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Minimum Wall Thickness for Supercritical CO_2 Pipeline

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Abstract

Determining the minimum wall thickness for supercritical CO_2 pipelines requires consideration of multiple factors: internal design pressure, ductile fracture arrest, and dynamic pressure surges. While the design thickness for internal pressure can be readily calculated using ASME B31.4, the impacts of ductile fracture and surge pressures (similar to water hammer in liquid pipelines) are often discussed but seldom addressed in practical wall-thickness calculations.

This article presents practical methods to calculate wall thickness based on ISO 27913 standard to arrest ductile fracture. It also calculates wall thickness under hydraulic shock conditions, drawing on established approaches from Perry's Chemical Engineers' Handbook. Together, these methodologies provide engineers with clear, quantitative tools to design CO_2 pipelines that are not only safe and reliable, but also cost-effective.

1. Introduction

With growing global concern about climate change, many countries are turning to carbon dioxide (CO_2) sequestration as a viable pathway to reduce greenhouse gas emissions. Despite government incentives, the economics of CO_2 sequestration projects remain challenging. To lower capital expenditures, CO_2 pipeline operators are motivated to minimize pipeline wall thickness wherever possible. However, several incidents of pipeline fracture, particularly ductile fracture, have underscored the risks of reducing wall thickness too aggressively. This raises an important question for both designers and regulators: how can we determine the minimum wall thickness that is both cost-effective and ensures public safety?

2. Wall Thickness Calculation

Determining the appropriate wall thickness requires consideration of three key factors. First, the design must satisfy the internal design pressure requirements specified by local and national codes. Second, ductile fracture resistance must be evaluated. Several pipeline incidents have demonstrated catastrophic "unzipping" failures when fracture control was insufficient. Third, the potential for water hammer must be assessed. Rapid valve closure or sudden flow changes can generate severe transient pressures.

2.1 Internal Design Pressure

The wall thickness required to withstand internal pressure is governed by the ASME B31.4 code. The applicable formula is shown below:

$$t = \frac{P_i \times D_o}{2 \times F \times E_j \times SMYS} \quad \text{Eq. 1}$$

All variables and units are defined in the nomenclature section. As indicated by the equation, the required wall thickness increases with internal design pressure and outside diameter, and decreases with higher design factor, joint efficiency, and specified minimum yield strength (SMYS).

2.2 Ductile Fracture

Ductile fracture has been extensively investigated over the past several decades. In 1974, W. A. Maxey of Battelle's Columbus Laboratories presented a landmark paper, "Fracture Initiation, Propagation and Arrest," at the Fifth Symposium on Line Pipe Research. Although Maxey's work focused on natural gas pipelines, the underlying methodology remains highly applicable to CO_2 pipeline design. Building on this foundation, DNV issued Recommended Practice DNV-RP-F104 in 2021, "Design and Operation of Carbon Dioxide Pipelines," providing updated guidance specific to CO_2 transport. More recently, in 2024, ISO published ISO 27913, "Carbon Dioxide Capture, Transportation and Geological Storage – Pipeline Transportation Systems," further consolidating best practices for safe and reliable CO_2 pipeline operation.

2.2.1 Battelle Method

The methodology proposed by W. A. Maxey is known as the Battelle Two-Curve Method (TCM). It is based on the relationship between two characteristic curves: the J-curve (also referred to as the fracture or material curve) and the fluid decompression curve. When these two curves intersect, fracture propagation may occur; if they do not, the pipeline is considered self-arresting.

The Two-Curve Method has been extensively referenced and validated in subsequent research. A lesser-known but important reference is Figure J-12, titled "Determination of the Arrest Stress Level." This figure divides the behavior into two distinct regions: the Propagation Zone above the dividing line and the Arrest Zone below it. The boundary curve, illustrated in orange, defines the transition between these two regions. The corresponding X and Y parameters can be calculated using the following formulas:

$$X = 1000 \times \frac{C_v}{A_c} \times \frac{E}{\sigma_f^2 \times \sqrt{R \times t}} \quad \text{Eq. 2}$$

$$Y = \frac{P_b \times D_o}{2 \times t \times \sigma_f} \quad \text{Eq. 3}$$

2.2.2 DNV Method

Building on W. A. Maxey's original work, DNV later developed a corresponding graph specifically for CO_2 pipelines, reflecting the distinct decompression behavior of CO_2 compared to natural gas. In this version, the diagram is divided into three zones rather than two. In Figure 1 the area enclosed by the solid green lines represents the Arrest Zone, where fracture propagation is expected to stop. The region above the dashed green line and the upward-sloping solid green line defines the Propagation Zone, where running fractures are likely to occur. A third region, introduced to address more complex cases, is termed the Assessment Zone. This rectangular area

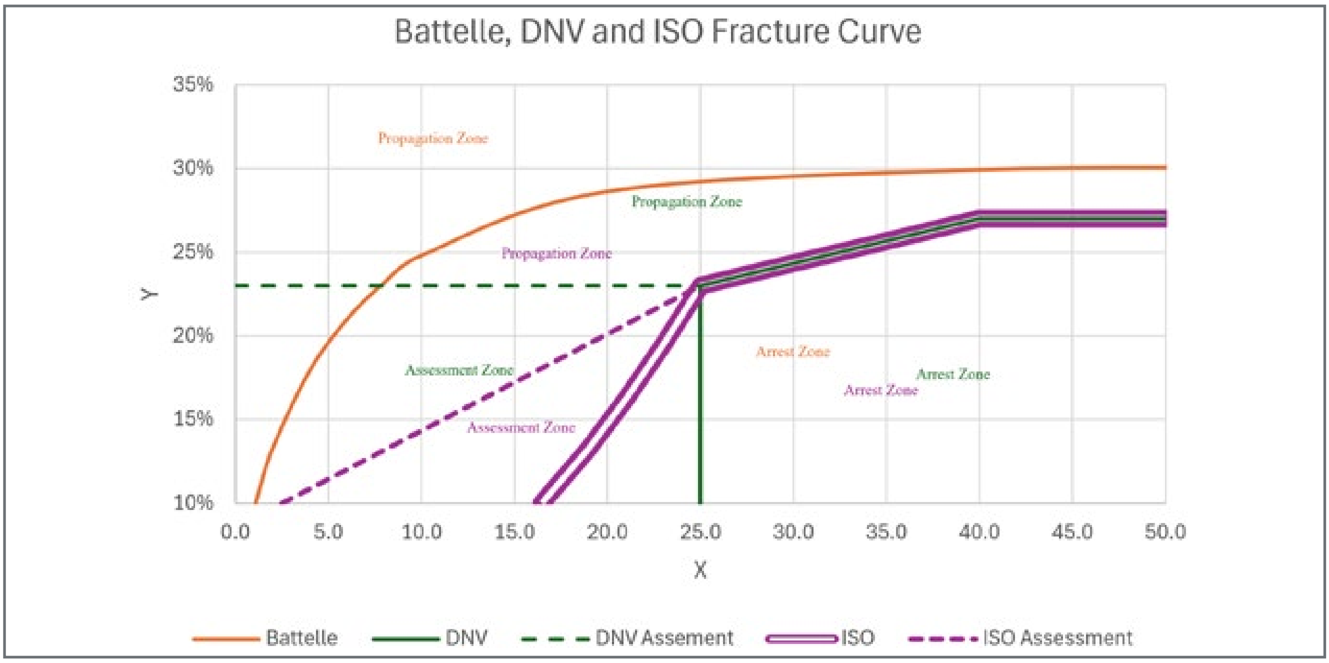

Figure 1: Ductile fracture zones for various methods

lies between the dashed green line and the vertical solid green line and indicates conditions that require further evaluation to determine the likelihood of fracture arrest.

2.2.3 ISO Method

The ISO method, published in November 2024, further refines the DNV approach and is also tailored specifically for CO_2 pipelines. Similar to the DNV method, the diagram is divided by purple lines into three zones. However, the Propagation Zone and Arrest Zone are expanded, while the Assessment Zone is reduced in size compared to the DNV model.

The ISO method is recommended for current design work, as it reflects the latest research and experimental data on CO_2 fracture behavior. Using Equation (4), the minimum self-arrest value, Y_A, can be determined. By comparing Y_A with the calculated Y value, engineers can assess whether the pipeline is self-arresting, prone to fracture propagation, or requires further evaluation under special conditions, using Equation (5).

2.3 Water Hammer

When a flowing liquid in a pipeline is suddenly brought to rest by a rapidly closing valve, a pressure wave travels upstream toward the inlet and reflects back, creating oscillations commonly referred to as water hammer. Although carbon dioxide in a dense-phase pipeline is not a true liquid, its behavior is similar due to its high mass density and low compressibility factor.

$$Y_A = \begin{cases} 0.000368 \times X^2, if\ 16.48 \le X < 25 \\ 0.002667 \times X + 0.1633, if\ 25 \le X < 40 \\ 0.27, \quad if\ X \ge 40 \end{cases}$$

$$Y_B = 0.005778X + 0.085556, if\ 2.5 \le X < 25 \qquad \textit{Eq. 4}$$

If $X \le 2.5$, then Propagation Zone
If $2.5 < X \le 16.48$
  If $Y \le Y_B$, then Assessment Zone
  If $Y > Y_B$, then Propagation Zone
If $16.48 < X \le 25$
  If $Y \le Y_A$, then Arrest Zone
  If $Y_A < Y \le Y_B$, then Assessment Zone
  If $Y > Y_B$, then Propagation Zone
If $X > 25$
  If $Y \le Y_A$, then Arrest Zone
  If $Y > Y_A$, then Propagation Zone

Eq. 5

The maximum transient pressure rise can be estimated using the Joukowski equation:

$$\Delta P_{max} = \frac{\rho \times a \times \Delta v}{1{,}000{,}000} \qquad \textit{Eq. 6}$$

where a can be calculated as:

$$a = 1000 \times \sqrt{\frac{\beta \div \rho}{1 + \frac{\beta}{E} \times \frac{D_i}{t}}} \qquad \textit{Eq. 7}$$

The predicted pressure rise depends strongly on the valve closure rate. For cases where the valve closure time tc exceeds the pipe wave period τ, the peak pressure can be approximated using the relationship shown in Equation (8) and (9).

$\Delta P = \Delta P_{max} \times \frac{\tau}{t_c}, \quad if\ t_c \geq \tau$	*Eq. 8*
$\tau = \frac{2 \times L}{a}$	*Eq. 9*

2.4 Corrosion Allowance

Once the wall thickness has been determined based on the three governing factors: internal pressure, ductile fracture, and water hammer. the nominal wall thickness must be equal to or greater than the calculated value plus the specified corrosion allowance.

$t_n \geq t + CA$	*Eq. 10*

3. Example

The following example illustrates the application of the above methods.

A pipeline company operates a CO_2 transmission line with the following design parameters:

P_i = 15.32 MPa(g) D_o = 323.85 mm

SMYS = 415 MPa (API 5L Grade L415M)

F = 0.72 E_j = 100% (ERW pipe)

CA = 1.587 mm C_v = 200 J

Pb = 8 MPa(g)

Two nominal wall thicknesses under evaluation: 10 mm and 14.27 mm

3.1 Internal Design Pressure

Using Equation (1): t = (15.32 × 323.85) / (2 × 0.72 × 1.00 × 415) = 8.302 mm

Including the corrosion allowance:

t_n ≥ 8.302 + 1.587 = 9.889 mm

Therefore, both 10 mm and 14.27 mm wall thicknesses satisfy the internal pressure design requirement.

3.2 Ductile Fracture

Since two wall thicknesses are used, separate calculations are performed.

3.2.1 10 mm thickness

After deducting the corrosion allowance, t = 8.413 mm.

Applying Equations (2) and (3):

X = 60.35 Y = 0.318

From Figure 1, the X value exceeds the chart maximum of 50, and Y lies above the ISO purple line. It falls within the Propagation Zone.

3.2.2 14.27 thickness

X = 49.49 Y = 0.211

From Figure 1, this condition falls within the Arrest Zone, meaning any initiated crack will self-arrest and not propagate.

3.2.3 Minimum self-arresting thickness

From the above results, the 10 mm pipe is too thin for self-arresting, while the 14.27 mm pipe is sufficient.

By trial-and-error, the minimum self-arresting thickness is achieved when Y = Y_A. For this example:

t = 9.913 mm, t_n = 11.5 mm

3.3 Water Hammer

To calculate water effect, the following information is given:

ρ = 621 kg/m³ β = 71.5 MPa flow = 330.506 m³/h

3.3.1 10 mm thickness

v = 1.266 m/s a = 337.5 m/s ΔP_{max} = 0.265 MPa

3.3.2 14.27 mm thickness

v = 1.34 m/s a = 338.1 m/s ΔP_{max} = 0.281 MPa

The water hammer effect in CO_2 pipelines is generally mild. Because CO_2 has a lower modulus of elasticity than water, its pressure wave velocity is about 340 m/s—much lower than water's typical 1500 m/s. As a result, water hammer is seldom a design concern for CO_2 systems. If necessary, the impact can be mitigated by increasing the valve closure time, as shown in Equation (8).

3.4 Final Answer

Based on internal pressure, the minimum nominal wall thickness is 9.889 mm. To ensure ductile fracture arrest, the minimum self-arresting thickness is 11.5 mm.

While water hammer does not significantly affect the required thickness, valve closure time should still be verified.

To balance cost and safety, the pipeline company selects 10 mm wall thickness for the majority of the line, and installs 14.27 mm wall sections approximately every 100 meters as fracture arrestor segments.

4. Conclusion

CO_2 pipelines can be both safe and cost-effective when wall thickness is determined through a comprehensive evaluation of internal design pressure, ductile fracture control, and water hammer effects. This article provides the essential methodology and reference framework to guide engineers in performing accurate and reliable thickness calculations, ensuring designs that balance safety, performance, and economy.

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Nomencalture

- CA: corrosion allowance in mm
- t: pipeline wall thickness in mm, CA excluded
- t_n: nominal wall thickness in mm
- Do: outside diameter of pipe in mm
- Di: inside diameter of pipe in mm, = (Do - 2 × t)
- R: average pipe radium in mm, = (Do - t) / 2
- Pi: internal design gage pressure in MPaG
- Pb: CO_2 bubble point gage pressure in MPaG
- ΔPmax: maximum pressure rise in MPa due to water hammer
- ΔP: pressure rise in MPa if valve closure time exceeds pressure wave round trip travel time
- F: Design factor, ≤ 0.72
- Ej: weld joint efficiency, ≤ 1
- E: pipe wall modulus of elasticity in MPa, = 2.06×10^5 MPa for carbon steel
- SMYS: pipe specified minimum yield strength in MPa
- σf: flow stress in MPa, = SMYS + 69
- X: value on the horizontal x-axis chart
- Y: value on the vertical y-axis chart
- YA: maximum Y value that is self-arrested. Self -arrested if Y ≤ YA
- YB: Y value on the Assessment Line if 2.5 < X ≤ 25
- Cv: Charpy V-notch absorbed energy value in J of the pipeline steel, measured in the transverse direction
- Ac: cross-section area of the notched-bar impact specimen, = 80 mm2 for a full-sized specimen
- a: pressure wave velocity in m/s
- Δv: velocity change in m/s
- L: pipe straight length in m
- tc: valve closure time in seconds
- τ: pressure wave round trip travel time in seconds
- ρ: CO_2 fluid mass density in kg/m3
- β: CO_2 bulk modulus of elasticity in MPa

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