The Possibility of CO_2 Pipeline Transport for Enhanced Oil Recovery Project in Poland

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Abstract. Enhanced oil recovery schemes involve the transportation of large volumes of carbon dioxide from the capture source to the utilisation site. This research presents the possibilities of carbon dioxide transport using pipeline from the selected emission point to the oil reservoir located in Poland where greenhouse gas can be used as injecting fluid to improve oil production. In the first step, the different CO_2 thermodynamic states are analyzed. For the design purpose, length, operating pressures and flow rates are determined, then pipeline diameter is calculated. Furthermore, the pipeline transmission schemes for CO_2 transport are proposed. The study revealed, that the large amount of CO_2 produced at source power plant can be transported to the oilfield site more efficiently when CO_2 is converted into the liquid state. As a result, the smaller pipeline diameter can be applied for the transmission. Moreover, temperature decrease is observed when CO_2 is transported in gaseous state and temperature increase is present when CO_2 is in the liquefied state.

1 Introduction

Enhanced oil recovery (EOR) is a term used for a wide variety of techniques for increasing the amount of crude oil that can be extracted from an oil field. Carbon dioxide injection has been found to be commercially successful to improve oil production [1]. The process of CO_2-EOR project is divided into the stages of preparation, transport and injection of CO_2 into oil reservoir. Main methods of carbon dioxide land transportation are pipeline transmission. [2].

The most developed network of carbon dioxide pipelines is located in the United States. First CO_2 pipelines were constructed in the USA in the 70's of the twentieth century. Present, the overall length of CO_2 pipelines across the globe is above 6500 km. Million tons of CO_2 per year is transported using pipeline network [3].

Depending on thermodynamic properties, CO_2 can be transported in gaseous phase, in liquid state or in supercritical conditions. In this research, the possibilities of carbon dioxide transportation by buried pipeline from anthropogenic emission source to oil reservoir for CO_2-EOR project in Poland are presented.

2 Analysis of CO_2 thermodynamic states

2.1 CO_2 pipeline transmission in gas phase

The thermodynamic conditions of CO_2 gaseous phase are limited for pipeline transport. The first problem is the maximum operating pressure in the pipeline [4]. In Poland the ground temperature during Spring/Autumn at the depth of 1 m below ground (the pipeline level) does not exceed 10°C. As result, the maximum operating pressure in the pipeline can be equal of 4 MPa. During Summer time, ground temperature of 20°C at the depth of pipeline placement allow to increase the maximum operating pressure to 4.8 MPa. During Winter, it is often that at a depth of one meter temperature is close to 0°C. In these conditions the maximum allowable operating pressure drops below 3 MPa. Such restrictive values of maximum operating pressure for CO_2 transmission are related to thermodynamic boundaries. Increase of pressure above saturation pressure at given temperature causes phase transition into liquid phase, what pose a risk to the transmission equipment. For these reasons, CO_2 pipeline transport in gas phase should be considered for short distance [5].

2.2 CO_2 pipeline transmission in liquid phase

Carbon dioxide in the liquid phase has higher density than in the supercritical state or in gaseous state, this fact together with slight compressibility of the liquid CO_2 lead to the smaller pressure drops along the pipeline. Consequently, it is possible to transport liquid CO_2 at relatively long distances using smaller pipe diameters comparing to other ways of transport. As a result the much larger quantities of CO_2 can be transported efficiently [6]. However, viscosity pose a problem for the transportation of CO_2 in the liquid phase because its value is greater than in the gas phase and in the supercritical state. The great threat in liquid CO_2

transportation is uncontrolled pressure drop in the pipeline what may result in liquid-gas two-phase system flow [7].

In Poland the possible operating range of the liquid pipeline CO_2 transport is within the pressure of 3.5-5.8 MPa for ambient temperature from 0 to 20°C. Taking into consideration the temperature fluctuation during the year, carbon dioxide should be transported in pressure above 5.8 MPa. Despite the challenges associated with liquid CO_2, the pipeline transmission is the most advantageous way transportation due to the favorable thermodynamic parameters.

2.3 CO_2 pipeline transmission in supercritical phase

Supercritical state of carbon dioxide can be obtained by exceeding the critical parameters: pressure 7.4 MPa and temperatures 31.1°C. Supercritical carbon dioxide has a density comparable to the liquid state and its viscosity and compressibility are comparable the gas phase. These supercritical CO_2 characteristics determine that the thermodynamic transport of CO_2 in the supercritical state as advantageous solution [8]. Due to the high critical temperature, additional CO_2 heating stations are required. Moreover, in case of temperature or pressure drop below the critical value, the occurrence of a two-phase system can be observed. This fact will result in the CO_2 density decrease and pressure drop is observed [9]. Energy consumption and additional costs make transport CO_2 in supercritical state as unprofitable in Poland.

3 CO_2 pipeline design

3.1. Pipeline diameter calculation

Pipeline diameter has a decisive influence on the flow characteristics and the energy loss. In order to analyse the most important factors such as mass flow rate, pipeline operating pressure range and land elevation change on pipeline diameter, the following formula can be used:

$$D = \sqrt[5]{\frac{16 \cdot \lambda \cdot z^2 \cdot R^2 \cdot T^2 \cdot L \cdot M^2}{\pi^2 \cdot [z \cdot R \cdot T \cdot (P_1^2 - P_2^2) - 2 \cdot g \cdot P_{av}^2 \cdot \Delta h]}} \quad (1)$$

Where: λ-friction factor, z-compressibility factor, R-gas constant, T-temperature, L-length, M-mass flow rate, P_1-ilet pressure, P_2-outlet pressure, g-gravity acceleration, P_{av}-average pressure, Δh-elevation difference.

Design calculations and cost comparative analysis allow the investors to choose a pipeline transport of carbon dioxide using larger diameters and less pumping stations or smaller diameters with more pumping stations. For this reason, the design of the CO_2 transport pipeline should be customized to the efficient transfer of contracted CO_2 quantities, while maintaining the lowest capital expenditures and the operating expenses.

3.2. Pipeline route

The proposed pipeline length from CO_2 source (EDF Krakow power plant) to Grobla oilfield is equal to 34.8 km. The pipeline will be located in the densely populated and industrial areas of Krakow. There are numerous collisions with the linear infrastructure (public roads, power lines, water pipelines, gas pipelines, etc.). Moreover, it will be necessary to create a crossing under the Vistula River e.g. by using trenchless technology. The route of the planned pipeline is shown in the Figure 1.

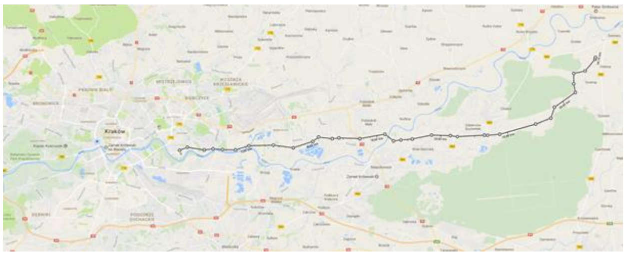

Figure. 1. The proposed route for the pipeline connecting EDF Krakow (CO_2 emitter) with Grobla oilfield.

2.4 Pipeline operational range

Maximum operating pressure for carbon dioxide in gas phase should not exceed 3 MPa in Winter and 4 MPa during Summer. Climate conditions in Poland determine these limits. Dew point for carbon dioxide at temperature of 0°C is equal to 3.4 MPa and for temperature of 20°C about 5.6 MPa. In case of necessity to transport relatively large amount of captured CO_2 from the emission source to the Grobla injection site, the transmission of CO_2 in the liquid phase will also be considered. Worldwide experience with liquid CO_2 transmission indicates the minimum operating pressure above 8 MPa. The CO_2 transmission flow rates for injection into Grobla oil reservoir are assumed as:

a) minimum flow rate equal to 9 750 Nm^3/hr,

b) maximum flow rate equal to 107 650 Nm^3/hr,

f) variant for 60% and 30% of maximum carbon dioxide source capacity,

e) above flow rates of gaseous CO_2 transferred in the liquefied state.

3.3. CO_2 pipeline transmission

2.1.1 Gas phase

For the CO_2 transmission in gaseous state, the double compression system is proposed. At first, CO_2 from the capture installation for pipeline transport is pressurized for the purpose of transmission and prior to injection, CO_2 is compressed the second time at oilfield site. In Figure 2 the schematic sketch for CO_2 pipeline transportation in gaseous state from source to oilfield injection site is presented.

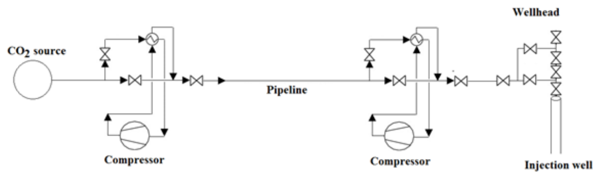

Figure. 2. Schematic sketch for CO_2 pipeline transportation in gaseous state from source to oilfield injection site.

2.1.1 Liquid phase

In the second transmission method, CO_2 is transferred in liquid state what allows for higher operating pressures. For this purpose, after capturing CO_2, gas is compressed to 10 MPa, then cooled and converted into the liquid phase. In the next stage carbon dioxide is sent by pipeline using pumps. Depending on the required injection pressure, it is possible to place the additional CO_2 injection pump at the end of pipeline - directly before injection well. This method eliminates using large pipeline diameters at high flow rates because the pressure drop for liquid flow is lower comparing to gas flow. However, the construction of pumping station, heat exchangers and condensers to convert CO_2 into liquid phase, which also significantly increases the investment costs. The CO_2 booster pump demands less input energy than the compressors. Scheme of second proposed method is presented in Figure 3.

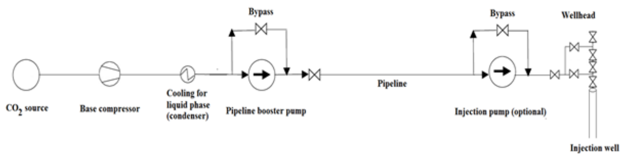

Figure. 3. Schematic sketch for CO_2 pipeline transportation in liquid state from source to oilfield injection site.

4 Results and discussion

The most influential parameters on determining the pipeline diameter are: length, flow rate and operating pressure. It was assumed that the inlet pressure for gaseous carbon dioxide pipeline transmission is equal to 3 MPa for Winter and 4 MPa for Summer. For liquid phase, the minimum operating pressure is set above 8 MPa. For the pipeline diameter determination, several variants of flow rate were taken into consideration which are described in the previous section. The calculated diameters for the designed pipeline as function of pressure are presented in Figures 4 - 8 for the assumed variants.

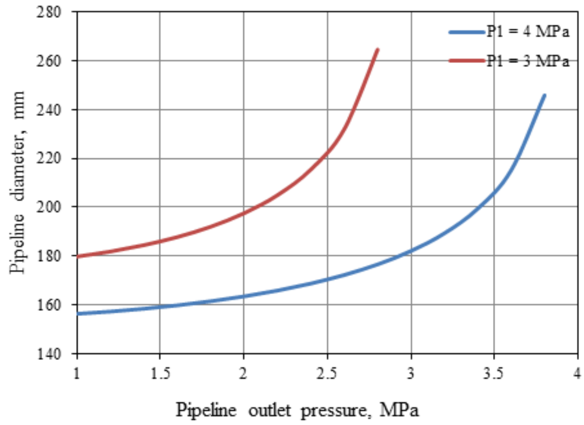

Figure. 4. Diameter estimation for pipeline from EDK Krakow source for minimum flow rate variant and two inlet pressures as a function of outlet pressure

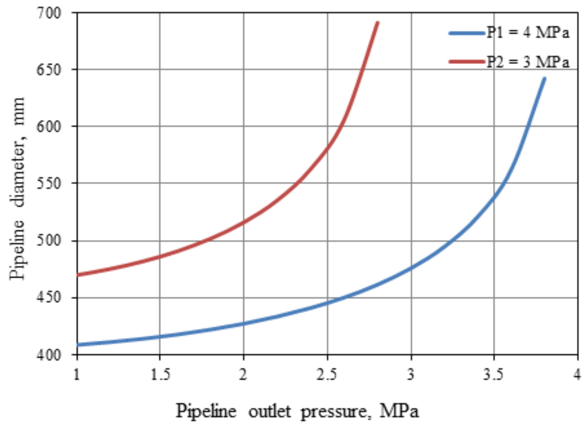

Figure. 5. Diameter estimation for pipeline from EDK Krakow source for maximum flow rate variant and two inlet pressures as a function of outlet pressure

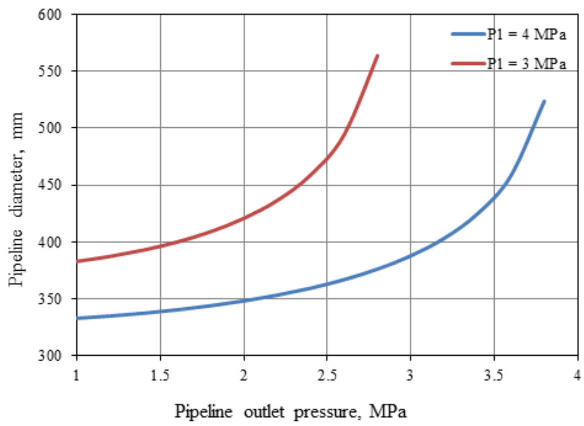

Figure. 6. Diameter estimation for pipeline from EDK Krakow source for 60% of maximum flow rate variant and two inlet pressures as a function of outlet pressure

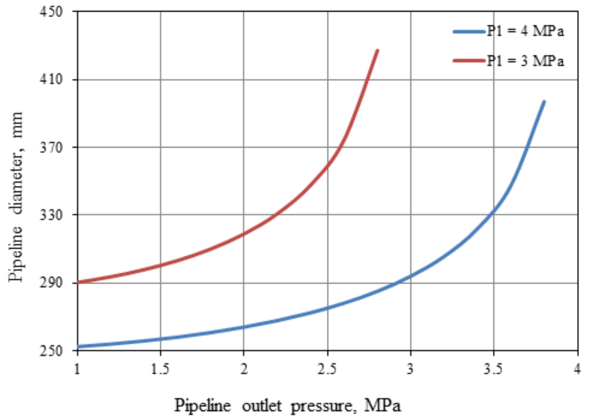

Figure. 7. Diameter estimation for pipeline from EDK Krakow source for 30% of maximum flow rate variant and two inlet pressures as a function of outlet pressure

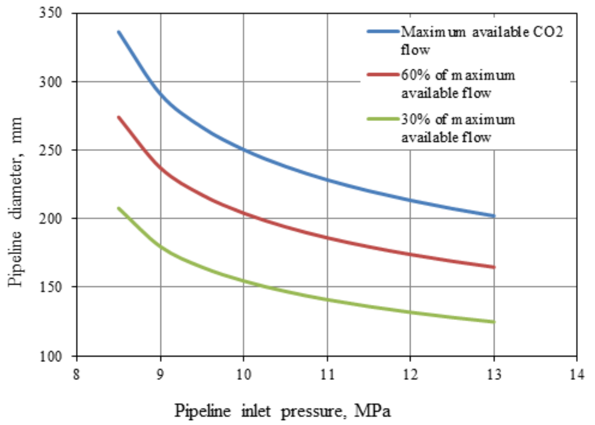

Figure. 8. Diameter estimation for liquid CO2 pipeline from EDK Krakow source for three variants of flow rate as a function of pipeline inlet pressure.

Figures 4-8 show the pipeline diameters for pipeline from EDF Krakow CO_2 emission source to the Grobla oil reservoir for the different flow rate variants as function of the pipeline pressure. For the projected pipeline, the optimum diameter for the minimum gaseous CO_2 flow rate variant is 200 mm. As a result, the outlet pressures will be 3.4 MPa for higher inlet pressure and 2.2 MPa for lower inlet pressure, respectively. For the maximum flow rate variant (gaseous CO_2), the optimum pipe diameter is equal to 500 mm and outlet pressures will be 1.75 MPa for lower inlet pressure and 3.2 MPa for higher inlet pressure. For lower inlet pressure the pipe diameter of 600 mm should be considered to obtain outlet pressure of 2.6 MPa. For gaseous state, two more variants of flow rates were analyzed - 60% and 30% of maximum declared CO_2 flow rate. In the first case, the proposed pipeline diameter should be 400 mm and in the second case 350 mm. For liquid carbon dioxide transportation calculated diameters are lower than for gaseous phase. The proposed diameter for maximum variant of flow rate is 250 mm (for assumed 2 MPa pressure drop in the pipeline). The diameters for liquefied CO_2 transfer in quantity of 60% and 30% of the maximum flow rate are equal to 200 mm and 150 mm, respectively.

In Figures 9-14 pressure and temperature profiles as function of pipeline length are presented for the maximum assumed flow rate variant and determined pipeline diameters. The surrounding ground temperatures are related to the ambient temperatures for Summer and Winter.

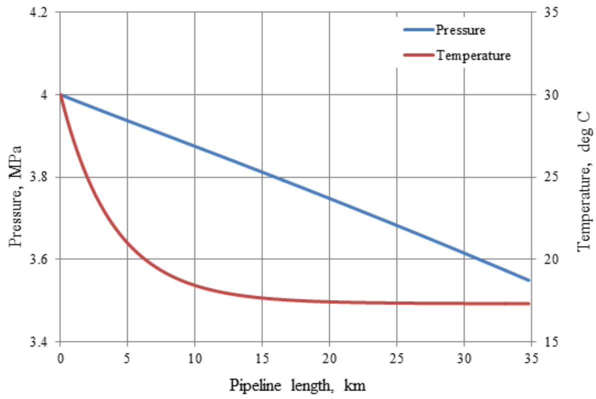

Figure. 11. Pressure and temperature profiles of gaseous carbon dioxide as a function of pipeline length for 500 mm, minimum available flow rate, inlet pressure 4 MPa, inlet temperature 30°C, the surrounding ground temperature 18°C.

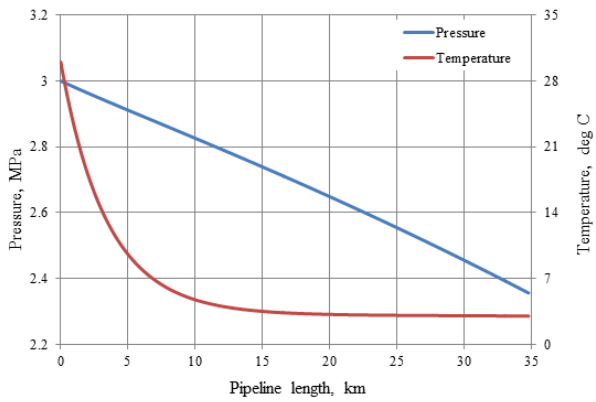

Figure. 12. Pressure and temperature profiles of gaseous carbon dioxide as a function of pipeline length for 500 mm, minimum available flow rate, inlet pressure 3 MPa, inlet temperature 30°C, the surrounding ground temperature 4°C.

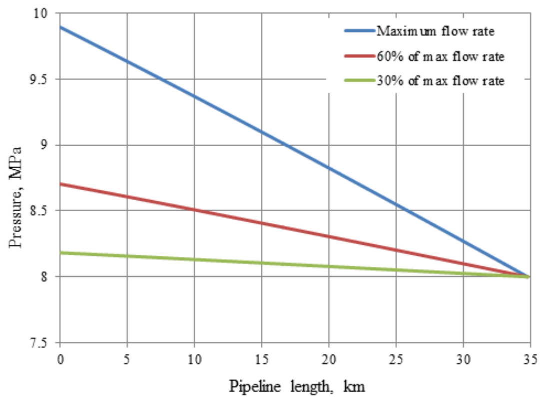

Figure. 13. Pressure profiles of liquid carbon dioxide as a

function of pipeline length for 200 mm, the three flow rate variants, outlet pressure 8 MPa, inlet temperature 10°C, the surrounding ground temperature 18°C.

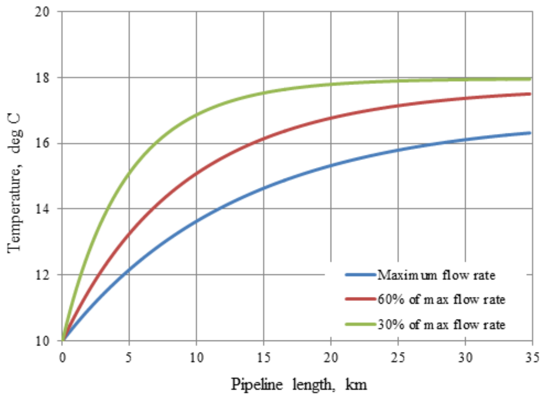

Figure. 14. Temperature profiles of liquid carbon dioxide as a function of pipeline length for 200 mm, three variants of flow rate, outlet pressure 8 MPa, inlet temperature 10°C, the surrounding ground temperature 18°C.

For gas and liquid cases of the transport, the pressure and the temperature profiles along the 34.8 km long pipeline were determined. The linear pressure drop is observed in Winter and Summer. In terms of temperature drop for gaseous CO_2 transport, carbon dioxide reach the temperature of the surrounding ground after 20 km distance for both summer and winter periods. For the liquid CO_2, temperature increase of 8°C is observed at oilfield site when 30% of maximum carbon dioxide source capacity is transported. For the maximum flow rate variant, more than 6°C increase is registered. Temperature increase is caused by the surrounding temperature of pipeline, since it is higher than the CO_2 fluid temperature at inlet point. The pressure and temperature drops obtained in this study are in line with the literature [10].

4 Conclusions

In this study, two methods were used to transport CO_2 over long distance: either as a gaseous state or as a subcooled liquid. Gas phase transport is disadvantaged by the low density and consequently large pipe diameter. Carbon dioxide in the gas phase is relatively heavy and its density causes high pressure drop. This is the reason that carbon dioxide is transmitted in the gas phase mainly for short distances with small flow rates. Gaseous CO_2 transport is additionally limited by the maximum pressure. For the winter conditions in the case of low temperature, the maximum allowable operating pressure cannot exceed 3 MPa, above which carbon dioxide may condense in the pipeline. In the analyzed cases, pipeline transport for the CO_2 gas phase is possible, however, for the maximum flow rate variant, the required pipeline diameters is equal to 500 mm. The application of large pipeline diameter significantly raises the project investment costs. Therefore, in the case of large quantities of carbon dioxide, the more efficient way of transport is to convert CO_2 into the liquid phase. This solution requires heat exchanger installation, however, the pump booster application allows for a significant operating cost reduction comparing to the gas compressors.

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