Understanding the Depressurization Process of Liquid CO_2 Pipelines: Insights from Terrain-Based Experiments

Introduction

Long-distance pipeline transportation of CO_2 offers a cost-effective solution for various storage projects. These pipelines typically operate under high pressure, utilizing liquid or supercritical CO_2 to maximize transport capacity. A significant challenge in this context is understanding the thermodynamic and hydrodynamic behavior of CO_2 during depressurization events, such as pipeline ruptures or leaks. Accurately estimating these processes is crucial for effective pipeline design and for predicting CO_2 dispersion behavior in the event of such incidents.

Numerous studies have investigated the CO_2 depressurization process in single horizontal pipes [Munkejord et al., 2020, Cao et al., 2020]. In these experiments, the depressurization process is simulated either through a disk rupture, mimicking pipe failure, or via an orifice to represent a leak. High-resolution pressure measurements capture the pressure wave propagation during the initial phase of depressurization, while temperature sensors positioned at various locations reveal temperature segregation within the flow throughout the process. These experimental findings are crucial for model development and validation.

To investigate the influence of pipeline geometry on the depressurization process, a dedicated experimental study was conducted at Equinor's multiphase flow rig in Porsgrunn from 2021 to 2023. This study involved detailed measurements of mixture density at various locations within the test facility, examining the effects of pipe inclination and potential liquid accumulation during the depressurization process. The data collected from this experiment are unique and valuable for model validation.

In this work, we present selected experimental results highlighting the impact of pipe topology on the depressurization of pure liquid CO_2. The commercial OLGA code is employed to address some challenges associated with modeling this process.

Test Facility and Experimental Observations

The schematic of the CO_2 depressurization test facility is presented in Figure 1. This facility is equipped with a low-resolution pressure sensor and a temperature sensor, along with several gamma densitometers strategically positioned to measure phase fractions. During the CO_2 depressurization tests, these gamma densitometers provide mixture density measurements at the centerline.

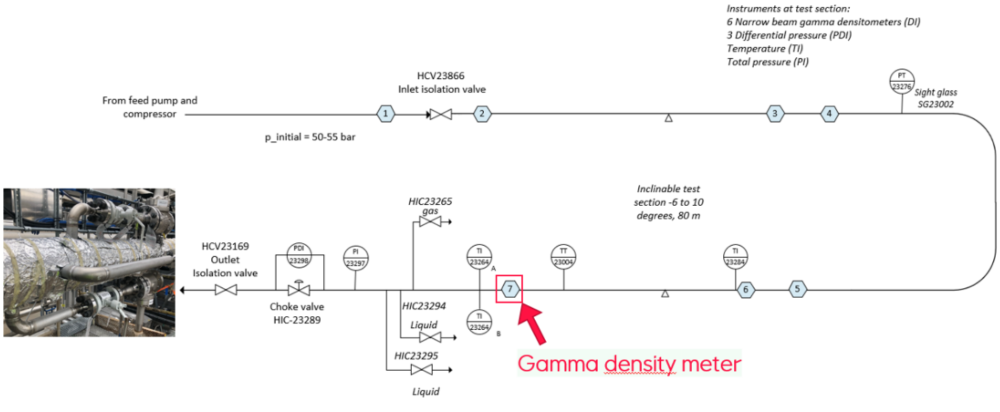
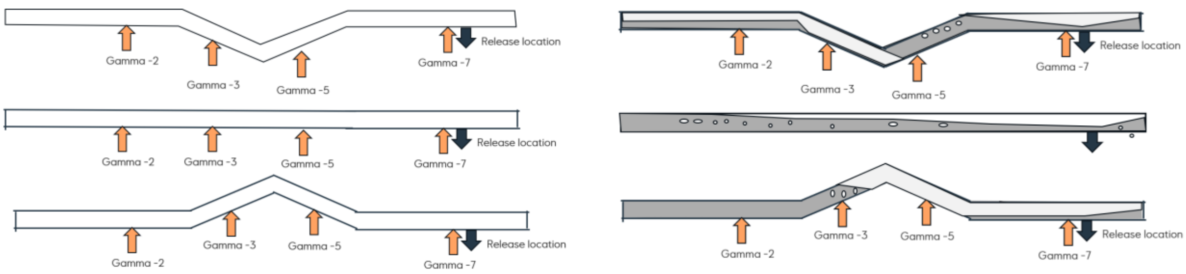


Figure 1 *Sketches of Equinor's multiphase flow rig for CO_2 depressurization tests: photo shows three different release pipes: from top, middle and bottom*

The experiments utilize a pipe with an internal diameter of 0.0779 m and a length of 140 meters. The inclinable section of the facility is tilted at angles of -6°, 0°, and 5° to investigate the impact of pipe topology on the depressurization process of pure CO_2. The depressurization is initiated using a quick-opening valve at three designated positions: pipe top, middle and bottom, as shown in Figure 1, and concludes when the system pressure reaches 20 bar by closing the release valve.

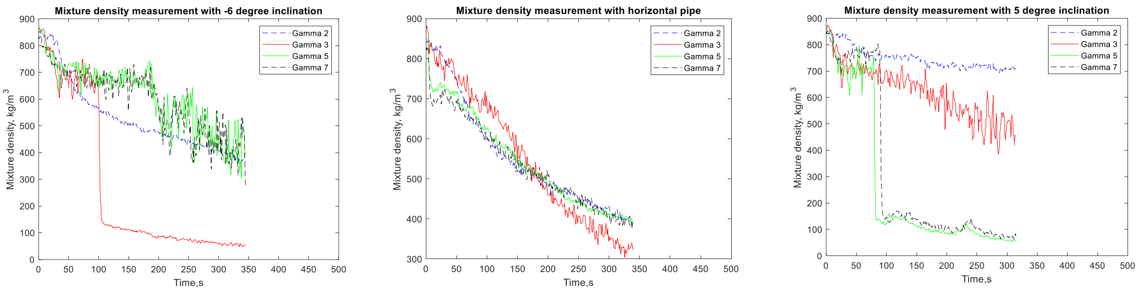
Figure 2 shows the details of the pipe topology and potential flow behavior of three different tests. The flow behavior in the pipe can be reflected by the gamma measurement at four different locations for these three different tests as shown in Figure 3. In the horizontal pipe configuration, gamma sensors No. 5 and 7, located near the release valve, show a rapid drop in mixture density at the onset of testing, indicating swift evaporation due to pressure reduction. The other two sensors exhibit a more gradual decrease. These sensors suggest similar flow behavior across all locations.



(a) (b)

Figure 2: *Pipe configuration (a) and potential flow behavior at late stage (b) of depressurization test at Equinor's multiphase flow rig with inclinable section inclination: - 6 (upper), 0 (middle)and 5 degrees (bottom).*

With the inclinable section set to -6° downward, gamma sensor No. 3 shows a rapid decline in density around 100 seconds, indicating a transition from two-phase flow to nearly single-phase gas. Gamma sensor No. 2 records a slower density reduction than No. 3 but faster than the others, indicating a gas column in the downward section. In the upward section, liquid accumulation leads to a slower reduction in gamma sensor No. 5's measurements compared to the horizontal case. Due to continuous CO_2 liquid supply from an upward pipe section, the gamma No.7 shows a slower density reduction than that of a horizontal pipe.



(a) (b) (c)

Figure 3: *Mixture density measurement in a pipe with inclinations during depressurization process: (a) with a downward inclinable section; (b) only horizontal pipe; (c) with an upward inclinable section;*

When the inclinable section is set to 5° upward, liquid accumulation is observed near gamma sensor No. 3, while a rapid decrease occurs at the downward section where gamma sensor No. 5 is located. As liquid depletes, gamma sensor No. 7 shows a rapid reduction of mixture density simply due to stoppage of liquid supply from a downward section as shown by gamma No. 5.

As illustrated in Figure 4, pipe topology significantly affects pressure and temperature variations during the depressurization process due to distinct flow behaviors: (1) Pressure Reduction Rate: The rate of pressure reduction is influenced by upstream flow conditions. Liquid accumulation can accelerate this reduction. (2) Gas Column Formation: The presence of a gas column upstream of the release section facilitates gas release only, resulting in a faster pressure reduction. (3) Temperature Segregation: Temperature measurements near gamma sensor No. 5 indicate that horizontal pipe topology exhibits earlier temperature segregation compared to the other two configurations. In tests with inclinations, temperature begins to deviate from saturation when the pipe is predominantly filled with CO_2 gas. Liquid accumulation in this section or upstream hinders temperature segregation.

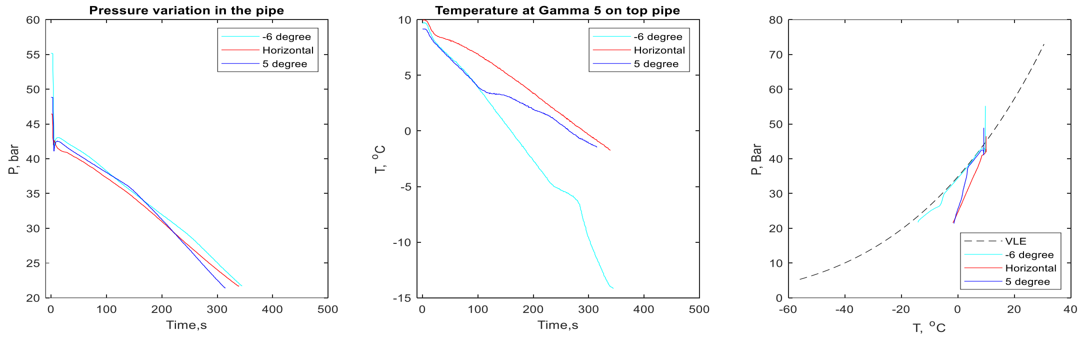


Figure 4: *Pressure and temperature variation in pipeline with different topology (inclinations) during depressurization process*

Overall, the depressurization process in a pipeline influenced by terrain is complex. Pipe topology affects two-phase flow dynamics, which in turn impact upstream flow conditions at the release point. These local flow conditions play a critical role in mass flow rate and pressure reduction rate.

Numerical simulation

In this study, the commercial flow assurance tool: OLGA code is utilized to analyze the experimental results presented earlier. Originally developed for oil and gas production systems, the OLGA code has undergone significant enhancements in recent years, enabling effective two-phase flow simulations for CO_2 applications (Nemoto et al., 2025). The current version of the OLGA code assumes thermal equilibrium for CO_2 two-phase flow and employs a single energy conservation equation for the mixture.

The simulation is conducted solely for the case with a 5° upward inclination. Among the various uncertainties in the flow model, the most significant arises from the model used for orifices or valves, where CO_2 often experiences critical flow during depressurization. As shown in Figures 5 and 6, the predicted pressure variation closely aligns with the experimental results. Temperature measurements indicate that the low-frequency sensor detects temperature segregation beginning around 100 seconds, while the OLGA code predicts liquid depletion at the gamma 5 location around 180 seconds. The presence of liquid in this section has minimal impact on gas temperature, as indicated by the measurements, while the single-temperature assumption used in the OLGA code only predicts saturation temperature. The gamma measurement provides centerline density, whereas the OLGA code calculates the average density across the pipe's cross-sectional area. Overall, the code effectively predicts the processes of phase accumulation and depletion.

Despite several limitations, the OLGA code delivers accurate predictions of the depressurization process in pipelines with varying terrain. It is crucial to note that these results were obtained through tuning the valve model. Verification and validation of the valve/orifice model should be conducted using dedicated experimental data.

Conclusions

The experimental study on pure CO_2 depressurization investigates the impact of pipeline topology. The results demonstrate that pipeline topology significantly influences CO_2 two-phase flow dynamics, leading to distinct upstream flow conditions at the release location, which in turn govern both mass and pressure release rates. Terrain variations can cause liquid accumulation in the pipeline, resulting in lower temperatures and the potential formation of dry ice if the pressure reaches the triple point. The commercial OLGA CO_2 module effectively describes the depressurization process in pipelines, although improvements are needed, particularly in the valve and orifice models.

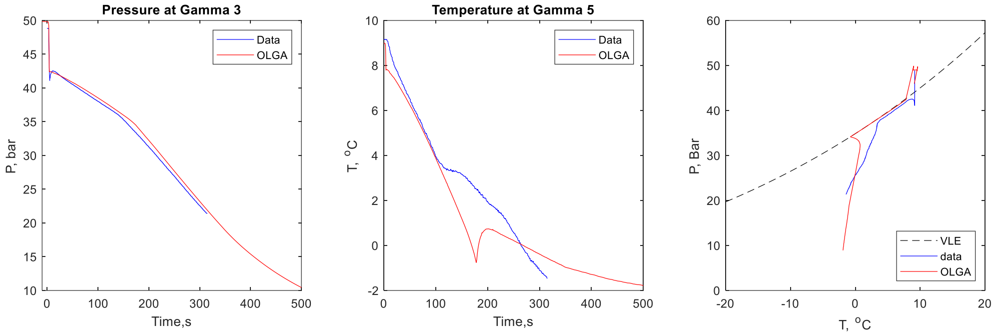


Figure 5: *The prediction of OLGA code on pressure and temperature variation of depressurization tests with the inclinable section of 5 degree upward*

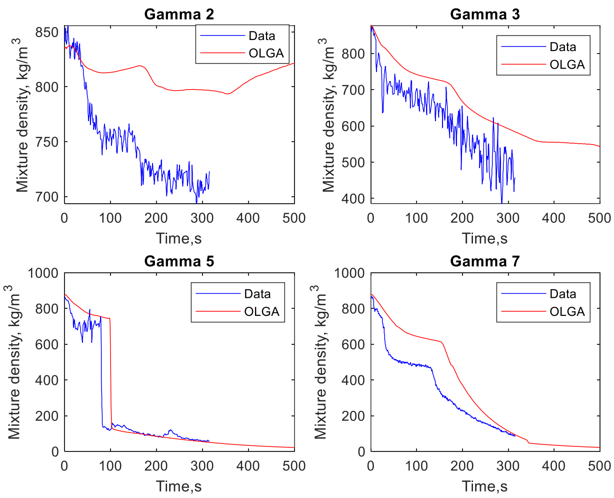


Figure 6: *The prediction of the OLGA code on mixture density at different locations of depressurization tests with the inclinable section of 5 degree upward*

Acknowledgements

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