer stirring or heating. Stepišnik Perdih et al. [3] showed that HC can speed detergent dissolution and improve stain removal compared to conventional mixers. Motivated by pioneering research efforts in the field, in this study, we used a Venturi-type HC reactor to dissolve powder detergent (4.5 g L^{-1}) in water. The dissolution is quantified via UV–Vis peak absorbance. We also examined how various cavitating flow patterns influence the mixing enhancement.

2.EXPERIMENTAL SETUP AND PROCEDURE

Powder detergents as commercial laundry detergents were tested. The powder detergents were prepared according to the IEC EN 60456 standard formulation for detergent performance tests.

Both Venturi reactors are 220 × 70 mm acrylic chips with a 30° converging section, 1 mm throat length, and 18° diverging section were fabricated by 3D printing techniques. Figure 1 represents schematics of printed venturi reactors.

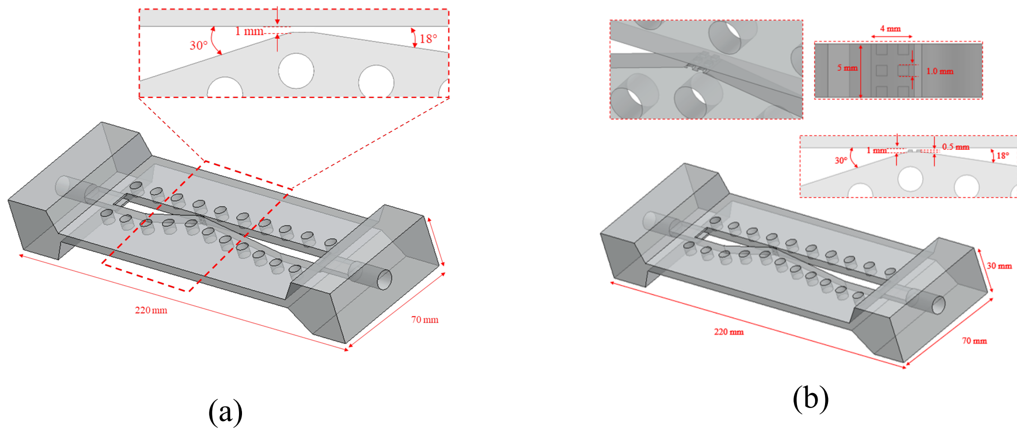


Figure 1. (a) Venturi A (smooth): polished throat, 4 mm diameter, converging 30°, diverging 18° (b) Venturi B (rough): identical geometry plus an array of 2 mm-diameter posts (1 mm pitch) in the throat, seeding cavitation

An open-loop system (3.5 L tank, high-pressure nitrogen tank, flowmeter, pressure gauges) passed the detergent suspension through reactors to ambient. Three regimes were defined according to the upstream pressure and measured flow rate (Tables 1). Cavitation inception was confirmed visually using the utilized high speed camera (Photron VEO710).

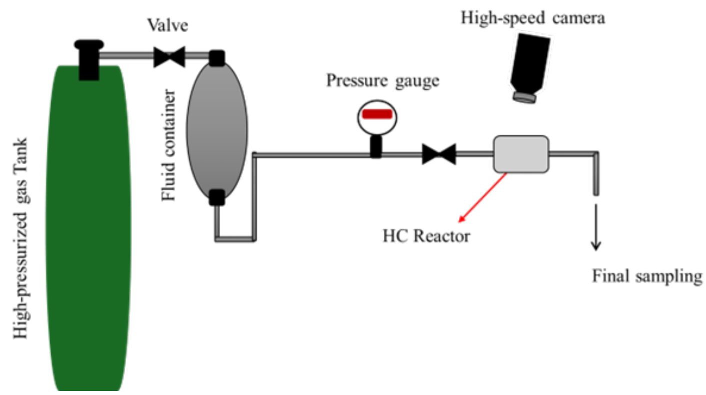


Figure 2. Schematic of experimental setup including nitrogen tank, container, HC reactor, and high-speed camera

Solution preparation, single-pass cavitation, dilution for UV–Vis at 223 nm, and power measurements were performed All tests were performed in triplicate.

Table 1.Flow conditions for both Venturi reactors.

Smooth Venturi A Regimes		Rough Venturi B Regimes	
Pressure (psi)	Flow Rate (L/s)	Pressure (psi)	Flow Rate (L/s)
40	0.036–0.037	40	0.035–0.036
65	0.045–0.052	100	0.056–0.060
90	0.055–0.061	150	0.068–0.071

3. RESULTS AND DISCUSSION

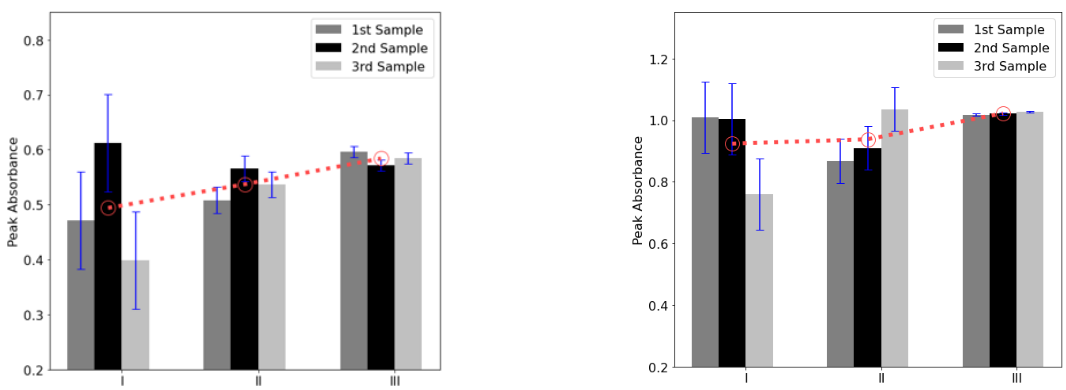
Inception in Venturi B was observed at the upstream pressure 40 psi, while it was 30 psi for Venturi A, confirming that roughness significantly lowers the pressure threshold for cavitation inception [4], [5]. The peak absorbances for measured upstream pressures for venturi devices were measured as:

Mean (±SD) peak absorbances for venturi A (Figure 3a):
- Upstream pressure of 40 psi: 0.49 ± 0.090
- Upstream pressure of 65 psi: 0.53 ± 0.030
- Upstream pressure of 90 psi: 0.58 ± 0.010

Mean (±SD) peak absorbances for venturi B (Figure 3b):
- Upstream pressure of 40 psi: 0.90 ± 0.120
- Upstream pressure of 100 psi: 0.94 ± 0.080
- Upstream pressure of 150 psi: 1.03 ± 0.005

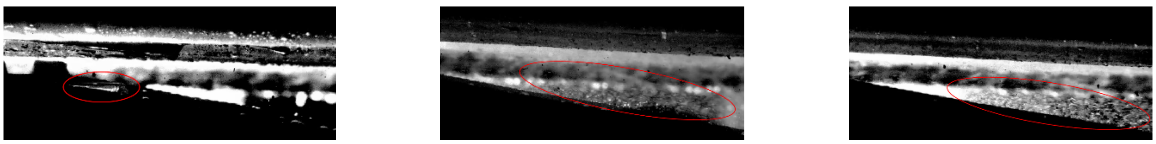
These results suggest that cavitation strongly affects the distribution rate of powder [6] while the roughness elements contribute to the cavitation intensity. By breaking agglomerates into finer fragments, these jets increase the total surface area exposed to water, allowing more detergent to dissolve at once. At the same time, the turbulent eddies and micro-streaming caused by cavitation continuously renew the thin liquid layer around each particle. This constant refreshing of the solid-liquid boundary film prevents concentration stagnation on the particle surface and maintains a steep concentration gradient, which drives rapid mass transfer [7].

Figure 4 displays flow patterns in venturi B at 3 different upstream pressures, namely 40,100 and 150 psi. as indicated in figure inception occurs at 40 psi. By increasing the upstream pressure, the static pressure of the throat falls more sharply, lowering the cavitation number and prolonging two phase conditions, so vapor nuclei coalesce into a longer, thicker sheet cavity, maximizing interfacial area, collapse intensity, and overall process efficiency.



(a) (b)

Figure 3. (a)Venturi A (smooth) and (b) venturi B (roughened) peak absorbance vs. regimes



(a) (b) (c)

Figure 4. Visualization of venturi B at upstream pressures of (a) 40 psi, (b)100 psi, (c)150 psi

4. CONCLUSIONS

This study proves that hydrodynamic cavitation escalates the solution rate of powder detergent, which is attributed to the increased surface of particles due to the impact of microjets generated by collapse of bubbles. Further investigation regarding the chemical effects of cavitation on general characteristics of powder will be made in our future studies.

5. ACKNOWLEDGEMENTS

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