An evaluation of key challenges of CO₂ transportation with a novel Subsea Shuttle Tanker

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Abstract. Recently, a novel Subsea Shuttle Tanker (SST) concept has been proposed to transport carbon dioxide (CO₂) from ports to offshore oil and gas fields for either permanent storage or enhanced oil recovery (EOR). SST is a large autonomous underwater vehicle that travels at a constant water depth away from waves. SST has some key advantages over subsea pipelines and tanker ships when employed at marginal fields. It enables carbon storage in marginal fields which do not have sufficient volumes to justify pipelines. Further, in contrast to ships, SST does not require the use of a permanently installed riser base. This paper will evaluate the key challenges of using such vessel for CO₂ transportation. It discusses the most important properties such as thermodynamic properties, purity, and hydrate formation of CO₂ at different vessel-transportation states in relation to cargo sizing, material selection, and energy consumption.

Keywords: Subsea Shuttle Tanker; Carbon Capture and Storage; CO₂ Transportation

1. Introduction

The most critical agreement adopted in Conference of the Parties 2021 (COP 21) is a legally binding international treaty on climate changes to control the global mean temperature increase within 2 °C above pre-industrial levels by limiting this value to 1.5 °C before mid-century [1]. To achieve this target, tremendous effort from all parties is required. The Intergovernmental Panel on Climate Change (IPCC) indicates that the global CO₂ emission should be reduced by 50 - 85% from 2000’s 28.2 Gt/yr level [2]. However, the world is slipping further away from the target. Tollefson [3] reports that the annual emission has grown in 2019 to 35.9 Gt/yr, though there is a slight reduction in 2020 (33.6 Gt/yr) due to the lower economic activity related to the Covid pandemic.

Carbon Capture and Storage (CCS) is one of many approaches to mitigate climate change. It enables the reduction of CO₂ emission from fossil fuels which will in the foreseeable future still contribute substantially to the global energy mix as this is required to preserve our current way of living [4]. In the CCS process, CO₂ is captured at various sources, processed, and then transported to selected storage sites. It is finally injected into the reservoir for Enhanced Oil Recovery (EOR) [4] or permanent storage [5]. During the transportation, different tools are used depending on the EOR/storage location. CO₂ can be transported by pipelines, trucks, and railway if the geological formation for storage is onshore. Subsea pipelines and ships can be used for transportation of CO₂ to be injected at offshore fields.

Recently, a novel Subsea Shuttle Tanker (SST) concept was proposed to be an alternative to pipelines and tanker ships for offshore CO₂ transportation [6]. It aims to be an enabler for the CCS utilisation of marginal field. It has some key advantages over the above-mentioned conventional methods. First, it...
can be applied to small fields without sufficient CO2 storage capacities to economically justify subsea pipeline installation. Second, in contrast to tanker ships, SST does not require the use of a permanently installed riser base [7]. Third, SST operates underwater and is not exposed to wind and waves, i.e., it is weather-independent. Fourth, SST travels at a slow speed to minimise drag resistance and consequently it has a low energy consumption, i.e., lower carbon footprint compared to pipelines and ships [6]. Last, the SST is designed to be fully autonomous. This increases safety and reduces marine operations costs when compared to a conventionally manned vessel.

Using SSTs for CO2 transportation was first proposed by Equinor in two research disclosures [8][9]. Xing et al. [7] went on to discuss the most important design considerations of an SST system for liquid CO2 transportation. Recently, a 164 m SST conceptual baseline design was developed by University of Stavanger (UiS) and presented in Ma et al. [6] (illustrated in Figure 1). In Xing et al. [7] and Ma et al. [6], discussions on design issues related to the CO2 transportation aspect of SST were made. This paper continues these discussions by performing an initial evaluation of key challenges faced by UiS SST such as CO2 thermodynamic properties, CO2 purity, cargo tanks sizing, material selection, energy consumption, and CO2 hydrate formation. The objective of this paper is to provide insights on managing and reducing the high levels of uncertainties associated with the CO2 transportation aspect of SST.

Figure 1. The UiS baseline SST.

2. CO2 properties

2.1. Thermodynamic properties
The purity or quality of the CO2 has critical impact on the cargo tank design of the SST since impurities can cause erosion and increase the risk of hydrate formation. This property is largely affected by the thermodynamic properties which can be shown via a phase diagram as presented in Figure 2. Depending on the pressure and temperature combination, CO2 can exist in four phases: solid phase, liquid phase, vapor phase, and supercritical phase. The triple point (5.1 bar, 56 °C) is where CO2 exists simultaneously in vapor, liquid, and solid phase. CO2 turns into supercritical phase when the pressure and temperature increase beyond the critical point (74 bar, 32 °C).
As presented in Figure 2, the state of CO₂ varies between different transportation methods. Pipelines transport CO₂ in a high-pressure, high-temperature supercritical phase. In contrast, ships carry CO₂ as a saturated liquid. In this condition, CO₂ is constantly boiling and as a result, the pressure and temperature will be naturally maintained at a setpoint. Such cargo may be carried under one of the three states along the saturation line: refrigerated state (7 bar, -55 °C), semi-refrigerated state (15 bar, -30 °C), or pressurised state (45 bar, 10 °C) [10][11]. The selection of the transportation state depends on the vessel size. Larger vessels such as Very Large Gas Carriers (VLGC) can transport CO₂ liquid at a refrigerated state since the design and construction cost of large pressure vessels with high pressure capacities is uneconomical. Therefore, refrigeration is used for very large CO₂ carriers with capacities over 20,000 m³ [12]. For smaller ships around 10,000 m³ capacity, semi-refrigeration is more attractive. Since the scale of current offshore CCS projects are not very large, many CO₂ carriers are designed to transport semi-refrigerated CO₂, e.g., the Northern Light project CO₂ carrier [13] and Kokubun’s CO₂ carrier [10]. The UiS SST [6] transports CO₂ as a pressurised liquid which means CO₂ can be transported at an intermediate-temperature and high-pressure state (10 - 30 °C, > 80 bar) (data from [13][14]).

The main processes in CO₂ transportation are presented in Figure 3. It envisioned that transporting CO₂ in refrigerated, semi-refrigerated, and pressurised states provide different challenges to SST. In the refrigerated and semi-refrigerated states, liquefaction and heating systems are required to transport CO₂ at a low temperature at the port and offloading destination, respectively. During the offloading at the wellhead, inter-heaters and compressors are required to bring the temperature from sub -20 °C to above 10 °C and boost the pressure from approximately 10 bar to above 80 bar. In this process, boil-off gas is generated and must be re-captured using re-liquefaction systems. On the contrary, transporting CO₂ as a pressurised liquid (UiS SST) is more cost- and energy-efficient. At the port, CO₂ does not need to be conditioned before loading. Further, since the saturated liquid CO₂ can passively regulate its pressure and temperature with the environment, no cost-intensive re-liquefaction system is needed. At the wellhead, the liquid CO₂ which is at approximately 40 - 60 bars can also be injected directly using a single stage booster pump into the reservoir [6].
2.2. CO₂ Impurities

Fossil fuel combustion is the dominant human-activity-related CO₂ source. It contributes 92.4% of the total CO₂ emission in the US in 2008 [15]. Within this, electricity generation and transportation accounts for 34.5% and 32.6% of the total emission, respectively. The other main components apart from CO₂ include N₂, H₂O, and O₂ [4]. Besides, sulphur oxides SOₓ, hydrogen sulphide (H₂S), and nitrogen oxides NOₓ are also very common contents in typical carbon sources like coal-fired power plants [16]. The amounts and types of contaminants in the captured CO₂ vary significantly with the carbon source as well as capture and separation technology [4]. As an example, Figure 4 presents the purities of the captured CO₂ from three different combustion methods. Table 1 shows the CO₂ impurity limits in several CCS projects together with SST’s design limits. It lists the reference values provided from the projects Northern Lights [13], Dynamis, Schwarze Pumpe Oxyfuel pilot [17], and a cement plant from ICF International [15]. It is common to have a purity level above 95%; in Northern Lights, Schwarze Pumpe, and ICF, the CO₂ concentration is higher than 99.9%. However, these high purity levels may not be necessary for most transportation, storage, or EOR purposes. The purity levels can be optimised to reduce the energy consumption and purification cost [17]. Therefore, it is attractive to identify an optimal purity level required for SST. On the other hand, a high level of impurity in liquid CO₂ can lead to higher pressure requirements applied on the cargo tanks to avoid the risk for hydrate formation and corrosion. Besides, impurities also constitute volume and affect the compressibility of CO₂ which reduces cargo tank carrying capacities [7].

2.2.1. Free water. The most undesirable impurity in liquid CO₂ is free water (H₂O). Free water causes hydrate formation and can under suitable environments lead to corrosion since it easily reacts with majority of acid gas components. Figure 5 presents the study from Visser et al. [20] which documented the solubility of water in CO₂ in different pressures and temperatures. The solubility of water in CO₂ is low at low pressures and temperatures. This indicates that transporting CO₂ in refrigerated or semi-refrigerated condition would place higher requirements on the purity level, since less H₂O can dissolve in CO₂ and more of free H₂O would appear. In contrast, the SST transports CO₂ liquid in pressurised conditions which have CO₂ solubilities higher than 2000 ppm. In the authors’ knowledge, the value of 2000 ppm is higher than the requirements defined in many CCS projects including the ones presented in Table 1. This means no free H₂O would appear if the SST is utilised on these projects.
Figure 4. Expected levels of impurities from different CCS methods [4].

Table 1. CO₂ impurity levels in different projects.

| Component               | North Lights (Various sources) | Dynamis (Hydrogen production) | Schwarze (PowerICF plant) | UiS SST |
|-------------------------|---------------------------------|-------------------------------|--------------------------|---------|
| Carbon dioxide, CO₂     | >99.9%                          | >95.5%                        | >99.9%                   | 99.8%   | >95.5% |
| Water, H₂O              | 30 ppm                          | 500 ppm                       | <5 ppmv                  | 640 ppmv | 500 ppm |
| Sulphur oxides, SO₂     | 10 ppm                          | 100 ppm                       | 1.3 ppmv                 | <0.1 ppmv | 100 ppm |
| Nitrogen oxides, NO₂    | 10 ppm                          | 100 ppm                       | 3-10 ppmv                | 0.86 ppmv | 100 ppm |
| Hydrogen sulphide, H₂S  | 9 ppm                           | 200 ppm                       | -                        | -       | 200 ppm |
| Carbon monoxide, CO      | 100 ppm                         | 200 ppm                       | <2 ppmv                  | 1.2 ppmv | 200 ppm |
| Oxygen, O₂              | 10 ppm                          | Aquifer <4 vol% EOR 100-1000 ppm | <0.001 vol%             | 35 ppmv  | Aquifer <4 vol% EOR 100-1000 ppm |
| CH₄                     | -                               | Aquifer <4 vol% EOR <2 vol%   | -                        | 0.026 ppmv | Aquifer <4 vol% EOR <2 vol% |
| Amines, RNH₃            | 10 ppm                          | non-considerable gases <4 vol% | -                        | -       | non-considerable gases <4 vol% |
| Ammonia, NH₃            | 10 ppm                          | -                             | -                        | -       | - |
| Hydrogen, H₂            | 50 ppm                          | -                             | -                        | -       | - |
| Formaldehyde, HCHO      | 20 ppm                          | -                             | -                        | -       | - |
| Acetaldehyde, CH₃CHO    | 20 ppm                          | -                             | -                        | -       | - |
| Dinitrogen & Argon, N₂ & Ar | -                        | -                             | <0.01 vol%              | 904 ppmv | - |
2.2.2. SO\textsubscript{x} and NO\textsubscript{x}. Projects like Dynamis placed limits on these gases as they are toxic to humans. It is postulated that no limits on these gases are required for SST as it is an unmanned vessel. However, more detailed investigations in this are required as SO\textsubscript{2} and NO\textsubscript{2} may cause negative effect on water solubility and therefore can increase the risk of hydrate formation. This was shown in a study performed by Ahmad and Gersen [21]. However, this study was performed at pressures of 90 - 120 bar and temperatures of 10 - 45 °C which are outside of SST’s operating region.

2.2.3. Other impurities. The SST places limits other impurities like CH\textsubscript{4}, N\textsubscript{2}, and amines to mitigate hydrate formation since these impurities reduce the solubility of H\textsubscript{2}O [22].

3. Cargo tank design

3.1. Sizing

Current CO\textsubscript{2} carriers transport liquid CO\textsubscript{2} in the semi-refrigerated state [10][12][13][23][24][25]. This results in lower pressures of about 6 to 22 bar at -50 to -15 °C and allows the use of large cargo tanks of up to volumes of 4000 m\textsuperscript{3}. For example, Northern Lights project [13] uses a 7500 m\textsuperscript{3} gas carrier with two 3750 m\textsuperscript{3} type-C storage tanks. This is also similar for LPG carriers that transport semi-frigerated LPG. For example, the typical size range for a type-C LPG tank is between 4000 m\textsuperscript{3} to 22,000 m\textsuperscript{3} [26]. No VLGCs are yet used for refrigerated CO\textsubscript{2} transportation, but they have been utilised for LNG. LNG carriers carry refrigerated LNG at 1 to 2 bars at -165 °C and utilise cargo tanks of volumes up to 20,000 m\textsuperscript{3}.

The SST transports liquid CO\textsubscript{2} at environmental temperature which leads to higher pressures of 40 to 60 bars and therefore requires a more demanding burst pressure design. For thin-walled cylinder-shaped pressure vessels, the burst failure is dominated by the yielding of the material. Following Barlow’s formula, the internal pressure that a thin-walled cylinder-shaped pressure vessel can withstand is calculated as 

\[ p = \frac{2\cdot SF\cdot \sigma_y}{t/D_o} \]

where \( \sigma_y \) is the yield stress, \( t \) is the wall thickness, \( D_o \) is the external diameter of the cylinder, and \( SF \) is the safety factor. Xing et al. [8] used this method to estimate the internal pressure capacity of the SST cargo tanks when stainless steel 304 (yield strength \( \sigma_y = 207 \) MPa) is applied. A safety factor \( SF = 0.72 \) is used. The results, i.e., internal pressure capacities are presented in Table 2 for different vessel diameters and wall thicknesses. As observed in Table 2, the \( W/V \) ratios
are the same for all cases. This is because $W/L$ and $V/L$ are directional proportional to $(\text{diameter})^2$. This means designing larger cargo tanks does not save structural weight or increase cargo capacity. However, the bending and welding of thicker plates can be more complex. For this reason, the UiS SST uses several smaller tanks instead of a single large tank. Seven 5 m diameter main cargo tanks and six 2.5 m diameter auxiliary cargo tanks are used. The volumes are 1931 m$^3$ and 483 m$^3$, respectively which are much smaller than the semi-refrigerated cargo tanks discussed above. However, the cargo weight still constitutes a large portion (53%) of the SST’s total weight [6]. For reference, surface tanker ships have about 80% [7].

| Diameter (m) | Wall thickness (mm) | Internal pressure capacity (bar) | Weight/length, $W/L$ (kg/m) | Cargo volume/length, $V/L$ (m$^3$/m) | Ratio, $W/V$ |
|--------------|---------------------|---------------------------------|-----------------------------|-----------------------------------|------------|
| 0.5          | 7.5                 | 45                              | 92                          | 0.20                              | 471.02     |
| 1            | 15.1                | 45                              | 370                         | 0.79                              | 471.02     |
| 1.5          | 22.6                | 45                              | 832                         | 1.77                              | 471.02     |
| 2.5          | 37.7                | 45                              | 2312                        | 4.91                              | 471.02     |
| 5            | 75.5                | 45                              | 9248                        | 49.64                             | 471.02     |
| 10           | 151.0               | 45                              | 36,993                      | 78.54                             | 471.02     |
| 15           | 226.4               | 45                              | 83,235                      | 176.71                            | 471.02     |

3.2. Material selection

The UiS SST transports CO$_2$ at environmental temperatures which allows the use of highly weldable carbon steels which have poor brittle fracture properties at low temperatures. UiS SST uses SA-738 Grade B which is a high strength carbon steel broadly applied on welded pressure vessels subjected to moderate or low temperatures [6]. In contrast, due to the low service temperatures experienced by LNG and LPG carriers, DNV recommends the use of fine-grained carbon-manganese structural steels and nickel alloy steels [27]. Higher manganese and nickel content allow a lower design temperature. For semi-refrigerated CO$_2$ tanks, DNV grade VL 4-4 is a suitable candidate. It has a manganese content between 0.7-1.6%. This steel also has a high tensile strength between 490 and 610 MPa. This avoids the heavy structural design with thick plates. However, the lowest design temperature for carbon-manganese steels is -55 °C. This barely satisfies the fully refrigerated condition. When the temperature is below such value, nickel alloy steels are used. High nickel alloy steels are used in the refrigerated transportations as these steels have excellent strength and toughness at low temperature in both base metal and welding joints [28]. One potential candidate for fully refrigerated cargo tanks is VL 2.25Ni (-65 °C design temperature). These materials are more expensive and complex to weld compared to the carbon steel used in UiS SST.

4. SST operation

4.1. Energy consumption

In a typical CO$_2$ transportation by vessels, the energy consumption can be divided into three categories, (i) cargo processing, (ii) propulsion and (iii) pumping. The energy consumption related to cargo processing includes liquefaction and cargo conditioning. The energy required for this is significant. This is because the boil-off gas liquefaction process requires multi-stage cooling and compression. However, since the UiS SST transport CO$_2$ in environmental conditions, it does not require any cargo processing. This means a huge amount of energy is saved. For example, Aspelund et. al. [23] conducted concept analysis for transporting CO$_2$ with a fully refrigerated 20,000 m$^3$ vessel, the specific energy consumption of ship transportation is 25 kWh/tonne CO$_2$ for a 1500 km round trip. As comparison,
energy consumption for using UiS SST for the same distance is listed as Table 3. The propulsion energy costs for UiS SST are calculated to be 289 kw at 6 knots speed and account for 40,139 kwh for 1500 km. The pumping energy consumption comes from the cargo and ballast pumps used during the loading and offloading process and is calculated to be 3900 kWh per trip [6]. As observed, the UiS SST transportation energy consumption is nearly 90% lower than the reference surface ship.

Table 3. SST energy consumption and comparison with ships.

| Transportation method | SST environmental temperature [6] at -52 °C [23] |
|-----------------------|-----------------------------------------------|
| Propulsion            | 40,139 kWh                                    |
| Pumping               | 3900 kWh                                      |
| Other hotel loads     | 4861 kWh                                      |
| Total energy consumption | 48,900 kWh                                  |
| Specific energy       | 3.19 kWh/tonne 25 kWh/tonne                  |

4.2. Hydrate formation

Hydrate formation in the cargo tanks should be carefully avoided. Operating the SST inside the hydrate formation zone may cause blockage and sealing issues in some of the critical systems [7], such as piping and seals. Figure 6 presents the hydrate phase equilibrium points of pure CO₂. As presented, hydrate formation is easier formed at very low temperatures of -40 to 0 °C. Therefore, transporting with refrigeration requires CO₂ liquid to be properly dried. On the contrary, when CO₂ is transported at environmental temperature (>8 °C), hydrate formation is unlikely to appear.

![Figure 6](image_url)  
**Figure 6** Hydrate formation zone of CO₂ and transportation states [29].
5. Conclusion

CO₂ may be transported by the SST as a saturated liquid under one of the 3 states: Refrigerated state (6 bar, -50 °C), semi-refrigerated state (22 bar, -10 °C), or pressurised state (45 bar, 10 °C). This evaluation discussed CO₂’s key properties during transportation and SST operation, such as thermodynamic properties, purity captured from the source facility, and hydrate formation. This paper found that transporting CO₂ under pressurised state at room temperature has a number of advantages. First, it can reduce energy consumption significantly by avoiding liquefaction requirements. Second, using carbon steels can reduce the complexity of cargo tank welding and further reduce the manufacturing cost. Third, the solubility of water in CO₂ increases with temperature. Therefore, the risk of free water and corrosion can be mitigated. Last, the risk of hydrate formation is significantly lower when the CO₂ temperature is above 8 degree and therefore reduce risk of blockage in the piping and pumps. In addition, the authors also identified that there are still knowledge gaps to be bridged by future research such as the actual effects of saturated CO₂ liquid with different purity levels under various pressure and temperature conditions for SST.

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