

Influence of Flow Conditions on Water Wetting in Dense-Phase CO₂ Streams for Corrosion Risk Assessment

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ABSTRACT

Carbon capture and storage (CCS) is a critical strategy in global efforts to mitigate climate change. A key component of CCS is the safe and efficient pipeline transport of carbon dioxide (CO₂), which often contains impurities—most notably water. The presence of water in the CO₂ stream can result in two-phase flow, increasing the risk of internal pipeline corrosion. Corrosion is minimized when water remains fully entrained as dispersed droplets within the continuous CO₂ phase. However, when water separates and forms a settled layer along the pipe wall, corrosion becomes severe. This study investigates the conditions that govern water distribution across the pipe cross-section. A mechanistic model is developed to evaluate the interplay between hydrodynamic forces, operating conditions, and pipe wall wettability. The results provide criteria for predicting entrainment or deposition behavior of the water phase, with implications for corrosion risk assessment and pipeline design in CCS applications.

Key words: CO₂-water flow; carbon capture; water wetting; corrosion; pipeline integrity; entrainment

INTRODUCTION

Carbon dioxide transport in pipelines is a critical component of carbon capture and storage (CCS) systems, which are crucial for mitigating climate change impacts by reducing atmospheric emissions of CO₂. There are operational challenges associated with the transportation of the captured gas. CO₂ is transported as a supercritical fluid due to its favorable density and compressibility properties¹, and it can contain some impurities such as NO_x, SO_x, H₂S, O₂². Some amount of soluble water can also be present in the dense CO₂ phase. Due to the flow conditions, this water may exceed its solubility limit and form a different phase as water droplets, leading to multiphase flow. Water droplets in the dense CO₂ phase can separate and settle at the bottom of the pipeline due to differences in density and phase behavior.

In multiphase flow, distinct flow patterns exist based on the distribution of the water³. In CO₂ pipelines, where the water content is typically less than five percent, two regimes are most relevant. The dispersed flow, where water droplets are entrained in the dense phase, and stratified flow, characterized by the formation of a continuous water layer along the pipe bottom⁴. In the former, the water droplets remain suspended within the bulk flow, avoiding direct contact with the pipe walls, thereby minimizing the risk of corrosion. On the other hand, the presence of a stratified water layer leads to the formation of acids through reactions with impurities, and these acids contact the pipe walls, creating conditions for severe

corrosion in the pipeline. Maintaining a stable dispersion of water droplets and thereby preventing stratification is crucial for ensuring pipeline integrity.

A fundamental understanding of the dispersed and stratified flow patterns, as well as the transition boundaries between them, is critical to predicting corrosion risk and estimating corrosion rates. This transition occurs when entrained water droplets coalesce and grow large enough to deposit at the pipe wall, initiating water wetting. The present work develops a mechanistic model to predict the prevailing flow regime at any location within the pipeline and to estimate the critical velocity below which water wetting is likely to occur.

The modeling framework is based on balancing the hydrodynamic forces that govern droplet entrainment and deposition. Previous studies have proposed transitional criteria for various multiphase systems, particularly oil–water flow, and these have been validated with experimental data^{5,6}. However, experimental evidence and reliable numerical models for CO₂-water multiphase flow are limited. Despite this gap, the same principles apply, as they are governed by similar physical mechanisms and system parameters, including pipe diameter, inclination, droplet contact angle, turbulence intensity, and dense-phase shear forces.

Mechanistic models, derived from first principles, can thus be adapted for CO₂-water systems by incorporating CO₂-specific fluid properties. In this study, a model was developed to predict the droplet concentration profile across the pipe cross-section, and using this distribution, the conditions for water layer formation were determined⁷. This model quantifies both the maximum stable droplet size and the resulting steady-state droplet distribution near the pipe bottom, which together provide the criteria for predicting water wetting.

BACKGROUND

The operating conditions for dense-phase CO₂ transport pipelines are summarized in Table 1¹. The ranges of temperature and pressure fall within the supercritical region, as illustrated in Figure 1, where CO₂ has the favorable properties of both liquids and gases. Carbon dioxide behaves like a liquid due to its high density, which reduces the volume requirements of the pipeline. It also acts like a gas, maintaining a relatively low viscosity that reduces frictional losses. This balance of properties makes supercritical CO₂ the most efficient phase for transporting carbon capture and storage (CCS) via pipelines.

Table 1: Range of conditions for dense phase CO₂ pipeline transport

Parameter	Conditions
Pressure	7.4 – 20 MPa
Temperature	283 – 333 K
Flow velocities	0.9-2.6 m/s
Pipe diameters	0.39-1.26 m
Pressure drop	5.5×10^{-5} - 16×10^{-5} bar/m

Despite these advantages, as mentioned earlier, the presence of small amounts of water can introduce significant challenges. When fully entrained as fine droplets in the CO₂ stream, water is unlikely to cause damage. However, if droplets separate and accumulate at the pipe wall, they may form a continuous aqueous film that reacts with impurities (e.g., SO_x, NO_x, O₂) to generate corrosive acids. The conditions in Table 1 can often result in a turbulent flow regime.

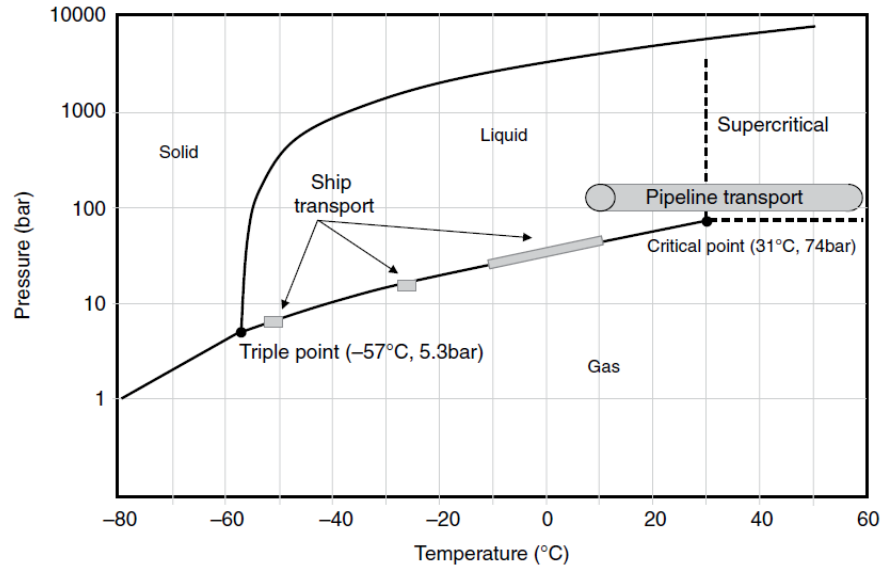


Figure 1: Phase diagram for CO₂ showing the typical temperatures and pressures for pipeline transport⁵.

Stability of Dispersed Flow

The flow pattern observed when the water droplets remain suspended in the dense phase is called the dispersed flow regime and is shown in Figure 2. This flow pattern is stable when the flow conditions permit the continuous entrainment of droplets in this phase. The stability of the dispersed flow regime is determined by the balance of forces that lead to droplet breakup (turbulence and shear forces in the CO₂ phase) and those that cause droplet coalescence (surface tension forces), and then deposition if the droplets are heavy enough (driven by gravity)⁷. This balance is expressed in terms of the phase inversion (IP), which represents the critical water holdup where the water becomes the continuous phase and CO₂ the dispersed phase. Below the inversion point, water droplets remain suspended, and the CO₂ phase remains the continuous phase. It is then necessary to determine this inversion point. Due to gravity, this critical point is located at the bottom of the pipe for horizontal and near-horizontal flows. Above the phase inversion concentration, droplets coalesce into a stratified layer at the bottom of the pipe. Since droplet concentration is naturally highest near the bottom of the pipe, this location is used in the model. Hence, for droplets not to form a water layer at the bottom of the pipe, the criterion can be expressed as:

$$C_{b,t} < IP \quad (1)$$

where $C_{b,t}$ is the droplet concentration at the bottom of the pipe, and IP is the inversion point. Figure 2 shows the concentration profile of water droplets across a pipe's cross-section. Concentration here is defined as the amount of the dispersed droplets per unit volume of CO₂ at that position.

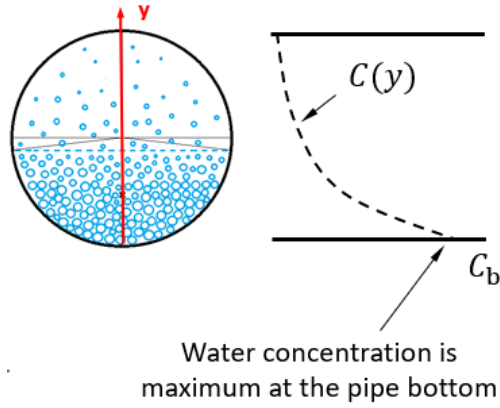


Figure 2: Typical concentration profile of suspended droplets in a pipe's cross-section.

To determine the concentration profile, we use an advection-diffusion model proposed by Karabelas in 1977⁹, which was a revision of the work by O'Brien¹⁰. The model is applicable for turbulent flow with suspended spherical particles. Turbulent energy tends to carry the suspended water droplets to the interior of the fluid. In turbulent flow,

$$\tau = \epsilon \frac{du}{dr} \quad (2)$$

where τ is the average shearing force, ϵ is the eddy viscosity, and du/dr is the velocity gradient. These turbulent eddies, which transfer momentum, are responsible for the vertical distribution of suspended particles in the fluid. The distribution of spherical particles vertically in pipe flow is then given as:

$$U_s C + \epsilon \frac{\partial C}{\partial y} = 0 \quad (3)$$

where ϵ is the droplet turbulent diffusivity that is assumed to be constant across the pipe section, U_s is the settling velocity of the mean droplet size, and y is the vertical coordinate with respect to the pipe direction. The first part of equation (3) considers the settling velocity of the droplets due to gravity, and the second, the turbulent diffusion of the droplets in the pipe's core. This is a balance between the gravity forces, which tend to pull the droplets to the bottom, and turbulence, which tends to keep them suspended. Then, it is possible to determine the concentration of water droplets, C_w in the continuous phase. Assuming a dispersed, steady-state flow with water droplet concentration varying only in the pipe's vertical direction and at low particle concentration, equation (3) can be modified to:

$$U_s C_w (1 - C_w) \cos \beta - \epsilon \frac{\partial C_w}{\partial y} = 0 \quad (4)$$

The effect of the inclination angle on gravity is considered by the $\cos \beta$ term, where β is the pipe inclination angle. The turbulent diffusivity, ϵ , measures the transport of particles, momentum, and energy in turbulent flow. This parameter is a function of the eddy diffusivity, which represents the effective mixing of particles in the dense phase caused by eddies, the mixture velocity, and the density of the phases. U_m , and ρ_m , the density of the continuous CO₂ phase ρ_{CO_2} , and is calculated as:

$$\epsilon = \zeta \frac{D}{2} \sqrt{\frac{\rho_m f}{2 \rho_{CO_2}}} U_m \quad (5)$$

where ζ is the dimensionless eddy diffusivity that can be considered as constant with a value of 0.255, and the friction factor (Blasius correlation for the Darcy–Weisbach friction factor in turbulent flow through smooth pipes or channels) is given as:

$$f = 0.046Re_m^{-0.2} \quad (6)$$

$$Re_m = \rho_m DU_m / \mu_m \quad (7)$$

Here, mixture viscosity, μ_m is approximately the same as the viscosity of the continuous phase μ_{co2} , as the water droplets do not contribute significantly to the viscosity of the mixed phase, and is assumed to be the same. On the other hand, the mixture density depends on the water holdup ε_w in the dense phase. The water holdup is the fraction of the total pipe cross-sectional area or volume occupied by the water phase.

$$\rho_m = \varepsilon_w \rho_w + (1 - \varepsilon_w) \rho_{co2} \quad (8)$$

$$\text{The setting velocity is } U_s = \sqrt{\frac{4}{3} \frac{d|\rho_w - \rho_{co2}|g}{\rho_{co2} C_D}} \quad (9)$$

where, d is the mean droplet size, taken to be 50 percent of the maximum droplet size. The method for calculating this value is presented in the next section. C_D is the drag coefficient that is approximated with the Schiller-Naumann correlation for solid spheres¹¹:

$$C_D = \frac{24}{Re_p} (1 + 0.15Re_p^{0.687}) \quad (10)$$

With the Reynolds number of the particle (droplet) as:

$$Re_p = \frac{\rho_{co2} d U_s}{\mu_{co2}} \quad (11)$$

and,

$$K = \frac{DU_{s,y}}{2\varepsilon} \quad (12)$$

Equation (4) can be solved with a mass conservation constraint,

$$\int C(y) dA = \varepsilon_w A \quad (13)$$

Where A is the cross-sectional area of the pipe, to give the solution to the equation:

$$C(y) = \left[1 + 2 \frac{(1-\varepsilon_w)}{\varepsilon_w} \frac{I_1(K)}{K} \exp \left[K \left(\frac{2y}{D} - 1 \right) \right] \right]^{-1} \quad (14)$$

at the bottom of the pipe, $y = 0$, and equation (14) becomes:

$$C_{b,t} = \left[1 + 2 \frac{(1-\varepsilon_w)}{\varepsilon_w} \frac{I_1(K)}{K} \exp(-K) \right]^{-1} \quad (15)$$

The inversion point can be approximated using the mechanistic model proposed by Brauner and Ullmann for multiphase turbulent flow, which assumes that, at the inversion point, the surface energies of both configurations (water completely entrained into CO₂ and vice versa) are the same⁸:

$$IP = \frac{1}{1 + \left(\frac{\rho_{CO2}}{\rho_w}\right)^{0.6} \left(\frac{\mu_{CO2}}{\mu_w}\right)^{0.4}} \quad (16)$$

Determination of Maximum Droplet Size

The parameters in the model are known, except for the maximum size of the suspended water droplets in the dense phase. Physically, droplet size plays a key role in determining whether the droplets remain dispersed or settle. Larger droplets require greater turbulent energy to stay suspended in the pipe core. In turbulent flow, the droplet size is typically much smaller than the large energy-containing eddies. The maximum droplet size, d_{max} , is governed by the smallest turbulent length scales, known as the Kolmogorov microscale I_k , where viscous dissipation of the eddies, ϵ dominates. If droplets exceed this scale, the local turbulent stresses are insufficient to prevent breakup, and coalescence or settling may occur. Assuming homogeneous and isotropic turbulence, d_{max} can therefore be related to the Kolmogorov length scale, which represents the equilibrium between turbulent kinetic energy k and viscous dissipation¹². And so:

$$k^2 = 2(\epsilon d_{max})^{2/3} \quad (17)$$

provided that,

$$I_k = \left(\frac{\mu_{CO2}^3}{\rho_{CO2}^3 \epsilon}\right)^{1/4} \ll d_{max} < 0.1D \quad (18)$$

Then,

$$d_{max} \left(\frac{\rho_{CO2}}{\sigma}\right)^{3/5} \epsilon^{2/5} = C = 0.725 \quad (19)$$

The value of C is obtained from fitting experimental data of various liquid-liquid dispersions. In pipe flow, the mean rate of turbulent energy dissipation expressed in terms of the friction factor is:

$$\epsilon = \frac{2U_{CO2}^3 f}{D} \frac{\rho_m}{\rho_{CO2}(1 - \epsilon_w)} \quad (20)$$

$$\rho_m = \epsilon_w \rho_w + (1 - \epsilon_w) \rho_{CO2} \quad (21)$$

Substituting the expression for the friction factor from equation (6), an expression for d_{max} can be arrived at as:

$$d_{max,o} = \frac{1.88 \rho_m^{0.4} \sigma^{0.6} D^{0.48}}{\rho_c^{0.92} (1 - \epsilon_w)^{-0.4} \mu^{0.08} U_c^{1.12}} \quad (22)$$

This is known as Hinze's model for the maximal droplet size¹³. It is referred to as $d_{max,o}$ as it considers a single droplet without considering the effect of droplet interactions. This approach is valid for dilute dispersions, i.e., at low water holdups, where droplet concentrations are small enough that droplet interactions can be neglected. Brauner¹³ suggested a model for dense dispersions:

$$d_{max,\epsilon} = \left(6C_H \frac{\epsilon_w}{(1 - \epsilon_w)}\right)^{3/5} \left(\frac{\sigma}{\rho_c}\right)^{3/5} \epsilon^{-2/5} \quad (23)$$

For CO₂-water systems, it is predicted that the amount of water, if present, will occupy a low volumetric fraction. It can hence be deduced that this model for dilute dispersions ($d_{max,o}$) can be applied to this multiphase system.

Mlynek and Resnick suggest a correcting factor for the value of $d_{max,o}$ for liquid-liquid systems for the effect of the water holdup¹⁴.

$$d_{max} = d_{max,o}(1 + C_{\varepsilon w}\varepsilon_w) \quad (24)$$

Where $C_{\varepsilon w}$ is a parameter that depends on the fraction of volume occupied by the dispersed phase, water.

$$C_{\varepsilon w} = \begin{cases} 5.4, & \varepsilon_w \leq 0.2 \\ \sim 3, & \varepsilon_w > 0.2 \end{cases} \quad (25)$$

RESULTS

The model calculations are validated against oil–water systems, as experimental data for CO₂–water multiphase flow is not available. The physical properties of the oils used to validate the model are given in Table 2, along with their flow properties.

Table 2: Properties of the Fluids Used for the Validation of Model

Parameters	Valle (2000) ¹⁵	Elseth (2001) ¹⁶	Angeli and Hewitt
ρ_o (kg/m ³)	755	790	801
ρ_w (kg/m ³)	1000	1000	1000
μ_o (mPa.s)	0.88	1	1.6
μ_w (mPa.s)	0.5	0.001	1
σ (mN/m)	20	43	17
D (m)	0.0563	0.0563	0.024
Pipe Inclination	Horizontal	Horizontal	Horizontal

Figures 3 and 4 present the concentration profiles of water droplets across the pipe's vertical axis, y/D , for two oil–water systems. As expected, in both cases, the highest concentration of water droplets occurs at the bottom of the pipe ($y = 0$). Using the criterion in equation (1), the critical velocity for dispersion was determined through an iterative procedure, and the outcomes are shown in Figure 5. The velocity required to keep the water droplets suspended under these conditions ranges from approximately 0.2 to 6 m/s as the water content in the pipeline increases to about 60 vol.%. Naturally, when the water fraction in the pipe is high, stronger turbulence is needed to break up the droplets and maintain suspension. Consequently, the critical velocity must increase.

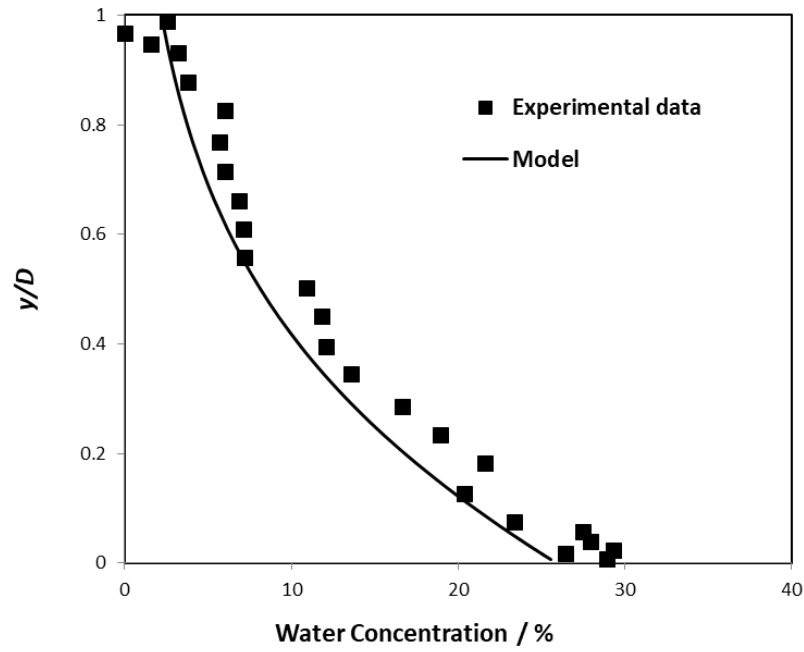


Figure 3: Validation of $C(y)$ model with oil-water system for a horizontal pipe at 2 m/s ($D = 56.3$ mm, $\rho_{oil} = 755$ kg/m³, $\rho_{water} = 1000$ kg/m³, $\mu_o = 0.88$ mPa.s, IP = 48.56 %)

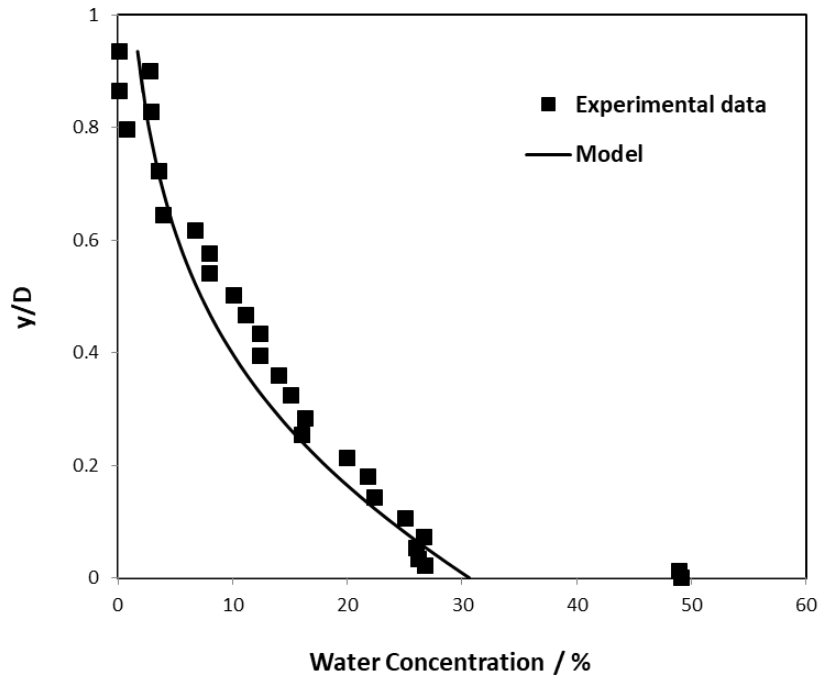


Figure 4: Validation of $C(y)$ model with oil-water system for a horizontal pipe at 2m/s ($D = 56.3$ mm, $\rho_{oil} = 790$ kg/m³, $\rho_{water} = 1000$ kg/m³, $\mu_o = 1$ m Pa.s, IP = 49 %)

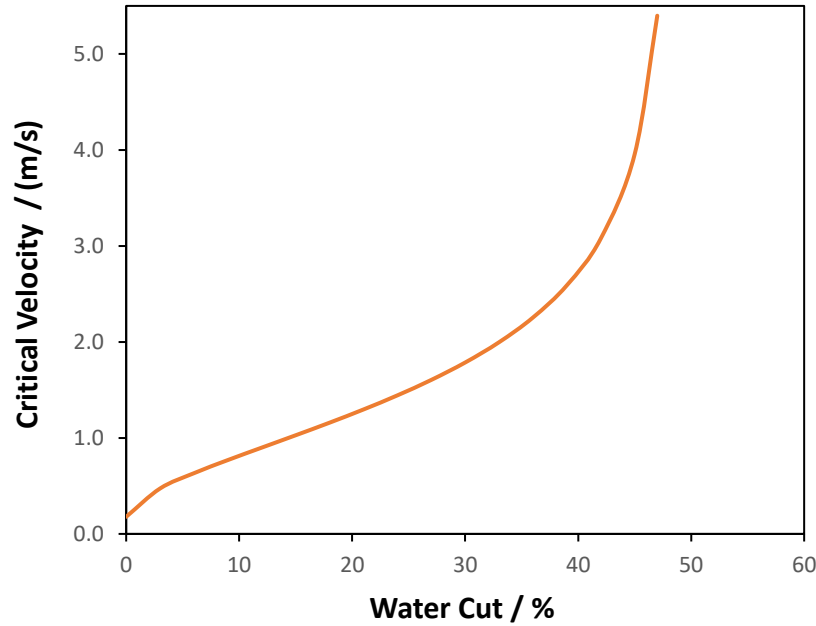


Figure 5: Critical velocity of oil-water system for a horizontal pipe ($D = 24$ cm, $\rho_{oil} = 801$ kg/m³, $\rho_{water} = 1000$ kg/m³, $\mu_o = 1.6$ mPa.s, IP = 48.75 %)

This new model is then implemented for the CO₂-water system, for supercritical CO₂, with fluid properties and flow conditions outlined in Table 3. The inversion point, IP, is calculated using the expression in equation (16).

Table 3: Properties of Supercritical CO₂ fluid.

Parameters	Fluid 3
T (K)	304
P (MPa)	8
ρ_{CO_2} (kg/m ³)	683.31
ρ_w (kg/m ³)	1000
μ_{CO_2} (mPa.s)	0.053756
μ_w (mPa.s)	0.001
σ (mN/m)	35.4
D (m)	0.4
Pipe Inclination	Horizontal

Figure 6 compares the water droplet concentration profile as a function of water cut along the vertical axis of the pipe, for three different water cut percentages: 0.003, 2, and 5 percent. As seen in the graph, at higher water holdups, the concentration of water droplets remains higher throughout the pipe, indicating that more water is distributed across the cross-section. The inversion point is 80.18%. This number is significantly higher than that of typical oil-water systems, particularly for a very dense CO₂ phase. This indicates that it is easier for CO₂ to suspend the droplets in its core.

For all situations, the water concentration at the bottom of the pipe is less than 80.18%, the system's inversion point. This indicates that even with the relatively higher concentration of water droplets at the pipe's bottom, the droplets do not settle into a water layer.

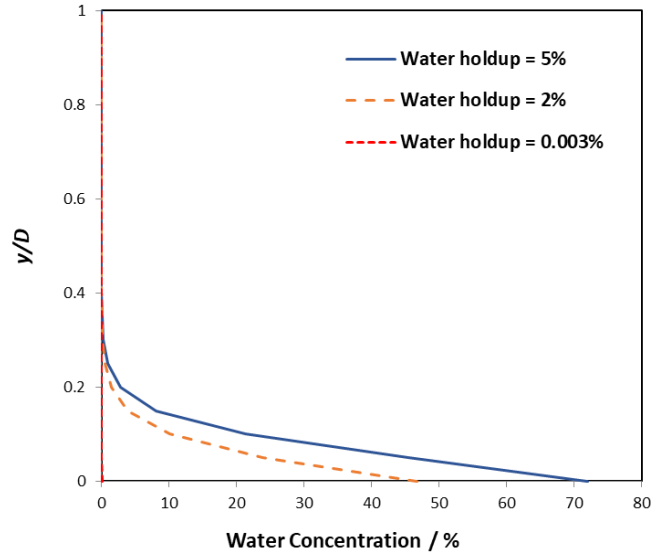


Figure 6: Concentration profile of water droplets in CO₂ for a horizontal pipe at 2 m/s (D = 100 mm, $\rho_{CO_2} = 683.31 \text{ kg/m}^3$, $\rho_{water} = 1000 \text{ kg/m}^3$, $\mu_{CO_2} = 0.054 \text{ mPa.s}$, IP = 80.18 %)

Figure 7 compares the effect of different mixture velocities (2 m/s, 3 m/s, and 4 m/s) on the vertical distribution of water droplets at a constant holdup of 5%. At lower velocities, the distribution of water droplets is more uniform along the vertical axis of the pipe. As the velocity increases to 3 m/s and 4 m/s, the concentration of water droplets near the bottom becomes steeper, indicating a greater number of water droplets at higher positions within the pipe cross-section and a more even distribution. At higher mixture velocities, the water droplet concentration at the bottom of the pipe reduces to 45% and 30%, as more droplets are suspended at the upper part of the pipe's cross-section. This is due to an increase in turbulent forces carrying the droplets upward.

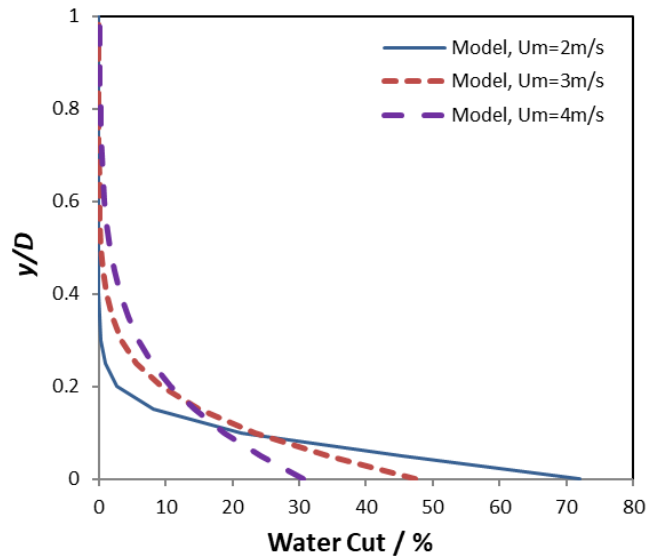


Figure 7: Concentration profile of water droplets in CO₂ at 5% water holdup for different velocities (D = 0.1 m, $\rho_{CO_2} = 683.31 \text{ kg/m}^3$, $\rho_{water} = 1000 \text{ kg/m}^3$, $\mu_{CO_2} = 0.054 \text{ mPa.s}$, IP = 80.18%)

As indicated throughout this report, there is a direct correlation between the water cut and the critical velocity. Figure 8(a) illustrates this. For the same fluid properties, as the water cut increases, the critical velocity required to maintain dispersed flow also increases.

In Figure 8(b), as the angle of inclination increases, the critical velocity required to maintain stable dispersed flow decreases. At near-horizontal inclinations (close to 0°), the critical velocity is around 0.35 m/s. However, as the angle increases towards 60° , the critical velocity drops significantly, approaching 0.10 m/s. This trend reflects the influence of gravity on the behavior of water droplets in the CO_2 -water system. When the pipe is more horizontally inclined, the effect of gravity is felt more by the droplets, requiring higher velocities (turbulence) to keep them suspended.

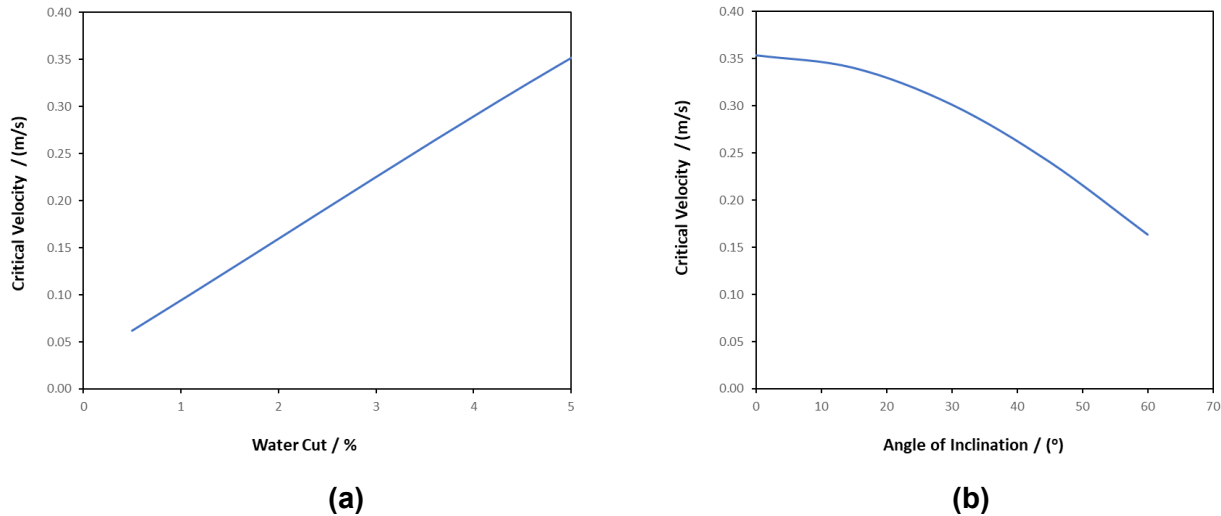


Figure 8: Critical velocity for suspension of water droplets in CO_2 for a horizontal pipe as a function of (a) water cut (b) angle of inclination at 5% water cut.

CONCLUSIONS

We developed a model to predict droplet distribution in a pipe's cross-section for dispersed turbulent flow of dense-phase CO_2 and water droplets. The results from the model indicate that the critical velocity required to maintain a stable dispersed flow increases with higher water cuts. This suggests that as more water is introduced into the system, greater flow velocities are needed to prevent droplet coalescence and settling.

The critical velocity decreases with increasing pipe inclination. This result underscores the significance of gravity's influence on the flow regime. More inclined or vertical pipelines can maintain dispersed flow with lower velocities, reducing operational energy costs.

Although initially validated for oil-water systems, the model has been successfully adapted and applied to CO_2 -water multiphase flow. These findings are useful for the design and operation of pipelines transporting CO_2 in multiphase flow conditions, where stable dispersed flow is desired to minimize water phase separation and wetting of the pipeline walls. As such, there is some confidence that this mechanistic model can be adapted to multiphase flow for different fluid systems. Further work is needed to validate the water-wetting model for CO_2 -water multiphase flow.

This work developed a model to determine the formation of a water layer and assess corrosion risk. The critical velocity to prevent water layer formation can be defined for any flow operating condition. As long as the flow velocity is above this value, the risk of corrosion is minimized.

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