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SAFETY AND PIPE INTEGRITY : FROM NATURAL GAS TO CO_2 TRANSPORT BY PIPES

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ABSTRACT

CCS – for Carbon Capture and Storage – has been identified as a key abatement technology for achieving a significant reduction in CO_2 emissions to the atmosphere. Pipelines are likely to be the primary means of transporting CO_2 from point-of-capture (power plants or other industry activities or hydrocarbon production) to geological storage sites (e.g. depleted oil/gas field, deep saline aquifers, etc.) where it will be stored permanently to avoid its release to the atmosphere.

Pipelines can efficiently transport large quantities of supercritical CO_2 and most of the know-how already available from natural gas transport network could be used. This approach has already been adopted in some places where pure CO_2 has been transported, mostly through sparsely populated regions, since the early 1970's (mainly in the USA…) for EOR (Enhanced Oil Recovery) applications. However, there are significant differences between the US experience with pure CO_2, and the transport requirements for CCS. For instance, for technical and economic reasons, CO_2 to be transported is not pure and for different fuels and capture processes, there would be different impurities such as SO_2, H_2S, Ar, O_2, N_2... To design CO_2 pipelines, thermodynamics properties of CO_2-fluid, corrosion, safety and structural integrity issues are to be considered. For example, water content is the "pivotal" variable when assessing corrosion risks in dense and supercritical CO_2 fluid. Nature of impurities present in the fluid (and their concentration level) is the second important variable. The other main variables are partial pressure of CO_2, fluid temperature and velocity (flow regime in case of multi-phase flow – ideally to be avoided). These changes in properties will further affect the design, operation and cost of CO_2 transport.

More globally, transport operating conditions are linked to the capture processes (upstream) and to the geological conditions into the storage (downstream): capture, transport and storage set composition constraints; storage and pipe length set pressure and temperature operating conditions. All these conditions feed the corrosion, the materials and the health and safety studies of a CO_2 transport project. For example, ductile fracture propagation is an issue, like in the USA where, in some cases, pipe material did not have sufficient toughness to arrest propagating ductile fractures for the given operating conditions and therefore crack arrestors were required along these pipelines. This experience highlights the need to define a toughness threshold, in particular when considering impurities effect on the CO_2 decompression behaviour, to assess the possible need for crack arrestors.

Transporting CO_2 from the capture site to the storage is thus an industrial process that needs to be optimized and that needs specifications to guarantee safe design and operation of anthropogenic CO_2 pipeline networks. This know-how will result from academic researches and from industrial pilot plants.

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Pipelines can efficiently transport large quantities of supercritical CO_2 and most of the know-how already available from natural gas transport network could be used. But even if CO_2 transport is not so far different from natural gas transport expertise (they are similar in many respects in design and operation to NG pipelines), there are still some significant differences :

- CO_2 transport pipelines are operated at higher pressure range (more than 80 bar)
- Pumps should be used rather than compressors
- Thicker-walled pipes should be used
- CO_2 is heavier than methane
- Handling CO_2 with different quality from different sources

This approach has already been adopted in some places where pure CO_2 has been transported, mostly through sparsely populated regions, since the early 1970's (mainly in the USA…) for EOR (Enhanced Oil Recovery) applications.

1. MOST OF CO_2 TRANSPORTED BY PIPELINES IS "NATURAL CO_2" USED IN ENHANCED HYDROCARBON RECOVERY (EHR)

Today, CO_2 is mainly transported in pipelines for industrial purposes. The majority of natural CO_2 pipelines are found in North America, where there is over 30 years of experience in transporting CO_2, mainly from natural deposits and gas processing plants for EHR. Natural CO_2 is relatively pure: for EHR all components of the CO_2 stream that raise the minimum miscibility pressure of CO_2 with crude oil are removed because they raise the injection pressure uneconomically. For that reason the phase behaviour of a CO_2 stream for EHR is similar to that of pure CO_2. Up to now with one exception[1], there are no existing CO_2 transport pipelines from power plant capture. Therefore the existing CO_2 pipeline quality requirements are dictated by the effects of impurities on the EHR process rather than economic, safety or hydraulic considerations.

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[1] A 1000 tons/day (42 tons/hour) CO_2 recovery plant at Lubbock, Texas (USA) used the Fluor Daniel econamine process to remove CO_2 from the flue gas of a natural gas power plant. The facility was designed to pipe CO_2 for EOR at the nearby Garza field. The plant was shut down following the collapse in the crude oil price in 1986.

Figure 1: Current composition of natural and anthropogenic sources of CO2 in US pipelines (left). Operating pipeline quality specification (KM: Kinder Morgan; CRC: Canyon Reef Carriers) (right).

However, there are significant differences between the US experience with pure CO_2, and the transport requirements for CCS. For instance, for technical and economic reasons, CO_2 to be transported is not pure and for different fuels and capture processes, there would be different impurities such as SO_2, H_2S, Ar, O_2, N_2... For CCS, particularly from power plant capture schemes, it is difficult to determine, in advance, the exact levels of impurities that may be present in the transported CO_2. This is because the purity of the CO_2 is affected, not only by the differences in processes within the same capture technology, but also by economics (i.e. the increased capture cost associated with the removal of impurities to low levels), regulatory requirements, specifications and safety considerations.

2. IMPURITIES PRESENT IN CO_2 FLOW IMPACT ON ITS THERMODYNAMIC PROPERTIES

One of the effects of the impurities is to change the physical properties of the CO_2. Therefore, in order to undertake the pipeline hydraulic modelling, an understanding of the impurities that could be present in the pipeline and their impact on the physical properties of the CO_2 stream is required.

Figure 2: Composition of anthropogenic sources of CO2

Figures 2 and 3 show that purity levels of post-combustion and EOR CO_2 are comparable, except from H_2O which may be more present in post-combustion flue gas. The amount and type of impurities in the CO_2 stream captured from power plant are dependent on the capture process, the technology, the fuel source and also economic considerations. There are three main process routes for capturing CO_2 from power plant: post-combustion capture, pre-combustion capture or IGCC (Integrated Gasification Combined Cycle) and oxycombustion [1], [2].

Figure 3: Composition after capture processes on flue gas

The analysis of compositions of the CO_2 captured from different sources via the three process families listed above, as well as their industrial maturity shows that while there are common impurities, their concentrations can be very different, and in addition, there is one capture process that results in significantly lower impurity levels than the other ones: post-combustion.

To design CO_2 pipelines, thermodynamics properties of CO_2-fluid, corrosion, safety and structural integrity issues are to be considered. For example, water content is the “pivotal” variable when assessing corrosion risks in dense and supercritical CO_2 fluid. Nature of impurities present in the fluid (and their concentration level) is the second important variable. The other main variables are partial pressure of CO_2, fluid temperature and velocity (flow regime in case of multi-phase flow – ideally to be avoided). These changes in properties will further affect the design, operation and cost of CO_2 transport.

More globally, transport operating conditions are linked to composition constraints set by the capture processes but also to the geological conditions into the storage.

3. TRANSMISSION PIPELINE OPERATING CONDITIONS AS DETERMINED BY STORAGE [3], [4], [5]

In 1993, the European Commission began the Joule II Non-nuclear Energy Research Program, which studied sequestration of industrially produced CO_2. This study concluded that:

- shallow reservoirs do not provide sufficient storage for carbon dioxide because it would be in gaseous form,
- for maximum storage capacity, carbon dioxide has to be stored as a supercritical fluid - which requires reservoirs deeper than 800 m,
- such deep reservoirs could be depleted oil or gas reservoirs or structures containing aquifers,
- if carbon dioxide is stored in aquifers, then to avoid contaminating shallower potable water sources, carbon dioxide would be sequestered in aquifers deep below the North Sea,
- if carbon dioxide is injected into a limestone reservoir, carbonate dissolution could occur around the injection wells causing subsidence,
- the cost of carbon dioxide separation out of flue gas is significantly higher than that of transporting and injecting carbon dioxide in reservoirs

The constraints propagate from capture processes to storage operating conditions, thus bracketing CO_2 transport: capture, transport and storage set composition constraints; storage and pipe length set pressure and temperature operating conditions. All these conditions feed the corrosion, the materials and the health and safety studies.

Figure 4: Link between segments of the CCS chain, operating parameters and subjects.

To summarize, transport operating conditions are linked to the capture processes (upstream) and to the geological conditions into the storage (downstream): capture, transport and storage set composition constraints; storage and pipe length set pressure and temperature operating conditions. For example, the operating storage conditions influence the following parameters of transported CO_2:

- Composition: a too dry gas would dry out of the reservoir rock
- Operating pressure and temperature:
  - injecting in an aquifer is possible at ambient or even higher temperatures and on a narrow pressure range
  - injecting in a depleted oil or gas field requires a relatively hot gas, as gas expansion may cool CO_2 below the minimum storage temperature, which may be relatively high in this case. So CO_2 is either transported hot, or is heated at the wellhead. The latter is easier onshore than off-shore.

Figure 5 : Operating conditions for CO_2 transport and storage.

All these conditions feed the corrosion, the materials and the health and safety studies of a CO_2 transport project.

For example, ductile fracture propagation is an issue, like in the USA where, in some cases, pipe material did not have sufficient toughness to arrest propagating ductile fractures for the given operating conditions and therefore crack arrestors were required along these pipelines. This experience highlights the need to define a toughness threshold, in particular when considering impurities effect on the CO_2 decompression behaviour, to assess the possible need for crack arrestors.

4. SAFETY and PIPE INTEGRITY CONDITIONS AS DETERMINED BY MODELLING

With the development of the CO_2 grid and structure, the loss of containment of a pipe or a vessel and consequently the accidental atmospheric dispersion of a vapour, a liquid or a supercritical CO_2 (more than 73.8 bar pressure and 31 ° C temperature. See Figure 6) becomes a key issue for the safety and human protection.

Figure 6: Phase diagram of CO_2 (Pc = 73.8 atm, Tc = 31.1 ° C).

GDF SUEZ has developed over the past twenty years a set of integral models to quantify the risks and consequences of accidental discharges and dispersion of natural gas or LNG at all points of the natural gas chain. However, ongoing R&D works performed within GDF SUEZ CCS research program aims at adapting these models to CO_2 pipelines safety and integrity studies.

The first step has been to consider how CO_2 behaves into the pipeline in case of release. We used the software OLGA$^{®}$ and compared its simulation results with experimental data consisting in pressure and temperature variations along a pipeline for different lengths and diameters. OLGA$^{®}$ simulations for flow conditions description agreed with the experimental data:

- fluid properties are fully described along the line
- transient description of the leakage mass flow evolution, depressurisation path and gas cooling are well described
- phase transitions are taken into account

Figure 7 : CO_2 mass flow rates (liquid and gas) calculated into an horizontal 4 m in length pipe (6 mm diameter) at initial pressure of 120 bara.

OLGA results can thus be used as input data for dispersion models. Indeed, it provides accurate description of the flow behavior inside the pipeline, it can complete monitored data and allows extrapolation for non investigated conditions. The second step consists in modeling the dispersion of CO_2 outside the pipe using, as input data, OLGA modeling results.

Because CO_2 is stored in a cold liquid state and its transportation from the capture to the storage areas is efficient when it operates in a supercritical state, a depressurisation of a supercritical CO_2 to ambient pressure following an accidental release from a vessel or a pipe can produce a solid phase. Thus, the quantification of vapour, liquid and solid phases have to be taken into account through the mass and energy balances.

To adapt existing in-house natural gas safety software based on integral models, we proceeded firstly to the modelling of the thermodynamic equations of state based on SPAN & WAGNER paper [6].

The evolution of the vapour and liquid (drops) phases in the atmosphere and the vaporization of a liquid pool are already taken into account in the current model. The next step will be to add to the discharge and dispersion integral model the calculation of the solid property, taking in account impurities in CO_2.

The model will consist in three modules: the first one allowing to calculate the flow rate for pressurized release through punctures in pipelines, gravity based discharge from spherical or cylindrical tanks (vertical or horizontal) and for rupture of horizontal or inclined pipes (with or without a pump). The second module will calculate the dry ice accumulation on the ground and/or the liquid pool extension on land or water and evaluate the vaporization rate of the dry ice and/or the liquid pool. And a third module will deal with the dispersion of the vapour phase releases after a puff release, a vaporisation of the dry ice, a vaporization of a pool in taking into account the variation of pool size and vaporization rate or after a pressurized release (flashing liquid jet).

Finally, the GDF SUEZ discharge and dispersion integral models results will be compared with commercial, integral and CFD codes. A large validation step will be carried out with experimental release data on pure CO_2.

5. CONCLUSIONS

Transporting CO_2 from the capture site to the storage is thus an industrial process that needs to be optimized and that needs specifications to guarantee safe design and operation of anthropogenic CO_2 pipeline networks. This know-how will be provided by academic researches and by industrial pilot plants.

CO_2 transport is similar in many respects in design and operation to NG pipelines, but CO_2 is a gas with its own specificities. This is why experimental data are needed for updating modeling tools (usually used for NG) so that safety and integrity of inhabitants and pipes are guaranteed.

6. ACKNOWLEDGEMENT

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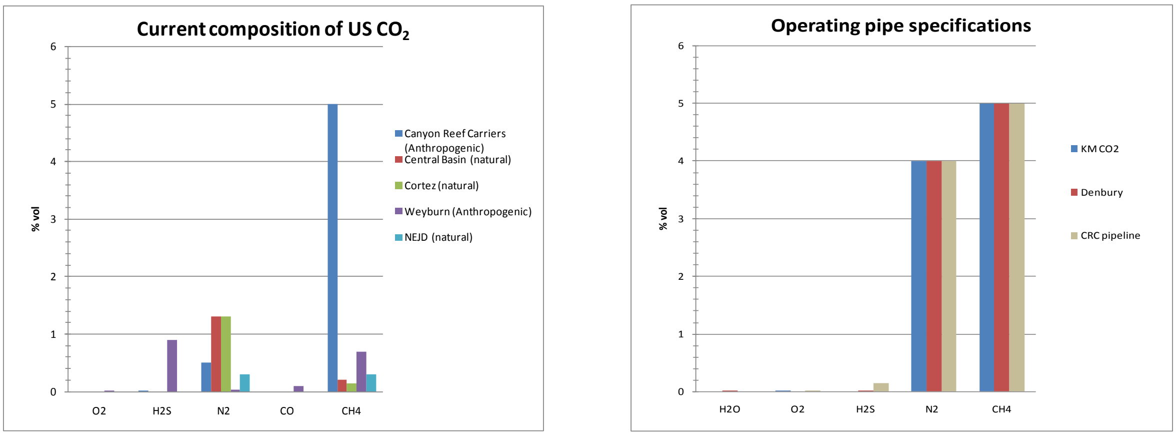

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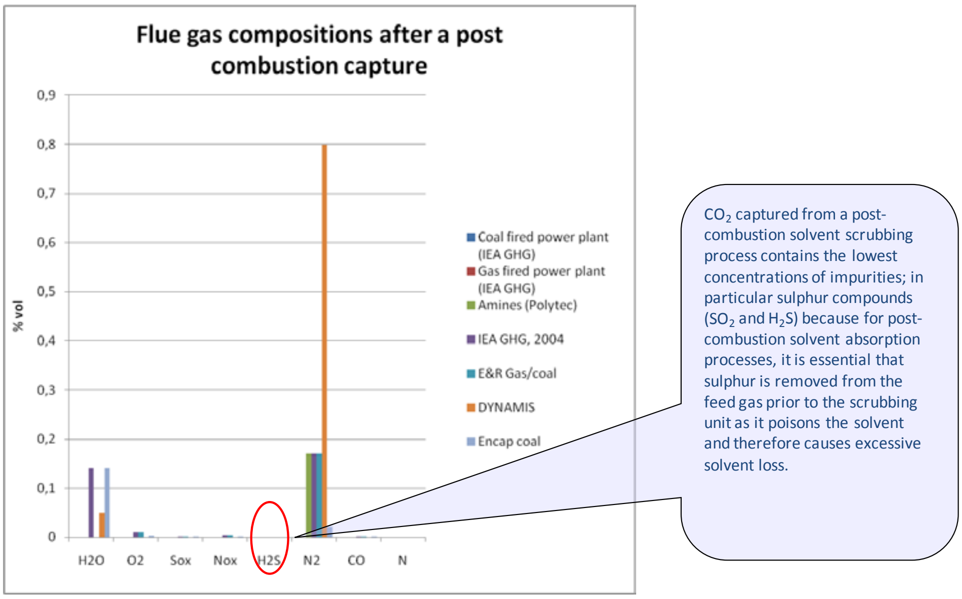
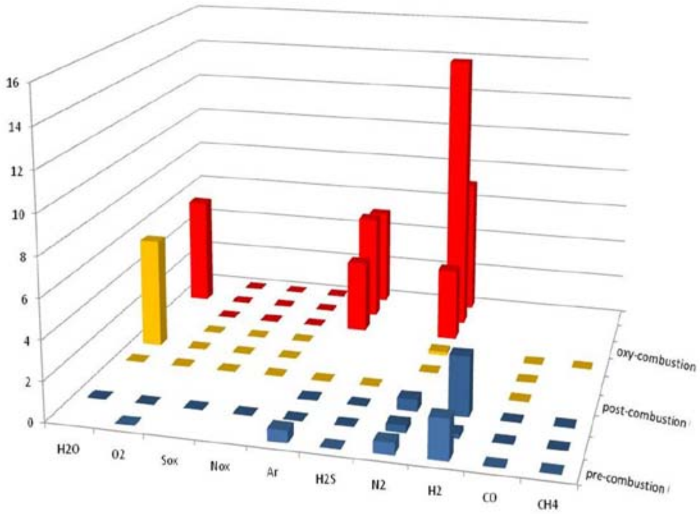


CO_2 captured from a post-combustion solvent scrubbing process contains the lowest concentrations of impurities; in particular sulphur compounds (SO_2 and H_2S) because for post-combustion solvent absorption processes, it is essential that sulphur is removed from the feed gas prior to the scrubbing unit as it poisons the solvent and therefore causes excessive solvent loss.

Figure 2: Composition of anthropogenic sources of CO_2



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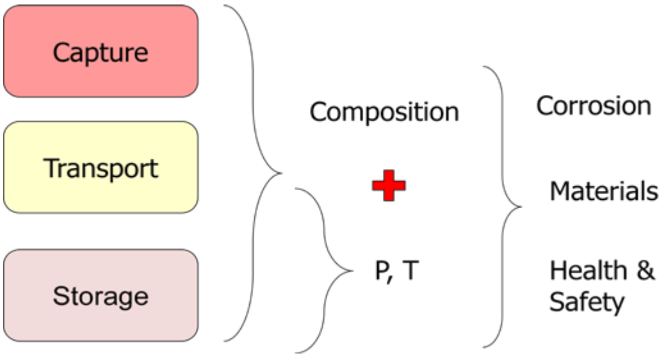

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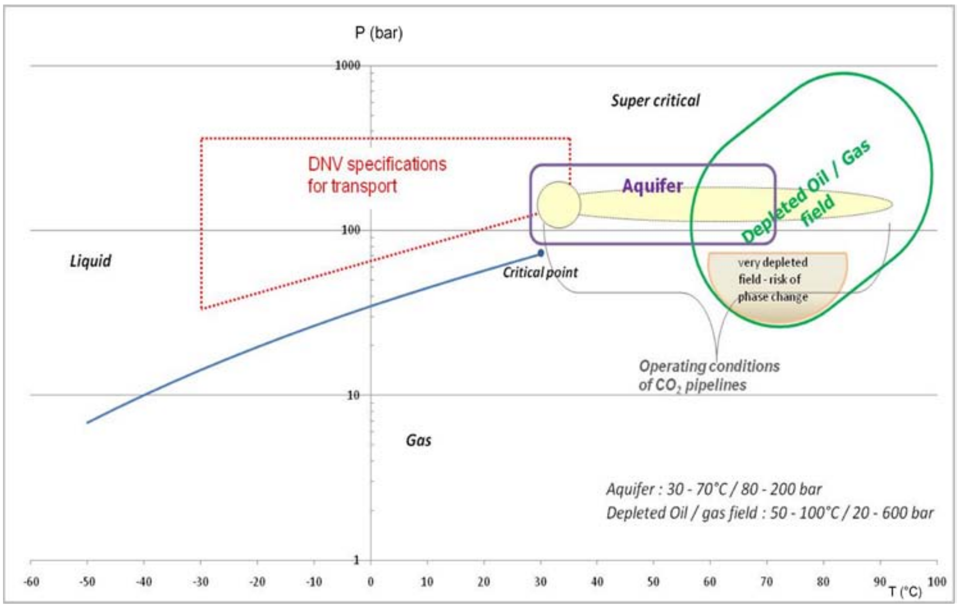
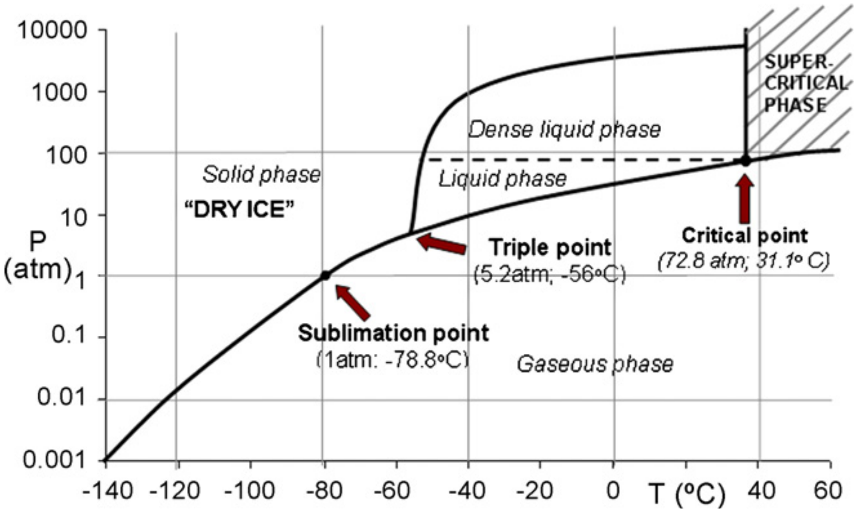


Figure 5: operating conditions for CO_2 transport and storage.



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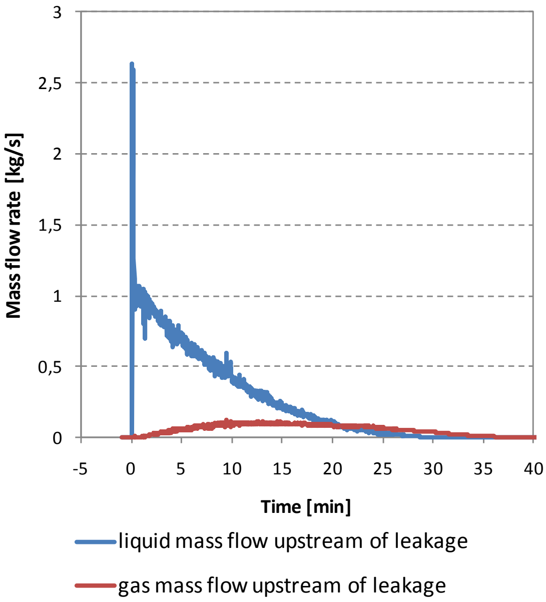

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