



Article

Evaluating the Influence of Noncondensable Impurities on Multi-phase CO₂ Flow Behaviour in Pipelines

Academic Editor: Professor Rashid

Received: 10.05.2026

Revised: 26.08.2026

Accepted: 05.09.2026

Published: 09.09.2026

Citation: Okoromah, V., Ndubuisi, S., & Temple, E. (2026). Evaluating the influence of noncondensable impurities on multiphase CO₂ flow behaviour in pipelines. Hensard Journal of Environment, 1, 2. <https://doi.org/10.65757/hjev1n24>

Copyright: © 2026 by the authors. This manuscript is submitted for possible open-access publication under the terms of the **Creative Commons Attribution (CC BY) Licence** (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Victor Okoromah ¹, Shammah Ndubuisi ^{2,*} and Emeline Temple ³

¹ Department of Petroleum Engineering, Rivers State University; okoromahvic@gmail.com

² Faculty of Environmental Science, Hensard University; shammahchidi4@gmail.com

³ Department of Petroleum Engineering, Rivers State University; Emeline.temple@ust.edu.ng

* Correspondence: shammahchidi4@gmail.com;

Abstract

Carbon capture, utilisation and storage depend on the reliable transport of carbon dioxide through pipelines, yet captured streams commonly contain noncondensable impurities that can alter flow behaviour and compromise transport efficiency. This study investigated the influence of these impurities on multiphase carbon dioxide flow via steady-state compositional simulations in PIPESIM. Two pipeline models were developed under representative operating conditions: a baseline case containing pure carbon dioxide and an impurity-laden mixture containing nitrogen, oxygen, argon, hydrogen, methane, carbon monoxide, light hydrocarbons and water. The thermodynamic behaviour was modelled with the Peng–Robinson equation of state, whereas the hydraulic performance was evaluated through phase behaviour, pressure profile, pressure gradient and Reynolds number analyses. The results show that impurities expand the phase envelope and reduce the stability of dense-phase transport, increasing the likelihood of two-phase flow. Compared with pure carbon dioxide, the impurity-laden stream exhibited a nonuniform pressure decline, localised pressure gradient spikes and greater fluctuations in the Reynolds number, indicating more complex hydraulic behaviour despite remaining in the turbulent flow regime. These findings demonstrate that impurity composition significantly influences carbon dioxide transport performance and should be explicitly incorporated into pipeline design and flow assurance assessments for future carbon capture, utilisation and storage infrastructure.

Keywords: Carbon capture, Emission reduction, Flow assurance, Pipeline transport, Multiphase flow, Steady state, Noncondensable impurities.

1. Introduction

1.1 Background and context

The increasing concentration of carbon dioxide (CO₂) in the Earth's atmosphere, which has been attributed primarily to the combustion of fossil fuels since the Industrial Revolution, poses a significant threat to the global climate. According to the International Energy Agency (2020) and Ritchie et al. (2020), carbon capture, utilisation, and storage (CCUS) has emerged as a critical technology aimed at capturing CO₂ emissions from large stationary sources such as power plants, crude oil processing facilities, and industrial operations. The captured CO₂ can then be either utilised in various industrial processes or permanently stored in deep geological formations, preventing its release into the atmosphere. This bolsters the importance of CCUS as a key strategy for achieving substantial reductions in global CO₂ emissions, suggesting that CCUS is essential for limiting global warming to acceptable levels (Consoli et al., 2025). Figure 1 illustrates the CO₂ value chain from its capture in the atmosphere, transport through pipelines and ships, to its example

storage in deep offshore reservoirs. For CCUS technology to be effectively deployed on a large scale, a robust and efficient transportation infrastructure is paramount, with CO₂ pipelines recognised as the most viable option for moving large volumes of CO₂ from capture sites to storage facilities or utilisation centres.

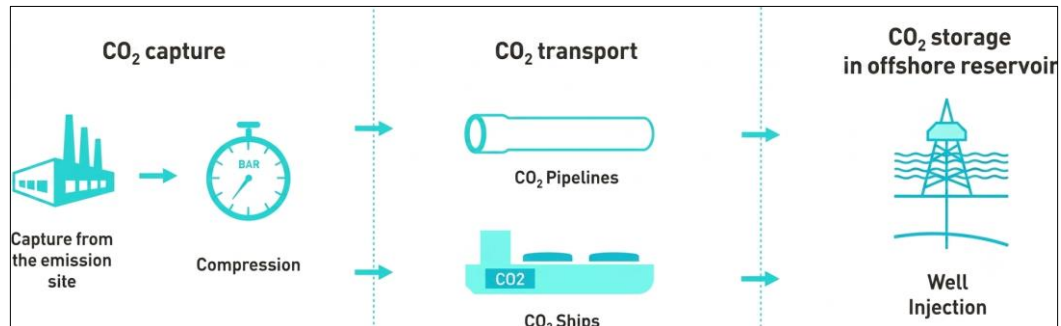


Figure 1: Representation of the CO₂ value chain (Ansaloni et al., 2020).

According to the Global CCS Institute (2024), the increasing global focus on climate change and the recognised potential of CCUS technologies highlight the urgency and relevance of in-depth research into the efficient and safe transport of CO₂ through pipeline networks. Importantly, the transport of CO₂ in pipelines, while often occurring in a dense phase (supercritical or liquid-like), can involve multiphase flow under certain conditions, especially in the presence of noncondensable impurities that may lead to the formation of gas–liquid mixtures (Porter et al., 2015). Multiphase flow in pipes is defined as the simultaneous movement of gaseous and liquid phases within the conduit. This phenomenon can manifest in various forms depending on the flow orientation, including vertical, horizontal, inclined, and directional flow. The interaction between gas and liquid phases is intricate, with the interface between them adopting diverse configurations that result in distinct flow patterns, such as stratified flow, wavy flow, slug flow, and annular flow (Raimondi, 2014). Furthermore, the reliance on CO₂ pipelines is projected to grow substantially in the coming decades as nations worldwide strive to meet ambitious net-zero emission targets (Sultan, 2018). The United States, which currently possesses the most extensive CO₂ pipeline network globally, is primarily established for enhanced oil recovery (EOR) and anticipates a significant expansion of this infrastructure. Projections suggest a four- to eighteen-fold increase in the length of CO₂ pipelines within the US by 2050 to accommodate the anticipated scale of CCUS deployment (Stokes et al., 2023).

Globally, the existing CO₂ pipeline infrastructure spans more than 6,500 km, with the majority of this network located within the United States. This existing infrastructure has primarily supported CO₂ transport for enhanced oil recovery operations. There is also growing momentum in developing CO₂ pipeline infrastructure, with approximately 14,500 km of such pipelines currently under development across various regions. Significant new CO₂ pipeline projects are in the planning and development phases across various regions, particularly North America and Europe. Notable examples include the Alberta Carbon Trunk Line in Canada, which was designed to transport CO₂ from industrial sources to an EOR site, and several projects in the North Sea region, such as the Project Greensand in Denmark and the Northern Lights project in Norway, which aimed to transport and store CO₂ in offshore geological formations (Lu et al., 2020). This existing infrastructure and the ambitious expansion plans indicate a growing reliance on CO₂ pipelines as a cornerstone of carbon management strategies, emphasising the need for comprehensive research to ensure their efficient behaviour and operational effectiveness. While the expansion of CO₂ pipeline infrastructure is crucial, the captured CO₂ streams transported through these pipelines are not typically composed of pure CO₂. Depending on the source of emissions and the specific capture technology

employed, these streams contain varying amounts of impurities (Noothout et al., 2014). Among these impurities, noncondensable gases such as nitrogen, oxygen, and argon are commonly found and can significantly alter the thermodynamic and flow behaviour of CO₂ within pipelines (Raimondi, 2014). A thorough understanding of how these impurities, particularly those that remain in the gaseous state under typical pipeline operating conditions, affect CO₂ flow characteristics is paramount to ensuring the safe and efficient operation of these critical transport systems.

1.1.1 Nigerian context

Carbon capture and storage in Nigeria is unfolding within a broader shift toward low-carbon energy systems, yet its domestic deployment remains at an early and formative stage. Recent subsurface assessments, particularly the Nigerian CO₂ Storage Atlas, indicate that the country holds substantial geological storage capacity, estimated at approximately 10,700 Gt within saline aquifers and depleted hydrocarbon reservoirs concentrated in the Niger Delta (International Finance Corporation [IFC], 2025). This suggests that storage availability is unlikely to constrain future CCS deployment; rather, the key limitations lie in incomplete regulatory structures, limited operational experience, and the absence of fully integrated capture, transport, and storage networks. Within this context, the efficient and safe transport of CO₂ through pipelines has become a central requirement for scaling CCUS initiatives, particularly in industrial hubs such as Rivers State. However, the presence of noncondensable impurities in captured CO₂ streams introduces a critical layer of complexity, as these impurities can significantly modify multiphase flow behaviour, influencing the pressure drop, flow regime transitions, and overall transport efficiency. In addition, certain impurity species, especially those containing sulfur, present corrosion risks that may compromise long-term pipeline integrity and operational safety. Despite the strategic policy direction provided by frameworks such as the Climate Change Act (2021) and the Energy Transition Plan (2022), which recognise CCS as essential for decarbonising hard-to-abate sectors, there remains a limited understanding of how varying impurity compositions affect CO₂ transport under conditions representative of Nigeria's subsurface and infrastructure realities (Federal Ministry of Environment, 2021; IFC, 2025). Consequently, this study addresses a critical gap by investigating the influence of noncondensable impurities on CO₂ flow behaviour.

1.2 Research objectives

The specific objectives of this study are as follows:

1. A baseline model for pure and impurity-laden CO₂ flow in pipelines underrepresentative operating conditions was established via PIPESIM.
2. Evaluate the impact of noncondensable impurities on flow behaviour, with emphasis on flow regime transitions, pressure drop, and liquid holdup.
3. The sensitivity of CO₂ flow characteristics to variations in key operating parameters, including temperature, pressure, and flow rate, in the presence of impurities was quantified.
4. The simulation results are validated and contextualised through a comparison with literature on impurity effects in CO₂ pipeline transport.

1.3 Theory of The Study

1.3.1 CO₂ Flow Behaviour and Pipeline Transportation

CO₂ flow behaviour addresses various aspects of how carbon dioxide moves through a pipeline, including its physical state, velocity, and pressure and the manner in which it interacts with the pipeline and any other phases present. In pipeline transport, as shown in Figure. 2, CO₂ is often maintained in a dense phase, typically either a supercritical fluid or a liquid, to maximise the amount of CO₂ that can be transported for a given pipe diameter and to increase energy efficiency (Sultan, 2018). The specific flow behaviour of CO₂ is governed by several factors, including the operating

pressure and temperature within the pipeline, the rate at which CO₂ flows, and the intrinsic physical properties of CO₂ itself, such as its density, viscosity, and compressibility (Ritchie & Roser, 2020).

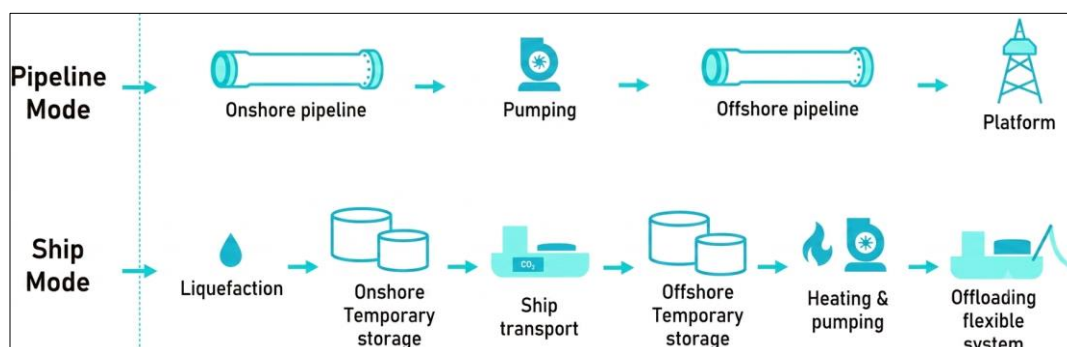


Figure. 2: Steps involved in the CO₂ transport process via pipelines or ships (Ansaloni et al., 2020).

The presence of impurities within the CO₂ stream can significantly influence these properties and lead to deviations from the flow behaviour expected of pure CO₂. For example, impurities can alter the phase envelope of CO₂, which defines the conditions under which it exists as a gas, liquid, or supercritical fluid, potentially leading to the formation of multiple phases during transport (Chapoy et al., 2011). The phase envelope is a critical tool for understanding the thermodynamic behaviour of CO₂ mixtures, showing the boundaries between different phase regions as functions of temperature and pressure. When noncondensable impurities are present, the phase envelope expands, creating a larger two-phase region where both gas and liquid coexist under conditions where pure CO₂ remains in a single phase. Understanding these phase transitions is essential for pipeline design and operation because the presence of two phases dramatically changes the hydraulic characteristics of the flow. Two-phase flow results in greater pressure drops, more complex flow patterns, and greater potential for operational problems such as slugging and phase separation. These phenomena can lead to increased pumping costs, reduced transport capacity, and elevated risks of pipeline damage or failure (Li et al., 2024).

1.3.2 Noncondensable Impurities in Captured CO₂ Streams

While the expansion of CO₂ pipeline infrastructure is crucial, the captured CO₂ streams transported through these pipelines are not typically composed of pure CO₂. Depending on the source of emissions and the specific capture technology employed, these streams contain varying amounts of impurities (Noothout et al., 2014). Among these impurities, noncondensable gases such as nitrogen, oxygen, and argon are commonly found and can significantly alter the thermodynamic and flow behaviour of CO₂ within pipelines (Raimondi, 2014). Common examples of noncondensable impurities frequently encountered in captured CO₂ streams include gases such as nitrogen (N₂), oxygen (O₂), argon (Ar), hydrogen (H₂), and methane (CH₄). Table 1 lists typical noncondensable impurities in CO₂ streams. These impurities are introduced into the CO₂ stream during the capture process, with their specific types and concentrations being dependent on the particular CO₂ capture technology employed (postcombustion, precombustion, and oxyfuel combustion) and the source of the CO₂ emissions (Al-Siyabi, 2013). A key characteristic of noncondensable gases is their tendency to remain in the gaseous phase within the operational envelope of CO₂ pipelines (Sultan, 2018). The concentration of impurities can vary significantly depending on the capture technology. Postcombustion capture typically produces streams with nitrogen concentrations ranging from 0.2% to 5.8% by volume, whereas oxyfuel combustion may result in higher oxygen and argon contents. Precombustion processes may introduce hydrogen and carbon monoxide into the CO₂ stream. These variations in impurity composition and concentration have important implications

for pipeline transport, as different impurities affect the thermodynamic and transport properties of the CO₂ mixture in different ways. These compositional shifts have been shown to meaningfully increase hydrate formation risk and expand the two-phase region in CO₂-rich systems (Chapoy et al., 2011), whereas Peletiri et al. (2017) similarly demonstrated that noncondensable impurities degrade key CO₂ pipeline hydraulic performance metrics, including pressure drop and transport efficiency.

Table 1: Typical noncondensable impurities in CO₂ streams (source: adapted from Porter et al. (2015) and Noothout et al. (2014))

Impurity	Typical Concentration (vol%)	Primary Source
Nitrogen (N ₂)	0.2 - 5.8	Postcombustion, Oxyfuel
Oxygen (O ₂)	< 1 - 4.7	Oxyfuel, postcombustion
Argon (Ar)	0.03 - 4.5	Oxyfuel, postcombustion
Methane (CH ₄)	< 0.1 - 4.0	Precombustion, Natural Gas
Hydrogen (H ₂)	< 0.1 - 1.0	Precombustion
Carbon Monoxide (CO)	< 0.1	Precombustion

1.3.3 Multiphase flow fundamentals

The key parameters that govern the behaviour of multiphase flow in pipelines include the pressure drop, flow regime, and liquid holdup (Jacobson et al., 2014). The pressure drop, the loss of pressure as the fluid moves along the pipeline, is influenced by factors such as friction between the fluid and the pipe wall, gravitational forces due to elevation changes, and acceleration forces related to changes in flow velocity (Neele et al., 2017). To predict pressure loss in multiphase flow, engineers rely on various empirical and mechanistic correlations that are often based on the general energy equation, which describes the energy balance within the flow system. The prediction of flow regimes is equally important, as different flow patterns exhibit distinct characteristics in terms of pressure drop and liquid holdup. Mechanistic models, in particular, aim to predict these patterns by applying fundamental physical principles and considering the forces acting on each phase.

The primary flow regimes encountered in horizontal pipelines include stratified flow, where gas and liquid separate into distinct layers; wavy flow, characterised by waves at the gas–liquid interface; slug flow, featuring alternating plugs of liquid and gas; and annular flow, where liquid forms a film around the pipe periphery with gas flowing in the core. Liquid holdup, defined as the fraction of the pipeline volume occupied by the liquid phase, is another crucial parameter that is affected by phenomena such as gas slippage and density differences between phases (Jacobson et al., 2014). In gas–liquid flow, the gas phase typically travels faster than the liquid phase does because of buoyancy effects, resulting in a liquid holdup that differs from the input liquid fraction. This slippage effect becomes more pronounced as the density difference between phases increases, which is particularly relevant for CO₂ systems with noncondensable impurities where the gas phase has a significantly lower density than the liquid phase. In the context of CO₂ transport with noncondensable impurities, studies have shown that the presence of noncondensable gases can significantly impede the rate at which the vapour condenses into a liquid. This occurs because noncondensable gas tends to accumulate at the interface between the vapour and liquid phases, creating a diffusion barrier that slows the condensation process (Wang et al., 2011). This phenomenon, known as the diffusion barrier effect, can maintain two-phase conditions over a wider range of pressures and temperatures than would be observed with pure CO₂.

2. Materials and methods

2.1 Simulation Software

The simulations were conducted via the SLB Pipeline Simulator (PIPESIM) software, a commercial steady-state simulator designed for analysing the performance of oil, gas, and water

production and transportation systems. PIPESIM supports various functionalities, including the modelling of pipeline networks, the incorporation of different equipment such as compressors and pumps, and the use of advanced fluid property models, such as compositional analysis. This ability to handle complex fluid mixtures and their phase behaviour under varying pressure and temperature conditions makes it suitable for investigating the effects of impurities on CO₂ flow. PIPESIM employs a compositional approach to fluid property calculations, which is essential for accurately modelling CO₂ streams containing impurities. The thermodynamic behaviour of the CO₂ mixtures was described via the Peng–Robinson equation of state, which is related to the pressure, temperature, and molar volume of the fluid and enables accurate prediction of phase behaviour under various conditions.

$$P = \frac{RT}{V-b} - \frac{a}{V(V+b) + b(V-b)} \quad (1)$$

These calculations are performed at each point along the pipeline, considering the local pressure and temperature conditions. The compositional approach ensures that the effects of changing composition due to phase transitions are properly accounted for in the hydraulic calculations. The Reynolds number was also calculated. The multiphase flow correlations available in PIPESIM include industry-standard models such as the Baker–Jardine, Beggs–Brill (Baker et al., 1970), Beggs–Brill (Beggs & Brill, 1973), and Hagedorn–Brown correlations. These correlations have been extensively validated against experimental data and field measurements, confirming their applicability to a wide range of flow conditions. For this study, PIPESIM's automatic correlation-switching logic was applied, using the Baker–Jardine correlation for near-horizontal sections and Hagedorn–Brown correlation for near-vertical sections, with a 45° swap angle governing the transition, which is consistent with standard practice for horizontal gas–liquid pipeline flow.

2.2 Pipeline Model Setup

The CO₂ pipeline system was modelled in PIPESIM via a steady-state compositional framework. The flow path was defined by connecting a source node representing the capture facility to a sink node representing the storage site, with an intermediate compressor included to compensate for pressure losses along the pipeline. The flow behaviour within the system is governed by the conservation of mass, expressed through the continuity relationship, whereas pressure variations along the pipeline are influenced by frictional and thermodynamic effects captured within the simulator.

$$\dot{m} = \rho Av \quad (2)$$

The pipeline was specified with a total length of 10,000 ft, horizontal orientation, and burial in moist clay soil with a thermal conductivity of 0.4478 Btu per hour per degree Fahrenheit per foot, using the standard 2000 burial method. Multiphase flow behaviour was evaluated via established correlations, including those of Baker–Jardine and Hagedorn–Brown, with a no-slip assumption and a swap angle of 45 degrees to account for flow regime transitions. Erosional effects were assessed via the API 14E criterion (eqn. 2) with a corrosion efficiency factor of unity.

$$v_e = \frac{c}{\sqrt{\rho}} \quad (3)$$

Pipeline diameter and wall thickness were selected on the basis of typical design ranges for CO₂ transport, ensuring that operating pressures remained within safe limits while maintaining sufficient throughput. The horizontal configuration was adopted to isolate compositional effects on flow behaviour, whereas burial conditions were incorporated to account for heat exchange with the surrounding formation, which influences the temperature profile and, consequently, fluid properties along the pipeline.

2.3 Fluid Model Definition

Accurately modelling the thermodynamic and physical behaviour of the CO₂ stream with and without impurities necessitates the use of a compositional fluid model in PIPESIM. This approach calculates fluid properties on the basis of the specific chemical components present and their mole fractions, accounting for phase transitions. In essence, the mixture parameters were computed via classical mixing rule equations 3 and 4, allowing the contribution of each impurity component to be reflected in the overall thermodynamic behaviour of the CO₂ stream.

$$a_{mix} = \sum_i \sum_j x_i x_j a_{i,j} \quad (4)$$

$$b_{mix} = \sum_i x_i b_i \quad (5)$$

Two fluid models were developed: the compositional fluid model in PIPESIM requires the specification of all the components present in the mixture along with their respective mole fractions. For each component, the software accesses a database of physical properties, including the critical temperature, critical pressure, acentric factor, and molecular weight. These properties are used in the equation of state calculations to determine mixture properties under the prevailing pressure and temperature conditions.

2.3.1 Model 1: Pure CO₂

This baseline model consisted of 100% carbon dioxide (CO₂) with a mole fraction of 1.0. The phase envelope for pure CO₂ showed a single-phase region under the operating conditions, indicating that the fluid would remain in a dense phase throughout the pipeline. The critical point of pure CO₂ is at approximately 87.8°F and 1,070 psia, and the operating conditions of 86°F and 800 psia inlet pressure place the fluid well within the dense phase region, ensuring single-phase behaviour throughout the transport process.

2.3.2 Model 2: CO₂ with Impurities

This model represented a CO₂ stream containing 30% noncondensable impurities by volume, with the following composition.

Table 2: Fluid Composition for the Impure CO₂ Model

Component	Chemical Formula	Mole Fraction (%)
Carbon dioxide	CO ₂	70
Nitrogen	N ₂	5
Argon	Ar	5
Oxygen	O ₂	5
Hydrogen	H ₂	5
Carbon Monoxide	CO	2
Methane	CH ₄	2
Ethane	C ₂ H ₆	2
Water	H ₂ O	2
Propane	C ₃ H ₈	2
Total		100

2.4 Boundary conditions

Upon definition of the pipeline network and compositional fluid models, appropriate boundary conditions were specified to constrain the hydraulic simulation. Pressure losses along the pipeline were evaluated via momentum balance equation (5), accounting for both frictional and gravitational effects under steady-state flow conditions.

$$\frac{dP}{dL} = - \frac{f \rho v^2}{2D} - \rho g \sin\theta \quad (6)$$

The inlet boundary at the source was defined by a pressure of 800 psia and a temperature of 86°F, whereas the outlet pressure at the sink was computed via PIPESIM as part of the solution of the governing flow equations. These conditions provide the necessary constraints for resolving the pressure and temperature profiles along the pipeline. The selected inlet pressure ensures that the fluid enters the system within the dense phase region, given the critical pressure of pure CO₂ (1,070 psia), while still allowing for pressure decline along the pipeline. The inlet temperature reflects typical subsurface conditions in the Niger Delta and serves as a realistic basis for thermal analysis

3. Results

3.1 Phase behaviour and liquid dropout

Figure 1 shows the phase envelope for pure CO₂, confirming a liquid dropout of zero across the entire pipeline length. The phase diagram for pure CO₂ shows that, under the operating conditions used in this study (800 psia and 86°F), the fluid remains within the dense phase region and does not approach the phase boundary. This is important because CO₂ is transported as a single phase throughout the pipeline, with no phase separation expected along the flow path. From a hydraulic standpoint, this explains the relatively smooth pressure behaviour observed in the baseline case.

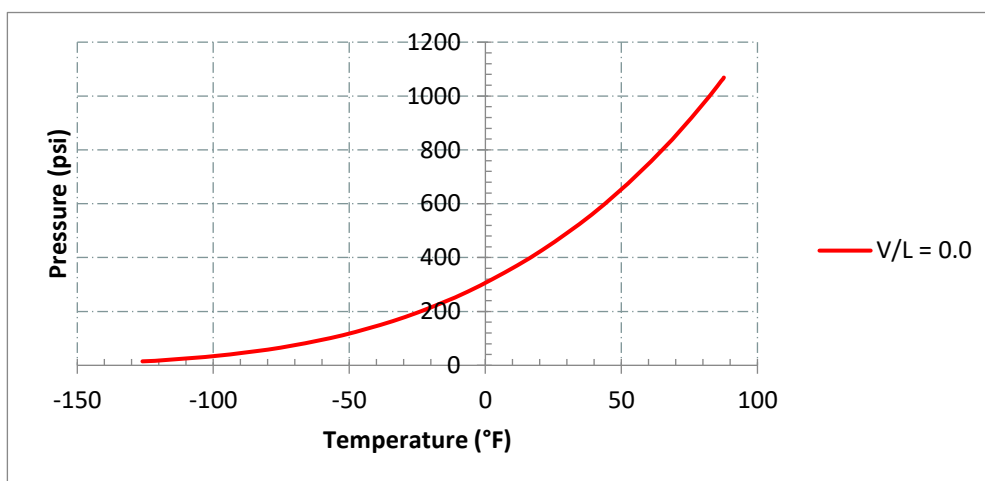


Figure 1: Pure CO₂ phase envelope

Since the flow remains in a single phase, pressure losses are due mainly to friction, and the system does not experience additional losses associated with phase interactions. In other words, there are no effects from slip between phases or intermittent flow structures, which simplifies both the flow dynamics and the interpretation of the results. Another point worth noting is how far the operating conditions are from the phase boundary. This gives a reasonable margin of stability, meaning that small changes in pressure or temperature along the pipeline are unlikely to push the fluid into a two-phase region. As a result, the flow remains predictable and stable over the length of the pipeline. Within the context of this study, this behaviour provides a useful reference case. The impure CO₂ stream shows dual-phase behaviour, as shown in Figure 2, which suggests a prominent two-phase region for this mixture. The two-phase region involves the coexistence of CO₂ and condensable gaseous impurities, which can lead to an unstable flow regime, such as slug flow. The shift from single-phase to two-phase flow is the most consequential effect of impurities.

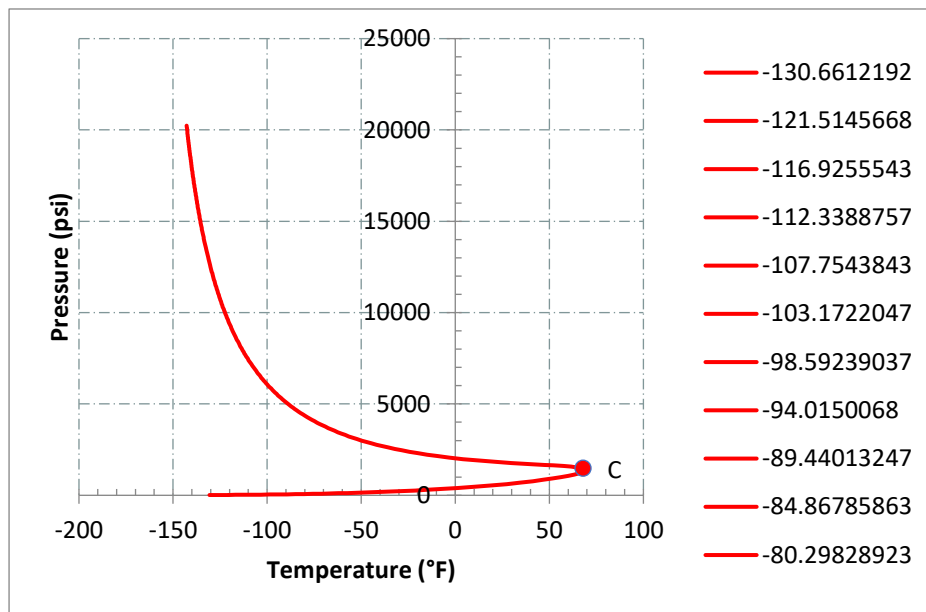


Figure 2: Phase envelope of CO₂ with impurities

The phase diagram for the impure CO₂ stream shows a noticeably different behaviour compared with that of the pure case. The presence of noncondensable components expands and shifts the phase envelope, particularly toward lower temperatures and pressures. As a result, the operating point (approximately 800 psia and 86°F) lies much closer to the phase boundary than in the pure CO₂ case, reducing the margin of phase stability along the pipeline. This phenomenon has direct consequences for flow behaviour. With the system operating near the phase envelope, even modest pressure drops along the pipeline can move the fluid into a two-phase region. Unlike the pure CO₂ case, where the flow remains stable and single-phase, the impure mixture is more susceptible to phase splitting. This introduces gas–liquid interactions, which complicate the flow structure and increase hydraulic resistance. In practical terms, this helps explain the deviations observed in the pressure profile for the impure case. Once phase separation begins, additional losses arise from slip between phases and uneven phase distributions across the pipe cross section. These effects are not present in single-phase flow and typically lead to higher and less predictable pressure drops. The broader phase envelope also suggests that the fluid properties are more sensitive to changes in temperature and pressure, which further contributes to the variability in flow behaviour. Another important observation is that the inclusion of lighter components such as nitrogen, hydrogen, and methane tends to lower the effective critical properties of the mixture, making it easier for the system to transition out of the dense phase region. This finding reinforces the idea that the impurity composition, not just the concentration, plays a role in determining transport stability. Within the context of this study, the phase diagram confirms that the introduction of impurities fundamentally alters the thermodynamic behaviour of the CO₂ stream. This provides a clear link to the observed changes in pressure drop, flow regime, and liquid holdup and supports the need for composition-specific modelling when designing and operating CO₂ transport systems.

3.2 Pressure profile behaviour

The pressure profiles for both the pure and impurity-laden CO₂ streams show a continuous decline along the length of the pipeline, which is consistent with the expected behaviour for compressible flow under frictional losses. For the pure CO₂ case, as shown in Figure 3, the pressure decreases nearly linearly from the inlet to the outlet. This relatively uniform gradient reflects stable single-phase flow conditions, where the dominant mechanism of pressure loss is wall friction, and fluid properties vary smoothly with pressure.

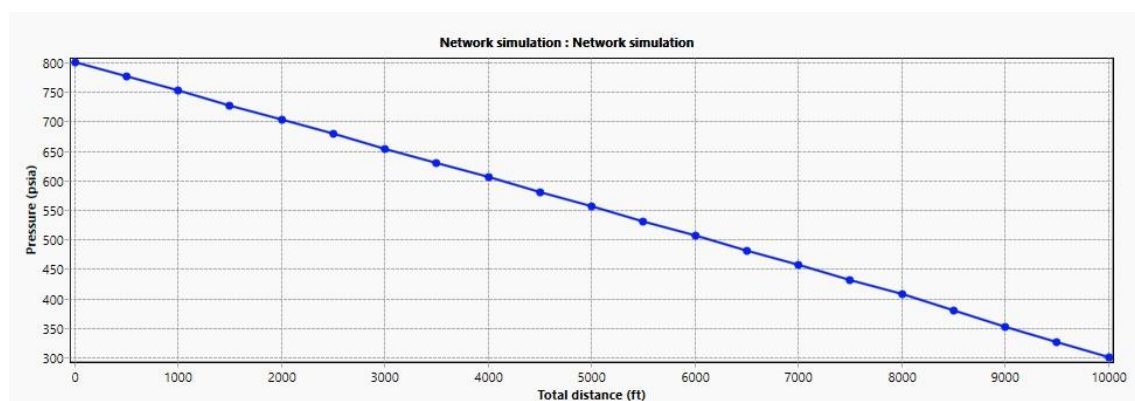


Figure 3: Pressure profile behaviour for pure CO₂

In contrast, the impure CO₂ stream exhibits a similar overall decline but with subtle deviations from linearity, particularly at larger distances along the pipeline. While the pressure still decreases monotonically, the rate of decline becomes slightly more pronounced toward the downstream section. This suggests that the hydraulic resistance is not entirely uniform along the pipeline in the presence of impurities. The difference between the two profiles can be linked to compositional effects on fluid properties. In the pure CO₂ case, the fluid remains in a dense single phase, and changes in density and viscosity occur gradually as the pressure decreases. However, for the impurity-laden mixture, variations in composition and proximity to the phase envelope can lead to more noticeable changes in effective fluid properties. These changes influence the velocity and frictional losses, resulting in a slightly steeper pressure decline in certain sections of the pipeline.

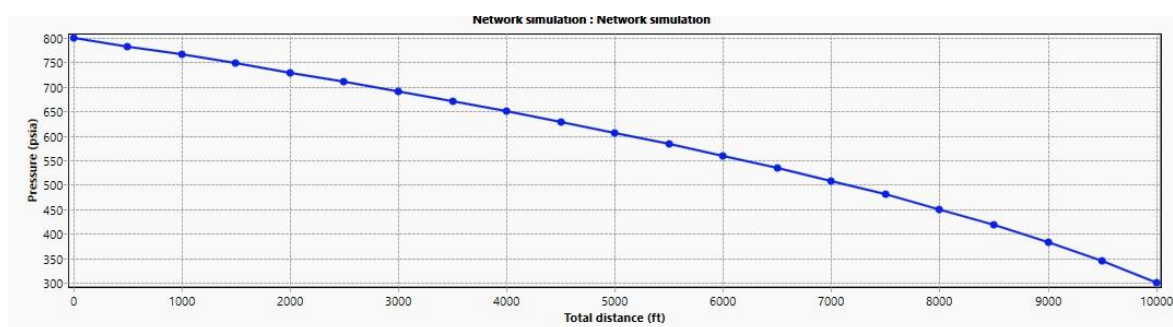


Figure 4: Pressure profile for impure CO₂

Although the deviation is not extreme, it is significant from a design perspective. The impure CO₂ profile indicates that assuming uniform hydraulic behaviour along the pipeline may lead to underestimation of pressure losses, particularly towards the outlet region. This has implications for compressor design, pressure management, and overall system efficiency. Overall, the comparison shows that while both systems follow the expected trend of pressure reduction with distance, the presence of impurities introduces a degree of nonuniformity in the pressure response. This reinforces the need to account for fluid composition in pipeline design and analysis, especially when operating near conditions where thermodynamic effects become more pronounced.

3.3 Pressure Gradient Behaviour

The pressure gradient results clearly distinguish between the hydraulic behaviour of pure CO₂ and the impurity-laden mixture along the pipeline. For the pure CO₂ case, as shown in Figure 5, the pressure gradient increases progressively with distance, exhibiting a smooth and consistent trend. This behaviour is expected under single-phase dense flow conditions, where changes in pressure are governed primarily by frictional losses and gradual variations in fluid properties. As pressure

decreases along the pipeline, the corresponding reduction in density leads to an increase in flow velocity, which in turn increases the frictional component of the pressure gradient. The absence of a phase change ensures that this increase remains stable and predictable throughout the pipeline.

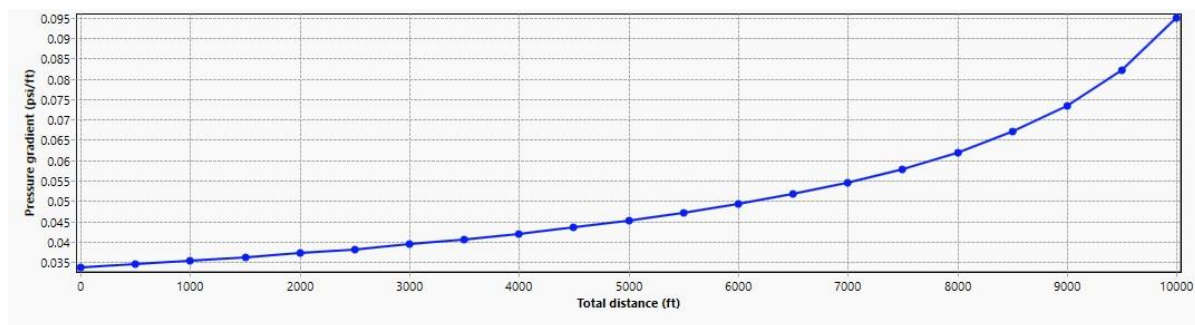


Figure 5: Pressure gradient behaviour for pure CO₂

In contrast, the impure CO₂ stream in Figure 6 shows a less uniform profile. Although the overall pressure gradient remains within a similar range, the trend is disrupted by a pronounced spike at intermediate pipeline distances, followed by a partial decline and subsequent stabilisation. This deviation from the smooth behaviour observed in the pure case suggests the influence of additional mechanisms beyond simple frictional losses. The most likely contributor is the onset of localised phase interactions, driven by the proximity of the mixture to its phase envelope. As the fluid approaches conditions where phase separation becomes possible, changes in effective density and viscosity can occur more abruptly, leading to transient increases in hydraulic resistance.

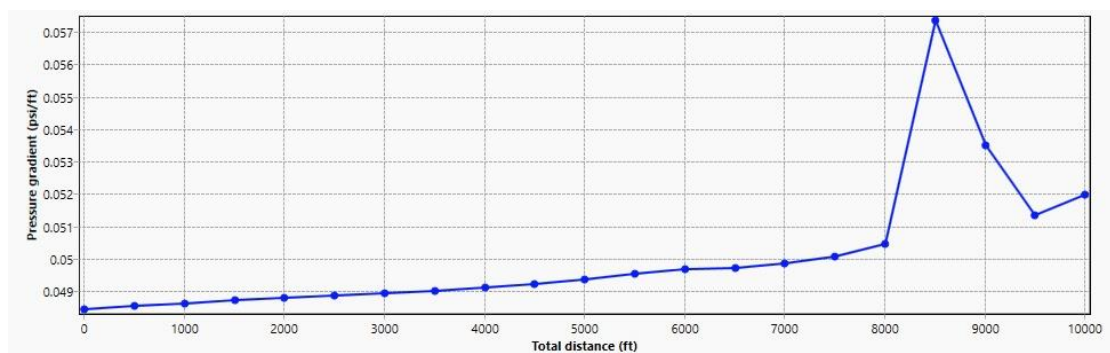


Figure 6: Pressure gradient behaviour for impure CO₂

The spike in the pressure gradient is particularly significant, as it indicates a localised region of intensified energy dissipation. This may be associated with the formation of incipient two-phase flow structures or increased slip between phases, even if full phase separation is not sustained along the entire pipeline. This behaviour introduces variability into the flow system, making the hydraulic response less predictable than that in the pure CO₂ case. From a practical perspective, these results highlight an important design consideration. While pure CO₂ flow can be reasonably approximated via smooth, single-phase assumptions, the presence of impurities introduces localised disturbances that can lead to underestimation of pressure losses if not properly accounted for. This has implications for compressor sizing, pipeline integrity, and overall system efficiency. This finding reinforces the need for compositional modelling and careful evaluation of operating conditions when transporting CO₂ streams with noncondensable impurities.

3.4 Reynolds number behaviour

The Reynolds number profiles for both the pure and impurity-laden CO₂ streams show that the flow remains firmly within the turbulent regime along the entire length of the pipeline. For the pure CO₂ case, we see in Figure 7 that the Reynolds number gradually increases with distance, which can be attributed to changes in fluid properties as pressure decreases along the pipeline. In particular, the reduction in density with decreasing pressure leads to an increase in velocity for a given mass flow rate, thereby increasing the Reynolds number.

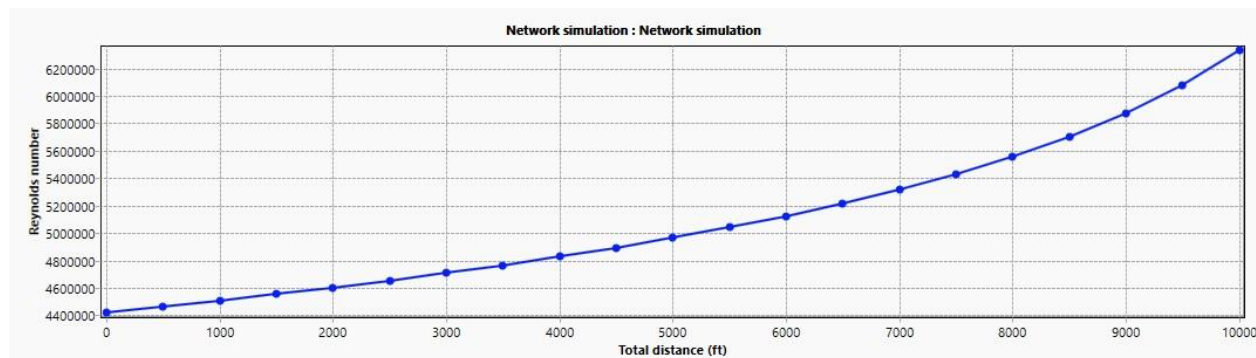


Figure 7: Reynolds number for pure CO₂

In contrast, the impure CO₂ stream in Figure 8 displays a more irregular trend. While the flow remains turbulent throughout, fluctuations in the Reynolds number are observed along the pipeline, including a noticeable spike at intermediate distances. This behaviour reflects the added complexity introduced by the presence of noncondensable impurities. Unlike the pure case, where fluid properties vary smoothly, the impure mixture experiences more pronounced changes in density and viscosity because of compositional effects and proximity to the phase boundary.

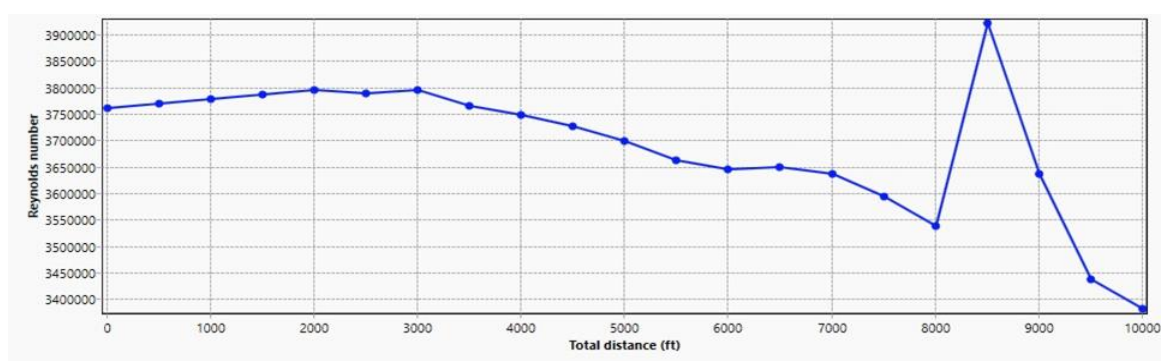


Figure 8: Reynolds number for impure pure CO₂

These variations suggest that the flow structure in the impure case is less stable, even though it does not transition out of the turbulent regime. Localised changes in phase behaviour or partial phase separation can alter the effective fluid properties, leading to transient increases in velocity and corresponding spikes in the Reynolds number. This aligns with earlier observations from phase diagrams, where the impurity mixture operates closer to the phase envelope and is therefore more sensitive to pressure and temperature changes. From a design perspective, the key implication is that while both systems can be treated as turbulent flows, the assumption of uniform flow behaviour is more valid for pure CO₂ streams than for impurity-containing streams. The variability observed in the impure case indicates that additional attention must be given to flow assurance and hydraulic

modelling, as localised changes in flow conditions may influence pressure loss, erosion potential, and overall system performance.

Comparison with the literature

The findings of this study are consistent with those of previous studies on the effects of impurities on CO₂ transport. Wang et al. (2011) demonstrated that noncondensable gases accumulate at phase interfaces, impeding condensation rates and promoting two-phase conditions. Similarly, Porter (2022) highlighted the challenges associated with meeting CO₂ transportation specifications in European contexts, emphasising the importance of impurity control. The phase behaviour results align with the work of Al-Siyabi (2013), who investigated the effects of impurities on CO₂ stream properties and reported that noncondensable gases significantly alter the critical point and phase envelope of CO₂ mixtures. These results are further corroborated by Peletiri et al. (2017), who reported that the presence of impurities measurably degrades CO₂ pipeline hydraulic performance, and by Chapoy et al. (2011), who identified noncondensable impurities as a primary driver of elevated hydrate formation risk in CO₂-rich systems, directly supporting the hydrate risk implications raised in this study's conclusions. The present study extends these findings by quantifying the hydraulic consequences of these thermodynamic changes in a realistic pipeline configuration. These results are also consistent with the broader literature on multiphase flow in pipelines. The observed pressure drop characteristics, liquid holdup behaviour, and flow regime transitions are all consistent with established theories and empirical correlations for gas–liquid flow. This agreement provides confidence in the simulation results and their applicability to real-world pipeline systems.

4. Conclusions

This research investigated the impact of noncondensable impurities on the flow behaviour of CO₂ within a pipeline transportation context. Through a comparative steady-state simulation of a pure CO₂ stream and a high-impurity CO₂ stream (30% noncondensable content), the study demonstrated that noncondensable impurities fundamentally alter the hydraulic and thermodynamic characteristics of the flow, even under conditions where pure CO₂ remains stable in a single phase. This conclusion is supported by three key outcomes:

- **Phase behaviour shift:** The phase envelope of the impure CO₂ mixture expanded and shifted toward the operating point, narrowing the margin of single-phase stability and introducing the possibility of two-phase (vapour-liquid) flow, which is absent in the pure CO₂ case.
- **Nonuniform pressure response:** Unlike the smooth, nearly linear pressure decline of pure CO₂, the impure stream exhibited a pronounced pressure gradient spike at intermediate pipeline distances, indicating localised intensification of hydraulic resistance consistent with the onset of phase interaction.
- **Flow instability signature of the Reynolds number:** While both streams remained turbulent throughout, the impure stream showed irregular Reynolds number fluctuations rather than the smooth trend observed in pure CO₂, indicating that its flow structure was less predictable.

These findings point to likely downstream consequences, including slug flow, erosion-corrosion risk from elevated local velocities, and hydrate risk from autorefrigeration, which were not directly quantified in this steady-state comparison and represent priority targets for follow-up simulation work incorporating liquid holdup, velocity, and temperature profile outputs.

Recommendations

On the basis of the findings of this study, a number of practical and research-oriented recommendations can be drawn. From an industry and policy standpoint, the results underscore the need for tighter control of the CO₂ stream composition at the point of capture. High impurity levels, such

as those examined in this work, introduce measurable penalties in flow behaviour and raise concerns around pipeline integrity. This suggests that CO₂ purity should not be treated as a secondary consideration but rather as a design parameter in its own right. In practice, this means that capture systems will likely need to incorporate more robust separation and purification stages. While this increases the upfront cost, the trade-off becomes justified when viewed against the operational risks and inefficiencies associated with transporting impure streams. Therefore, there is a need for techno-economic studies that define realistic purity thresholds tailored to transport conditions rather than relying on arbitrary limits.

From a pipeline design and operations perspective, the assumption of pure CO₂ behaviour is no longer adequate once impurities are present. The results show that even moderate deviations in composition can alter flow regimes, pressure gradients, and phase distributions in ways that are not captured by simplified models. This reinforces the need for composition-aware modelling during the design stage. In addition, pipelines expected to handle impure CO₂ streams should be designed with flow assurance and integrity in mind from the outset. This includes selecting materials that can withstand corrosive environments, accounting for potential erosion effects, and incorporating facilities such as slug catchers where multiphase flow is likely. Operationally, maintaining flow within safe velocity limits becomes important, particularly in sections where phase interactions are more pronounced. The role of monitoring also becomes more critical in this context. Continuous tracking of pressure, temperature, and flow behaviour can provide early indications of instability, allowing operators to respond before issues develop into failures.

Author Contributions: V.O.: Conceptualisation; Methodology; Writing—Original Draft; Writing—Review & Editing. S.N.: Conceptualisation; Methodology; Writing—Review & Editing. E.T.: Validation; Writing—Review & Editing; Supervision.

Funding: This research received no external funding.

Conflicts of interest: The authors declare no conflicts of interest.

References

1. Ansaloni, L., Alcock, B., & Peters, T. A. (2020). Effects of CO₂ on polymeric materials in the CO₂ transport chain: A review. *International Journal of Greenhouse Gas Control*, 94, 102930.
2. Baker, O., Brainerd, H. W., Coldren, C. L., Flanagan, O., & Welchen, J. K. (1970). *Gas-Liquid Flow in Pipelines. II Design Manual*. AGA-API.
3. Beggs, H. D., & Brill, J. P. (1973). A study of two-phase flow in inclined pipes. *Journal of Petroleum Technology*, 607–617.
4. Chapoy, A., Burgass, R., Tohidi, B., Austell, J. M., & Eickhoff, C. (2011). Effect of Common Impurities on the Phase Behaviour of Carbon-Dioxide-Rich Systems: Minimising the Risk of Hydrate Formation and Two-Phase Flow. *SPE Journal*, 16, 921–930. <https://doi.org/10.2118/123778-PA>
5. Consoli, C., Zapantis, A., Grubnic, P., & Irlam, L. (2025). Modelling rapid CO₂ pipeline buildout using historical precedents from oil and gas pipelines. *Environmental Science and Pollution Research*, 32(11), 17481–17493.
6. Federal Ministry of Environment. (2021). *Nigeria's Nationally Determined Contribution – 2021 update*. Federal Government of Nigeria. <https://unfccc.int>
7. Global CCS Institute. (2024). *2024 Global Status of CCS Report*.
8. International Energy Agency. (2020). *CCUS in Clean Energy Transitions*.
9. International Finance Corporation (IFC). (2025). *Nigerian CO₂ Storage Atlas*. World Bank Group.
10. Jacobson, G. A., Kerman, S., Choi, Y. S., Dugstad, A., Nesic, S., & Papavinasam, S. (2014). Pipeline corrosion issues related to carbon capture, transportation, and storage. *Materials Performance*, 53, 24.
11. Lu, H., Ma, X., Huang, K., Fu, L., & Azimi, M. (2020). Carbon dioxide transport via pipelines: A systematic review. *Journal of Cleaner Production*, 266, 121994.
12. Neele, F., Koornneef, J., Jakobsen, J. P., Brunsvold, A., & Eickhoff, C. (2017). Toolbox of effects of CO₂ impurities on CO₂ transport and storage systems. *Energy Procedia*, 114, 6536–6542.

13. Noothout, P., Wiersma, F., Hurtado, O., Macdonald, D., Kemper, J., & Van Alphen, K. (2014). CO2 Pipeline infrastructure – lessons learnt. *Energy Procedia*, 63, 2481–2492.
14. Peletiri, P. S., Rahmanian, N., & Mujtaba, I. M. (2017). Effects of impurities on CO2 pipeline performance. *Chemical Engineering Transactions*, 57, 355–360. <https://doi.org/10.3303/CET1757060>
15. Porter, R. (2022). *Challenges and opportunities of achieving European CO2 transportation and storage specifications*.
16. Porter, R. T. J., Fairweather, M., Pourkashanian, M., & Woolley, R. M. (2015). The range and level of impurities in CO2 streams from different carbon capture sources. *International Journal of Greenhouse Gas Control*, 36, 161–174. <https://doi.org/10.1016/j.ijggc.2015.02.016>
17. Raimondi, L. (2014). CO2 transportation with pipelines – model analysis for steady, dynamic and relief simulation. *Chemical Engineering Transactions*, 36.
18. Ritchie, H., & Roser, M. (2020). CO2 emissions. *Our World in Data*.
19. Stokes, S., Haghighi, H., & McKay, C. (2023, June). Impact of Chemical Impurities on the Integrity of Carbon Dioxide Transport Pipelines. In *International Conference on Offshore Mechanics and Arctic Engineering* (Vol. 86854, p. V003T04A027). ASME.
20. Sultan, R. A. (2018). *A comprehensive study on multiphase flow through pipeline and annuli using CFD approach* (Doctoral dissertation, Memorial University of Newfoundland).
21. Wang, J., Ryan, D., Anthony, E. J., Wildgust, N., & Aiken, T. (2011). Effects of impurities on CO2 transport, injection and storage. *Energy Procedia*, 4, 3071–3078.

Disclaimer/Publisher's Note: The views, opinions, and data expressed in articles published in the *Hensard Journal of Environment* are solely those of the author(s) and contributor(s). They do not necessarily reflect the position of the Journal, the editors, or Hensard University. The Journal and its editorial team disclaim responsibility for any harm, injury, or loss that may result from the use of ideas, methods, instructions, or products discussed in the published content.