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Supercritical CO_2 Foam Stability and Mobility for Enhanced Oil Recovery and CCUS: Experimental Evaluation in Simulated Reservoir Conditions

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Abstract

This study explores the behavior of supercritical CO_2 ($ScCO_2$) foam under conditions that simulate enhanced oil recovery and carbon sequestration, focusing on a heterogeneous sand pack that closely mimics complex reservoir environments. Conducted at a constant pressure of 1,200 psig and temperature of 150°C, the experimental setup investigates the impact of varying foam flow rates from 90 ml/min to 180 ml/min and foam qualities between 65% and 97%. The study confirms that the viscosity of $ScCO_2$ foam peaks at a quality of 95%, a crucial point for enhancing sweep efficiency and structural integrity. This research uniquely demonstrates the consistency of this viscosity peak under high flow rates and within a heterogeneous medium, reinforcing the potential of $ScCO_2$ foam for tailored applications in advanced oil recovery and carbon capture, utilization, and storage (CCUS) strategies. These insights help optimize the operational parameters of CO_2-based technologies, ensuring effective deployment in diverse geological settings.

Introduction

Foams play an important role in the oil and gas industry, particularly in CCUS applications and oil recovery (EOR), where their unique rheological properties reduce gas mobility and enhance oil displacement efficiency (Majeed et al., 2021; Taha et al., 2022). $ScCO_2$ foams are utilized as fracturing fluids due to their enhanced viscosity and stability, which are crucial for effective proppant transport and minimizing environmental impacts by reducing water usage (Abdelaal et al., 2021; Zhou et al., 2020). The stability and rheology of these foams are significantly affected by operational parameters such as foam quality and temperature, with existing studies demonstrating how temperature accelerates foam decay (Chen et al., 2016; Fu and Liu, 2021).

In this study, $ScCO_2$ foam behavior is examined within a heterogeneous sand pack designed to simulate complex reservoir conditions, distinct from the fractured core method utilized at a different scale by Samarkin et al., 2024. Experiments are conducted at a constant pressure of 1,200 psig and a temperature of 150°C, with foam flow rates varying from 90 ml/min to 180 ml/min and foam qualities adjusted between 65% and 97%. The utilized setup enables a comprehensive evaluation of the foam's performance across varying permeabilities and porosities typical of geothermal and EOR environments. The objective of this work was to enhance the understanding of $ScCO_2$ foam dynamics under these conditions, providing insights into its potential effectiveness for improving oil recovery and facilitating effective CCUS strategies in heterogeneous geological formations.

Methodology

This study examines the behavior of $ScCO_2$ foam using a detailed experimental setup designed to assess its performance under conditions that simulate actual reservoir environments, as depicted in Figure 1. The setup incorporates a CO_2 injection line and a surfactant-brine mixture system, combined in a mixing chamber where $ScCO_2$ foam is generated. The system includes a liquid injection pump to manage the surfactant mixture delivery and a flow control system to adjust foam flow rates between 90 ml/min and 180 ml/min. Pressure and temperature sensors, along with a sight glass, are installed throughout the system to monitor the operational conditions and visually inspect the foam's structure before and after the sand pack during experiments. The experimental setup includes a heterogeneous sand pack with layers of coarse and fine sand, mimicking geological formations with varied permeability zones. Particle size analysis shows coarse sand with a median diameter (Dv[50]) of 434 microns and permeability of 121.4 Darcy, and fine sand at 158 microns with 16.8 Darcy, effectively simulating realistic reservoir conditions.

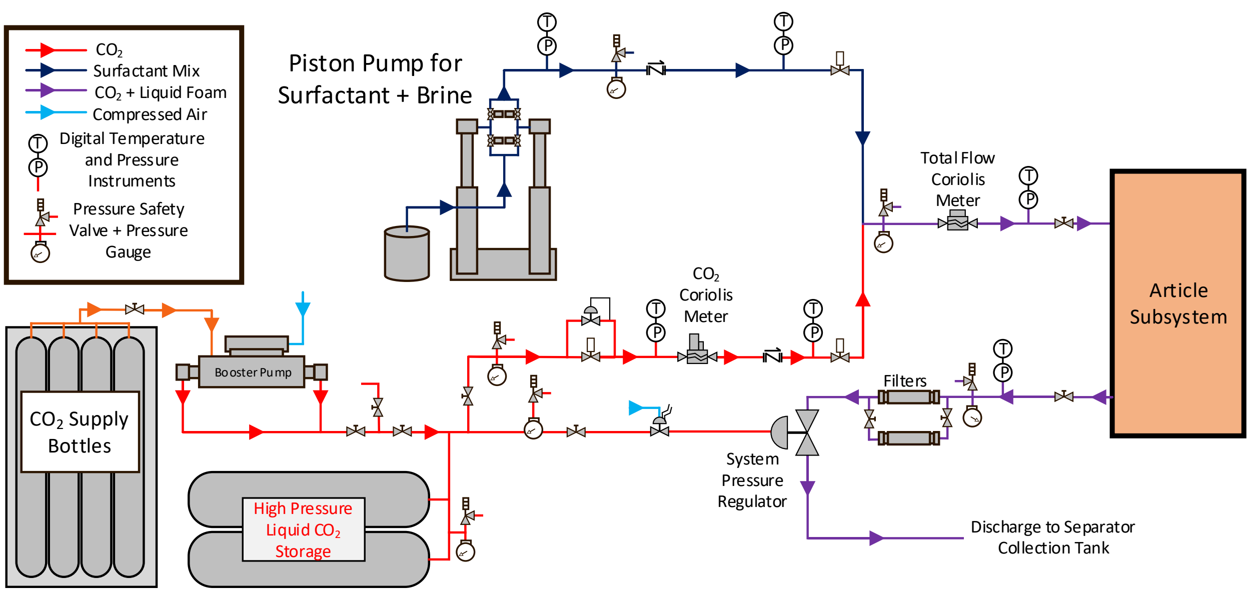

Figure 1. Schematic Diagram of the Experimental Setup for the CO_2 Foam System: This schematic illustrates the entire experimental setup, including the CO_2 injection line, surfactant mix, and CO_2 + liquid foam flow pathways. The diagram color-codes different flow paths for clarity. Key elements, like the CO_2 source, liquid injection pump, and mixing points are highlighted to show how the CO_2 and surfactant mix are combined to form the foam. The layout also details the control points for managing pressure and flow rates throughout the system, as well as the points where instrumentation was installed to monitor and measure fluid parameters.

Foam quality is a critical variable in this study, influencing the foam's density and rigidity by adjusting the gas-to-liquid ratio. This ratio, known as foam quality, affects the foam's rheological properties, as documented in prior research (Belyadi et al., 2017; Xiao et al., 2017; Abdelgawad et al., 2022; Osei-Bonsu et al., 2016). Apparent viscosity is calculated from differential pressure measurements across the sand pack and capillary tubes, providing insights into how changes in foam quality influence the foam's behavior.

Results

Figure 2 illustrates the apparent viscosity of $ScCO_2$ foam as a function of foam quality across various foam flow rates ranging from 90 ml/min to 180 ml/min. The data indicate an increase in apparent viscosity with both rising flow rate and foam quality up to a critical point. Notably, at a foam quality of 95%, the apparent viscosity peaks, after which it begins to decline, suggesting a pivotal change in the flow regime. This decline marks a phase where the foam structure potentially becomes less stable, leading to decreased viscosity. Additionally, Figure 3 provides a detailed view of the apparent viscosity changes within the sand pack for foam qualities from 65% to 97%. At lower foam qualities, such as 65%, the data reveal a substantial increase in viscosity as flow rates rise, indicating that lower-quality foams are less capable of maintaining structural integrity under higher flow conditions. Conversely, as foam quality nears 95%, there is a marked increase in viscosity, reaching a maximum before the structure begins to deteriorate.

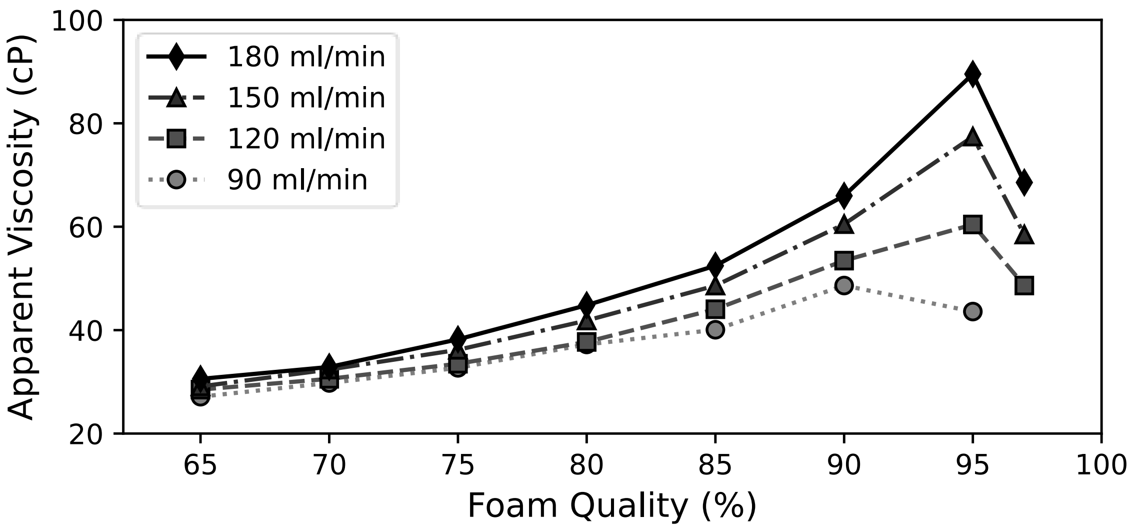

Figure 2. Apparent Viscosity Measurements Across Experimental Components: This figure includes three subfigures displaying variations in apparent viscosity within the sand pack under different conditions. It shows the effects on viscosity of changing foam flow rates from 90 ml/min to 180 ml/min, foam qualities from 65% to 97%, and an oven temperature of 150°C.

Discussion

Figure 3 illustrates the relationship between foam quality and apparent viscosity at a flow rate of 150 ml/min and a temperature of 150°C, noting that the highest viscosity occurs at 95% foam quality, indicating a transition to a drier and denser foam state. This increase in viscosity, which is visually confirmed by a denser foam texture in the sight glass, suggests a critical operational threshold that enhances the foam's ability to block high-permeability channels, thus improving sweep efficiency for EOR and CO_2 storage. However, as foam quality exceeds this point, reaching 97%, the structure begins to break down into a mist regime, decreasing its viscosity and effectiveness.

These observations are critical as they indicate the optimal conditions under which $ScCO_2$ foam maintains its structural integrity and efficacy for enhanced oil recovery applications. Understanding these thresholds allows for better tailoring of foam characteristics in operational settings, ensuring maximum efficiency and effectiveness. The insights from these data aid in identifying the operational limits of foam stability and guide the design of injection strategies that optimize the recovery process while minimizing resource wastage and enhancing overall recovery efficiency in heterogeneous reservoir environments.

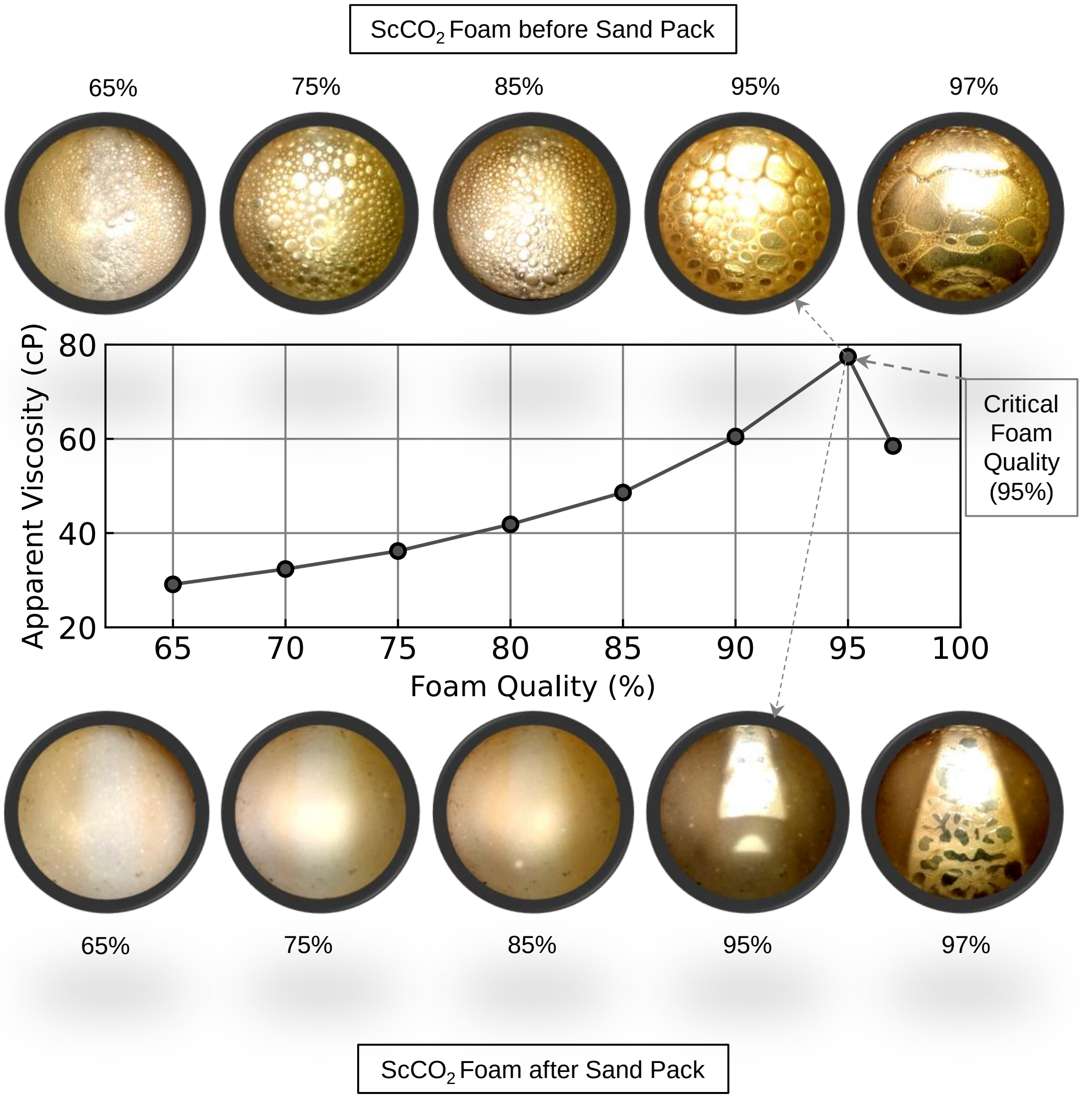

Figure 3. Visual Observation of CO_2 Foam Before and After the Sand Pack: The images captured from the flow-through sight glass show CO_2 foam at 150 ml/min and 150°C, with foam qualities ranging from 65% to 97%. The top image depicts the foam before passing through the sand pack, and the bottom image shows the foam after the sand pack, illustrating the structural changes and stability of the foam under the specified conditions, more pronounced at foam qualities of 95% and higher.

Conclusions

This investigation into $ScCO_2$ foam behavior, conducted within a heterogeneous sand pack at 1,200 psig and 150°C, reveals critical insights into its application for EOR and CCUS. With varying foam flow rates from 90 ml/min to 180 ml/min and foam qualities between 65% and 97%, optimal performance is noted at a 95% quality level, where the peak in viscosity significantly enhances sweep efficiency and structural integrity. Beyond this point, particularly at 97%, the foam shows a transition to a less stable mist regime, reducing its effectiveness. These findings emphasize the necessity for precise management of foam quality within porous media to achieve maximum operational efficiency in EOR and CO_2 sequestration, providing valuable guidelines for deploying $ScCO_2$ foam effectively in complex geological settings.

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