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4.2.2 High pressure CO2 pipelines and equipment

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Abstract

The reason for this literature survey is growing interest to limit CO_2 emissions. One solution for that is carbon capture and storage which includes transportation of CO_2 in the ocean or in the geological storage place underground. This literature survey assesses the requirements for the materials in CO_2 transportation pipelines. It focuses on the mechanical and corrosion properties of metallic materials commonly used in CO_2 transportation pipelines including pipes, pumps and compressors.

CMn steel can be used for CO_2 pipelines, but for some parts that are exposed for example to cooling, it is good to use some corrosion resistant alloy. CO_2 is possible to transport in a gas phase, as a supercritical fluid or in a subcooled liquid state. It is most efficient to transport CO_2 in liquid or supercritical form, because then the density is the highest and two-phase areas, which are difficult to handle, do not occur so easily. The supercritical phase occurs above CO_2's critical point, 31,1 °C and 7,38 MPa, so CO_2 has to be warmed for transportation, whereas in the liquid state CO_2 has to be cooled or transportation happens in ambient pressure.

To protect the pipeline from external corrosion it is good to use external coating. Inner corrosion depends mostly on the impurities. Both the composition and the amount of the impurities highly depend on the source of CO_2, so it is difficult to estimate exactly the impurities and their concentration. Water is the biggest threat, since it forms carbonic acid with CO_2, so dehydrating the CO_2 mix before transportation is a good option

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Foreword

This report is a literature review that concentrates on high pressure CO_2 pipelines and equipment and possibility to apply them in CO_2 transportation in Finland. It is part of the Cleen Ltd's CCS programme, which covers all the parts of the CCS chain and also other aspects to it, like health and safety aspects. Topics have been divided into five packages, and this report is part of the working package 4: Processing and logistics of captured CO_2, more specific, part of the subtask 4.2.2 High pressure CO_2 pipelines and equipment, which is led by Gasum Oy. The main objectives were to assess safety, corrosion and material issues in high pressure CO_2 processing.

Sari Siitonen and Janne Lumme are working in this project in Gasum Oy and Antero Pehkonen and professor Simo-Pekka Hannula in Aalto University School of Chemical Technology Department of Materials Science and Engineering.

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Symbols and abbreviations

API	American Petroleum Institute
Ar	argon
CCS	carbon dioxide capture and geological storage
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
DEG	diethylene glycol
EOR	enhanced oil recovery
Fe	iron
$FeCO_3$	iron carbonate
Fe_3C	cementite
H_2	hydrogen
H_2CO_3	carbonic acid
H_2O	water
H_2S	hydrogen sulfide
ksi	kilopound per square inch
MEG	monoethylene glycol
MPa	megapascal
MSA	molecular sieve adsorption
N_2	nitrogen
O_2	oxygen
pig	internal pipeline inspection device
ppm	parts per million
psi	pound force per square inch
SFC	supercritical fluid chromatography
SFE	supercritical fluid extraction
SSCC	sulfide stress corrosion cracking
TEG	triethylene glycol

1 Introduction

Carbon dioxide (CO_2) appears naturally in the Earth's atmosphere, but its amount has been growing since the industrial revolution [1]. It has been predicted that the concentration might reach twice the preindustrial level, which was 278 parts per million [2] by 2100. At the beginning of the year 2012, the concentration was 393 parts per million [2]. CO_2 is a greenhouse gas, so increasing of its concentration stimulates climate change. The biggest reason for an increase in the concentration of CO_2 is the burning of carbon rich fossil fuels. Increasing amount of CO_2 is too big to handle for forests in the world. The majority of world's present energy needs are covered with fossil fuels, so switching to alternative energy sources will take time. This is why storing CO_2 is important in order to help nature to cope with CO_2. [1]

Transporting CO_2 has been used mostly in the oil industry but after emission standards for CO_2 from the use of fossil fuels, the capture and storage of CO_2 has excited more interest also in other industries [3]. Likely storage place for captured CO_2 is in the ocean or in the underground [1]. There are no suitable places to sequester CO_2 in Finland, and seas of Finland are too low for CO_2 storage, so captured CO_2 should be transported to the North Sea or the Barents Sea [4].

2 Results

Most of the articles that were found about the subject were handling the transportation of CO_2 in the pipelines either onshore or offshore. Most of the examples that were found are about pipelines in the United States.

2.1 Properties of CO_2

The critical point of CO_2 is 31,1 °C and 7,38 MPa [5]. Above this point CO_2 is in the supercritical phase and its properties are similar to liquid, but its density is higher [6]. Phase diagram of CO_2 is shown in Figure 1.

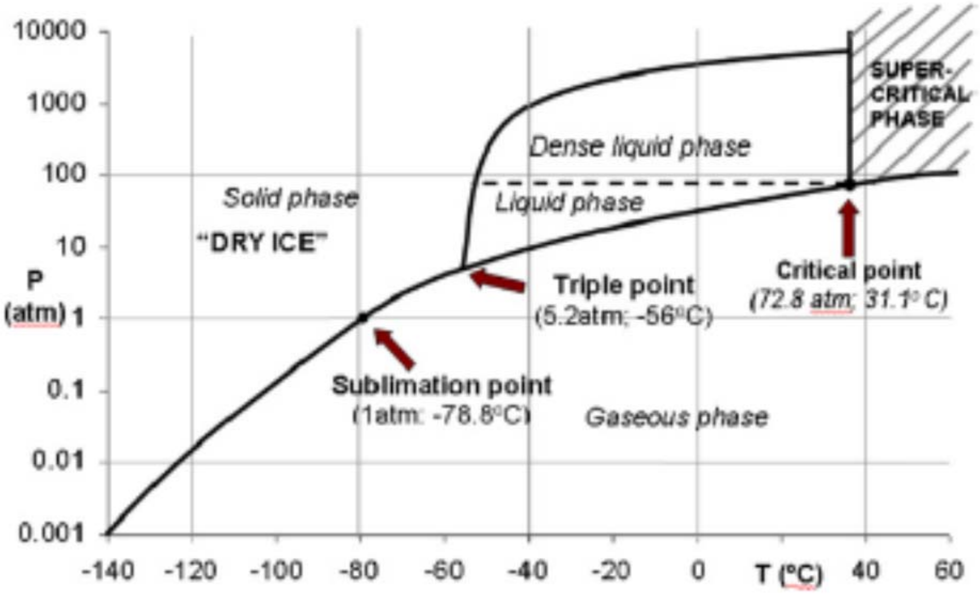

Figure 1. CO_2 phase diagram. [7]

According to Zhang et al. (2006), it is technically possible to transport CO_2 in a gas phase, as a supercritical fluid or in the subcooled liquid state [5]. For an efficient transportation CO_2 should have high density [6]. As it can be seen from Table 1, the highest density is in the liquid or in the supercritical state. If the density is not high enough, there might occur two-phase areas, for example on the top of the hills, where pressure is lower [6].

Table 1. Properties of gaseous, supercritical and liquid CO_2. [5]

Properties	Gas	Supercritical	Liquid
Density (g/cm^3)	~0,001	0,2–1,0	0,6–1,6
Diffusivity (cm^2/s)	0,1	0,001	0,00001
Viscosity (g/(cm s)	0,0001	0,001	0,01

2.2 Transportation

In Nordic countries it might be sensible to transport CO_2 in ambient temperature, in other words, the temperature of CO_2 would be the same as the soil, where the pipelines are. During winters, soil temperature is a few degrees minus, and in summer times it warms up to 6-8 °C [6]. If transportation is in ambient pressure, it might not be necessary to cool CO_2 down in a liquid phase, especially since in the transportation depth the temperature stays above 0 °C, or only a little cooling is needed, comparing with the transportation in a supercritical phase. In transportation in supercritical phase it is necessary to isolate the pipeline and warm CO_2 to the temperature where it is in a supercritical phase, that is, above 31,1 °C. In a supercritical phase, the pressure should be above 7,38 MPa whereas in the liquid phase the pressure should be between 3 and 5 MPa. Below this pressure, the density and capacity are too small for efficient transportation for CO_2 [6]. In transportation, one should pay more attention that there does not occur many two-phase areas, since it is difficult to handle two-phase flow, especially with compressing and pumping [6]. According to Zhang et al. (2006) under both isothermal and adiabatic conditions, it is the most efficient and it has the lowest cost to transport CO_2 over long distances in a subcooled liquid phase [5]. On the other hand, Skovholt (1993) says that supercritical phase is practical in many ways for the transportation of CO_2, so he assumes in his calculations that CO_2 is in the supercritical or dense phase [6]. Skovholt also assumes that the pipes are high quality carbon steel, which is coated to avoid external corrosion [6].

When pressure is above the critical point, but temperature is below, the CO_2 is in liquid state and its density increases with decreasing temperature [8]. According to Serpa (2011), for pipeline transportation the most efficient state of CO_2 is a dense phase liquid [8]. Zhang et al. (2006) has compared CO_2 transport in a supercritical state and in a subcooled liquid state with an identical pipe diameter. Figure 2 presents schemes of CO_2 pipeline transport both in a supercritical and in a liquid state. Both systems contain the capture of concentrated CO_2 from the source, the compression of the CO_2 to the desired pressure level and optional cooling of CO_2, pipeline transport, intermediate recompression via compressor or repressurization via pump booster stations (if required), distribution, injection pressurization (if required), and storage. For subcooled liquid CO_2 transportation cooling utility is needed in order to keep the CO_2 below its critical temperature, especially in the summertime. [5]

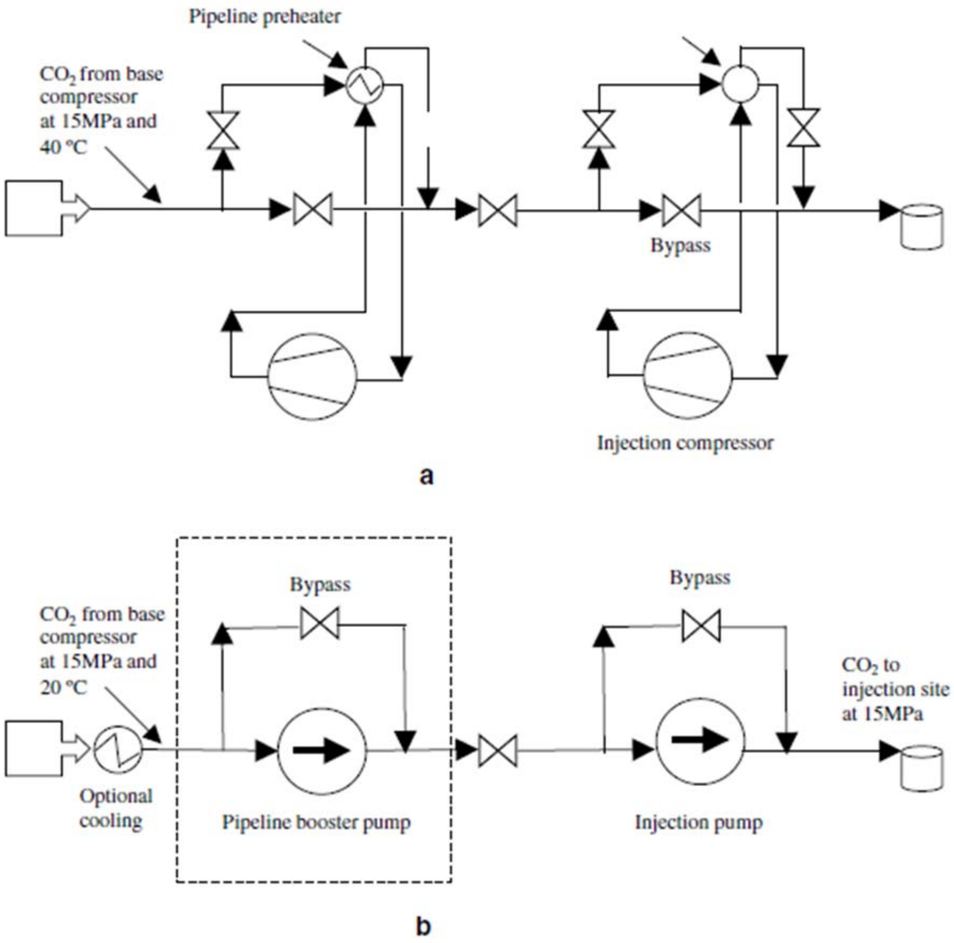

Figure 2. Schemes of CO_2 transport: a) supercritical transport of CO_2 using compressors and b) liquid transport of CO_2 using pumps. [5]

According to Zhang et al. (2006), “CO2 transportation in the subcooled liquid state has some advantages over supercritical state transport, most importantly because of the lower compressibility and higher density of the liquid within the pressure range considered here, which permits smaller pipe sizes or lower pressure losses”. Because of these reasons, the subcooled liquid state in favourable climate conditions can result in significant energy savings comparing with supercritical phase transportation. Over distances 350 km or more, transporting CO_2 in a subcooled liquid state should also reduce capital costs by 16% comparing with a supercritical state. In the transportation of CO_2 in a subcooled liquid state, the safe distance between booster stations is 46% higher than in supercritical state transportation. In a liquid state, when using adiabatic state instead of isothermal, it is also possible to increase the safe distance between booster stations up to 25%. The safe distance depends on the pressure drop along the pipeline. The pressure drop is depends on the flow rate, length of the pipeline, its diameter etc. It is possible to calculate the optimum economic pipe diameter; Zhang et al. (2006) used the following formula:

$$D_{i,opt} = 0{,}363 m_v^{0{,}45} \rho^{0{,}13} \mu_c^{0{,}025}, \qquad (1)$$

where $D_{i,opt}$ represents optimum inner diameter of the pipe, m_v is CO_2 volumetric flow rate in the pipeline (m^3/s), ρ means the density of CO_2 at average temperature through the pipeline (kg/m^3), and μ_c is average CO_2 viscosity (Pa•s). Zhang et al. (2006) has also some other assumptions, and conclusions from all of them and the equation gives an optimum inner diameter of 0,29 m at a CO_2 flow rate of 245 tonne/h with the inlet conditions of 15,0 MPa and 40 °C, so the CO_2 flow is in a supercritical phase. [5]

2.3 Pipeline material

According to Heggum (2005), CO_2 pipelines can be made from CMn steel, like American Petroleum Institute (API) X65. If carbon steel is used, CO_2 should not include free water and temperature should be higher than - 46 °C. If these terms do not fill, it is necessary to use special steel, for example low temperature steel or stainless steel. Generally, carbon steel can be used also for the equipment of the compression train. For the parts that are exposed to cooling and so on, should consider using some corrosion resistant alloys. These parts are scrubbers, coolers, critical components in the compressors as well as piping near these parts. [9]

In order to avoid the initiation and propagation of longitudinal running fractures it is typical to use fracture arresters in the pipelines. They are typically installed every 500 meters. Also steel of lower strength and thicker walls in the pipeline pre-empt the fractures. Optimum strength and wall thickness for the pipeline depends on the temperature and pressure of the CO_2 flow. CO_2 pipelines usually have an external coating to reduce external corrosion. It can be for example fusion bonded epoxy or polyurethane with full cathodic protection. [10]

In addition to X65-grade steel, for example API X60- or X80-grade materials are good for the pipelines [10]. All of these steels are seamless and welded pipe for pipeline transportation systems, for liquid and gas, onshore and offshore [11]. With X60 minimum yield strength is about 60 kilopound per square inch (ksi) and with X80 the minimum yield strength is about 80 ksi [11]. 1 ksi is 1000 pound force per square inch (psi) and 1 psi is 6894,757 pascal (Pa) [12].

As an example, X65 pipe was used in SACROC (Canyon Reef Carriers) CO_2 pipeline, the first large CO_2 pipeline in the USA. It is buried at least 0,9 m underground and there is a block valve within 16 km at any point of the pipeline. The main pipeline (290 km) has 406,4 mm outside diameter and 9,53 mm wall thickness, and shorter section (60 km) has 323,85 mm outside diameter and 8,74 mm wall thickness. Near the glycol dehydrator, upstream, corrosion-resistant alloy 304L was used instead of grade X65. [13]

2.4 Main existing long-distance pipelines

The main existing long-distance pipelines from natural and anthropogenic sources of CO_2 are presented in Table 2. It includes above mentioned Canyon Reef Carriers pipeline, which has been in service for almost 40 years already. Also the longest CO_2 pipeline, the Cortez pipeline, is in the table. Cortez pipeline is over 800 km long and its capacity is almost 20 Mt of CO_2 per year. [8]

Table 2. Existing long-distance pipelines with natural and anthropogenic sources of CO_2 [8].

Pipeline	Location	Operator	Capacity (Mt/yr)	Length (km)	Diameter (mm)	Pressure (bar)	CO_2 Source	Year
Cortez	USA	Kinder Morgan	19,3	808	762	186	McElmo Dome	1984
Sheep Mountain	USA	BP Amoco	n/a	296	508	n/a	Sheep Mountain	1983
Sheep Mountain North	USA	BP Amoco	n/a	360	610	132	Sheep Mountain	1983
Bravo	USA	Kinder Morgan	7,3	350	508	165	Bravo Dome	1984
Central Basin	USA	Kinder Morgan	20	278	400-650	170	Danver City hub	1985
Bati Raman	USA	Turkish Petroleum	1,1	90	n/a	170	Dodan field	1983
Canyon Reef Carriers	USA	Kinder Morgan	4,4	352	400	140	Gasifica-tion plants	1972
Val Verde	USA	Petro Source	2,5	130	250	n/a	Gas plant	1998
Bairoil	USA	n/a	8,3	180	n/a	n/a	Gas manu-facturing plant	1986
Weyburn	USA & Canada	North Dakota Gasification Co.	5	328	305-356	152	Gasificatio n plants	2000

As it can be seen from Table 2 the diameter of pipeline varies from 250 mm to 762 mm. According to Skovholt (1993), with the smallest diameter the pipeline cost per meter is the lowest and with the biggest diameter the cost per meter is the highest. On the other hand, the bigger the pipeline diameter is, the greater is the flow capacity of the pipeline, as it can be seen in Figure 3 [6]. In conclusion, Skovholt presents transportation rates for onshore and offshore pipelines in $ per ton across a 250 km pipeline section, Figure 4 [6].

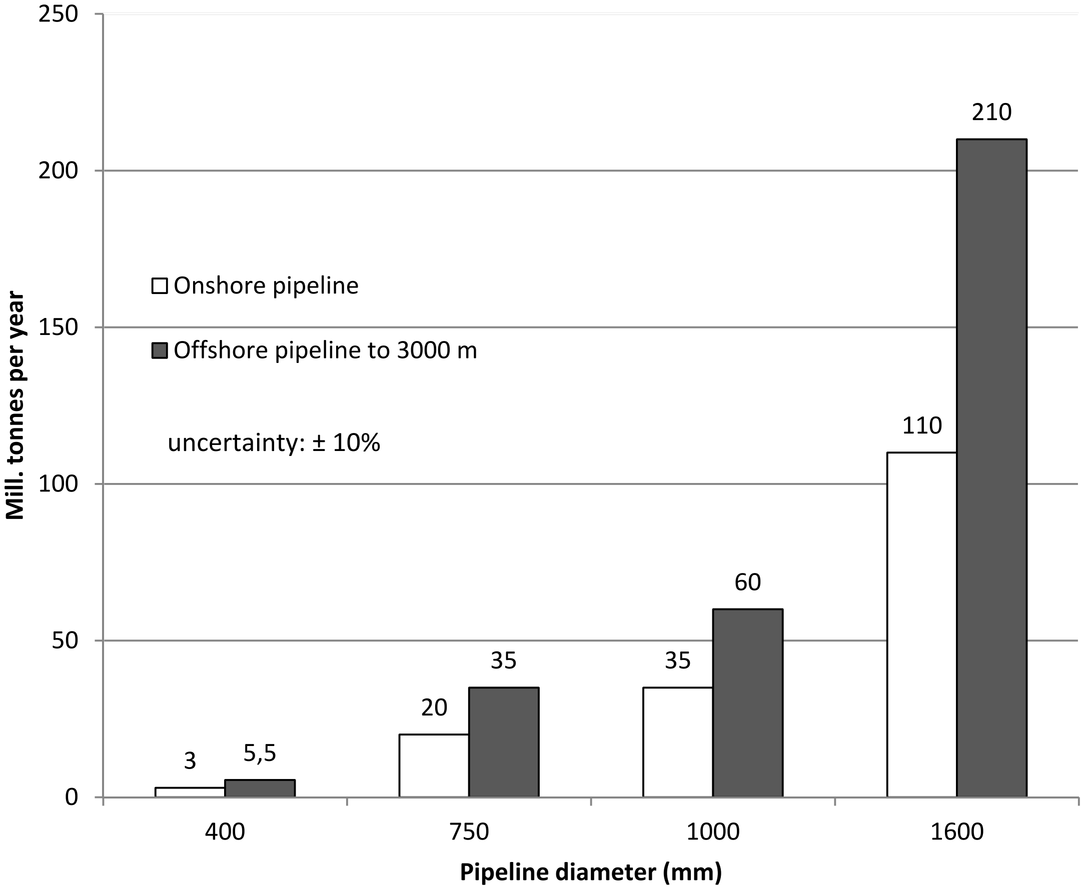

Figure 3. Pipeline flow capacities [6].

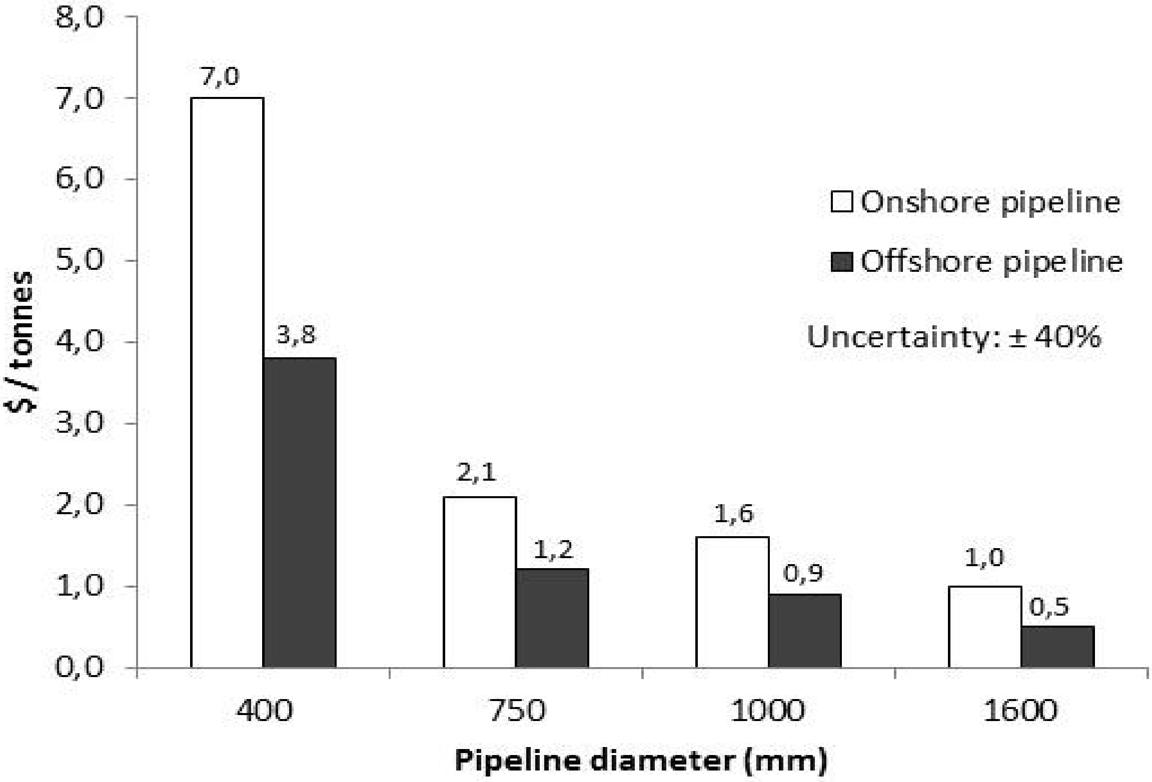

Figure 4. Transportation rates for onshore and offshore pipelines in $ per ton across a 250 km pipeline section [6.]

2.5 Water and other impurities in the CO_2 flow

The water content and the water solubility in the CO_2 affect strongly the corrosion rates of carbon steel pipeline [9]. CO_2 reacts with water and forms carbonic acid, which can affect carbonic acid corrosion, which is also called “sweet gas” corrosion, and it damages carbon steels [14]. CO_2 should be dehydrated in order to avoid corrosion [15]. One possibility to avoid corrosion, if CO_2 is not dehydrated, is to use for example monoethylene glycol (MEG) to obtain low corrosion rate and if the water requirement is relaxed it is also possible to use diethylene glycol (DEG) or triethylene glycol (TEG) instead of MEG [9]. For additional drying one possibility is to use molecular sieve adsorption (MSA), so there would not be free water in the mixture. MSA has low investment costs, good operating experience and some other advantages, so it is considered as a good drying method. It is also possible to reduce the amount of water with coolers and scrubbers, but it might be more efficient to use some other ways, described above. [9]

Aspelund and Jordal (2007) have gathered information about gas quality in gram molecular percentage of solution and pressure, and temperature from various capture processes and concluded them in Table 3. As it can be seen, H_2 (hydrogen), CO (carbon monoxide), O_2 (oxygen) and CH_4 (methane) are minor impurities and they appear only in some capture processes. Ar (argon) is bigger impurity but it appears only in certain capture processes. The biggest impurity is H_2O (water) and other one that is good to notice is N_2 (nitrogen). [16]

Table 3. Gas quality (mol%) and pressure and temperature from the various capture processes.[16]

Process	CO_2	H_2O	H_2	CO	N_2	O_2	CH_4	Ar	P (bar)	T (°C)
Amine (post-combustion)	94,39	5,61	0	0	0	traces	0	0	1,01	35
ATR (pre-combustion with amine)	98,21	1,79	0	0	0	0	0	0	1,01	16
Water cycle	59,74	32,84	0	0,01	2,81	1,00	0	3,59	0,045	13
S-Graz	61,65	30,90	0	0	2,91	0,85	0	3,69	1,01	337
Oxyfuel (CC)	93,82	4,16	0	0	0,28	1,38	0	0,35	1,01	30
SOFC + CT	35,90	63,84	0	0	0,26	0	0	0	1,01	439
AZEP HP	35,90	63,84	0	0	0,26	0	0	0	15,38	248
AZEP LP	35,90	63,84	0	0	0,26	0	0	0	1,01	111
CLC	34,66	65,06	0	0	0,28	0	0	0	1,01	415
MSR-H2 HP	62,44	35,49	0,92	0,57	0,45	0	0,12	0	63,94	578
MSR-H2 LP	63,44	35,49	0,92	0,57	0,45	0	0,12	0	1,04	98

According to Barrie et al. (2004) hydrocarbons in the CO_2 flow affect overall pipeline pressure so it might lead to two-phase areas. CO_2, hydrocarbons and water may also combine to form hydrates that can plug up the system [14]. As for Heggum et al. (2005) say that typically the flow includes up to 5 % CH_4, 5 % N_2, 0,5 % H_2O, 0,01 % H_2S and an unknown amount of amines. In this case it is considered safer to use the pure compression process instead of pumping, to handle composition ranges of this kind [9]. As an example, the composition of the gas carried by the Weyburn pipeline is typically: CO_2 96%, H_2S 0,9%,

CH_4 0,7%, C_{2+} hydrocarbons 2,3%, CO 0,1%, N_2 less than 300 ppm, O_2 less than 50 ppm and H_2O less than 20 ppm [13].

In addition to depending on the impurities in the CO_2 flow, the water solubility in CO_2 depends on the pressure and the temperature in CO_2 pipeline as well, so it is difficult to give any straight answers about the free water amount. Figure 5 shows comparison to water solubility in CO_2 at ~26 °C [9]. According to Aspelund and Jordal (2007) the CO_2 product can contain maximum 50 ppm of water. They add that this is from a thermodynamic point, so it is lower than necessary and probably hydrates and corrosion does not occur before the water content is over 10 times higher than 50 ppm [16]. Whereas according to ASTM E 1747-95 standard guide for the purity of carbon dioxide used in supercritical fluid applications says that a maximum limit for water in carbon dioxide in supercritical fluid in supercritical fluid extraction (SFE) and supercritical fluid chromatography (SFC), that is considered acceptable, is 1 ppm [17]. CO_2 transportation company, the USA based Kinder Morgan, which is an experienced transportation company of CO_2 in North America [18], has also a drying requirement for CO_2 pipelines. In this case, the pipelines are used for enhanced oil recovery (EOR), and the maximum allowed amount of water is 600 ppm [9]. On the other hand, any free water makes hydrate formation and corrosion problems for carbon steel possible, so this should be taken into consideration. Heggum et al. (2005) also show an example of the Cortez pipeline, where CO_2 is cleaned, dehydrated and compressed to 145 bar before it is pumped down the pipeline. Pumps are used instead of compressors in this pipeline, this way the operational costs are 10 % less than with compressors. [9]

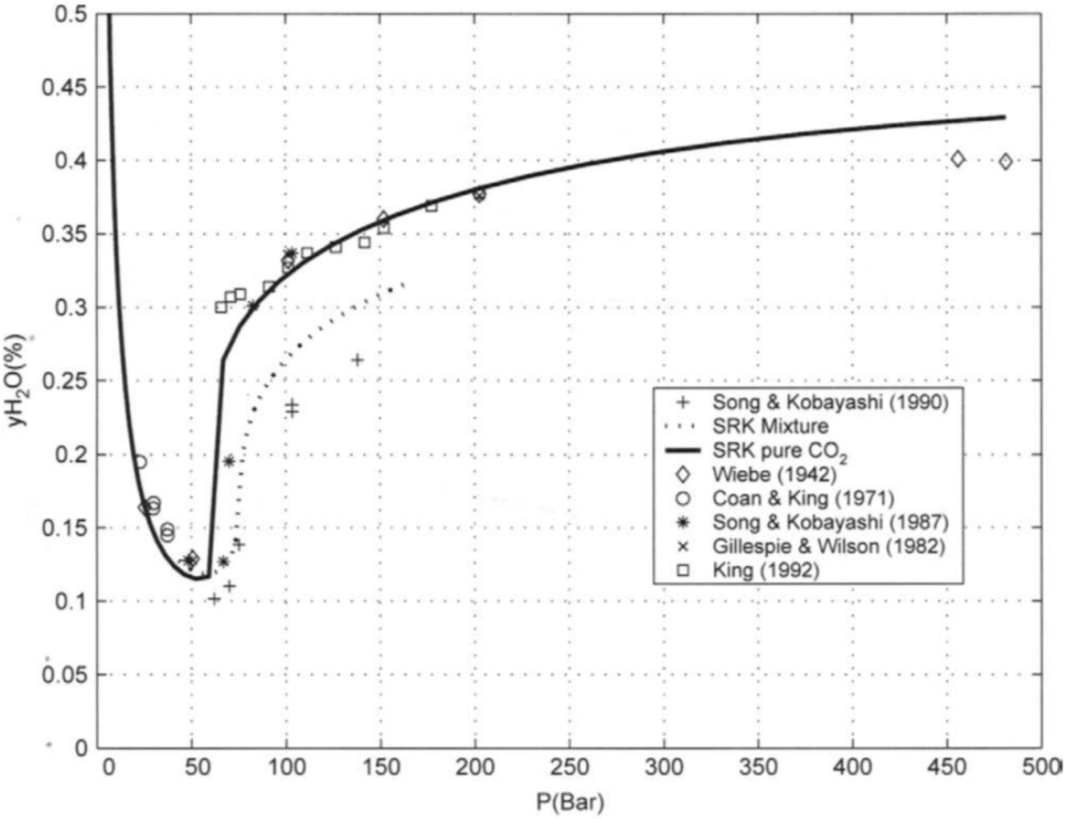

Figure 5. Comparison of model calculations at 26 °C with measurement data (from 24 to 28 °C) for the solubility of water in CO_2 (solid line) and in a mixture of CO_2 and 5.3% CH4 (dotted line) [9].

2.6 Corrosion

As mentioned above, the water content and the water solubility in the CO_2 have strong effect on the corrosion rates of the carbon steel pipeline [9]. CO_2 with water effects even greater corrosion rates than corrosion rates in strong acids at the same pH, even though carbonic acid is a weak acid compared with mineral acids [19]. When water and carbon dioxide are in the same solution, the following equilibrium happens [20]:

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-} \quad (2)$$

Carbon dioxide with water in low alloy steel equipment or pipeline can lead to iron carbonate as a reaction product [19]:

$$CO_2 + H_2O + Fe \rightarrow FeCO_3(iron\ carbonate) + H_2 \qquad (3)$$

According to Kermani and Smith (1997), CO_2 corrosion shows either as general thinning or as localized attack [19]. Carbonic acid (H_2CO_3) occurs in CO_2 mix only when free water is present [20] and the water has to wet the steel surface [19]. The time while the water wets the surface affects the severity of the corrosion attack. The main things influencing water wetting are water ratio, flow rate and regime, surface roughness and cleanliness, water drop-out (low spots), the mixing effect and chancing flow profile in bends and welds, which cause water shedding. [19]

Also hydrogen sulfide (H_2S) in CO_2 mix with free water might cause severe corrosion or sulfide stress corrosion cracking (SSCC) problems in equipment and pipelines in contact with the CO_2 flow [21]. On the other hand, the small amount of H_2S at ambient temperature might protect the steel surface as well, since the facilities exposed to gas with little H_2S may corrode at a lower rate comparing with completely sweet system. Interaction of H_2S and CO_2 with carbon steel without water in present is not known properly yet. In addition to forming protective layers it might affect localized corrosion as well. With a high concentration of H_2S, the corrosion rate might be higher and also cracking of carbon and low alloy steels might happen. [19]

Carbon and low alloy steels are widely used in the industry for many applications because they are ideal materials for construction although generally they exhibit poor CO_2 corrosion resistance. In addition to dehydration of the CO_2 flow and possible inhibitors, it is also possible to take account pH of the flow and the composition and microstructure of the steels. For example chromium as an alloying element in steel improves corrosion resistance in wet CO_2 environments. Also carbon can have an effect on the corrosion via the microstructure. The effect of the carbon is linked to cementite (Fe_3C), the carbide phase. With low carbon content in the steel (<0,1% C) like in new pipeline steels, the effect of cementite is less important. With high carbon content (> 0.15% C) the cementite can act as a framework for a protective corrosion film. Other effect of cementite in increasing the corrosion rate is when iron carbide is exposed at the steel surface when the iron is dissolved, so cementite acts as a cathode in a galvanic effect. Other parameters affecting CO_2 corrosion design are presented in Figure 6. [19]

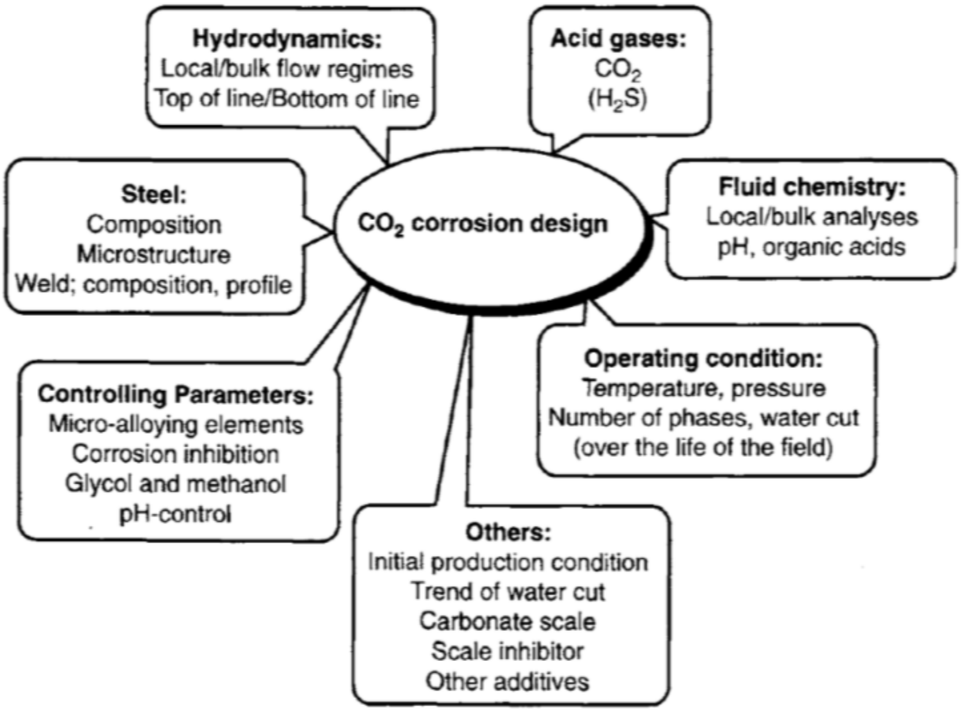

Figure 6. Parameters affecting CO_2 corrosion design.[19]

According to Kermani and Smith (1997) in practice it is possible to allow some corrosion. This will give some time to detect corrosion. If there are corrosion inhibitors in the flow, the corrosion allowance in practice is typically 6 or 8 mm, which still can be protected by corrosion inhibitors. Corrosion inhibitors are useful only when there is free water in the flow. The corrosion allowance adds the total wall thickness, which affects the inner diameter, since there is a limit for the pipe diameter, where it is still possible to manufacture and weld the pipe. Smaller inner diameter also makes it more difficult to inspect the pipeline. [19]

2.7 Valves and odourization

The amount of valves in the pipelines is also one thing to consider. With many valves it is easier to isolate and repair leakages from the pipeline but on the other hand, extra valves also mean more possible leakage places. It is also important to take a notion about bigger temperature changes near valves, because they can cause the embrittlement of the components in valves. Generally brittle fractures in the pipeline systems are more dangerous because they needs less energy to propagate than ductile fractures. That is why it is important to pay attention especially to cold temperature, since brittle fractures occur in lower temperature than ductile fractures. It is also possible to determine needed toughness for the pipeline steel with required fracture toughness to support a critical crack size, so it is easier to avoid fractures in the material. [14]

There is a possibility to scent CO_2 so it would be easier to notice even small leakages [14]. Some other possible ways to check the pipeline are on foot or by aircraft with thermal imaging or inspect the pipelines internally by “pigs” (internal pipeline inspection devices). Pigs move along the pipeline by the pressure of the gas. They can measure for example internal and external corrosion, mechanical deformation and the exact position in the pipeline. Pigs are earlier used at least in hydrocarbon pipelines. [13]

2.8 Pipeline incidents

Gale and Davison (2004) presented a table about the statistics of pipeline incidents in the USA, Table 4. They concluded that CO_2 pipelines are not less vulnerable to incidents than natural gas pipelines. The low number of incidents in CO_2 pipelines makes it more difficult to compare CO_2 pipelines with natural gas transmission and with pipelines for hazardous liquids. In general it should be safe to say that CO_2 pipelines are safer than pipelines for hazardous liquids. Also CO_2 pipelines had the lowest property damage rate per 1000 km per year. In addition to this, CO_2 incidents did not cause any fatalities or injuries. Out of total 10 CO_2 pipelines incidents between 1990 and 2001 the causes were: 4 relief failures, 3 weld/gasket/valve packing failures, 2 corrosion cases and 1 because of outside force, while with natural gas pipelines the greatest number of incidents were because of outside force, then corrosion, then “other”, then weld and pipe failures and the lowest number of incidents were because of an operator error. Outside force means basically the incidents by a third party and “other” means vandalism etc. Reason for a low number in outside force incidents with CO_2 pipelines is probably connected with the fact, that in years 1990-2001 there were not so many CO_2 pipelines, especially near human settlements. [15]

Table 4. Statistics of pipeline incident in the USA [15].

Pipelines	Natural gas transmission (1986-2001)	Hazardous liquids (1986-2001)	CO_2 (1990-2001)
No. incidents	1287	3035	10
No. fatalities	58	36	0
No. injuries	217	249	0
Property damage	US $ 285 M	US $ 764 M	US $ 469 000
No. incidents per 1000 km pipeline per year	0,17	0,82	0,32
Property damage per 1000 km pipeline per year	US $ 37 000	US $ 205 400	US $ 15 200

2.9 Standards and directives close to CO_2 transport

Directive 2009/32/EC, the geological storage of carbon dioxide concludes carbon dioxide capture and geological storage (CCS) as a technology that will contribute mitigating climate change. It also emphasizes the importance of protecting the environment and human health from the risks posed by the geological storage of CO_2. The directive does not especially specify specifications for CO_2 transport, but it gives an idea about the norms for the whole CCS process. Comparing with the articles that have been discussed in this report, the directive does not particularly give any new information. It says that CO_2 stream should consist mostly carbon dioxide and “pipelines for CO_2 transport should, where possible, be designed so as to facilitate access of CO_2 streams meeting reasonable minimum composition thresholds”. It also handles the storage places in member states area, but that part is out of this report’s field. [22]

869/1999 Pressure Equipment Act is a translated act of Finnish “Paineastialaki”, that is one of the acts of Finnish Parliament. According to the act, “pressure equipment means vessels, piping and other technical assemblies which are over pressurized or where overpressure may build up, and technical assemblies intended to protect pressure equipment”. The act gives generally norms for ensuring the safety of pressure equipment, supervising them and also for coercive measures and sanctions. [23]

Finnish Chemical law (Kemikaalilaki) 14.8.1989/744 gives general norms for acting with chemicals, but it does not include transporting chemicals on the roads or rails, by air or in ships or in post. It does not include chemicals that are just transported via Finland and not storage or handled there. According to this, carbon dioxide belongs to this law, but it does not give any special orders about carbon dioxide or its transportation, probably because the subject is still so new in Finland. The main thing concerning carbon dioxide is that quarter responsible for handling or transporting the chemical has to give necessary information about the chemical and take care of its dangerousness and ways to prevent accidents. [24]

ASTM E 1747-95 standard guide for the purity of carbon dioxide used in supercritical fluid applications concludes purity standards by speciality gas suppliers. The standard was made because of the development of carbon dioxide that is used in supercritical fluid supercritical fluid extraction (SFE) and supercritical fluid chromatography (SFC). With the standard it is possible to ensure that liquefied carbon dioxide gas is suitable for SFE and SFC applications, because standard “defines quantitation, labeling, and statistical standards for impurities in carbon dioxide that are necessary for successful SFE or SFC laboratory work”. Carbon dioxide that is used for SFE or SFC is isolated from petrochemical side streams or as a by-product of ammonia or fermentation synthesis, so it contains impurities of all kind. [17].

In addition to directives and standards, in Norway is recommended practise DNV-RP-J202, that has been developed for guidance to manage risks especially the in transportation of CO_2 in pipelines, because worldwide there is not so much experience in dense phase pipeline transportation in CCS scale. The Recommended Practise “sets out criteria for the concept development, design, construction and operation of steel pipelines for the transportation of CO_2” bot onshore and offshore. It emphasizes that local laws and regulations might variate a bit from international ones, so the pipeline operator needs to ensure the compliance. [25]

3 Discussion

Most of the main existing long-distance CO_2 pipelines are in the USA and many of them are operated by Kinder Morgan. The diameter of pipeline varies from 250 mm to 762 mm and the optimum strength and wall thickness for the pipeline depends on the temperature and pressure of the CO_2 flow. In an example pipeline, the wall thickness varies between 8,74 and 9,53 mm. It is sensible to use block valves and fracture arresters in the pipelines. Also external coating is sensible since it reduces external corrosion. External coating can be for example fusion bonded epoxy or polyurethane with full cathodic protection.

CO_2 pipelines can be made from CMn steel, X65-grade steel is used at least in some CO_2 pipelines. Corrosion resistant alloy, like stainless steel 304L should be used in parts like scrubbers, coolers, critical components in the compressors as well as piping near these parts. In other words, near the parts that are exposed to cooling for example. In addition to X65-grade steel, for example API X60- or X80-grade materials are good for the pipelines. All of these steels are seamless and welded pipe for the pipeline transportation systems, onshore and offshore, for liquid and gas.

Transportation of CO_2 is possible in a gas phase, as a supercritical fluid or in a subcooled liquid state. Liquid and supercritical phases have the highest density, so the transportation is most efficient with those phases. In supercritical phase transportation, the pressure and temperature have to be over CO_2's critical point, 31,1 °C and 7,38 MPa. In liquid transportation, the pressure should be between 3 and 5 MPa. It is possible to transport liquid CO_2 with just a little cooling or in ambient temperature, in Nordic countries the soil temperature is in winters a few degrees minus and in summers up to 6-8 °C. Two-phase areas are bad since it is difficult to handle two-phase flow, especially with compressing and pumping.

It would be easier to study the corrosion in the pipeline with exact knowledge of the impurities and their concentration in the CO_2 flow. Both the composition and the amount of impurities highly depend on the source of CO_2. Generally it is known that water is not good in CO_2 transportation since it reacts with CO_2 and forms carbonic acid which can affect corrosion. This is why it would be sensible to dehydrate CO_2 before transportation. Other impurity which is important to notify is H_2S, since it can affect localized corrosion especially if the CO_2 flow includes water.

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