TRANSPORTATION INFRASTRUCTURE FOR CCS
– EXPERIENCES AND EXPECTED DEVELOPMENT

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Abstract

Commercialization of CO_2 Capture and Storage (CCS) from fossil-fuelled power plants requires an infrastructure for transportation of captured carbon dioxide (CO_2) from the sources of emission to the storage sites. This paper summarizes experiences and critical design criteria for pipeline and ship transportation and identifies and analyses type scenarios based on these modes of transportation. The results show that the transportation costs for a demonstration plant emitting 1Mt/y of CO2 range from 1€/ton to 7€/ton of CO2 depending on storage type and means of transportation. Corresponding figure for a coordinated network scenario of 40 Mt/y of CO2 with offshore storage is around 2€/ton of CO2, a figure which also should be valid for a large large-scale vision of 300 Mt/y of CO2.

Introduction

CO_2 Capture and Storage (CCS), i.e. capture and storage of carbon dioxide (CO_2) emitted from large point sources of emissions, has the potential of a significant and relatively quick response to climate change at reasonable cost. In order to reach widespread commercialization of CCS it is crucial to demonstrate the concept in large-scale projects, reduce costs, build infrastructures for transportation of CO2, establish a legal framework and reach acceptance by the public. Most research on CCS deals with capture technologies and storage possibilities (e.g. in connection to Enhanced Oil Recovery (EOR) projects and in saline aquifers). This, since capture represents the highest cost and storage is critical with respect to long-time security and monitoring. Still, there is a need to identify and structure transportation alternatives in order to analyse and evaluate future paths comprising CCS. In a previous work on transportation of CO2 [1] the costs and capacities have been investigated by means of analysing type scenarios for different means of transportation, i.e. truck, train, ship and pipeline. It was concluded that transportation by means of pipeline and ship gave feasible logistics and costs. Still, there were large variations in costs depending on the scenario studied (amount of CO2 transported). The present paper continues the previous work with the aim to illustrate how a CCS transportation infrastructure can be developed applying pipeline and ship transportation.

Pipeline transportation

Previous Experiences

CO2 pipelines have been in use since the early 1970s in the Enhanced Oil Recovery (EOR) industry. The first CO2 pipeline construction was completed in 1972 when the Canyon Reef Carriers (CRC) built a 354 km CO2 pipeline to the SACROC oilfield in Texas, USA. The largest existing CO2 pipeline is the 808 km long Cortez pipeline from Cortez in Colorado to Denver City in Texas, which was put into operation in 1984. The Cortez pipe line is made of API 5LX-65 carbon steel with a diameter of 762 mm [2], delivers about 20 Mt of CO2 per year to the CO2 hub in Denver and constitutes an important part of the CO2 infrastructure that delivers CO2 to the oilfields in Texas. Examples on other CO2 pipelines in use are the 330 km long Weyburn pipeline, the 648-km long Sheep Mountain pipeline and the 338-km long Bravo pipeline.

Design of a CO2 pipeline

Existing large-scale CO2 pipelines are all designed for dense phase/supercritical conditions, i.e. a CO2 pressure above 7.38 MPa. This gives a high density compared to gas transmission and material requirements for cryogenic conditions and frost heave are avoided. When using CO2 for EOR the miscibility pressure of CO2 in oil becomes important. The miscibility pressure of CO2 in oil is usually above 8.3 MPa and often as high as 16-20 MPa and the delivery pressure of the CO2 at the injection site is therefore often set at a relatively high level, i.e. a CO2 pressure above 10 MPa. To maintain the CO2 at this condition, typical operational intervals for temperature and pressure of the CO2 are 15-30ºC and 10-15 MPa, respectively [3]. However, due to the special properties of CO2 it is not easy to maintain the CO2 within such intervals. Pipelines suffer from pressure drops and to maintain the pressure between 10-15 MPa, recompression stations must be installed along the route. Further, the compressibility and density of CO2 show strong, nonlinear dependence on the pressure and temperature, which make it difficult to fully predict the CO2 flow. At the critical point of CO2 (7.38 MPa and 31ºC) a small change in temperature or pressure yields a large change in density, e.g. the density doubles with a change in temperature from 47 to 37ºC at a constant pressure of 9.0 MPa. Thus, due to that the flow behaviour for CO2 is complicated to predict, the calculations of the hydraulic characteristics for pipeline transportation of CO2 is important.

Small amounts of impurities also affect the properties of CO2, e.g. small additions of methane (CH4) affect the vapour pressure of CO2 [5]. Other impurities which normally occur are H2S, C2, N2 and water (H2O), which all change the CO2 properties and therefore need to be reduced to levels that can be handled. Among these impurities, water is most critical since CO2 in equilibrium with liquid water form an acid gas that causes so called sweet corrosion, and that CO2 in presence of water form hydrates (solid ice-like crystals), which can plug equipment and flow lines, fouling heat exchangers etc [6]. These problems make it necessary to dehydrate the CO2 to low water contents. The maximum allowable water content in the CO2 flow is typically 0.4×10-3 kg/m3n [5], although this figure depends on the amount of other impurities. Thus, it is recommended that the allowable water content at the proposed operating conditions is determined experimentally [6]. If possible, a common standard for levels of impurities in the CO2 fluid should be established.

The other main impurity that must be considered in EOR projects is H2S. This, since H2S is dangerous to life at concentrations as low as 300 ppm. In existing CO2 pipelines, the H2S concentration has been limited to less than 100 ppm in the CO2 flow [4].

Ship transportation

Experiences

Transportation of commodities by ship has always been very cost-effective due to the large loading capacity. Experiences of large-scale ship transportation of CO2 are limited with previous applications mainly found in the food and brewery industry with amounts transported in the range of some 100,000 tons of CO_2 annually, i.e. much smaller quantities than the amounts associated with CCS [1]. Since the transportation conditions for CO2 show similarities with Liquefied Petroleum Gas (LPG) [8], which is transported by ship at a relatively large scale, experiences and design criterion for LPG shipping can be used in the establishment of a large-scale CO2-transportation infrastructure.

Ship transportation

Existing CO2 ships are designed for transporting CO2 in the liquid phase at a pressure between 1.4 to 1.7 MPa and at a temperature interval of -25°C to -30°C [9]. The liquid phase gives a high density of the CO2, i.e. 1100 kg/m3, but due to the high pressure, the tanker size and thereby the capacity for existing CO2 ships is relatively low, i.e. between 850-1,400 tons of CO2. This capacity is too small to effectively transport the amounts of CO2 that is associated with CCS. For LPG, there are three types of ship design: low temperature type, which is designed to keep LPG liquid at a low temperature and atmospheric pressure, the pressure type which is designed against the boiling point of LPG maintaining the LPG liquid at ambient temperature and, the semi-ref type which is a combination of both, i.e. the ship is both pressurised and cooled. Seen from a bulk-transportation perspective, the low temperature type is preferable due to that this design does not require pressurised tankers. Existing low temperature ships have a capacity of up to 80,000 m3 [10]. This option is, however, not possible for CO2 ships due to that CO2 at atmospheric pressure only can exist in gaseous or solid phase, but not as a liquid. The best option for CO2 for bulk transportation is the semi-ref type design. A standard semi-ref LPG ship has a capacity of 22,000 m3, i.e. 24,000 ton CO2, and is designed for a pressure of 0.7 MPa and a temperature of -50°C. Such a ship should be suitable for CO2 transportation.

Since ship transportation does not allow a continuous flow from source to storage location, the logistics must include appropriate intermediate storage facilities to handle reloading of CO2 (e.g. in harbours). There are two main technologies for intermediate storage of LPG, either underground in great rock and salt caverns, or in large steel tanks above ground. At present only the steel tank technology is used for CO2, but also storage in cavern can be applied. Existing rock caverns for LPG have storage capacities of up to around 500,000 m3 LPG [11], which approximately correspond to 500,000 tons of CO2. Steel tanks have storage capacities up to 3,000 tons of CO2 [9].

Transportation scenarios

Based on the technical criterions for CO2 transportation by pipeline and ship, briefly outlined above, and the scenarios employed in the previous study [1], three scenarios have been further evaluated with respect to costs, capacity, distance, and means of transportation. The scenarios correspond to a small-scale "start-up" case of 1 Mt/y of CO2 (S1-1, S1-2 and S1-3), a large-scale single-source case of 10 Mt/y of CO2 (S2-1, S2-2 and S3-2), and a fully developed and coordinated infrastructure with a capacity of 40 Mt/y (S3-1). Table 1 lists the different scenarios with respect to combinations of transportation modules, transportation distance and capacity. The cost calculations have assumed a depreciation time of 25 years at 5% interest rate. The resulting costs obtained from the scenario calculations are given in Figure 1.

Discussion

Commercialization of CCS will mean that a transportation infrastructure must be developed and built over time. Such a development will, however, mainly depend on the transportation cost, which in turn depends on transportation distance between source and storage site and if coordinated networks are possible to establish. From Figure1 it can be seen that from a cost perspective a short distance is obviously the best option for both large and relatively small power plants (~1 Mt/y of CO2). Short distances may of course not always be an option. In addition, relocation of fossil-fuelled (especially lignite) power plants in order to achieve short transportation distances will probably not occur. Power plants are situated near the fuel reserves and/or electricity consumers in order to minimise freight and transmission costs and it is likely that also new power plants have to be located at such already developed sites. Still, if CCS is employed, there will be three commodities to be considered; CO2, electricity and fuel. The complexity and cost of a CO2 infrastructure are lower than the infrastructure cost of solid-fuel and of electricity transmission. This, since CO2 can be transported at steady-state flow in a pipeline whereas solid-fuel transportation is mostly carried out by railway and electricity transmission suffers from losses.

For a large power station located far from the disposal site, a single pipeline from source to sink could be used. A single network is, however, believed to have an upper capacity limit. This is not because of technical limitations but due to that single storage regions will have upper limits in receiving rate. If several power stations can use a coordinated network, the transportation costs are lowered. From a European perspective, such networks will probably be established offshore to take advantage of early EOR opportunities. A future large-scale vision of 300 Mt/y of CO2 will therefore be built up of several coordinated networks from suitable areas to neighbouring disposal sites, with capacity and infrastructure similar the case represented by scenario S3-1. This also means that the transportation cost per ton of CO2 is expected to be similar to that of S3-1, i.e. about 2 €/ton. Such a coordinated network could also include ship transportation. Ships are more flexible than pipelines when it comes to adaptability of capacity and transportation route, and a transportation system including both ships and pipeline will therefore make the infrastructure more adaptable to variations in the infrastructure of the storage location.

Conclusions

The development of an infrastructure for CO2 transportation is expected to start with a small-scale demonstration plant. For such a case onshore disposal near the CO2 source is the least expensive transportation alternative, with a cost of around 1€/ton of CO2 (S1-1). However, onshore storage may not be an option for a first demonstration project of this size and if so, the present analysis shows that the transportation costs to an offshore storage site would be 7€/ton of CO2 when transported by ship (S1-2). Obviously, coordinated networks must be established in order to bring down the transportation costs to the figures normally mentioned for CCS, i.e. to a cost of around 2€/ton as obtained in this study for the coordinated network (S3-1). The latter figure should also be valid for a large large-scale vision of 300 Mt/y of CO2, and can be compared with the target of 20€/ton of CO2 avoided, as set by the European Climate Change Programme (ECCP) [12].

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Table 1 Combinations of transport modes for the different scenarios.

Scenario	**Transportation modes**	**Distance [km]**	**Amount [Mt/y of CO_2]**
S1-1	Pipeline onshore, 203 mm	110	1.0
S1-2	Pipeline onshore, 203 mm Intermediate storage Water carriers, 1 x 22.000 m_3	100 500	1.0
S1-3	Pipeline onshore, 203 mm Pipeline offshore, 203 mm	100 500	1.0
S2-1	Pipeline onshore, 610 mm	110	10.0

S2-2	Pipeline onshore, 610 mm Intermediate storage Water carriers, 6 x 22.000 m^3	100 500	10.0
S2-3	Pipeline onshore, 610 mm Pipeline offshore, 508 mm	100 500	10.0
S3-1	Pipeline network onshore Pipeline network offshore	230 550	40.0

Figure 1. Comparison of specific costs from the scenarios given in Table 1.