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TECHNICAL AND ECONOMIC ISSUES OF OFFSHORE PIPELINE CARBON DIOXIDE TRANSPORTATION

1. INTRODUCTION

CO_2 pipeline transportation is one of method to transfer captured CO_2 from power plant to storage sites for geological sequestration or for enhanced hydrocarbon recovery at short or medium distance from capture plant location. In this paper the basic conditions of offshore carbon dioxide transportation are presented. Various flow conditions as well as the process of choosing of technological installations concept for efficient carbon dioxide pipeline transport are assumed in this paper. The flexible coiled-tubing pipeline was considered for capital investment costs reduction. Due to the limited availability of coiled-tubing pipes over 5” in diameter, for the transport of larger quantities of CO_2 it is required to use classical pipeline consisting of welded pipes. The pipeline is planned to be disposed on the seabed. It would be placed from a CO_2 preparation and pumping station on land to the offshore platform in the geological storage site area. In the area of a geologic structure the pipeline is linked to the platform installation above the sea level, and from that point carbon dioxide is pumped down to the reservoir structure. Also the costs of offshore pipeline transport are presented in this paper in comparison to onshore pipeline transport and ship transport costs.

2. COSTS OF CO_2 TRANSPORTATION

Based on worldwide experiences widely presented in journals, reports, and on workshops , it could be defined three different possibilities of CO2 transportation:

- by onshore pipeline;
- by offshore pipleline;
- by ships

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Figure 1. presents costs of CO_2 transportation by tree methods listed above as a function of distans from CO_2 source to destination point. Costs include: storage facilities (intermediate ,if needed), marine fees, fuel and loading/unloading costs.

In general, according to IPCC [1], costs of CO_2 transportation could be summarized into three categories. Various components of total costs CO_2 transportation by pipeline are presented in table 1. The examples of various costs might be found in Zero Emmision Platform Reports [2].

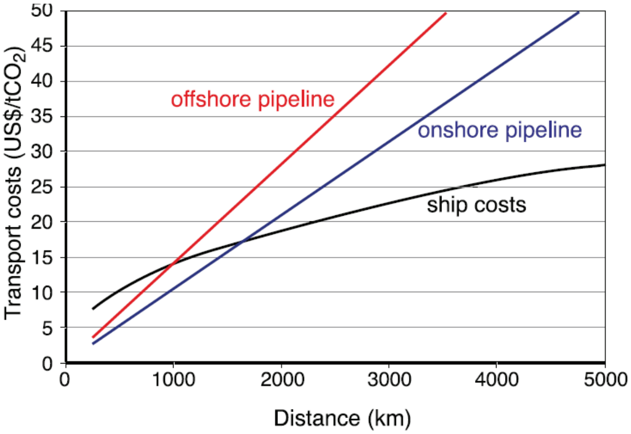

Fig. 1. CO_2 transport costs vs. distance for different transportation methods [1]

Table 1

CO_2 transportation costs [1]

Construction costs including:	Pipeline mentaince and operation costs including:	Other costs including:
– material & equipment cost; - pipe (steel price, coating e.g. 3 mm polypropylene) – -anti-corrosion protection systems (cathodic); – telecomunication and signal processing equipment; – booster station (compressors), if needed – pipeline building and equipment installiation expenditure (labour costs)	– monitoring & maintenance; – expenditure connected with energy usage	– pipeline project; – project managment; – insurance costs; – contingencies allowances; – right-of-way costs; – regulatory filing fees – other market factors

Costs of materials and equipment used in CO_2 transportation are a function of four main parameters listed below (IPCC, 2005):

- CO_2 flow rate in pipeline;
- pipeline diameter;
- pipelie length;
- quality of transported CO_2 (pressure and moisure content)

Figure 2 shows example of transportation costs as a function of CO_2 flow rate for onshore (red lines) and offshore (blue lines) pipelines on 250 km distance. High costs for onshore and offshore pipelines (dashed lines) and low costs for both (continuous lines) are presented [1].

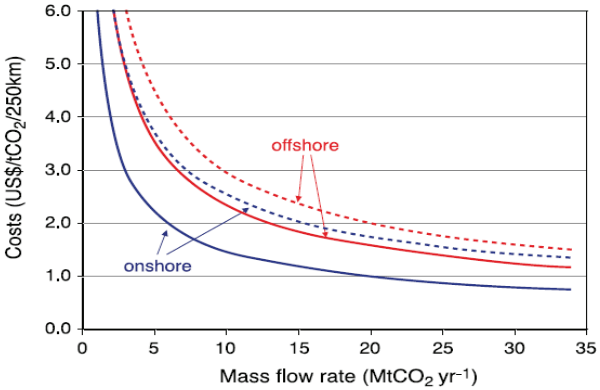

Fig. 2. Transportation costs vs. CO_2 mass flow rate [1]

Based on reports prepared by Zero Emmision Platform [2] and Welkenhuysen and Compernolle work [3], CO_2 transportation costs as a function of offshore pipelines length was calculated and shown on figure 3.

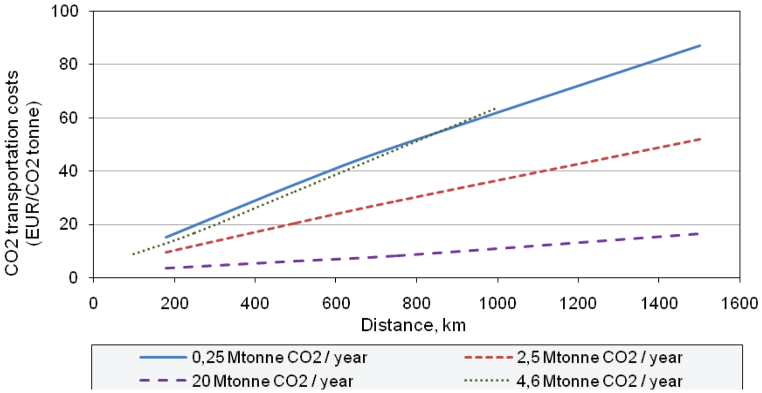

Fig. 3. CO_2 transportation costs vs. offshore pipelines length, based on: [2,3]

Total investment costs for onshore and offshore pipelines are shown on figure 4. For calculation capital charge rate of 15% was taken and 100% for load factor. Costs of CO_2 transportation as a function of diameter are presented on figure 5. For both cases capital expenditures do not include booster station.

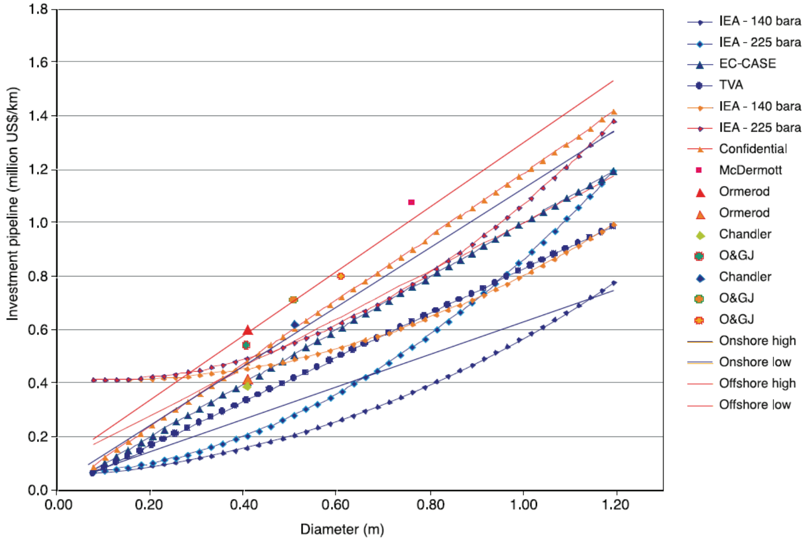

Fig. 4. Total investment costs for onshore and offshore pipelines without booster station costs [1,4,5,6,7,8,9,10,11,12]

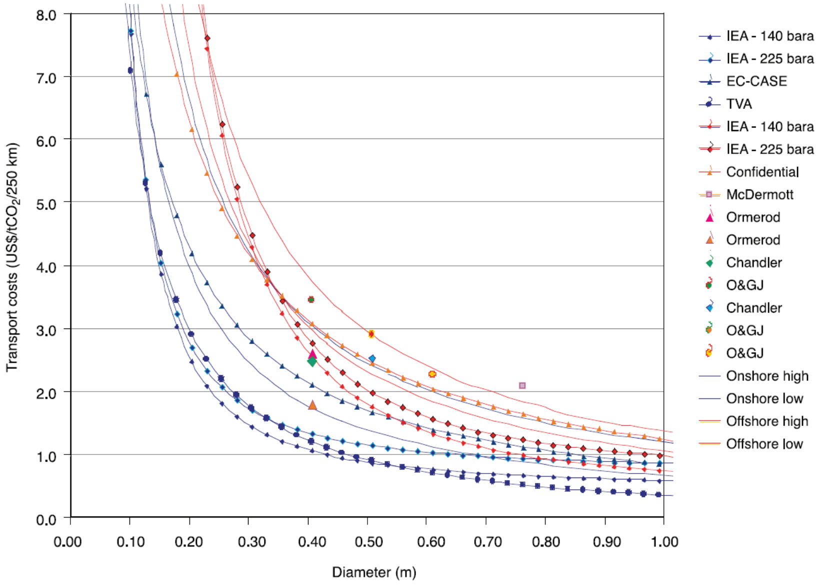

Fig. 5. Transport costs for onshore and offshore pipeline [1,4,5,6,7,8,9,10,11,12]

3. PIPELINE CONCEPTION AND IMPACT OF AMBIENT CONDITIONS

Trajectory of the exemplary offshore pipeline for carbon dioxide transport is 76 kilometers long, in its lowermost section is situated 84 meters b. s. l. The outlet point of the pipeline is disposed on the offshore platform, over the sea level. Scheme of offshore pipeline conception is shown in Fig. 6.

Ambient temperature has a high influence on the conditions of carbon dioxide pipeline transportation. In the summer, the surface layer of sea water (in moderate climate zone) heats up to about 20°C [13]. A thermocline (transient zone) is encountered at a depth of 20-30 m where shows significant drop of temperature to about 6-8°C [13]. The water temperature during the winter season in the coastal zone varies around 0°C, and with the depth slightly increases to a maximum level of about 4°C. Changes in ambient temperature as function pipeline length in summer and winter conditions are shown in Fig. 7.

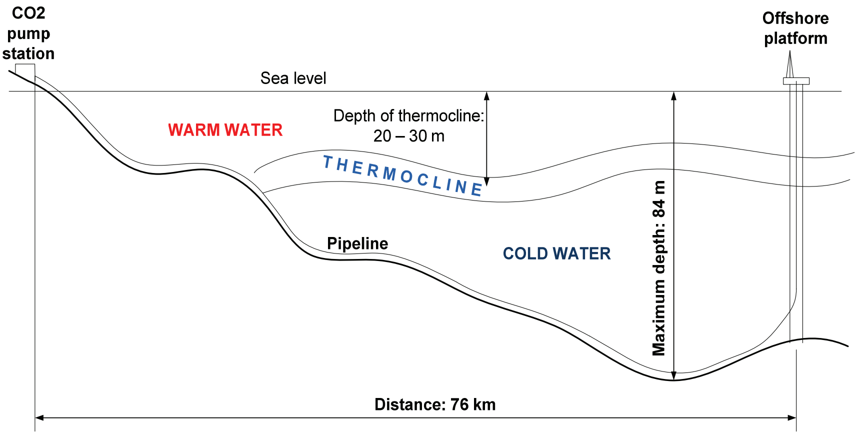

Fig. 6. Undersea offshore pipeline scheme

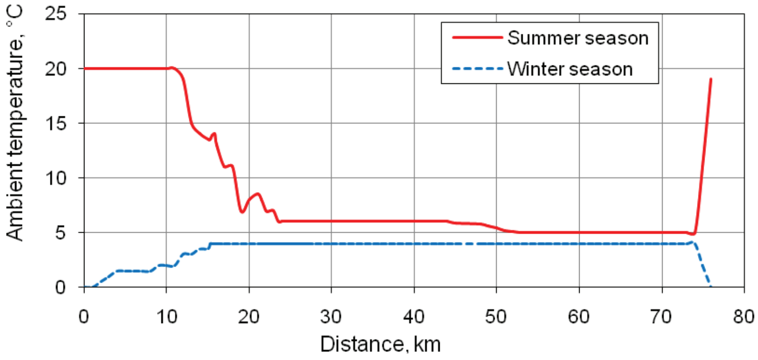

Fig. 7. Profile of ambient temperature along the proposed pipeline route, based on: [13]

4. THERMODYNAMIC ASSUMPTIONS

The thermodynamic properties of carbon dioxide are different from other fluids transported by pipeline, i.e. natural gas [14]. Carbon dioxide may be transported conventionally in the gas phase or in the liquid phase and as supercritical fluid. Examples of properties of CO_2 in each of these phases are shown in Table 2. CO_2 transport in gas phase is inefficient because of the low density of the carbon dioxide and high pressure drop as a function of pipeline length [14, 15, 16]. Carbon dioxide in liquid phase or supercritical state must be transported at a high pressure range - in the case of a supercritical state also above the critical point parameters (Table 2). Supercritical state is the most effective for pipeline transport, however, maintaining high temperature of carbon dioxide above the critical temperature is highly energy-intensive. From a technical point of view, an effective way of CO_2 transport is liquid phase transport. Liquid phase CO_2 may be transported in a wide range of pressure and temperature (the analysis of the phase envelope of mixture 99 % CO_2 and 1% N_2 - Figure 8). Above the critical pressure liquid phase occurs in a wide range of temperatures up to the critical temperature. For the liquid phase it is possible to reduce the pipeline operating pressure at a lower temperature of transported carbon dioxide. In this case, the pipeline transport of CO_2 has a higher energy efficiency, but it is necessary to control the temperature of transported CO_2 and impact of ambient conditions. The increase of temperature can result in the emergence of a two-phase system and consequently, a rapid drop of pressure in the pipeline because of lower density and then transition to the gas phase.

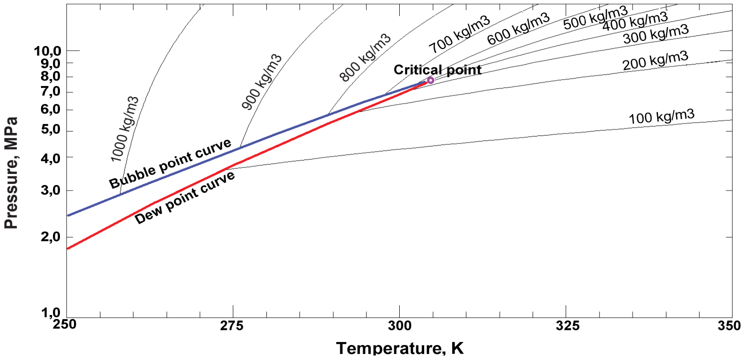

Fig. 8. Plot p-T (phase envelope) for a bi-component mixture of CO_2 (mole percentage 99%) and N_2 (mole percentage 1%)

Table 2

Exemplary properties of CO_2 in different phases for pipeline transport based on: [16]

	Gaseous	Liquid below critical pressure	Liquid above critical pressure	Supercritical	Critical point
Pressure, MPa	3 – 4	Above 6	Above 7.5	Above 7.5	7.38
Temperature, °C	10 – 15	Below 15	Up to 30	Above 35	31.1
Density, kg/m^3	70 – 100	800 – 900	700 - 1100	300 – 800	468
Viscosity, μPas	~ 15	~ 70 – 80	~ 80 - 110	~ 25 – 60	~ 40

5. SELECTION OF MATERIALS

Bearing in mind the assembly mode and the unevenness of the seabed, a coiled-tubing pipeline has been proposed. For this solution, relatively small diameters of pipelines are used (maximum 6” outer diameter –OD) which creates optimum conditions for the assumed rates of CO_2.

The coiled-tubing pipeline is laid on the seabed with the use of a drum method, i.e. the pipeline is unwrapped from a drum disposed on a floating vessel. In this way the operators can lower the investment costs, operational costs and the risk related to the project realization [17].

Covered pipes produced in the coiled-tubing technology can be 1500 m long for 5” OD and 7000 m long for 2 3/8” OD, which creates great construction possibilities for the undersea pipelines. In view of this, coiled-tubing pipelines are recommended for CO_2 transport to a reservoir area with a mass flow rate up to $0.3MtCO_2$/year. Simulations will be performed for this type of pipeline at the mass flow rate of $0.3MtCO_2$/year.

The proposed coiled-tubing pipelines should comply with the standard API 5LC. They should be made of steel X52C or X65C for nominal outer diameters 3.5” to 5”. In view of the expected operating pressure of the pipeline, the coiled-tubing pipelines of steel X52C with minimum thickness of pipeline walls were proposed for the calculations. The maximum admissible operating pressure for pipelines of given diameters are listed in table 3.

Table 3

Operating pressure and hydraulic test pressure for coiled-tubing pipelines
(parameters assumed from the producer’s catalog [18])

Outer diameter OD inch / mm	Inner diameter ID inch / mm	Maximum operating pressure psi / MPa	Hydraulic test pressure psi / MPa
5” / 127 mm	4.5” / 114.3 mm	3600 psi / 24.82 MPa	4500 psi / 31.03 MPa
4,5” / 114.3 mm	4” / 103.9 mm	3280 psi / 22.16 MPa	4100 psi / 28.27 MPa
4” / 101.6 mm	3.55” / 90.9 mm	4000 psi / 27.58 MPa	5000 psi / 34.48 MPa

6. CALCULATION AND SELECTION OF PIPELINE DIAMETER

The basic problem encountered of pipeline designing process is to determine optimum diameter. Pipeline diameter may be calculated using following formula for average temperature conditions (isothermal flow) based on Bernoulii equation and Peng-Robinson equation of state [19, 20]:

$$D = \left(\frac{16\lambda z^2 R^2 T^2 L M^2}{\pi^2 \left[zRt\left(p_2^2 - p_1^2 \right) \right] - 2 g p_{sr}^2 \Delta h} \right)^{\frac{1}{5}} \tag{1}$$

Where λ is linear friction factor, z is compressibility factor, R is specific gas constant, T is average temperature, L – pipeline distance, M – mass flow rate, p_1 – inlet pressure, p_2 – outlet pressure, g – gravity constant, p_{sr} – average pipeline pressure and Δh is level difference.

The basic assumptions for pipeline diameter selection have been found by simulation program. Two variants of mass flow rate were analyzed in the paper:

- 0.1 MtCO_2/year
- 0.3 MtCO_2/year – basic variant

Pressure at the pipeline output was determined in order to maintain the transported carbon dioxide in a liquid phase within the pressure and temperature range assumed for the pipeline operation:

- 6.0 MPa (T_{max} = 15°C - to maintain the liquid phase at a specified pressure 6 MPa);
- 7.0 MPa (T_{max} = 25°C - to maintain the liquid phase at a specified pressure 7 MPa).

Length of pipeline – 76 km;

Maximum change of ground level – 84 m;

Calculated diameter as a result of equation (1) was compared with available diameters from producer's catalogue. Tables 4 and 5 provide data on the basis of which the pipeline diameter and the pipeline's operating pressure (determined with simulation software) required for the assumed diameter and mass flow rate values can be determined.

Table 4

Required input pressure for selected diameters depending on the mass flow rate and assumed outlet pressure of 6 MPa, according to the performed simulations

Coiled tubing pipeline (steel X52C)				
Pressure at the pipeline outlet [MPa]	Outer diameter OD inch / mm	Inner diameter ID inch / mm	Mass flow rate [MtCO_2/year]	Pressure at the pipeline inlet in summer period [MPa]
6.0 MPa (T_{max} = 15°C)	5" / 127 mm	4.5" / 114.3 mm	**0.1**	**7.02**
			0.3	**11.38**
	4.5" / 114.3 mm	4" / 103.9 mm	**0.1**	**7.43**
			0.3	**14.44**
	4.0" / 101.6 mm	3.55" / 90.9 mm	**0.1**	**8.32**

Table 5

Required inlet pressure for selected diameters depending on the mass flow rate and assumed outlet pressure of 7 MPa, according to the performed simulations

Coiled tubing pipeline (steel X52C)				
Pressure at the pipeline outlet [MPa]	Outer diameter OD inch / mm	Inner diameter ID inch / mm	Mass flow rate [MtCO_2/year]	Pressure at the pipeline inlet in summer period [MPa]
7.0 MPa (T_{max} = 25°C)	5" / 127 mm	4.5" / 114.3 mm	**0.1**	**7.93**
			0.3	**12.30**
	4.5" / 114.3 mm	4" / 103.9 mm	**0.1**	**8.25**
			0.3	**15.35**
	4.0" / 101.6 mm	3.55" / 90.9 mm	**0.1**	**9.19**

Figure 9. presents a graphical dependence of the required inlet pressure vs. pipeline diameter for a few mass flow rate values.

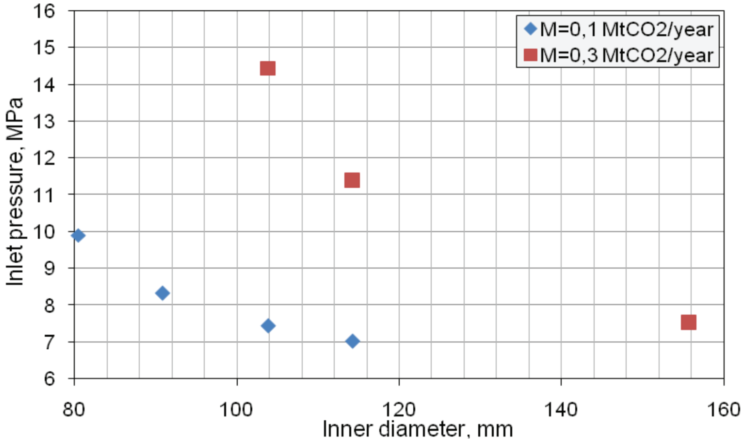

Fig. 9. Required pressure at the pipeline inlet vs. inner diameter of pipeline for the outlet pressure of 6 MPa

7. CONCEPT OF TECHNOLOGICAL SYSTEMS

Pipelines designed for CO_2 transport should be equipped with suitable technological systems for both: transport at a high pressure and also at the stage of preparation to the transport. This should ensure efficient and safe transport of CO_2.

Two variants of CO_2 pipeline transport are possible:

In the first variant the CO_2 preparation station, compression station and pumping stations are installed on land. Then carbon dioxide is pumped towards the reservoir area at such an input pressure, that the required wellhead pressure is obtained at the pipeline outlet and CO_2 can be injected to the geologic structure of the reservoir (Fig. 10).

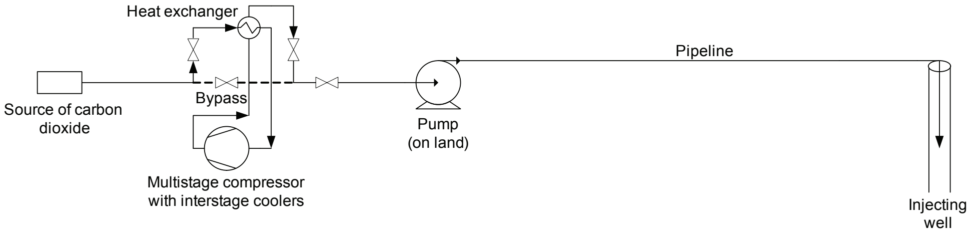

Fig. 10. CO_2 transport scheme – increase of pumping pressure to a value at which the pipeline transport from one place to the injection site and then injection of carbon dioxide to the wellbore is possible

In the second variant, apart from installations mentioned above, additional CO_2 pumping stations are proposed on the offshore platform within the area of the reservoir (Fig. 11). This should allow for the regulation of pipeline inlet pressure, which shall no longer depend on the required wellhead pressure. The CO_2 could be injected with the use of a pump installed on the platform. Apart from this, the operators could select the injection parameters directly on the platform.

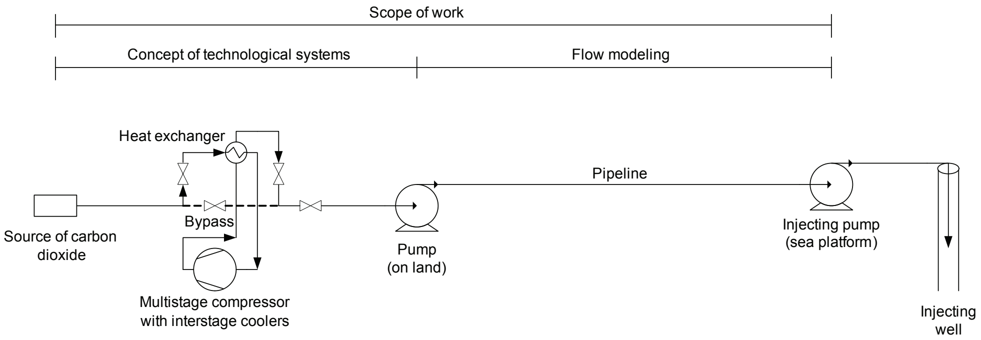

Fig. 11. CO_2 transport scheme – installation of pumps transporting CO_2 to a geological structure on a offshore platform

The second variant has many technological advantages, though the investment costs may be increased by the cost of installation of additional injection pumps. The minimum outlet pressure before the CO_2 injection pump was assumed to be of 6 MPa (at maximum temperature 15 deg C) to maintain CO_2 in liquid phase.

The basic technological systems accompanying CO_2 transport are:

- station where CO_2 is prepared for transport;
- CO_2 compression and pumping station;
- heat exchanger station.

The shut-off and relief systems will not be used in the offshore conditions; the shut-off fixtures should be used at the onshore section, before the undersea one begins. In the offshore conditions no diagnostic pig launchers and catchers will be applicable either. The inability to inspect the coiled-tubing pipeline and the classic pipeline makes it necessary to thoroughly clean and dry CO_2 prior to transporting it through the pipeline.

8. CARBON DIOXIDE COMPRESSION AND INTERSTAGE DRYING

When carbon dioxide is continuously delivered in a gaseous form and we want to fit in the proposed transport conditions, CO_2 should be compressed in multistage compressors with interstage cooling in heat exchangers, and reduced to the liquid state. Therefore, multistage piston compressors with electrical drive are proposed. Pumping systems which increase the CO_2 pressure to the assumed value should be used for transporting carbon dioxide to the platform within an exemplary reservoir area.

Carbon dioxide can be efficiently cleaned of water traces by interstage drying during multistage compression. Compression and interstage drying of CO_2 were simulated for the basic variant. The results are available in table 6.

The last stage of compression is followed by cooling of CO_2 to a temperature of 5°C as a consequence of which the gas obtains a liquid phase.

Table 6

Simulation of CO_2 compression in a 6-grade compressor with a demo software. Own study

Compression stage		**1**	**2**	**3**	**4**	**5**	**6**
Mass flow rate	Mt/year	0.3	0.3	0.3	0.3	0.3	0.3
CO_2 content	%	98.5	98.5	98.58	98.77	98.87	**98.91**
N_2 content	%	1.0	1.0	1.0	1.0	1.0	**1.0**
H_2O content	%	0.5	0.5	0.42	0.23	0.13	**0.09**
Pressure at the inlet	MPa	**0.1**	**0.2**	**0.41**	**0.81**	**1.68**	**3.41**
Pressure at the outlet	MPa	**0.21**	**0.42**	**0.85**	**1.72**	**3.48**	**7.07**
Input temperature	°C	**20**	**15**	**15**	**15**	**15**	**15**
Output temperature	°C	**70.8**	**66.8**	**67.4**	**68.5**	**71.0**	**75.2***
Steam directed to interdrying – parameters before compression at a given compression stage							
Mass flow rate	kg/h	-	-	10.6	28.4	13.6	5.1
CO_2 content	%	-	-	**0.3**	**0.6**	**1.2**	**2.4**
H_2O content	%	-	-	**99.7**	**99.4**	**98.8**	**97.6**

*- after compression the CO_2 stream should be cooled down and liquefied

9. PRESSURE AND TEMPERATURE CHANGES IN THE PIPELINE

The carbon dioxide pipeline transport from the land to an offshore platform was simulated with dedicated computer software based on numerical calculations for the assumed pipeline trajectory. The simulations cover pressure and temperature profile for the outer diameter 4.5” and 5” (coiled-tubing) and mass flow rates (0.1 $MtCO_2$/year and 0.3 $MtCO_2$/year – basic variant). Pressure profiles as a function of pipeline length for the selected pipe diameters 4.5 “and 5” and two mass flow rate variants are shown in Figure 12.

Due to the high variability of seawater temperatures in the surface zone (to about 20 m of depth) in a moderate climate zone, the temperature changes of transported CO_2 were simulated for summer season conditions. Presented in figure 13 simulations were made for a pipeline outlet pressure 6 MPa, pipeline outlet diameter of 5” and mass flow rate 0.3 Mt/yr for three variants: pipeline located on seabed, coated under the seabed and thermally insulated.

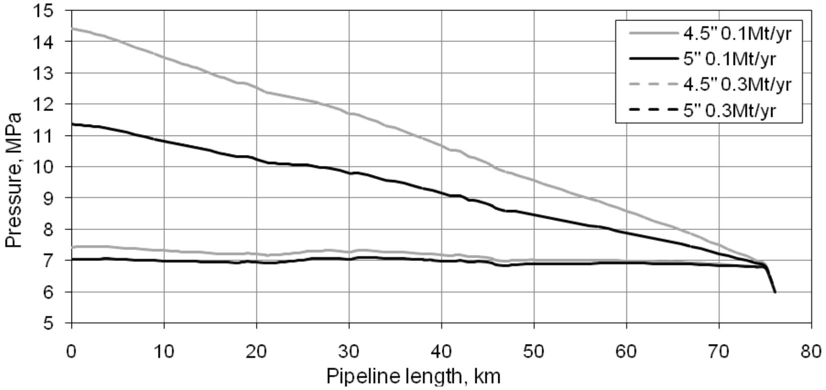

Fig. 12. Profile of pressure changes in a coiled-tubing pipeline with 4.5” and 5” outer diameter and assumed outlet pressure of 6 MPa for two variants of mass flow rate

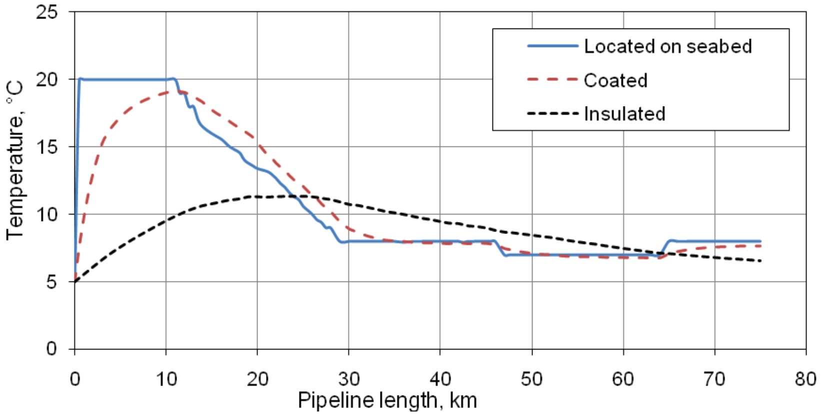

Fig. 13. Simulation of temperature changes in a coiled-tubing pipeline of 5” outer diameter at a mass flow rate of 0.3MtCO_2/year in summer season

The simulations of temperature changes confirmed that the liquid phase can be maintained at lower outlet pipeline pressure (min. 6 MPa) due to the temperatures on the seabed. The use of thermal insulation should be considered in coastal zone where the influence of ambient temperature is relatively high especially in summer season.

10. SUMMARY

The basic thermodynamic, technical and economic conditions in which carbon dioxide will be transported by offshore pipeline are presented in this paper.

In the preferred variant, CO_2 is to be transported in a liquid phase through a pipeline. A few pipeline diameter options were considered to determine the pipeline operating pressure for two maximum mass flow rate values. The analysis of the assumed variants reveals that carbon dioxide can be transported undersea with coiled-tubing pipelines at a distance of about 80 km.

The way in which materials for the pipeline construction are selected has been analyzed. The coiled-tubing pipeline is recommended for a mass flow rate up to 0.3 $MtCO_2$/year, and the classic steel pipeline (owing to the required larger diameter) for 0.6-0.9$MtCO_2$/year, respectively.

A few variants of pipeline diameter are proposed, depending on the mass flow rate value. For the basic variant (0.3$MtCO_2$/year) the proposed pipeline option is coiled-tubing pipe with outer diameter 5”. Coiled-tubing pipeline can reduce investments costs.

For the basic variant the inlet pipeline (5” OD) pressure should be equal to: 11.38 MPa for outer diameter of 5 inch and 14.4 MPa for outer diameter of 4.5 inch, respectively, so that carbon dioxide in a liquid phase is transported. The simulations of temperature changes and the analysis of the results confirmed that the liquid phase can be maintained at lower outlet pipeline pressure (min. 6 MPa) due to the temperatures on the seabed. The use of thermal insulation can be recommended to minimize the influence of ambient temperature amplitudes in the coastal zone, onshore section and the surface zone at the platform.

Costs of offshore pipeline transportation are relatively higher than onshore pipeline. For long distances the transport of CO_2 by ships might be considered.

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