

Overcoming challenges of CO₂ transportation and storage

Accurate quantity and quality measurement ensures efficiency and practicality in carbon dioxide applications and processes.

As we strive to enhance the capture of CO₂ emissions, the next step in the value chain involves transportation, which precedes both the storage and utilization of it.

Historically, CO₂ has been transported by truck in liquid phase, primarily for the carbonation of beverages in the food and beverage sector. The food and beverage industry is a major transporter, however the volumes transported are low and there is no need for large cargos. Large-scale transportation of CO₂ via pipelines in a dense/supercritical phase is gaining traction. There are notable exceptions in certain regions, such as North America and the Middle East, where CO₂ has been utilized for Enhanced Oil Recovery (EOR) for more than five decades.

In 2024, the European Parliament adopted the carbon removals and carbon farming (CRCF) regulation, which created first EU-wide voluntary framework for carbon removal. Innovative technologies are under implementation for long term CO₂ storage in geological formations.

One significant challenge in large-scale CO₂ pipeline transportation stems from the diversity of CO₂ sources, which may contain impurities depending on their origin. Additionally, the volume of CO₂ to be transported presents logistical challenges, particularly regarding the associated risks of operating pipelines in proximity to densely populated areas. Pipelines operate at high pressure in the dense phase and potential leaks are a concern, although safety interlocks are in place.

CO₂ has its critical point at 30.8 °C (87.4 °F) and 73.7 bar (1068.89 psi). Above this temperature and pressure, it is in the supercritical state (Figure 1). Transporting CO₂ in its supercritical phase facilitates more efficient transportation

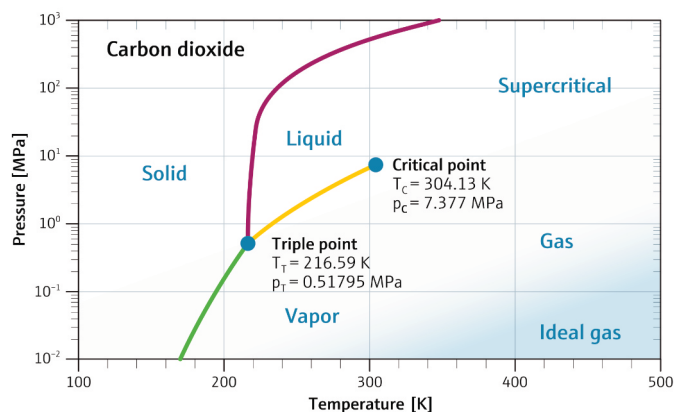


Figure 1: Different phases of carbon dioxide

processes due to enhanced density. In this state, it will fill the entire pipe like a gas, have a higher density resembling a liquid and have a low viscosity like a gas. It will be highly compressible near and at the critical point, and the fluid properties change very rapidly.

Addressing impurities in CO₂ transportation and storage

The types of impurities present in CO₂ streams can vary significantly depending on the source. These impurities have the potential to react chemically with one another and their environment, forming byproducts that may adversely affect asset design, operational efficiency, and potentially, integrity. A central concern is the integrity of materials, which can be compromised by corrosion and cracking.

Moisture (H₂O) is a notable impurity that can impact pipeline integrity, particularly through corrosion when present at elevated concentrations due to the formation of carbonic acid when reacted with CO₂. Consequently, it is



Figure 2: J22 TDLAS gas analyzer for moisture measurement

advisable to restrict the concentration of water to a maximum of 50 parts per million (ppm). The accurate and reliable measurement of moisture in the CO₂ stream is therefore of utmost importance. A proven measurement system, such as the J22 tunable diode laser absorption spectroscopy (TDLAS) gas analyzer, offers an excellent solution to enhance the safety and integrity of the pipeline (Figure 2).

It is essential to consider the possibility of chemical reactions occurring among various impurities in the CO₂ stream, which can then lead to the generation of new compounds such as elemental sulfur, sulfuric acid (H₂SO₄) and nitric acid (HNO₃). Careful monitoring of other impurities – specifically hydrogen sulfide (H₂S), oxygen (O₂), methane (CH₄), nitrogen (N₂), carbon monoxide (CO) and hydrogen (H₂) – is imperative, particularly when transporting CO₂ from multiple sources.

Towards the end of the CO₂ value chain, the injection site and within the reservoir, it is critical to monitor stream impurities to mitigate potential issues such as pitting and cracking. Additionally, monitoring serves to prevent geological storage concerns related to capacity, injectivity, and integrity that may arise from enhanced material dissolution attributed to sulfur oxides (SO_x), nitrogen oxides (NO_x), hydrogen sulfide (H₂S), carboxylic acids, oxygen (O₂) and water (H₂O), as well as from mineral precipitation resulting from these impurities.

There are various measurement technologies to analyze multiple or specific types of impurities in CO₂, but given the fact that the carbon capture, utilization and storage (CCUS)

business is often cost-driven, low cost of ownership plays a key role in the technology decision-making process.

A critical aspect of CO₂ monetization is related to two key factors: accurate quantity and quality measurement with appropriate allocation and reporting. For long-term economic benefits, laser-based technologies such as TDLAS are being adopted as the preferred way to reduce total cost of ownership without compromising measurement accuracy and reliability.

Measuring carbon dioxide quantity

While the measurement of CO₂ in dense or supercritical phases is well established within the industry, recent advancements have emphasized the need for efficient and high-accuracy measurement techniques for large volumes, even in impure CO₂ processes.

The industry has agreed on the use of metric tons as the standardized unit of measurement for CO₂, defined in million tons per annum (MTPA) to indicate flow rates. The volumes of CO₂ addressed by projects or hubs can range from 0.1 MTPA to 20 MTPA.

Regulatory requirements may differ across geographical regions, introducing an additional layer of complexity to the measurement of CO₂ concerning quantification, verification and reporting.

A variety of measurement technologies are available for CO₂ assessment, each presenting specific challenges and limitations based on CO₂ phase, composition and operational conditions. When selecting an appropriate measurement technology, it is important to consider whether direct mass or indirect mass measurement is preferred, as conversion from volume to mass may require supplementary devices to measure pressure, temperature and density accurately.

Selecting appropriate technology for CO₂ transportation

Pipeline transportation of carbon dioxide (CO₂) in the dense/supercritical phase is recognized as the most cost-effective method for transporting substantial quantities in the most efficient and safe manner. This transportation method is advantageous for several reasons:

- **High density:** Enables the transport of larger volumes within a confined space
- **Low viscosity:** Reduces friction, facilitating smoother flow through pipelines
- **Efficient compression:** Supercritical CO₂ can be compressed more effectively than in its gaseous state
- **Reduced corrosion:** Typically, supercritical CO₂ is dehydrated, significantly lowering the risk of pipeline corrosion
- **Stable phase:** Supercritical CO₂ maintains stability across a wide range of temperatures and pressures, thereby simplifying operations

CO₂ in the transportation pipelines maintains the supercritical phase (temperature and pressure are higher

than the critical value), and the pressure is increased by the compressor unit. Unlike gas transportation, supercritical transportation needs to set the minimum pressure to keep its dense phase.

Despite these advantages, challenges exist concerning measurement, which include:

- Impurities present in CO₂ composition
- The choice between direct or indirect mass measurement
- Operating conditions at high pressure
- Requirements for maintenance and calibration

Flow measurement technologies for CO₂ in the dense/supercritical phase

1. Turbine flowmeter
2. Cone flowmeter
3. Venturi tube
4. Ultrasonic flowmeter
5. Orifice plate
6. Coriolis flowmeter

Each measurement technology is characterized by distinct advantages and disadvantages. A comparative analysis of these technologies reveals that there is no inherently perfect solution as shown in Table 1.

However, the Coriolis flowmeter (Figure 3), distinguishes itself due to the following attributes:

- Direct mass measurement capability
- No requirements for upstream or downstream straight meter runs
- Ability to be calibrated using alternative fluids
- High turndown ratio

There are several industry working groups in Europe (DNV) and the Americas (API) working towards establishing new standards for CO₂ measurement with the consensus that Coriolis technology offers the best measurement for CO₂ in the dense/supercritical phase.

CO₂ metering systems

Pre-assembled metering systems are a standard practice within the energy industry, as they provide significant advantages in ensuring the appropriate system design and installation of flowmeters and analyzers, which facilitates optimal performance of these instruments.



Figure 3: Proline Promass O 300 Coriolis flowmeter

In the context of dense or supercritical CO₂, which operates under high pressure, it is essential to consider specific factors to ensure safe and effective operation, such as:

- High-pressure Coriolis meters
- Double Block and Bleed valves at the inlet and the outlet of the metering systems
- Sampling nozzles upstream of the meter
- Duty and stand-by meters for measurement availability
- “Z” master meter arrangement for calibration verification capabilities
- Flow computer redundancy

When handling CO₂ at high pressures, it is important to prioritize safety. This includes considering safety measures such as rupture disks and utilizing advanced diagnostics in flowmeters that can provide alerts in case of any potential mechanical integrity issues.

It is essential to acknowledge the cooling effect of CO₂ when there are substantial pressure differentials within the process, as this may result in mechanical stress on the piping system. Therefore, it is advisable to incorporate redundant and fast response temperature monitoring devices as part of the metering system to effectively identify and address the issue.

Table 1: Measurement technologies advantages and disadvantages

Technology	Turbine	Cone	Venturi	USM	Orifice Plate	Coriolis
Density requirement for mass flow rate	Yes	Yes	Yes	Yes	Yes	No
Turndown	10:1	10:1	10:1	100:1	4:1	100:1
Upstream / downstream installation requirements	Yes	Yes	Yes	Yes	Yes	No
Calibration with alternative fluids	Yes	Yes	Yes	No	Yes	Yes
Cost	Medium	Low	Low	High	Low	High

Conclusions

The transportation and storage of CO₂ play a critical role in the broader effort to reduce carbon emissions and facilitate carbon capture and storage (CCS). While the use of pipelines for transporting CO₂ in its dense or supercritical phase offers significant advantages, such as moving a larger volume at a lower cost, challenges remain, particularly concerning impurities and their effects on both pipeline integrity and measurement accuracy.

The presence of impurities can cause material degradation and operational issues, making careful monitoring essential. The selection of appropriate technologies for CO₂ composition, impurities and flow measurement, such as advanced laser-based methods and Coriolis flowmeters, must balance cost, efficiency, reliability and total cost of ownership.

With the increasing focus on large-scale CCS projects, addressing these technical and economic challenges will

be critical for ensuring safe, efficient and cost-effective CO₂ transport and storage.

The emerging trend in CO₂ transport is the shift toward dense-phase transport, which offers greater efficiency compared to gas and liquid phases. This development aligns with the rapid growth in carbon capture and storage infrastructure, as highlighted by the Global CCS Institute's 2024 report. With 50 facilities now operational, including three dedicated to transport and storage and 44 under construction (seven focused on transport and storage), the sector is scaling significantly. The CCUS project pipeline has expanded to 628 projects as of July 2024, reflecting a remarkable 60% year-on-year increase, underscoring the accelerating momentum in addressing global decarbonization goals (Global CCS institute 2024).