SIMULATION OF AGGLOMERATION AND DEPOSITION OF HYDRATE IN CO_2 PIPELINES

● LOI HOANG HUY PHUOC PHAM - AN NGUYEN SI XUAN - HANH TRAN THI HONG - PHA BUI NGOC

ABSTRACT:

Impurities like water, which can form CO_2 hydrates under high pressure and low temperature conditions, hinder the transport of CO_2 through pipelines in Carbon Capture and Storage (CCS) systems. These hydrates can obstruct pipeline flow, leading to operational inefficiencies, pressure drops, and reduced heat transfer. This study uses validated Computational Fluid Dynamics (CFD) model simulations to investigate the agglomeration and deposition mechanisms of CO_2 hydrates in pipelines. The Eulerian-Eulerian two-fluid model was employed, combined with a Population Balance Model (PBM) to simulate hydrate particle interactions. The findings provide insight into the hydrate concentration.

Keywords: CO_2 hydrate, pipeline transportation, deposition, CFD, Eulerian-Eulerian model, hydrate agglomeration.

1. Introduction

Global climate change has prompted a shift towards the reduction of carbon dioxide (CO_2) emissions. One of the leading technologies for reducing industrial CO_2 emissions is Carbon Capture and Storage (CCS), which involves capturing CO_2 from industrial processes and storing it underground [1]. The transportation of CO_2 via pipelines, particularly offshore, is a key component of this process [2]. However, transporting CO_2 presents challenges due to the risk of hydrate formation, which occurs when water and CO_2 mix under high-pressure, low-temperature conditions, leading to the formation of crystalline solid hydrates [3].

The presence of hydrates in CO_2 pipelines can cause flow blockages, increase pressure drops, and affect heat transfer efficiency [4]. Although thermodynamic inhibitors, such as methanol and glycol, are often used to prevent hydrate formation, understanding the kinetics and growth of hydrates under real pipeline conditions is crucial for risk management [5-6]. This study focuses on simulating the formation, agglomeration, and deposition of CO_2 hydrates in pipelines using a validated CFD model [7], with the aim of providing insights into how different hydrate compositions affect pipeline performance.

2. Methodology

2.1. Description of a validated CFD model

The simulation of hydrate growth and deposition was conducted using a validated CFD-Fluent [7] that allows the modeling of multiphase flows. The Eulerian-Eulerian two-fluid model was

used to represent the gas phase (CO_2) and the dispersed solid phase (CO_2 hydrate). This model treats both phases as interpenetrating continua, allowing for the calculation of phase interactions, such as momentum transfer and mass exchange.

In addition, a Population Balance Model (PBM) was integrated with the CFD model to account for the size distribution of hydrate particles, which can break apart and re-agglomerate during transport. This integration provides a more accurate representation of hydrate behavior, especially in terms of deposition on pipeline walls and agglomeration into larger structures.

2.2. Geometry and mesh design

The geometry of the pipeline used in the simulations was based on experimental setups [8], with a total length of 4 meters and an inner diameter of 9.52 mm. The pipeline was modeled as a horizontal tube, surrounded by soil to simulate offshore conditions. The mesh design is critical for accurate simulation results. A final mesh with 362,400 cells was selected for its balance between computational cost and accuracy.

2.3. Boundary conditions

The boundary conditions were defined based on the experimental data [8]. A constant inlet pressure of 3 MPa was set, with a CO_2 -hydrate mixture at varying mole fractions (0.3, 0.4, and 0.6). The inlet temperature of the CO_2 mixture was maintained at 5.15^{o}C, while the wall temperature was set at 0^{o}C to simulate the cooling effect of the surrounding soil. A mass flow rate of 3.25 kg/min was imposed at the inlet boundary, consistent with the experimental flow conditions.

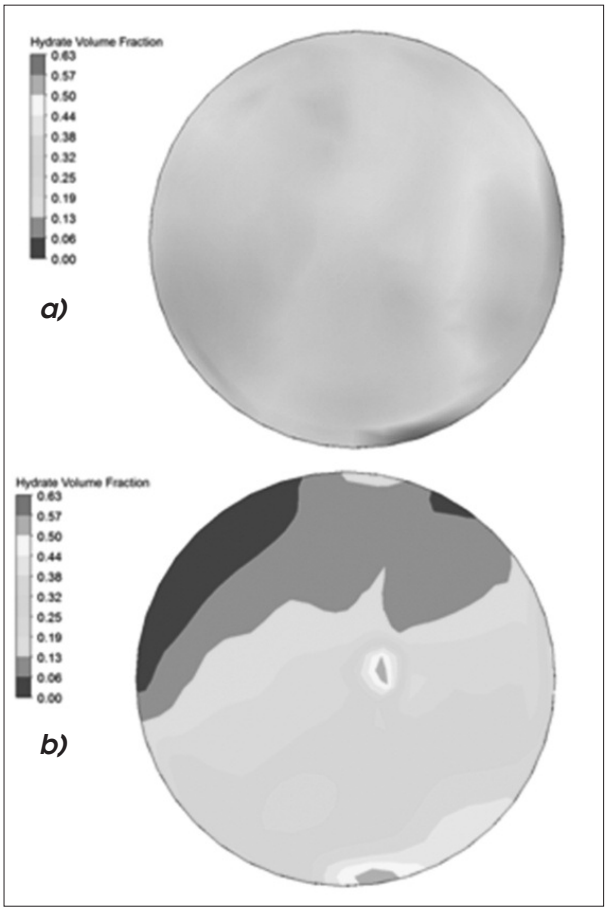
3. Results

The agglomeration and deposition of CO_2 hydrates in pipelines are critical factors affecting flow assurance and operational efficiency. The simulation results, as shown in Figures 1, 2 and 3, illustrate the varying degrees of hydrate distribution and deposition for different hydrate mole fractions (0.3, 0.4, and 0.6) along the pipeline.

At the lower hydrate mole fraction (0.3), Figure 1 indicates that the hydrate particles remain well-dispersed throughout the pipeline, with minimal coalescence. This dispersion is characteristic of the nucleation phase, where hydrate particles have yet to significantly agglomerate. As the hydrate concentration increases to 0.4 mole fraction, Figure 2 shows the beginning of particle coalescence, particularly near the bottom of the pipeline. This is due to gravitational effects, causing larger hydrate particles to settle.

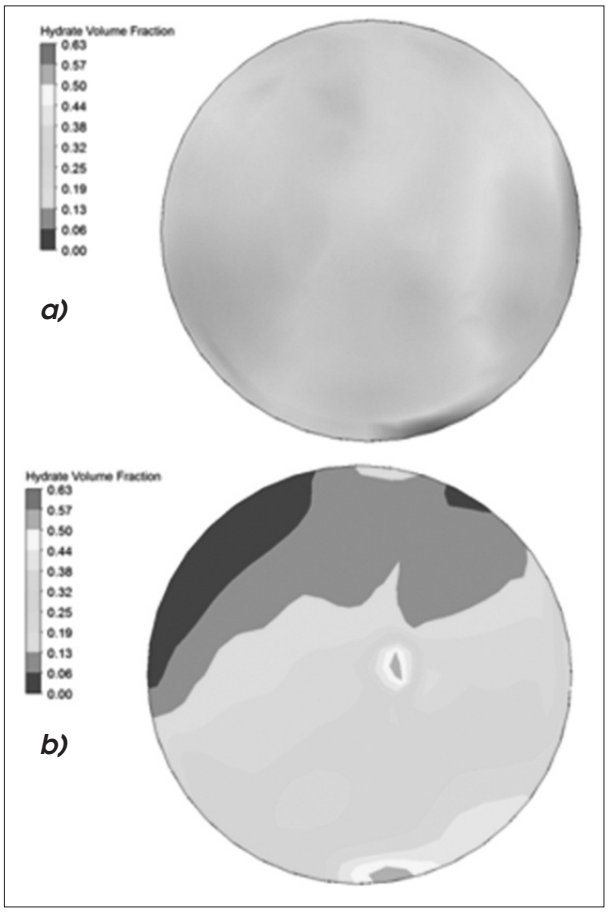
In the 0.6 mole fraction case, Figure 3 depicts extensive hydrate agglomeration, with hydrate clusters forming larger aggregates. The accumulation of these clusters near the pipeline walls, especially along the lower sections, leads to significant deposition. The hydrate volume fraction near the pipeline outlet increases considerably, indicating that the agglomeration phase transitions rapidly into deposition as the concentration of hydrates grows.

Fig. 1. Contours Of Hydrate Volume Fraction from the Simulation of Inlet of 0.3 Mole Fraction at: a) Inlet, b) Outlet



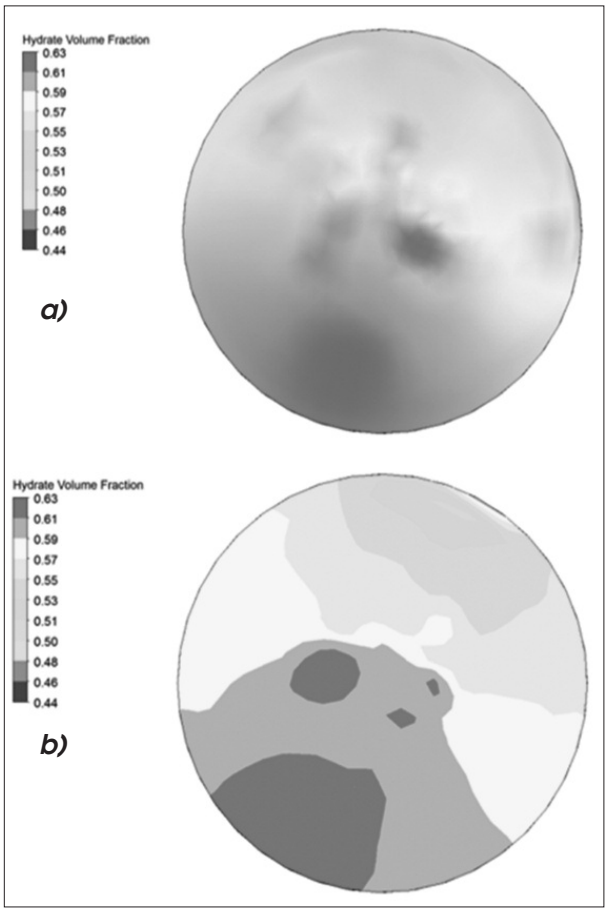
Source: Analysis by authors

Fig. 2. Contours Of Hydrate Volume Fraction from the Simulation of Inlet of 0.4 Mole Fraction at: a) Inlet, b) Outlet



Source: Analysis by authors

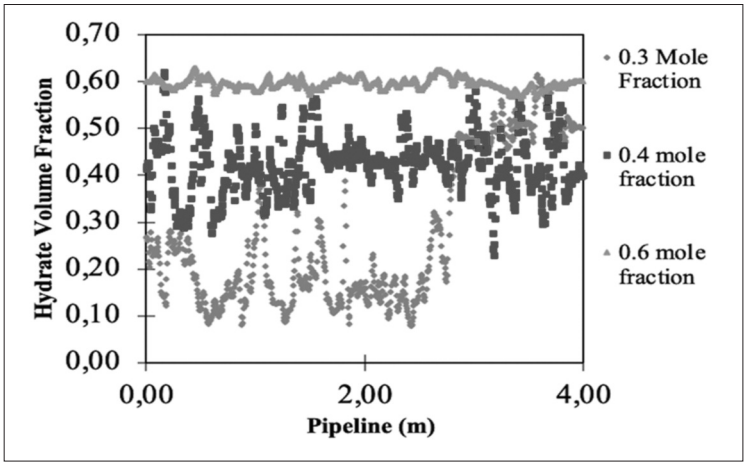
Fig. 3. Contours Of Hydrate Volume Fraction from the Simulation of Inlet of 0.6 Mole Fraction at: a) Inlet, b) Outlet



Source: Analysis by authors

The deposition behavior is particularly evident at higher hydrate mole fractions. Figure 4 highlights the variation in hydrate volume fraction at different points along the pipeline. For the 0.6 mole fraction case, the figure shows a substantial increase in deposition towards the pipeline outlet, where thick layers of hydrates accumulate along the walls. This deposition reduces the cross-sectional area available for fluid flow, creating a thermal resistance layer that inhibits efficient heat transfer between the CO_2-hydrate mixture and the surrounding environment.

Fig. 4. Prediction of hydrate volune fraction in center of pipeline



Source: Analysis by authors

The severe deposition seen in Figure 4 suggests that if left unmanaged, these hydrate layers could result in pipeline plugging. This underscores the importance of controlling hydrate formation through inhibitors or other mitigation strategies, especially in pipelines with higher water content and low temperatures.

4. Conclusion

This study developed and validated a CFD model to simulate the kinetic growth, agglomeration, and deposition of hydrates in CO_2 pipelines. The results demonstrate that hydrate deposition significantly impacts both heat transfer and pressure drop, especially at higher hydrate mole fractions. The integration of the Population Balance Model with the Eulerian-Eulerian approach provided a more accurate representation of hydrate particle dynamics.

These findings are critical for improving the design and operational strategies of offshore CO_2 pipelines, helping to prevent blockages and maintain efficient flow. Further research should focus on refining the model by incorporating more detailed thermodynamic data and exploring mitigation strategies for hydrate control in real-world pipeline systems ■

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MÔ PHỎNG SỰ KẾT TỤ VÀ LẮNG ĐỌNG CỦA HYDRAT TRONG ĐƯỜNG ỐNG CO2

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TÓM TẮT:

Việc vận chuyển CO_2 qua các đường ống trong hệ thống thu giữ và lưu trữ Carbon (CCS) gặp trở ngại bởi sự hiện diện của các tạp chất, chẳng hạn như nước, có thể dẫn đến sự hình thành hydrate CO_2 trong điều kiện áp suất cao và nhiệt độ thấp. Các hydrate này có thể cản trở dòng chảy trong đường ống, dẫn đến kém hiệu quả vận hành, sụt giảm áp suất, và giảm hiệu suất truyền nhiệt. Nghiên cứu này sử dụng mô phỏng động lực học chất lỏng tính toán (CFD) đã được xác thực để điều tra các cơ chế kết tụ và lắng đọng của hydrate CO_2 trong đường ống. Mô hình hai pha Eulerian-Eulerian được áp dụng, kết hợp với mô hình cân bằng mật độ (PBM) để mô phỏng sự tương tác của các hạt hydrate. Các kết quả nghiên cứu giúp hiểu rõ hơn đặc tính hình thành hydrate trong các đường ống CO_2.

Từ khóa: hydrate CO_2, vận chuyển qua đường ống, lắng đọng, CFD, mô hình Eulerian-Eulerian, kết tụ hydrate.