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Design Considerations for CO2 Transportation Pipelines

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Abstract. DESFA is exploring the benefits of large-scale aggregation of CO2 in Greece via pipelines and the development of a liquefaction and export terminal. Under this scope, several issues have arisen through the initial design phases that distinguish these pipelines from the transportation of other gases such as natural gas. This paper summarizes issues such as CO2 pressure and phase requirements, pipeline infrastructure and mechanical design, flow management and thermal stability as well as safety concerns.

1 Introduction

DESFA, the Natural Gas Transmission System Operator (TSO) of Greece is exploring the benefits of large-scale aggregation of CO2 in Greece via pipelines and the development of a liquefaction and export terminal. Under this scope, several issues have arisen through the initial design phases that distinguish these pipelines from the transportation of other gases such as natural gas. This paper summarizes these issues including areas as:

- CO2 Pressure and Phase Requirements
- Pipeline Infrastructure and Mechanical Design
- Hydraulic Flow Management and Thermal Stability
- Pipeline Safety and Environmental Concerns

It should be noted that the accumulation of CO2 from emitters in Greece and its transportation through pipelines to a liquefaction facility for further loading in vessels and transportation to underground storage facilities, presents challenges that are unique in Greece compared to other international applications. Such challenges include the relatively small distances but with a rugged terrain, already existing pipeline networks, population density along the pipeline routing, and the lack of central coordination between the emitters regarding the quality and the thermophysical properties of the captured CO2.

2 CO2 Pressure and Phase Requirements

2.1 Properties of CO2

The phase diagram for pure CO2 is shown in Figure 1. It contains two distinct features which are a "triple point" at the location marked as A at 0.52MPa, - 56 ºC; and a "critical point" at the location marked as B, at 7.38MPa, 31.1 ºC. At point A CO2 can exist as one of three phases, solid, liquid, or gas. The curve connecting points A and B in Figure 1 is the vapor-liquid line separating the gaseous and liquid phases. The "critical temperature" is the vapor temperature at the critical pressure. The region above the critical temperature and critical pressure is labeled as "supercritical region", while the region above the critical pressure, but below the critical temperature, is called the "dense phase region [1]

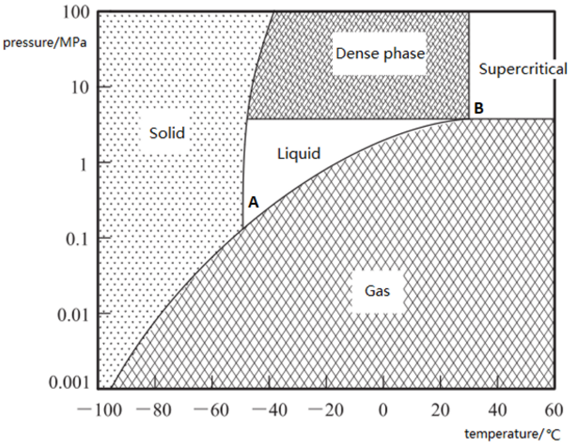

Fig. 1. Phase diagram for pure CO2.

2.2 CO2 Pipeline Transportation Process

Based on the properties mentioned in the previous paragraph it is clear that the CO2 phases can change very easily even with relatively small changes in temperature and pressure. The presence of impurities even in small quantities can further intensify these phase changes and create serious problems in the operation of the pipelines [2].

In case of CO2 transportation in the **gas phase**, the pressure will need to be kept at low levels (typically below 5 Mpa) [3] in order to avoid the presence of CO2 in the supercritical phase. A thermodynamic calculation is needed in order to determine whether insulation of the pipeline is needed, but this should be considered almost certain if subsea sections are included in the pipeline. Therefore, **gas phase transportation pipelines** have lower operating pressure and higher operation security; the pipe diameter is larger, and initial CAPEX is higher,

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so it is suitable for low throughput, short-distance transportation and for CO2 from gas phase source. It is also more suitable for densely populated areas compared to supercritical transportation.

For **dense/supercritical transportation** of CO2 the pipelines will need to operate at higher pressures both in order to achieve the desired CO2 phase but also to overcome terrain elevation differences and higher friction. Insulation of the pipeline will always be needed in order to keep its temperature above the critical point. In this mode of transportation, the pipeline is more efficient and can accommodate the transportation of higher CO2 quantities at a lower initial CAPEX cost. Aforementioned cost refers only to the pipeline and does not take into consideration additional costs for the required compression.
The safety coefficient of the pipeline is lower and it is considered a better option for long range transportation through low population density areas. CO2 transportation pipelines in **dense/supercritical phase** are widely used in cases where the CO2 is going to be transported directly in underground storage without vessel transportation or in applications of Enhanced Oil Recovery (EOR).

Taking into consideration the smaller distances through areas with high population density in Greece and the fact that most CO2 capture technologies have a gas phase output at the moment the decision is to proceed with CO2 Gas phase transportation pipelines.

3 Pipeline Infrastructure and Mechanical Design

3.1 Status of Applicable Codes and Standards

Currently there is a number of pipeline standards that can be considered as covering the many of the issues related to the design and construction of CO2 pipelines; however, there are some CO2 specific issues that are not adequately covered in these standards. [4] – [10]
Most of them are not “standalone” standards but are written as a supplement to other existing pipeline standards for natural gas or liquids for both onshore and offshore pipelines. The ambiguity that currently exists in the applicable technical codes and standards in Greece needs to be resolved with future National or European Regulations which will have to be established prior to the construction of these projects.

3.2 Location Classes and Design Factors

ISO 13623[5] and CSA Z662:23 [10] are the two standards that contain information regarding the class location and the corresponding design factor that needs to be taken into consideration during the design of a CO2 pipeline. In accordance with Table 1 of ISO 13623:2017, carbon dioxide is classified as a Category E fluid, thus Annex B which defines supplementary requirements for public safety of land pipelines is applicable to the design of the pipeline.

3.2.1 Location Classification

In terms of Location Classification, the carbon dioxide transmission system is classified into 5 categories, namely 1, 2, 3, 4 and 5, which are determined by the population density and concentration of people of the region it crosses. The application of categorized zones is associated with the use of maximum safety coefficients, which define the maximum allowed stress, which may be developed in the Transmission System for each maximum operating pressure and the determination, as the case may be, of the additional protective measures. For the determination of class locations, the population density, expressed as the number of persons per square kilometer, shall be determined by laying out zones along the pipeline route, located within a not less than 0.4km wide zone centered on the pipeline. This zone shall then be divided into random sections of 1.5 km in length such that individual lengths include the maximum number of buildings intended for human occupancy. According to ISO 13623 requirements the following location classification system is applicable for CO2 pipelines:

- **Class 1:** Locations subject to infrequent human activity with no permanent human habitation
- **Class 2:** Locations with a population density of less than 50 persons per square kilometre
- **Class 3:** Locations with a population density of 50 persons or more but fewer than 250 persons per square kilometre
- **Class 4:** Locations with a population density of 250 persons or more per square kilometre
- **Class 5:** Location with areas where multi-storey buildings (four or more floors above ground level) are prevalent and where traffic is heavy

3.2.2 Design Factors

Table 1 shows the corresponding design factors that are applied in the design calculations of each pipeline section according to its class location.

Table 1. CO2 Pipeline Design Factors per ISO 13623

Location Class	Design Factor
1	0.77
2	0.77
3	0.67
4	0.55
5	0.45

CSA Z662:23 adopts a slightly different system for assigning a class location to each section of a CO2 pipeline leading to less strict design factors to be used for the pipeline wall thickness calculations. Summarizing the above, the initial decision for the project under examination is to apply the requirements of ISO 13623 regarding the applicable class locations and the corresponding design factors.

3.3 Pipeline Materials

High strength steel materials typically used for Natural Gas pipelines are in general considered suitable for CO2 transportation pipelines provided that they have improved ductility and the ability to resist fracture propagation. The discharge and dispersion of high-pressure CO2 pipelines differs from the hydrocarbon pipelines in involving complex physics including very low temperatures due to the pronounced Joule Thompson effect, phase transition, sonic multiphase flow, and heavy gas dispersion. For these reasons improved toughness is needed in steel materials used for CO2 transportation pipelines.

In case some water is present in the CO2 pipeline corrosion problems could also appear. In the presence of water, the formation of carbonic acid can lead to extremely aggressive corrosion wherever the steel internal surface is directly exposed. This requires limits on water content that are appropriate to prevent formation of free water under the most stringent operating conditions; Potential upset conditions where CO2 with out of specification water content is accepted in the pipeline also need to be taken into consideration during design. For this reason, a 3mm corrosion allowance (significantly higher than the one used in natural gas pipelines) can be taken into consideration during the pipeline wall thickness calculation [11]. If the water content is kept under control no additional corrosion measures or anticorrosive internal lining is considered necessary.

3.4 Line Valve Stations

3.4.1 Valve Station Spacing

Valve stations shall be installed for the purpose of isolating the pipeline for maintenance and for response to operating emergencies. When determining the placement of valves for sectionalising the pipeline, consideration will be given to locations that provide continuous accessibility to the valves.

ISO 13623 does not give guidance on the maximum valve spacing, while CSA Z662 poses specific requirements for the spacing of isolation valves, depending on the Location Classification.

As specified by CSA Z662, the isolation valve spacing shall be considered at 15km for the transportation of CO2. It is noteworthy that this distance is smaller compared to the 25 km that is applied in Natural Gas pipelines in Greece and Internationally.

3.4.2 Valve Station Configuration

Block Valve Stations shall consist of, but not be limited to, the following:

- Main buried block valve, with electric actuator installed above ground;
- Bypass line with valve to assist in the equalization on pressure each side of the main block valve to allow it to be operated under minimum differential pressure;
- Buried isolation valves on each tee for the bypass line to allow maintenance of the bypass valve;
- Buried Vent line with valve to a vent stack;
- Vent valve by-passes with orifices
- Above ground connections for the temporary installation of a mobile compressor;
- Connections for pressure transmitters on either side of the bypass line.

Temperature gauges will be foreseen on both sides of the bypass valve to monitor the arrival temperature of the CO2 from the upstream pipeline section and enable checking the temperature drop when filling the downstream side. Temperatures upstream and downstream the main valve are also transmitted to the control centers.

Pressure will also be monitored (via pressure gauges and pressure transmitters on both sides of the bypass valve.

4 Flow Management and Thermal Stability

As already discussed, CO2 phase stability is very sensitive to pressure and temperature variations. The condition becomes even more complicated if significant amounts of contaminants especially water are present in the pipeline. In the project under examination the CO2 composition has been considered to cover the “Northen Lights” impurity limits as shown in table 2 below:

Table 2. Northen Lights composition - impurities

Component	Concentration, ppm
Water (H2O)	≤ 30
Oxygen (O2)	≤ 10
Sulphur oxides (SOx)	≤ 10
Nitric oxide/Nitrogen dioxide (NOx)	≤ 10
Hydrogen sulphide (H2S)	≤ 9
Carbon monoxide (CO)	≤ 100
Amine	≤ 10
Ammonia (NH3)	≤ 10
Hydrogen (H2)	≤ 50
Formaldehyde	≤ 20
Acetaldehyde	≤ 20
Mercury (Hg)	≤ 0.03
Cadmium (Cd), Thallium, (TI)	Sum ≤ 0.03

It remains to be verified whether these impurities levels can be consistently achieved during CO2 capture from the emitters.

For a CO2 stream composition containing overwhelmingly carbon dioxide, Peng-Robinson (PR) equation of state (EoS) is considered to provide sufficient accuracy as per DNV’s Recommended

Practice [6] and the most recent literature available. Therefore, this EoS has been used for the hydraulic calculations in the project under examination. Based on DNV, for CO2 mixtures containing significant levels of impurities, the applied EoS should ideally be tuned using experimental data. As a minimum the EoS should be verified against experimental data to assess the level of inaccuracy of the calculations.

The pressure/temperature envelopes obtained from hydraulic analyses are compared against the CO2 phase envelope and hydrate curve to demonstrate whether the system operates in the hydrate formation region. The rapid reduction in temperature is influenced by the heat exchanged with the pipeline environment (soil or sea temperature), frictional pressure drops, and the elevation profile of the pipeline, making it a complex issue to be resolved. Additionally for pipelines that collect CO2 emissions from various emitters the CO2 pressure and temperature conditions can change significantly when one or more of the emitters are closed for maintenance.

The following solutions may mitigate these temperature related issues:

- Heaters: The installation of heaters at strategic points along the route provides additional controllability of gas temperature, thus avoiding liquid drop-out and hydrate formation issues.
- Insulation Coatings: Insulation coatings are used for CO2 pipelines, particularly in applications where CO2 is transported over long distances from emission sources to storage sites. Figure 2 below shows a typical application of heating insulation for CO2 pipelines.

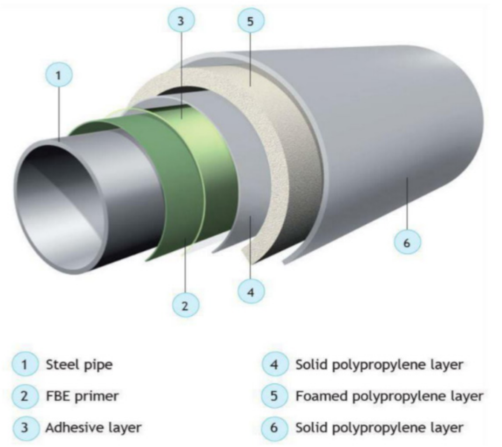

Fig. 2. Typical configuration of coating for CO2 pipelines.

Internal flow coatings are typically applied for enhancement of the flow rate. For a long-distance transmission pipeline, the application of internal flow coating is critical to enhance the flow rate. Flow improvement reduces friction in the pipe allowing an increase in the flow rate or a reduction in compressor discharge pressure (and thus fuel consumption) for the same flow rate.

Other advantages of flow coating are observed in the construction phase as internal coating prevents the accumulation of mill scale and rust, which occurs on steel line pipe and increases during the storage of the pipe.

CO2 streams, usually containing impurities, such as sulphur, water, etc, can cause blistering at the coating-steel interface. Internal coatings are not currently mature enough for feasible anticorrosion protection in CO2 pipelines. Therefore, no internal lining is considered in the initial stages of the project.

5 Pipeline Routing Safety and Environmental Concerns

Due to the relatively shorter industry experience of CO2 pipelines (compared to established technologies such as natural gas pipeline transport), the challenges related to the long-term management, surveillance, upkeep, and repair of these novel pipelines display some uncertainty and are currently studied. The safety record for CO2 pipelines cannot be definitively compared to that of oil and gas pipelines, as CO2 pipelines have been in operation for a shorter time and cover significantly smaller distances. As a result, evaluations of CO2 pipeline safety have not been able to determine if their safety performance would match that of oil and gas pipelines [12]

5.1 SAFETY CONSIDERATIONS & CHALLENGES

Conversely to the case of natural gas pipelines, the risk of fire or explosion is not present for CO2 pipelines. However, in case of Loss of Containment (LOC), CO2 may introduce health and safety hazards at certain concentrations. The accidental release of large inventories can pose an asphyxiation risk to human and other biologic life forms that needs to be assessed and mitigated. Inhaling CO2 at relatively low concentrations can pose a risk to human health. Exposure to CO2 levels exceeding 7% (or 70,000 ppm) poses a substantial toxicological hazard, while concentrations required for immediate lethal danger are 50% for asphyxiation and 15% for toxicological damage from inhalation. The asphyxiation hazards and disaster potential of CO2 releases have been documented in historical events (e.g., the lake Nyos gas disaster of 1986, in which a sudden and catastrophic natural release of large quantities of carbon dioxide asphyxiated over 1,700 people and countless animals living in the area [12]. In the coming years, the development of additional CCS projects might require CO2 pipelines to cross densely populated areas necessitating an accurate and dedicated risk assessment. When transporting CO2 via pipelines through populated areas, careful consideration must be given to the selection of the pipeline route, protection against overpressure, detection of leaks, and additional design considerations [14]

Figure 3 presents a visualization of a CO2 release from a pipeline. The release can be categorized into two distinct zones: the near-field, which encompasses phase change, expansion, air-mixing, and solid formation; and the far-field zone, characterized by the continued atmospheric dispersion of the CO_2 cloud over extensive distances. Understanding the dispersion behavior of carbon dioxide in the event of a release is important in determining the safe distance of pipelines and for risk assessment. This is commonly achieved by the application of gas dispersion models and/or Computational Fluid Dynamics (CFD) simulations.

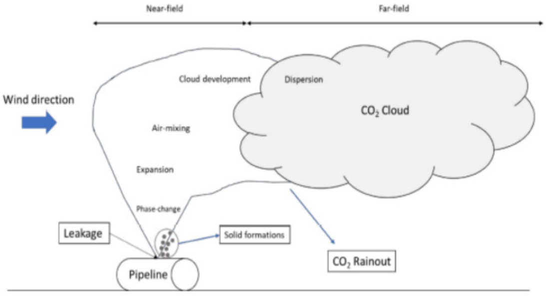

Fig. 3. Visualisation of CO2 release from a pipeline.

In addressing the critical importance of safety in CO2 pipeline operations, it is essential to delve into the specific challenges that underscore the need for rigorous safety protocols. Among these challenges, corrosion, fracture toughness of steels and the presence of impurities represent key areas that demand close attention. These factors are not isolated concerns but are interconnected issues that can significantly impact the integrity and reliability of CO2 pipeline systems.

5.1.1 Impurities

Flue gas, a byproduct of burning fossil fuels, primarily consists of nitrogen (N2), carbon dioxide (CO2), water vapor (H2O), and oxygen (O2), the latter due to the surplus air present in the combustion process. Among the impurities, nitrogen compounds are prevalent, particularly in the form of nitrogen oxides (NO and NO2), collectively referred to as NOx. Other common impurities include sulphur oxides (SO2 and SO3), known as SOx, and hydrogen sulphide (H2S). Therefore, when isolating the CO2 stream from the emissions of industrial facilities, the expected contaminants may include NOx, SOx, H2O, O2 and H2S depending on the fuel used.

It's important to note that these impurities can pose challenges in carbon capture and storage (CCS) technologies, requiring purification processes to ensure the CO2 is adequately purified before sequestration or utilization, to mitigate the various operational, safety or environmental issues that may be caused, such as pipeline corrosion. It is also important to note that to understand the impurities in the CO2 streams, the technology applied for CO2 capture or separation needs to be considered, as the expected impurities are different among the various technologies. ISO 27913 [6] recommends specific levels of impurities for pipelines transporting CO2 as shown in table 3.

The presence of free water within the CO2 stream is regarded as the impurity with the highest adverse effects. The existence of water in the system can lead to the formation of ice or gas hydrates, which may obstruct the flow, leading to potential safety issues. It also presents the potential to react with most of the acidic gas impurities. Additionally, a correlation has been demonstrated between the moisture content in the CO2 stream and the corrosion rate of the CO2 transport pipeline interior wall. It is typically necessary to minimize the water content not only to decrease the risk of corrosion but also to avert issues related to gas hydrates. This preventive measure is crucial for maintaining the integrity and smooth operation of the pipeline infrastructure.

Table 3. Recommended levels of impurities for CO2 transport via pipeline according to ISO 27913:2016

Component	Indicative levels
Water (H2O)	Corrosion, 20 to 630 ppmv, Hydrate, <200 ppmv
Oxygen (O2)	<4 % total for all non-condensable gasses, Downstream limitations
Sulphur oxides (SOx)	<100 ppmv – Health and Safety
Nitric oxide/Nitrogen dioxide (NOx)	<50 ppmv - Corrosion
Hydrogen sulphide (H2S)	<200 ppmv
Carbon monoxide (CO)	<0,2 mol
O2	<4 % total for all non-condensable gasses, Downstream limitations
CH4	
Hydrogen (H2)	<0,75 mol%
Amine	The presence of these and other water-soluble components will facilitate the formation of an aqueous phase (free water) and reduce the concentration of water in the CO2 at which a separate aqueous phase is formed. The maximum concentrations that are acceptable will depend on the concentration of the other impurities
Methanol	
Ethanol	
Glycol	

5.1.2 Corrosion

It has been established that CO2 without other impurities and water, well below the saturation limit, is non-corrosive to carbon steel at transportation pipeline operation conditions. In case of inadequate dehydration in a case of a steel pipeline transporting CO2, the internal corrosion poses a substantial threat to the structural integrity of the pipeline. The combination of free water and elevated CO2 partial pressure can lead to accelerated corrosion, mainly because of carbonic acid (H2C03) formation. At present, the industry lacks dependable models that can precisely predict corrosion rates under conditions of high CO2 partial pressure and the presence of free water.

However, research is actively being conducted to improve the understanding and predictive capabilities in this domain.

In the process of corrosion, water serves multiple roles: it can function as an electrolyte, a solvent, and a reactant for gases dissolved in it, including CO2, O2, and SO2. Oxygen (O2) plays a crucial rôle in corrosion processes, as it facilitates various cathodic reactions that allow corrosion to advance.

If present, additional impurities such as H2S, SO3 and NO3 will also segregate to the aqueous phase and thus may decrease the solution pH further, via the in situ formation of sulphuric and nitric acids(in addition to the existing carbonic acid). This presence of a second acidic aqueous phase can significantly increase the corrosion rate of pipeline steels.

5.1.3 Steel Toughness

Due to the decompression characteristics of CO2, pipelines transporting CO2 might be more prone to brittle fractures compared to those carrying hydrocarbon gases. To mitigate long fractures in CO2 pipelines, strategies include specifying a line pipe steel with sufficient toughness to ensure that the arrest pressure exceeds the saturation pressure or employing mechanical crack arrestors. Opting for control via steel toughness is favored as it guarantees shorter lengths of fractures, although several CO2 pipelines in the US have been equipped with crack arrestors at regular intervals, due to unavailability of higher pipeline toughness capabilities [15]

Pipeline propagating fractures in CO2 transport can happen through brittle or ductile failure modes. Brittle failures can unzip a pipeline at speeds nearing sound's velocity in metal (400+ m/s) at considerable distances (hundreds of thousands of meters). Ductile failures, while slower, also lead to significant material release if the crack propagation surpasses the depressurization rate.

It is important to note that impurities, including hydrogen and methane, profoundly influence the decompression properties of CO2, raising its 'saturation pressure'. Consequently, the presence of such impurities necessitates a greater toughness level for effectively arresting fractures than would be required for pure CO2 [16].

5.2 Mitigation Measures

During engineering design phases, Safety in Design practices aim in eliminating foreseeable risks of an accident, like loss of containment of a pipeline. However, it is documented that such incidents may still occur. Then, plant designs must incorporate additional appropriate features in order to minimize the resulting damage. Therefore, Emergency Isolation Valves are necessary to be installed at proper places on the pipeline, in order to rapidly stop the uncontrolled release of toxic CO2 gas. As mentioned in §3.4.1of this paper valves should be installed at a maximum distance of 15 km between each other. However, in order to reduce the pipeline inventory to be released, especially when the pipeline is routed near a densely populated area, valves should be installed at a closer distance. Additional safety measures that have been considered during routing selection in the project under examination include a minimum distance of at least 300m from residential areas.

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