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CO_2 transport systems development: Status of three large European CCS demonstration projects with EEPR funding

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Abstract

This paper addresses technical and operational aspects pertaining to the transport of CO_2. It deals with lessons learnt from the development of three large CCS demonstration projects: the UK-based Don Valley project, the Dutch ROAD project, and the Spanish Compostilla project. These projects were all selected by the European Commission in 2009 to receive funding under the European Energy Programme for Recovery (EEPR). The purpose of the demonstration projects is to verify feasible capture techniques (i.e. gasification, flue-gas cleaning, and oxy-coal combustion in circulating fluidised bed, respectively), and to demonstrate geological storage options, off-shore and on-shore. As the distance and elevation of the CO_2 transport system are inherently given by the project, the transport conditions for the CO_2 will generally differ from one project to another.

The demonstration projects have shown that the thermophysical nature of CO_2 is prone to complicate certain operational procedures mainly due to phenomena like phase change, hydrate formation and Joule-Thomson cooling. The front-end engineering design studies suggest, however, that the handling of CO_2 is quite feasible during normal operation, although customised solutions may be required to handle transients like emergency shut-down and pipeline re-pressurisation. This implies that CO_2 transport is *not* seen as an insuperable hurdle to the design and operation of large CCS systems.

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1. Introduction

In order to mitigate global warming, a balance must be established between the harnessing of fossil fuels and the impact of emitting carbon dioxide into the atmosphere [1,2]. Numerous studies conducted around the world clearly illustrate the importance of enabling sustainable CO_2 capture techniques.

The European Union supports the emergence of advanced technologies and CO_2 capture and storage demonstration via industrial initiatives. Pursuant to the European Strategic Energy Technologies Plan, adopted by the European Commission in 2008, the ambition was to co-finance 10-12 large CCS demonstration projects aimed to justify commercial operations by 2020 [3]. This strategy represents the first initiative of its kind uniting public and industrial efforts to accelerate CCS towards deployment [4]. In 2009, six large demonstration projects, each equivalent to at least 250 MW_e, were selected for funding under the European Energy Programme for Recovery (EEPR). Unfortunately, four of these demonstration projects have been cancelled, mainly due to regulatory issues, lack of foreseeable permit-granting procedures, and political impasse regarding transport and storage of the CO_2. However, the world's eight largest economies, the G8, have targeted 20 large CCS demonstration units to operate worldwide by 2020. In 2009, the newly installed Obama administration confirmed a similar number, seeing China as an integral part in the equation [5].

Several databases keep track of the inventory of CCS projects, such as the interactive Scottish Carbon Capture and Storage (SCCS) map [6] and the Massachusetts Institute of Technology (MIT) database [7]. They provide information on active *and* planned projects (mostly studies), albeit the standing of several projects appears to be somewhat vague.

The current status is that CCS is still not ready for commitment on sole commercial terms (except perhaps for some CO_2 projects intended for enhanced oil recovery in North America and China). Most CCS projects fail to provide a bankable business case, as funding issues are caused by commercial uncertainty and liability. In some cases lack or political or public acceptance create regulatory problems. However, no CCS project should today be prevented by technical risks. For this reason a foreseeable legal and regulatory framework is needed, including rules for the handling of liability issues, and institutional mechanisms for approval of CCS activities.

According to the Global CCS Institute's database (GCCSI) [8], the world has 12 integrated CCS operational projects: 8 projects are employed in the processing of natural gas, 2 in the fertiliser industry, 1 in a synthesis gas plant and 1 in a hydrogen production facility. Four projects are, or have been, fully integrated with measurements and verification. Only three plants are devoted strictly to greenhouse-gas mitigation (i.e. Sleipner, InSalah, Snøvhit). Although injection was suspended at the InSalah project in Algeria in the summer of 2011 due to pressure build-up, a comprehensive *measurement and verification* programme continues. At the Weyburn-Midale CO_2 Monitoring and Storage Project, however, which came to an end in 2011, the operators continue to inject CO_2 into the ground, without measurement and verification, for the sole purpose of enhancing the extraction of oil [9].

In the near future, new solutions are needed in the heavy industry, including iron and steel works, refineries, chemistry, gas processing, and cement kilns. In this pursuit, CCS demonstration projects are needed for the technical development and adaptation to large coal power plants and industry, responding to the commercial interests of the owners of such facilities [10].

According to the latest roadmap of the International Energy Agency (i.e. IEA Roadmap 2013) [9], OECD-Europe, comprising the European members of the Organisation for Economic Cooperation and Development (OECD), must, by 2050, deploy CCS to 70 GW_e of its power generation capacity. Whereas this corresponds to 60% of the CO_2 to be reduced via CCS, another 40% of CO_2 must be taken via CCS in the industrial sector. Common to all CCS projects, however, is the need for the captured CO_2 to be safely and efficiently handled. This calls for extended knowledge of the nature of CO_2 for the design and operation of reliable and robust CCS systems.

2. Status of the large European CCS demonstration projects with EEPR funding

The large European CCS demonstration projects, supported under the EEPR, have planned pipelines that are sized not just for the demonstration phase, but also with the intention to extend the use of the pipelines within a larger CCS chain to emerge in the future. Moreover, the projects have made significant efforts to justify their CO_2 transportation systems as required by the permit-granting process. This includes assessment of CO_2 release dispersion, fracture control measures, materials behaviour, thermophysical characterisation of pure CO_2 and CO_2-rich mixtures, flow assurance, environmental impacts, identification of hazards, quantitative risk assessment (QRA), and last but not least, front-end engineering design (FEED) studies. (Cf. Figure 1).

The CCS demonstration projects presented herein are co-financed by the European Union's European Energy Programme for Recovery. The sole responsibility of this publication lies with the authors. The European Union is not responsible for any use that may be made of the information contained herein.

Figure 1: Disclaimer

2.1. The transport infrastructure of the UK-based Don Valley project

The proposed CO_2 transportation infrastructure includes both onshore and offshore elements (cf. Figure 2 and Figure 3). The onshore element of the project comprises the construction of a proposed 68 kilometer long, 600 mm nominal diameter cross-country pipeline and associated infrastructure including pig traps, a multi-junction installation, three block valve installations and a pumping station at Barmston, South of Bridlington near the English East coast (cf. Figure 2). The onshore pipeline is designed to operate at (up to) 150 barg with a maximum capacity of 17 million tonnes of CO_2 per annum (Mtpa). The proposed multi-junction installation would enable the connection of multiple pipelines from regional CO_2 sources into the common transportation system. The offshore element of the project comprises the construction of a 90 kilometer long, 600 mm nominal diameter, sub-sea pipeline to a geological storage site (called 5/42). The sub-sea pipeline is designed to operate at (up to) 185 barg.

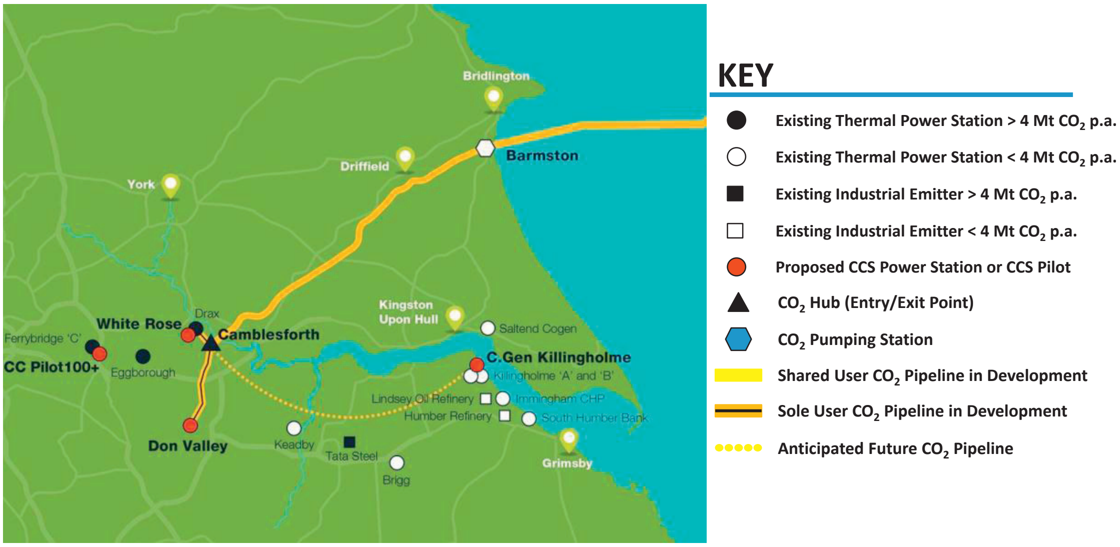

Figure 2: The location of the Don Valley project (and the White Rose project) in the Yorkshire and Humber region of the UK, with the planned transportations system comprising of a 68 kilometer onshore. At Barmston the onshore pipeline is connected to an offshore pipeline.

Multiple additional CO_2 sources close-by are being considered to utilise the pipeline capacity. This would allow CO_2 to be offered for enhanced oil recovery (EOR), which requires typically 5 Mtpa. Therefore, an offshore hub is planned to facilitate additional connections to alternative storage sites, including EOR in the North Sea.

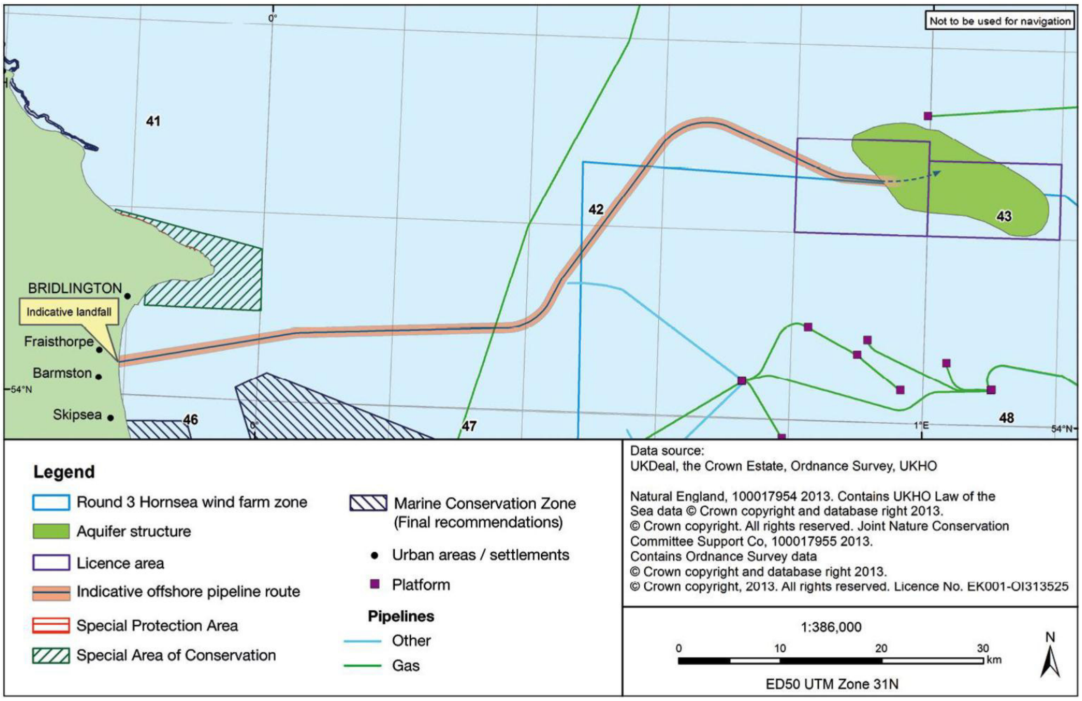

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Figure 3: The 90 kilometer offshore element of the Don Valley project (and the White Rose project) in the Yorkshire and Humber region of the UK.

2.2. The Spanish Compostilla project

The Spanish Compostilla project was based on a new coal-fired power plant using a 300 MW_e circulating fluidized bed concept based on Foster Wheeler technology. According to plan, the CO_2 would be stored in a saline aquifer, roughly 150 kilometer away from the power station, injected via three wells (cf. Figure 4). The project includes a 147 kilometer pipeline to handle the captured CO_2 flow (i.e. flowing up to 63.8 kg/s consisting of approximately 97.5% CO_2) in a steel pipeline buried 1.5 meters deep in the ground. The system allows for 50 parts per million (ppm) water content in the CO_2 flow, which is far below the level of free water formation, even at the low temperatures which may occur when crossing a high mountain pass at more than 1100 m altitude. The inlet pressure of the pipeline would be 150 barg with an outlet pressure of roughly 100 barg. The pipeline ends at the injection site at an altitude about 350 m higher than the level of the power plant supplying the CO_2. Hence, the proposed system is characterised by large differences in height (maximum 600 meters) and, hence, a significant hydraulic head.

In November 2013, however, after having completed the FEED study, Endesa decided to discontinue the Compostilla demonstration project due to unresolved regulatory issues in Spain.

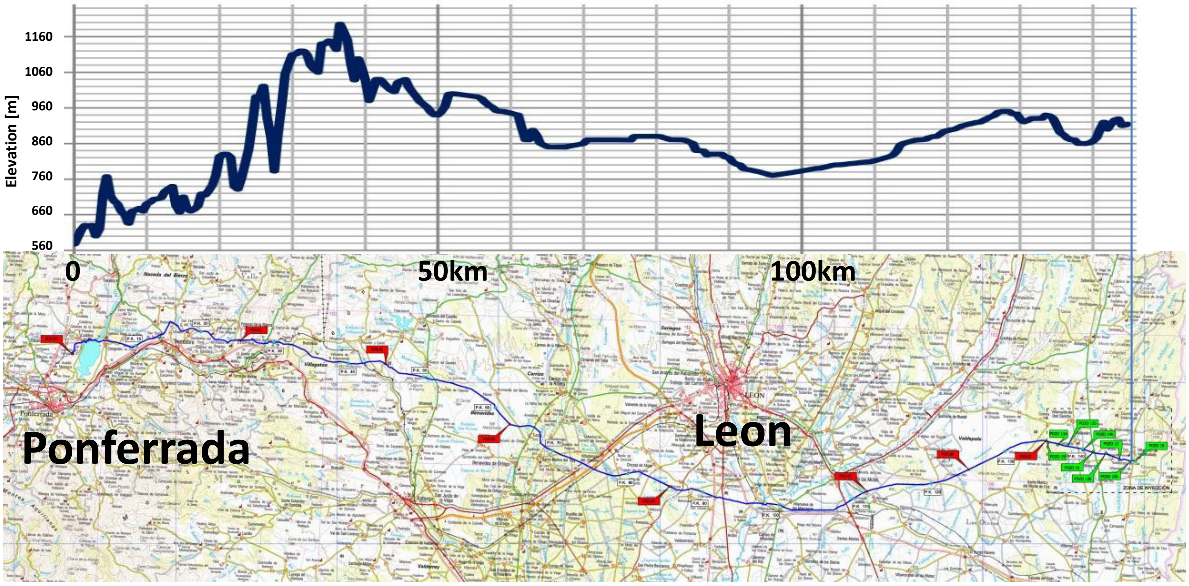

Figure 4: The pipeline trajectory of the Compostilla project, showing its geographical location in Northern Spain passing south of the city Leon from Ponferrada. The transportation system features one compression train (no booster pump) with inlet pressure 150 barg and outlet pressure 100 barg. Inlet-to-outlet height difference 350 meters, and maximum height difference 600 meters. Pipeline characteristics: length 147 kilometer, pipe nominal diameter 350 mm (14inch), pipe API 5L X70 with high density polyethylene (HDPE) external coating.

2.3. The Dutch ROAD project

The ROAD project is based on a slip-stream from a new power plant designated Maasvlakte Power Plant 3 located in the harbour of Rotterdam (cf. Figure 5).

Figure 5: Left: The capture-ready Maasvlakte Power Plant 3 under construction (ROAD project). Output 1.070 MW_e (without CCS), efficiency 46% (LHV). Hot commissioning started in 2013 with planned commercial operations in 2014. Right: Location of the ROAD project and its CO_2 transport lane at reclaimed land at the Rotterdam harbour. Pipeline characteristics: 5 km onshore, 20 km offshore. Diameter: 400 mm nominal diameter (16 inch) insulated steel pipe, transport capacity: 5 Mtpa (dense). Maximum design specifications: 140 barg, 80°C.

The pipeline comprises two sections: a 5 kilometer onshore pipeline and a 20 kilometer offshore pipeline. Both sections employ thermal insulation on the 400 mm (16 inch) nominal diameter pipe designed for a maximum pressure of 140 barg and a temperature of 80°C. The pipeline is capable of handling 1.1 Mtpa of CO_2 in the gaseous phase, initially captured from the ROAD Project. However, at a later stage, the flow will turn into dense phase as the back-pressure of the storage reservoir increases. The capacity of the pipeline will then be as large as 5Mtpa of CO_2, which will allow CO_2 from other sources to be connected.

In order to avoid the shipping lane and wind farms, the current pipeline system proposed for the ROAD project is designed to follow existing pipelines, rather than a straight line.

Options for the further development of the pipeline system have been considered, such as connecting to the existing CO_2 transport system of OCAP, which supplies CO_2 from the Shell Pernis refinery and from a bioethanol plant of Abengoa to greenhouses in South Holland [11]. This would create a functioning CO_2 hub in Rotterdam with scope for substantial additional CO_2 storage.

The demonstration phase will be based on a depleted subsea gas reservoir (P18-A) with a very low initial reservoir pressure (now below 20 bar) (cf. Figure 6). Only one injection well will be required to store the targeted 1.1 Mtpa of CO_2. The reservoir is located 3500 meter below the seabed, capable of receiving up to 8 Mt CO_2. An adjacent (almost depleted) gas reservoir (P18-2) may be used for additional storage at a later stage if the demonstration project proves to be successful. This will raise the total storage capacity to 35 million tonnes (Mt).

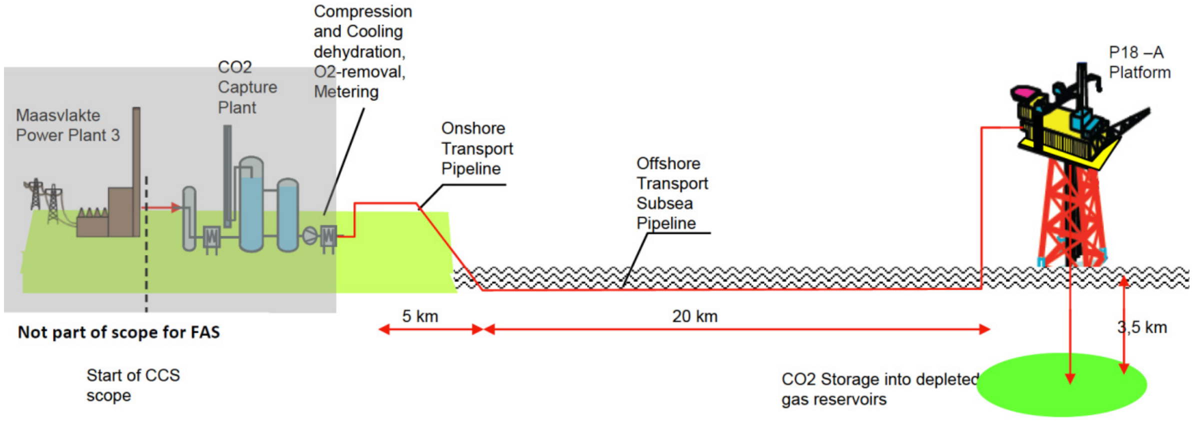

Figure 6: ROAD Project, maximum operational pressure: 129 bar, operating pressure range: 40 – 85 – 129 bar.

3. Flow assurance

All three projects have conducted rigorous flow assurance studies. The main conclusion is that transporting CO_2 through a pipeline system, at nominal conditions, is rather unsophisticated. For economical reasons, the projects independently decided that the CO_2 should be transported in the dense phase. At the outset, however, the ROAD project will transport the CO_2 in gaseous phase because of the very low initial reservoir pressure. Although the specific volume of the flowing CO_2 will then be substantially higher, the pipeline has been sized to allow this. As will be further explained below, rather than operating above the critical pressure, the pipeline system of the ROAD project will operate at a temperature well above the critical temperature for CO_2 (i.e. 31.1°C). This is made feasible by reducing the cooling at the outlet of the compression train. Warm CO_2 (up to 80°C) will then enter the transportation system which will have an insulated pipe.

3.1. CO_2 compression train

The compression trains of the three demonstration projects are rather similar. They feature roughly the same layout with a number of initial centrifugal compression stages, recycling wet and dry CO_2, before injecting the compressed CO_2 flow into a dehydration unit. From this unit, the dry CO_2 enters the high-pressure section of the pipeline, made from carbon steel. All projects have specified a water level for the CO_2 to be equal to or lower than 50 ppmv water vapour.

3.2. CO_2 flow system

Due to low initial back-pressure from the depleted gas reservoir, the ROAD project constitutes the most complicated and interesting case. For this reason, the project has performed detailed flow assurance studies, partly disclosed in publicly available reports [12,13]. Essential learning points from these studies are provided below, followed by a brief description of the prescribed operational philosophy.

3.3. Flow assurance of the ROAD project

ROAD is the only project targeting a depleted gas reservoir. At the start of CO_2 injection, the down-hole pressure will be below 20 bar. This implies a very low static wellhead pressure, with the possibility for a large pressure difference between the pipeline and the wellhead. Evidently, the large pressure relief is associated with a significant temperature drop, due to Joule-Thomson cooling. However, the impact of this cooling can be compensated for by increasing the temperature of the flowing CO_2 prior to injection (to a maximum of 80°C). As separate heating will not be used at the wellhead, ROAD is the only project to have a pipeline that intends to bring CO_2 to the wellhead at a temperature significantly higher than the ambient (sea) temperature in order to compensate for the Joule-Thomson cooling.

Should the CO_2 reach the wellhead in dense phase at a temperature approaching that of the ambient sea bottom, the immediate pressure drop would result in freezing conditions. As the down-hole temperature is considered to constitute a severe bottleneck, mainly because of the risk of hydrates formation, the temperature of the CO_2 should (preferably) be kept above 15°C in order to eliminate this risk. Combining this requirement with the Joule-Thomson cooling, a fairly hot CO_2 must be dispatched from the compression/dehydration train. This is possible due to the relatively short distance of the entire transport system (25 kilometer) allowing proper thermal insulation, combined with the availability of warm CO_2 from the compression train (above 80°C). This operating mode, using a warm pipeline, appears to be a unique feature of the ROAD project.

The design of the CO_2 transportation system accommodates operations under the following flow conditions:

- at steady-state: the reservoir pressure will dictate the wellhead pressure and the pressure along the entire pipeline. Conversely, the inlet temperature of the CO_2 will control the temperature along the pipeline. Proper adjustment of this temperature will ensure that the flow remains in single phase. Hence, the transport system can be controlled by adjusting the inlet temperature of the CO_2 flow and the flow rate.
- at cool-down: draining of the pipeline into the reservoir is essential in order to minimise the amount of CO_2 remaining in the pipeline. Hence, two-phase flow may be avoided (even initially with the very low reservoir pressure).
- at start-up and re-start: low pipeline temperatures can cause liquid CO_2 condensation in the pipeline, so the pressure control valve at the wellhead should be opened as early as possible to allow free flow into the well until warmer single phase, steady state conditions are recovered. It is expected that slugs will occur after longer shutdown periods at higher reservoir pressures. Hence, the pipeline and the platform will be designed accordingly.

Although the understanding of 'slugs' in a binary system conveying oil and natural gas (and water and gas), is well developed, there is little experience with slugging in flowing CO_2. More elaborate assessment of the occurrence, and the influencing parameters, of this phenomenon is still needed to ensure safe and resilient operation of CO_2 flow systems. Despite uncertainty, the flow assurance studies performed by the ROAD project suggest that slugs and two-phase flow in the 400 mm (16 inch) nominal diameter CO_2 pipeline will occur. Slugs are expected to occur after longer shutdown periods when high reservoir pressures prevent full depressurisation of the pipeline during shutdown.

Slug catchers have been investigated, but they were deemed rather impractical and therefore rejected. Typically, the occurrence of slugging will result in integrity issues, especially on control valves and pipeline bends. Due to repetitive pressure spikes, vibration may also affect the metering devices. It is assumed, however, that although slugs are expected, they will *not* have a detrimental impact, neither on the platform nor on the injection well, because of the low density ratio between liquid and gaseous CO_2. At any rate, slugs should never reach the bottom of the well.

3.4. Flow control philosophy of the ROAD project

The handling of initial operations at steady-state is quite important due to the very low back-pressure. Hence, by adjusting the temperature in the pipeline, the density of the CO_2 can be controlled in accordance with the required hydrostatic head. This head must increase gradually as the reservoir pressure builds up. In this way, the pipeline pressure can be kept constant without choking. Hence,

- initially, with very low reservoir pressure, the pipeline will carry warm CO_2 (above critical temperature, typically 80°C), whereby single gaseous phase is ensured in the pipeline and the well. This will limit the hydrostatic head in the well.
- later, as the reservoir pressure exceeds a certain threshold, the pipeline will transport colder CO_2 with higher density, thus increasing the gravity head in the well. The use of a choke valve at the platform is probable, as this will ensure the pipeline pressure to be kept above the critical pressure of CO_2.

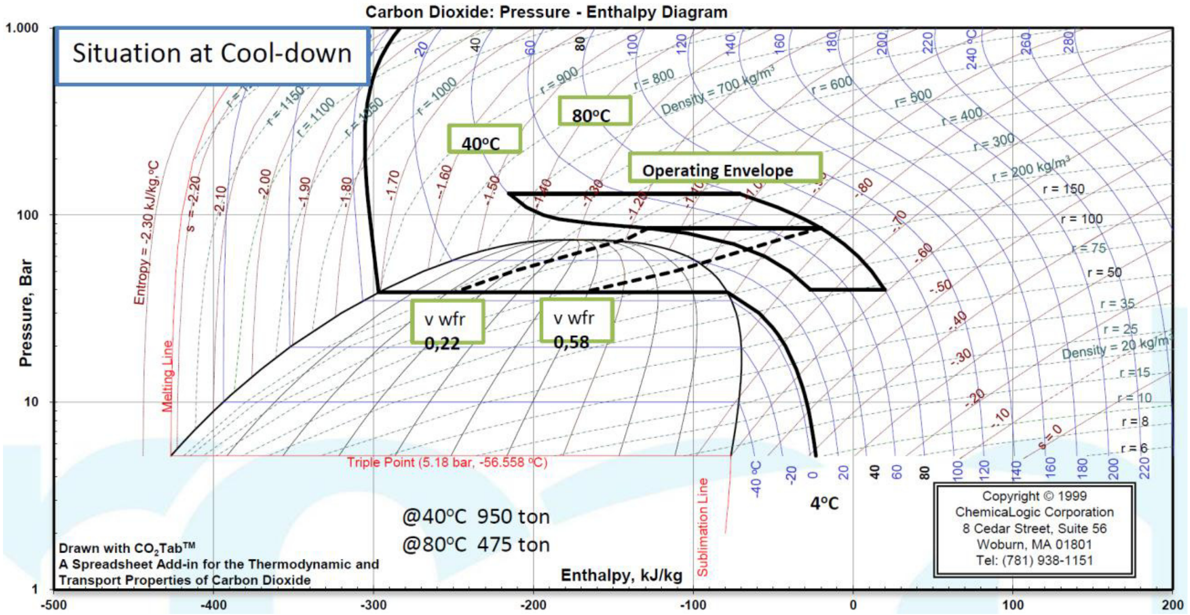

Figure 7: Operating envelope of the ROAD Project. Situation at cool-down. Initial case at 80°C. Normalised operation at 40°C.

The operating envelope of the pipeline, as shown in Figure 7, has an expected operating pressure at of about 85 barg. The figure shows how the pipeline would cool if it is simply shut-in from the normal operating conditions. In the worst case, the CO_2 flow in the pipeline will approach the lowest possible seabed temperature (4°C). The vapour weight fraction (v wfr) in the cooled pipe would then vary between 0.22 and 0.58, depending on the starting temperature. As the pressure is assume to be 85 barg, the range of this variation will be dictated by the temperature. In any case, the implication is a considerable presence of liquid CO_2.

In order to minimise, or if possible avoid this liquid CO_2 condensation, the pipeline should be emptied into the well on shutdown, to the extent allowed by the reservoir pressure. In this way, the remaining amount of CO_2 in the pipeline will be reduced, and, as the pipeline cools down, the amount of CO_2 condensate will be limited. Initially, at low reservoir pressure, the CO_2 in the pipeline would be kept in gaseous phase. However, at a later stage, with higher back-pressure and long shutdown periods, some CO_2 will condense, causing slugging at re-start, as already discussed.

Although the operating procedures for the initial start-up, shutdown and re-start are still subject to optimisation, they will include the following actions:

- on shutdown: empty the pipeline into the well.
- on start-up: start the flow to the well as soon as the pipeline pressure meets the required back-pressure.
- accept that some CO_2 may turn into liquid phase in the pipeline during shutdown, and admit slugs to flow through the wellhead on start-up (and re-start).
- design the wellhead platform to withstand slugs.

4. Conclusion

In accordance with the ambition of the European Union to develop successful CCS demonstration projects at an industrial scale, several projects are being developed, addressing all relevant aspects of the CCS chain. Although the future completion of these projects remains to be seen, a lot of knowledge has been acquired regarding the feasibility of transporting CO_2 from the capture plant to the injection site.

The large CCS demonstration projects under the EEPR have conducted extensive flow assurance studies concluding that CO_2 transport through pipelines is *not* a major hurdle. On the contrary, within certain operational limits, CO_2 pipelines can be designed and operated efficiently. The thermophysical nature of CO_2, however, makes two-phase flow possible, especially during transient operations such as shut-down and restart of a pipeline. The resulting dynamic behaviour of the two-phase flow, causing slugging, are still not fully understood and would require special attention in future developments.

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