A new stepwise and piecewise optimization approach for CO₂ pipeline

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Abstract: The process of CO₂ capture, transportation, enhanced oil recovery (EOR) and storage is one of the best ways for CO₂ emission reduction, which is also named as Carbon Capture, Utilization and Storage (CCUS). It has been noted that CO₂ transportation cost is an important component of the total investment of CCUS. In this paper, a novel stepwise and piecewise optimization is proposed for CO₂ transportation design, which can compute the minimum transportation pipeline levelized cost under the effect of temperature variation. To develop the proposed approach, several models are referred to lay a foundation for the optimization design. The proposed optimal algorithm is validated by using numerical studies, which show the approach can reduce the levelized cost and improve the optimization performance in comparison with the existing methods.

Keywords: CO₂ emission reduction; transportation pipeline; stepwise and piecewise optimization; levelized cost

1 Introduction

CCUS has been widely considered as an effective mean to prevent the increase of CO₂ concentration in the atmosphere (Faltinson et al. 2009; Middleton et al. 2012; Rubin et al. 2013; Scott et al. 2013). In general, the location of CO₂ capture is far away from EOR and storage site. There are two main manners to transport CO₂, that is, vehicles and pipelines. Pipeline is more efficient for the long distance transportation (Svensson et al. 2004). Figure 1 shows the process of CCUS. It is obvious that CO₂ transportation is the important link from capture location to the EOR and storage site, whose cost should not be overlooked in the whole investment of CCUS (Fimbres Weihs et al. 2012; Knoope et al. 2013; Middleton 2013).

![Figure 1. The flowsheet of CCUS](image)

In general, there are two types of construction of CO₂ pipeline: with and without boosting pump stations. Most of the transport models have not considered boosting pump stations (McCoy et al. 2008; Vandeginste
et al. 2008; Middleton et al. 2009; Morbee et al. 2012). For long pipelines, the inlet pressure without
boosting pumps will be much higher than those with boosting pumps. Furthermore, there will not be
sufficient pressure to ensure flow in the pipeline without adding booster stations. As a result, the wall
thickness will be thicker, and the cost of the pipeline will increase seriously. Obviously, the lack of boosting
pump stations is not economical in many case of the industrial practice.

The recent developments of the CO₂ pipeline design approaches are summarized in the following context.
Based on the research of (McCoy et al. 2008), the method for calculating the max length of pipeline is
developed by (Gao et al. 2011) without considering booster pump. The conditions of the requirement of the
boosting pump stations are given by (Zhang et al. 2006; Gao et al. 2011). The conditions of intermediate
recompression is presented by means of ASPEN PLUS (Zhang et al. 2006). It should be mentioned that
these methods just give the rules of the requirements of the inter-stage booster pumps. However, most of
them have not presented the computational algorithms. A simplified approach is used by fixing the distance
between pumping stations (Wildenborg et al. 2004; Van den Broek et al. 2010), which leads to a special
solution. However, the cost-effectiveness is not analyzed in these studies. There are some results not only
considering the boosting pump stations but also optimizing the number of them (Chandel et al. 2010; Zhang
et al. 2012; Knoope et al. 2014). Hydrodynamic models are presented to evaluate engineering and
economic performance (Zhang et al. 2012). However, the result does not use the concept of nominal
diameter and cannot be used in industrial applications directly. Literature (Chandel et al. 2010) studies the
potential economies of scale by using the engineering-economic model of CO₂ pipeline transportation.
However, the temperature and density are assumed constants, which does not conform the actual situation
well. Cost models are presented without insulation or heating of the pipeline in optimizing CO₂ pipeline
configuration, which can optimize the number of pumping station, the inlet pressure, the diameter, and the
wall thickness (Knoope et al. 2014). However, the temperature is assumed to be a constant value during all
seasons, which does not conform to the practice. Because the temperature is ever-changing in some area
among the different seasons. It should be noted that the pipeline diameter and wall thickness are computed
by using the given design conditions, but in practice the diameter is selected from the available nominal
pipe size which is larger than the computed one in general. Most of existing studies use the NPS in design
which may degrade the design performance indeed because the design conditions are not changed.

Seasonal temperature can affect the soil temperature directly (Zhang et al. 2012). Further, the soil
temperature is assumed to be the average temperature for CO₂ pipeline (McCoy et al. 2008). The pipeline
system is designed based on summer soil temperature which can operate well in winter (Zhang et al. 2012).
The subcooled liquid (low temperature) transport will maximize the energy efficiency and minimize the
cost of CO₂ transport (Zhang et al. 2006). But how to deal with the effect of seasonal temperature for
pipeline optimization design is not mentioned in the existing literatures. The soil temperature has
significant influence on the pressure drop behavior of CO₂ in the pipeline (Zhang et al. 2012). For example,
annual lowest and highest soil temperature at a 1.5 m depth in the Ningxia-North Shanxi district is 2 °C.
and 17 °C, respectively. Note that the seasonal temperature still can affect the design of buried pipeline with thermal insulating layer, CO₂ temperature approaches the soil temperature exponentially along the pipeline length (Zhang et al. 2012). How to deal with the influence of temperature is very important to minimize the levelized cost of the CO₂ transportation. Therefore, it’s necessary to optimize the operational pressure to minimize the levelized cost of CO₂ transportation in a range of temperature and then to decide the related pipeline parameters.

A new approach named stepwise and piecewise optimization is initially developed in this study to minimize the levelized cost of CO₂ transportation pipeline. Based on the optimization model constructed by least square method, a novel stepwise optimization approach is formulated to solve pipeline nominal diameter, wall thickness, operation pressure and the number of boosting pump stations. A piecewise optimization presents a criterion to deal with the effect of temperature. The proposed approach is illustrated by using numerical studies to validated the effectiveness of the proposed approach.

In conventional optimal design, the pipeline diameter and wall thickness are computed by using the given design conditions, but in practice the diameter is selected from the available nominal pipe size (NPS) which is larger than the computed one in general. Therefore, the stepwise optimization is proposed to improve the performance of the conventional optimization. The seasonal temperature has significant influence on the pressure drop behavior of CO₂ in the pipeline, but how to deal with the effect of seasonal temperature for pipeline optimization design is not mentioned in the existing literatures. The piecewise optimization presents a criterion to deal with the effect of temperature and find the better levelized cost.

The rest of this paper is given as: The problem description is given in Section 2. The optimization algorithms are developed in Section 3. The proposed approach is demonstrated by numerical studies and compared with existing methods in Section 4. Finally, in Section 5, some concluding remarks are given.

2 Problem description

Before transportation, the captured CO₂ should be compressed and cooled from flue gas of the power plant. Thereby the compression system (including compressor and cooler) should be used. In addition, the pressure will decrease along the pipeline. Hence, the boosting pump stations should be added in the pipeline design. The composition of CO₂ pipeline transportation is shown in Figure 2.

The pipeline segment length, inlet pressure, and minimum outlet pressure are all specified for each pipeline segment in the design. Once the CO₂ pressure drops below the pre-specified pressure, an inter-stage boosting pump station should be installed to re-increase the pressure. The outlet pressure of each inter-stage pipeline segment equals to the injection pressure (shown in Figure 2).
Figure 2. The process of CO₂ transportation

3 Stepwise and piecewise optimization approach

3.1 The optimization model

Based on the mathematical models, the optimization model is detailed as follows:

\[
\min \; LC(P_{\text{inlet}}, T_{\text{ave}})
\]
\[
\text{s.t.} \quad P_{\text{cap}} < P_{\text{inlet}}
\]
\[
P_{\text{max}} \leq P_{\text{inlet}} \leq P_{\text{min}}
\]
\[
t_{\text{cal}} \leq t_{\text{design}} \leq t_{\text{NPS}}
\]
\[
P_{\text{out}} < P_{\text{inlet}}
\]
\[
T_{\text{minop}} \leq T_{\text{pow}} \leq T_{\text{maxop}}
\]
\[
V < V_{\text{max}}
\]
\[
0 \leq N_{\text{pump}}
\]
\[
P_{\text{out}} = P_{\text{inlet}} - \Delta P_{\text{net}}L/(N_{\text{pump}} + 1)
\]

where \( P_{\text{inlet}} \) and \( T_{\text{ave}} \) are inlet pressure and average temperature along the pipeline respectively, which are selected as decision variables; \( P_{\text{out}} \) is the outlet pressure of the pipeline (MPa); \( \Delta P_{\text{net}} \) is the actual pressure drop (MPa/m); \( L \) is the length of the pipeline (m); \( N_{\text{pump}} \) is the number of boosting pump stations; \( LC(P_{\text{inlet}}, T_{\text{ave}}) \) is the function of levelized cost, which is the optimization goal (Knoope et al. 2014):

\[
LC(P_{\text{inlet}}, T_{\text{ave}}) = \frac{CRF_1 \times C_P \_cap + CRF_2 \times C_C \_cap + CRF_3 \times C_{\text{damp}} + C_{\text{f}} \_\text{OM} + C_{\text{f}} \_\text{energy}}{Q \_\text{in} \times 10^3 \times H \_\text{op} \times 3600}
\]

\[
CRF_i = \frac{r}{1-(1+r)^{-z}}
\]

\( CRF_1, CRF_2, CRF_3 \) are the capital recovery factors of pipeline, compressors and booster pumps, respectively; \( r \) is the discount rate (%); \( z_1, z_2, z_3 \) are the lifetime of pipeline, compressors and booster pumps, respectively (years); \( H \_\text{op} \) is the operation time of the transportation (hour/year). \( P_{\text{min}} \) is the minimum operational pressure. \( P_{\text{max}} \) is the maximum operational pressure. \( t_{\text{cal}} \) is the calculated thickness, \( t_{\text{design}} \) is the designing thickness, \( t_{\text{NPS}} \) is the final selected thickness of NPS. \( T_{\text{minop}}, T_{\text{maxop}} \) are minimum and maximum operational temperature for liquid CO₂ transport, respectively. \( V_{\text{max}} \) is a certain velocity.

The detail models can be found in the related literatures (Table 1).
Table 1: Detail models and the related literatures

<table>
<thead>
<tr>
<th>Literature</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Zhang et al. 2006)</td>
<td>Pipeline diameter/ $D_{inner}$</td>
</tr>
<tr>
<td>(Mohitpour et al. 2003)</td>
<td>Average pressure along the pipeline/ $P_{ave}$</td>
</tr>
<tr>
<td>(McCoy et al. 2008)</td>
<td>Pipe wall thickness/$t$</td>
</tr>
<tr>
<td>(Damen et al. 2007; Kuramochi et al. 2012; Knoope et al. 2014)</td>
<td>The capacity of the compressor/$W_{comp}$</td>
</tr>
<tr>
<td>(IEA 2002)</td>
<td>Capacity of the boosting pump station/$W_{cap}$</td>
</tr>
<tr>
<td>(McCollum et al. 2006)</td>
<td>The maximum length of pipeline without booster pump/$l_{max}$</td>
</tr>
<tr>
<td>(Vandeginste et al. 2008)</td>
<td>Pipeline capital cost/$C_{C_{cap}}$</td>
</tr>
<tr>
<td>(Knoope et al. 2014)</td>
<td>Inlet compressor capital cost/$C_{C_{cap}}$</td>
</tr>
<tr>
<td>(Rubin et al. 2008)</td>
<td>Boosting pump stations capital cost/$C_{B_{cap}}$</td>
</tr>
<tr>
<td>(Knoope et al. 2013)</td>
<td>Total annual O&amp;M cost/$C_{T_{OM}}$</td>
</tr>
<tr>
<td>(Knoope et al. 2014)</td>
<td>Total energy cost/$C_{T_{energy}}$</td>
</tr>
</tbody>
</table>

3.2 The stepwise optimization

A stepwise optimization approach is proposed to minimize the levelized cost for pipeline transportation, which can be divided into two steps: (1) the parameters optimization of diameter and wall thickness. (2) the parameters optimization of inlet pressure and the number of boosting pump stations. Then, the piecewise optimization is developed to give a criterion for dealing with the effects of temperature. The steps nested in the chosen order is used to deal with the influence of seasonal temperature variance. The advantages of the proposed approach is that it can improve the optimal performance. The disadvantages of the proposed approach is that it cannot deal the model uncertainty, which is under our study and will be reported as soon as we get the results.

For the first step optimization, the decision variable of $P_{inlet}$ satisfies the ideal condition for designing inner diameter and wall thickness. Figure 3 shows algorithm flow diagram of the first step optimization process. $\Delta P_{inlet}$ and $\Delta T_{ave}$ are the increment of temperature and inlet pressure respectively, the smaller $\Delta P_{inlet}$ and $\Delta T_{ave}$, the more accurate optimized results. The readers can find the required parameters, such as $OD_{NPS}$, $l_{max}$, $t_{NPS}$, $ID_{NPS}$, range of $D_{inner}$ in Appendix B.

Algorithm 1: The first step optimization (FSP)
Remark 1: Because the CO$_2$ pipeline diameters are smaller than 1 m in most of existing engineering projects, the proposed approach does not consider the cases $OD_{NPS} > 1m$. But it still can be used in the projects by using the appropriate NPS standard.

Remark 2: In the first step, enumeration method is used to solve the optimal issue. Hence, Algorithm compute all the NPS until it equals to 36.

By using the results of Algorithm 1, (1) can be transformed into:
\[
\begin{align*}
\min & \quad LC(P_{\text{inlet}}, T_{\text{ave}}) \\
\text{s.t.} & \quad P_{\text{min}} \leq P_{\text{inlet}} \leq P_{\text{max}} \\
& \quad T_{\text{minop}} \leq T_{\text{ave}} \leq T_{\text{maxop}} \\
& \quad V < V_{\text{max}} \\
& \quad 0 \leq N_{\text{pump}} \\
& \quad P_{\text{out}} = P_{\text{inlet}} - \Delta P_{\text{act}} L/(N_{\text{pump}} + 1)
\end{align*}
\]  

where the decision variable of \( P_{\text{inlet}} \) satisfies the first optimization result of diameter and wall thickness. 

\( P_{\text{max}} \) is the maximum pressure, which is calculated by \( t = P_{\text{max}} \times D_{\text{out}}/2 \times S \times F \times E \) based on the optimized diameter and wall thickness.

In the second step optimization, Algorithm 2 will solve the new optimal issue (4) and compute the final inlet pressure \( P_{\text{inlet}} \) and the numbers of boosting pump stations \( N_{\text{pump}} \). Figure 4 shows flow diagram of the second step optimization.

**Algorithm 2: The second step optimization (SSP)**

![Flow diagram of the second optimization](image)

Figure 4. Flow diagram of the second optimization
Remark 3: The $RT_u$ range division can be found in Sub-section 3.3.

Remark 4: All the pipeline diameter and wall thickness are computed by using

\[ t = P_{\text{inlet}} \times D_{\text{out}}/2 \times S \times F \times E \]

which is in line with international standards. Hence, the proposed optimization approach will not lead to the safety problems.

3.3 The piecewise optimization

The optimized diameter, wall thickness, inlet pressure and the number of boosting pump stations may not be the same at different temperature range. Once the design of transportation is finished, the designing parameters cannot be changed. According to (Zhang et al. 2012), the parameters of final optimization should select the ones in the highest soil temperature case. However, this method may not find an appropriate results. To address the mentioned problems, this paper presents a novel piecewise optimization approach. The minimum levelized cost is computed at each temperature range and the solution can be found for the optimal problem.

The piecewise optimization is embedded in Algorithm 2. For the same diameter and wall thickness, the operational temperature will be divided into several ranges. (4) can be re-written as:

\[
\begin{align*}
\min & \, LC(P_{\text{inlet}}, T_{\text{ave}}) \\
\text{subject to} & \, P_{\text{inlet}} \leq P_{\text{max}} \\
& \, V < V_{\text{max}} \\
& \, 0 \leq N_{\text{pump}} \\
& \, T_{\text{ave}} \in RT_u(u = 1, 2, 3...U) \\
& \, P_{\text{out}} = P_{\text{inlet}} - \Delta P_{\text{act}} \frac{L_f}{(N_{\text{pump}} + 1)}
\end{align*}
\]

where $RT_u$ is the divided temperature range, $U$ is the number of the ranges. It is obvious that the levelized cost is varying among different temperature ranges. Hence, the levelized cost can be reduced by using the proposed approach.

The rules of piecewise optimization approach are illustrated in Table 2 and the flow diagram is shown in Figure 5.

Table 2. A criterion for optimization design

<table>
<thead>
<tr>
<th>$t_{HH}$</th>
<th>$RT_1$</th>
<th>$RT_2$</th>
<th>$RT_{..}$</th>
<th>$RT_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$LC(t_{HH})$</td>
<td>$LC(r_{1})$</td>
<td>$LC(r_{2})$</td>
<td>$LC(r_{..})$</td>
<td>$LC(r_{u})$</td>
</tr>
<tr>
<td>Condition</td>
<td>$LC(t_{HH}) &lt; LC(r_{1})$</td>
<td>$LC(t_{HH}) &lt; LC(r_{2})$</td>
<td>$LC(t_{HH}) &lt; LC(r_{..})$</td>
<td>$LC(t_{HH}) &lt; LC(r_{u})$</td>
</tr>
</tbody>
</table>

Changing temperature of $RT_{HH}$ in

| $RT_1$ | $RT_2$ | ... | $RT_u$ |

where: $t_{HH}$ is the maximum $T_{\text{ave}}$ in the area; $RT_{HH}$ is the interval which includes $t_{HH}$, $H \in u$; $r_{u} \in RT_u$ and $r_{u} \not\in RT_{HH}$.

Algorithm 3: piecewise optimization
The piecewise optimization presents a criterion to deal with the effect of temperature, which is one of the main works of this paper. If the designer considers the inter-stage cooler and heat transfer theory in modelling pipeline transportation, it may obtain the global optimum solution.

### 4 Numerical studies and analysis

The basic parameters of the transportation are given in Table 3. The other detailed parameters are given in Table 4-5.

#### Table 3. Basic parameters of the transportation (Chandel et al. 2010; Zhang et al. 2012)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical operational temperature (°C)</td>
<td>$T_{ope}$</td>
<td>-20–35</td>
</tr>
<tr>
<td>District temperature (°C)</td>
<td>$T_{soil}$</td>
<td>2–17</td>
</tr>
<tr>
<td>CO$_2$ inlet pressure (MPa)</td>
<td>$P_{inlet}$</td>
<td>8.6–15.3</td>
</tr>
<tr>
<td>Altitude difference (m)</td>
<td>$H_1 - H_2$</td>
<td>0</td>
</tr>
<tr>
<td>Pipeline length (km)</td>
<td>$L$</td>
<td>150</td>
</tr>
<tr>
<td>CO$_2$ mass flow rate (kg/s)</td>
<td>$Q_{ma}$</td>
<td>252</td>
</tr>
<tr>
<td>Injection pressure (MPa)</td>
<td>$P_{inject}$</td>
<td>10</td>
</tr>
<tr>
<td>Operation time (hour)</td>
<td>$H_{ope}$</td>
<td>8760</td>
</tr>
</tbody>
</table>

#### Table 4. Detail parameter values of pipeline (McCoy et al. 2008; Vandeginste et al. 2008)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Specified minimum yield stress for X70 steel (MPa) $S$ 483
Longitudinal joint factor $E$ 1.0
Design factor $F$ 0.72
Price of steel pipeline (€/kg) $C_{ps}$ 0.9342
Material cost factor $f_M$ 22.4%
Percentage of capital cost for pipeline $f_{PC,M}^M$ 0.04

Table 5. Detail parameter values of compressor and boosting pump stations (Zhang et al. 2006; Kuramochi et al. 2012; Knoope et al. 2014)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ compressibility factor (1.013 bar, 15 °C)</td>
<td>$Z$</td>
<td>0.9942</td>
</tr>
<tr>
<td>Universal gas constant (J/mol K)</td>
<td>$R$</td>
<td>8.3145</td>
</tr>
<tr>
<td>Suction temperature (K)</td>
<td>$T_i$</td>
<td>313.15</td>
</tr>
<tr>
<td>Specific heat ratio ($c_p/c_v$)</td>
<td>$\gamma$</td>
<td>1.294</td>
</tr>
<tr>
<td>Molar mass (g/mol)</td>
<td>$M$</td>
<td>44.01</td>
</tr>
<tr>
<td>Number of stages for compression system</td>
<td>$N$</td>
<td>4</td>
</tr>
<tr>
<td>Isentropic efficiency</td>
<td>$\eta_{iso}$</td>
<td>80%</td>
</tr>
<tr>
<td>Mechanical efficiency</td>
<td>$\eta_{mech}$</td>
<td>99%</td>
</tr>
<tr>
<td>Suction pressure (MPa)</td>
<td>$P_1(P_{cap})$</td>
<td>0.101</td>
</tr>
<tr>
<td>Discharge pressure (MPa)</td>
<td>$P_2(P_{MOP})$</td>
<td>8.6</td>
</tr>
<tr>
<td>Base costs for calculating the compressor capital cost (ME)</td>
<td>$I_0$</td>
<td>21.9</td>
</tr>
<tr>
<td>Base scale of the compressor (MWe)</td>
<td>$W_{comp,0}$</td>
<td>13</td>
</tr>
<tr>
<td>Scaling factor</td>
<td>$y$</td>
<td>0.67</td>
</tr>
<tr>
<td>Multiplication exponent</td>
<td>$n$</td>
<td>0.9</td>
</tr>
<tr>
<td>Percentage of the capital cost for boosting pump stations</td>
<td>$f_{BO&amp;M}^B$</td>
<td>0.04</td>
</tr>
<tr>
<td>Efficiency booster pump</td>
<td>$\eta_{booster}$</td>
<td>0.5</td>
</tr>
<tr>
<td>Dollar- Euro exchange rate</td>
<td>$r_0$</td>
<td>0.7230</td>
</tr>
<tr>
<td>Operation time of compressor (hour)</td>
<td>$T_c$</td>
<td>8760</td>
</tr>
<tr>
<td>Operation time of boosting pump stations (hour)</td>
<td>$T_B$</td>
<td>8760</td>
</tr>
<tr>
<td>Price of electricity (€/per kilowatt hour)</td>
<td>$C_{PE}$</td>
<td>0.0584</td>
</tr>
</tbody>
</table>

Table 6. Parameter values of the levelized cost model (Knoope et al. 2013; Knoope et al. 2014)
Table 7 gives the comparisons of the first and second step optimization in a series of different mass flow rate. It is obvious the SSP can improve the optimization results. Though the improved percentage of the levelized cost is not large, the saved total cost is large enough. This can show the advantages of the proposed stepwise optimization. The reasons are given as: In FSP, the pipeline diameter and wall thickness are computed by using the given design conditions, but in engineering practice the diameter and wall thickness are selected by using nominal pipe size (NPS) which is larger than the computed one in general. (Knoope et al. 2014). Based on FSP results of diameter and wall thickness, SSP can re-optimize the inlet pressure and the numbers of boosting pump stations, which can improve the optimal results. For example, $Q_m$ is assigned to be 150 $kg/s$, $T_{av}$ is 15 $^\circ C$. The optimized inlet pressures are 11.8550 and 10.1855 MPa of FSP and SSP, respectively. The levelized cost is just saved 0.85 %. However, it should be pointed that the SSP saves 7580466 € over the design lifetime of 25 years.

Table 7. Comparison results of the first and second step optimization

<table>
<thead>
<tr>
<th>$Q_m$ (kg/s)</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
<th>350</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{av}$ (°C)</td>
<td>15</td>
<td>-10</td>
<td>17</td>
<td>30</td>
<td>-10</td>
</tr>
<tr>
<td>$P_{in}$ (MPa)</td>
<td>FSP</td>
<td>11.8550</td>
<td>11.7384</td>
<td>10.6042</td>
<td>10.8215</td>
</tr>
<tr>
<td></td>
<td>SSP</td>
<td>10.1855</td>
<td>10.1908</td>
<td>10.1325</td>
<td>10.1060</td>
</tr>
<tr>
<td>$D_{out}$ (m)</td>
<td>FSP</td>
<td>0.32385</td>
<td>0.3556</td>
<td>0.4064</td>
<td>0.45720</td>
</tr>
<tr>
<td></td>
<td>SSP</td>
<td>0.32385</td>
<td>0.3556</td>
<td>0.4064</td>
<td>0.45720</td>
</tr>
<tr>
<td>$t$ (m)</td>
<td>FSP</td>
<td>0.00635</td>
<td>0.00635</td>
<td>0.00635</td>
<td>0.007925</td>
</tr>
<tr>
<td></td>
<td>SSP</td>
<td>0.00635</td>
<td>0.00635</td>
<td>0.00635</td>
<td>0.007925</td>
</tr>
<tr>
<td>LC (€/t CO₂)</td>
<td>FSP</td>
<td>7.5560</td>
<td>7.0981</td>
<td>6.8231</td>
<td>6.8814</td>
</tr>
<tr>
<td></td>
<td>SSP</td>
<td>7.4919</td>
<td>7.0446</td>
<td>6.8062</td>
<td>6.8508</td>
</tr>
<tr>
<td>Total cost (€) (25 years)</td>
<td>FSP</td>
<td>893572560</td>
<td>1119228408</td>
<td>1344833010</td>
<td>1627588728</td>
</tr>
<tr>
<td></td>
<td>SSP</td>
<td>885992094</td>
<td>1110792528</td>
<td>1341502020</td>
<td>1620351216</td>
</tr>
<tr>
<td>Total saving (%)</td>
<td>0.85</td>
<td>0.75</td>
<td>0.25</td>
<td>0.45</td>
<td>0.25</td>
</tr>
<tr>
<td>cost (€)</td>
<td>7580466</td>
<td>8435880</td>
<td>3330990</td>
<td>7237512</td>
<td>4497822</td>
</tr>
</tbody>
</table>

Table 8. Results of the first step optimization

<table>
<thead>
<tr>
<th>$RT_i$ (-20 ~ 15.255)</th>
<th>$D_{out}$ (m)</th>
<th>$t$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0464</td>
<td>0.00635</td>
<td></td>
</tr>
</tbody>
</table>
Table 8 shows the first step optimization results under the range of operational temperature. Based on the same diameter and wall thickness, the operational temperature can be divided into two portions. Figure 6 shows the second step optimization results over \( RT_1 \) and \( RT_2 \) respectively. It shows that the levelized cost increases as the temperature rises. Table 9 further compares these results. From Table 9, one can see that the levelized costs in \( RT_2 \) are obviously larger than in \( RT_1 \). \( RT_H \) is one part of \( RT_2 \). By using the proposed piecewise optimization, if changing the temperature of \( RT_H \) into \( RT_1 \), the levelized cost will decrease obviously. For example, if we use the highest temperature of \( RT_1 \) as the \( T_{ave} \) of \( RT_H \), the levelized cost can be saved 5.19%−5.20%. The pipeline system designed based on higher temperature can operate well in lower temperature (Zhang et al. 2012). Therefore, the proposed approach can guarantee the operation conditions satisfy the seasonal conditions without the inlet pressure to be lowered necessary to ensure pipeline flow.

From table 9, it also can be seen that if the highest soil temperature is used, the levelized cost is 7.1655 €/t CO\(_2\). Keeping the temperature in 15.255 °C, the levelized cost is 6.7928 €/t CO\(_2\). That is, reducing the temperature not more than 1.745 °C, the levelized cost can be saved 5.20%. Therefore, using the highest soil temperature is not the best way to optimize the pipeline. It is convenient to reduce the temperature at lower temperature, therefore, selecting lower temperature is practical and reasonable.

To further illustrate the proposed approach, it will be compared with the existing methods (shown in Table 10). The distance is assigned to be 350 km, and the soil temperature is 17 °C.
Compared with the method of (Zhang et al. 2012), it can be seen that the levelized cost saves 13.14%. The main reasons are as follows: For the optimal design of pipeline, the inlet pressure and the numbers of boosting pump stations should be used as decision variable to find the optimal tradeoff between the pipeline and boosting pump station parameters. The diameter and wall thickness have to be enlarged in practice for the discrete NPS. However, the method of (Zhang et al. 2012) has not considered these tradeoff and the effects of discrete NPS.

Compared with the method of (Knoope et al. 2014), it can be seen that the levelized cost is just saved 0.156%. However, it should be pointed that the proposed method saves 2483460 € over the design lifetime of 25 years.

Table 10. Comparison results of the existing and proposed methods

<table>
<thead>
<tr>
<th>Method</th>
<th>$Q_m$ (kg/s)</th>
<th>$P_{inlet}$ (MPa)</th>
<th>$D_{out}$ (m)</th>
<th>$t$ (m)</th>
<th>$LC$ ((€/t CO$_2$))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Zhang et al. 2012)</td>
<td>100</td>
<td>13.8</td>
<td>0.27305</td>
<td>0.00635</td>
<td>10.4371</td>
</tr>
<tr>
<td>(Knoope et al. 2014)</td>
<td>250</td>
<td>10.6201</td>
<td>0.4064</td>
<td>0.00635</td>
<td>8.1002</td>
</tr>
<tr>
<td>The proposed approach</td>
<td>100</td>
<td>10.3710</td>
<td>0.27305</td>
<td>0.004191</td>
<td>9.0660</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>10.1908</td>
<td>0.4064</td>
<td>0.00635</td>
<td>8.0876</td>
</tr>
</tbody>
</table>

Though the annual saving is small but the whole saving in the pipeline life is very considerable. If the unexpected costs are existed in both traditional and the proposed methods, the optimal results will still be better by using the proposed one. For example, if the unexpected cost increase 2% of the inlet compressor capital cost (IC), boosting pump stations capital cost (BC), annual O&M cost (AC), energy cost (EC) for different cases, respectively. The proposed approach is compared with (Knoope et al. 2014). It can be seen that the total saving is very considerable over the design lifetime of 25 years (Table 11).

Table 11 Unexpected cost for different cases (Compared with Knoope et al. 2014)

<table>
<thead>
<tr>
<th>Cost</th>
<th>IC</th>
<th>BC</th>
<th>AC</th>
<th>EC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total saving /(€)</td>
<td>9903882</td>
<td>9837436</td>
<td>9881446</td>
<td>10204212</td>
</tr>
<tr>
<td>25 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The optimized levelized cost is lower by selecting the minimum temperature for the pipeline design, but the design cannot satisfy the following constraint (Knoope et al. 2014).

$$ P_{out} = P_{inlet} - \Delta P_{inlet} \frac{L}{(N_{pump} + 1)} $$

Table 12 gives the comparison of optimization results based on the minimum temperature and the proposed methods. Assuming $L=140km$, $P_{out}=10MPa$, the minimum and maximum CO$_2$ temperatures along the
pipeline are 2 and 15 °C, respectively. It is important to note that \( P_{\text{out}} = 10 \text{MPa} \) is the minimum injection pressure (Zhang, D et al. 2012). For example, if \( Q_{\text{in}} = 120 \text{kg/s} \), based on 2 °C, the optimized nominal outer diameter and wall thickness are 0.32385 m and 0.00635 m respectively; the optimized inlet pressure is 13.0276 MPa. \( P_{\text{out}} \) decreases from 10 to 9.7702 MPa as the temperature increases. Therefore, if the optimization design is applied based on the minimum temperature, \( P_{\text{out}} \) is smaller than 10 MPa at higher temperatures, this lead to the design unsuitable.

Based on the proposed approach, \( P_{\text{out}} \) decreases from 10.2283 to 10 MPa as the temperature increases.

The proposed method meet the constraint. From above analysis, it can be seen that the proposed approach is applicable in pipeline engineering.

### Table 12 Comparison optimization results based on the minimum temperature and proposed methods

<table>
<thead>
<tr>
<th>Method</th>
<th>( Q_{\text{in}} ) (kg/s)</th>
<th>120</th>
<th>130</th>
<th>140</th>
<th>145</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( D_{\text{out}} ) (m)</td>
<td>0.32385</td>
<td>0.32385</td>
<td>0.32385</td>
<td>0.32385</td>
</tr>
<tr>
<td></td>
<td>( t ) (m)</td>
<td>0.00635</td>
<td>0.00635</td>
<td>0.008382</td>
<td>0.008382</td>
</tr>
<tr>
<td></td>
<td>( P_{\text{in}} ) (MPa)</td>
<td>13.0276</td>
<td>13.5480</td>
<td>14.3985</td>
<td>14.7137</td>
</tr>
<tr>
<td></td>
<td>( P_{\text{out}} ) (MPa)</td>
<td>10–9.7702</td>
<td>10–9.7352</td>
<td>10–9.6781</td>
<td>10–9.6578</td>
</tr>
<tr>
<td>The proposed method</td>
<td>( D_{\text{out}} ) (m)</td>
<td>0.32385</td>
<td>0.32385</td>
<td>0.32385</td>
<td>0.32385</td>
</tr>
<tr>
<td></td>
<td>( t ) (m)</td>
<td>0.00635</td>
<td>0.00635</td>
<td>0.008382</td>
<td>0.008382</td>
</tr>
<tr>
<td></td>
<td>( P_{\text{in}} ) (MPa)</td>
<td>13.2537</td>
<td>13.8080</td>
<td>14.7134</td>
<td>15.0479</td>
</tr>
<tr>
<td></td>
<td>( P_{\text{out}} ) (MPa)</td>
<td>10.2283–10</td>
<td>10.2636–10</td>
<td>10.31920–10</td>
<td>10.3388–10</td>
</tr>
</tbody>
</table>

### 5 Conclusion

Based on the least square method, the pipeline diameter model are contrasted over different operational temperature ranges. A new stepwise and piecewise optimization approach is initially proposed for CO\(_2\) pipeline transportation. The enumeration method is employed to develop the optimal algorithms. In the numerical studies, the proposed approach can save the levelized cost obviously by comparing with the existing optimization methods. Because several realistic engineering problems are considered explicitly, this paper presents an optimization method for CO\(_2\) pipeline design indeed.

### Acknowledgments
This work is partially supported by the National Science and Technology Support Program under Grant 2012BAC24B03, the key technology of low-carbon for major projects of CNPC under Grant 2011E2403, the National Nature Science Foundation of China under Grant, 61273188, 61473312, the postdoctoral researcher applied research project of Qingdao and the Fundamental Research Funds for the Central Universities under Grant 15CX06053A. Finally the authors are grateful to the editor and the anonymous reviewers for their helpful comments and constructive suggestions with regard to the revision of the paper.

Appendix A

Pipe diameter

Based on the data from National Institute of Standards and Technology (NIST), Pipeline diameter can be calculated as (Zhang et al. 2006):

\[ D_{ave} = 0.363Q^{-0.45} \cdot [f_P(P_{ave}, T_{ave})]^{-0.32} \cdot f_T(P_{ave}, T_{ave})]^{0.025} \]  

(6)

where \( P_{ave} \) is the average pressure along the pipeline (\( MPa \)); \( T_{ave} \) is the soil temperature around the pipeline (\( ^\circ C \)). \( f_P(P_{ave}, T_{ave}) \) is the function of density that depends on the \( P_{ave} \) and \( T_{ave} \) (\( kg/m^3 \)); \( f_T(P_{ave}, T_{ave}) \) is the function of viscosity that depends on the \( P_{ave} \) and \( T_{ave} \) (\( Pa\cdot s \)).

The density is given as a function of average pressure and temperature along the pipeline:

\[ f_P(P_{ave}, T_{ave}) = (BT)^P \]  

(7)

The viscosity is given as a function of average pressure and temperature along the pipeline:

\[ f_T(P_{ave}, T_{ave}) = (DT)^P \]  

(8)

where \( B \) and \( D \) are known constant matrixes which can be found in Appendix A; \( P \) is the matrix of \( P_{ave} \), \( T \) is the matrix of \( T_{ave} \):

\[
B = \begin{bmatrix} b_{55} & b_{54} & b_{53} & b_{52} & b_{51} & b_{50} \\ b_{45} & b_{44} & b_{43} & b_{42} & b_{41} & b_{40} \\ b_{35} & b_{34} & b_{33} & b_{32} & b_{31} & b_{30} \\ b_{25} & b_{24} & b_{23} & b_{22} & b_{21} & b_{20} \\ b_{15} & b_{14} & b_{13} & b_{12} & b_{11} & b_{10} \\ b_{05} & b_{04} & b_{03} & b_{02} & b_{01} & b_{00} \end{bmatrix}, \quad T = \begin{bmatrix} T_{ave}^5 \\ T_{ave}^4 \\ T_{ave}^3 \\ T_{ave}^2 \\ T_{ave}^1 \\ 1 \end{bmatrix}, \quad P = \begin{bmatrix} P_{ave}^5 \\ P_{ave}^4 \\ P_{ave}^3 \\ P_{ave}^2 \\ P_{ave}^1 \\ 1 \end{bmatrix}, \quad D = \begin{bmatrix} d_{55} & d_{54} & d_{53} & d_{52} & d_{51} & d_{50} \\ d_{45} & d_{44} & d_{43} & d_{42} & d_{41} & d_{40} \\ d_{35} & d_{34} & d_{33} & d_{32} & d_{31} & d_{30} \\ d_{25} & d_{24} & d_{23} & d_{22} & d_{21} & d_{20} \\ d_{15} & d_{14} & d_{13} & d_{12} & d_{11} & d_{10} \\ d_{05} & d_{04} & d_{03} & d_{02} & d_{01} & d_{00} \end{bmatrix}
\]

By using (7-8), (6) can be re-written as:

\[ D_{ave} = 0.363Q^{-0.45} \cdot [(BT)^P]^{-0.32} \cdot [(DT)^P]^{0.025} \]  

(9)

Remark 5: Based on the data from (NIST), the computational expressions are obtained by using least square approach for density and viscosity.

The matrixes of \( B \) and \( D \) have been programmed as two stand-alone spreadsheet models using Visual Basic in Microsoft Excel (Table 12, Table 13).

The values for the correlation coefficients—\( b_{ij} \) (\( i = 0, 1, 2, 3, 4, 5; j = 0, 1, 2, 3, 4, 5 \)— are listed in Table 12 for pressure (8.6 \( MPa \sim 15.3 \ MPa \)) and temperature (\(-20^\circ C \sim 35^\circ C \)). The ranges of pressure and temperature are detailed in the text.
Table 12. Value of $b_i$ coefficients in (7)

<table>
<thead>
<tr>
<th>$i$</th>
<th>$b_3$</th>
<th>$b_4$</th>
<th>$b_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3.41303419112014E-09</td>
<td>-6.27606343131403E-08</td>
<td>-1.83750350897551E-06</td>
</tr>
<tr>
<td>4</td>
<td>-2.1479352541565E-07</td>
<td>3.930766522791999E-06</td>
<td>0.000115547578911259</td>
</tr>
<tr>
<td>3</td>
<td>5.38395520369261E-06</td>
<td>-0.000097961427758237</td>
<td>-0.00289271196485396</td>
</tr>
<tr>
<td>2</td>
<td>-0.000067210883620396</td>
<td>0.00121424647915507</td>
<td>0.0360416517323296</td>
</tr>
<tr>
<td>1</td>
<td>0.000418099646923243</td>
<td>-0.00748487070134038</td>
<td>-0.223492778776728</td>
</tr>
<tr>
<td>0</td>
<td>-0.0010377856097512</td>
<td>0.0183499072848713</td>
<td>0.551534176694391</td>
</tr>
</tbody>
</table>

Table 13. Value of $d_{ij}$ coefficients in (8)

<table>
<thead>
<tr>
<th>$i$</th>
<th>$d_{i3}$</th>
<th>$d_{i4}$</th>
<th>$d_{i5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2.96979983755421E-16</td>
<td>-5.11790363405514E-15</td>
<td>-1.61341423050057E-13</td>
</tr>
<tr>
<td>4</td>
<td>-1.87118491886111E-14</td>
<td>3.2115785053841E-13</td>
<td>1.01460065638067E-11</td>
</tr>
<tr>
<td>3</td>
<td>4.69554059206441E-13</td>
<td>-8.0183431311157E-12</td>
<td>-2.53958254359596E-10</td>
</tr>
<tr>
<td>2</td>
<td>-5.86762907841313E-12</td>
<td>9.95470125149012E-11</td>
<td>3.16249472186625E-09</td>
</tr>
<tr>
<td>1</td>
<td>3.65292232605669E-11</td>
<td>-6.14360261245057E-10</td>
<td>-1.95888466031802E-08</td>
</tr>
<tr>
<td>0</td>
<td>-9.07040455852916E-11</td>
<td>1.50745813211555E-09</td>
<td>4.81654629878995E-08</td>
</tr>
</tbody>
</table>

Table 14. The modified NPS

<table>
<thead>
<tr>
<th>NPS</th>
<th>$OD_{NPS}$ (mm)</th>
<th>$t_{maxNPS}$ (mm)</th>
<th>$t_{maxOP}$ (mm)</th>
<th>$t_{max}$ (mm)</th>
<th>$t_{NPS}$ (mm)</th>
<th>$ID_{NPS}$ (mm)</th>
<th>Classified range (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/8</td>
<td>10.26</td>
<td>2.413</td>
<td>0.2257</td>
<td>0.889</td>
<td>0.889</td>
<td>8.4812</td>
<td>0 &lt; $D_{max}$ ≤ 8.4812</td>
</tr>
<tr>
<td>1/4</td>
<td>13.72</td>
<td>3.023</td>
<td>0.3018</td>
<td>1.245</td>
<td>1.245</td>
<td>11.23</td>
<td>8.4812 &lt; $D_{max}$ ≤ 11.23</td>
</tr>
</tbody>
</table>

The values for the correlation coefficients—$d_{ij}$ ($i = 0, 1, 2, 3; j = 0, 1, 2, 3, 4$)—are listed in Table 13 for pressure (8.6 MPa ~ 15.3 MPa) and temperature (-20°C ~ 35°C).

Appendix B. The modified nominal pipe size
Based on the exit data of CO$_2$ pipeline transportation, NPS should not be larger than 36, (Zhang et al. 2012). As the maximum operational pressure of 15.3 MPa (McCoy et al. 2008), the range of wall thickness of NPS can be modified.

Substituting the maximum operational pressure into $t = \frac{P_{\text{max}} \times D_{\text{out}}}{2 \times S \times F \times E}$, the maximum operational wall thickness ($t_{\text{maxOP}}$) is calculated for each original NPS (shown in Table 14). $t_{\text{maxNPS}}$ is the maximum wall thicknesses of corresponding original NPS. If $t_{\text{maxOP}} \leq t_{\text{maxNPS}}$, the suitable thickness of original NPS is selected as the maximum thickness of the modified NPS ($t_{\text{max}}$). If $t_{\text{maxOP}} > t_{\text{maxNPS}}$, $t_{\text{maxNPS}}$ is selected as $t_{\text{max}}$. Compared $t_{\text{max}}$ with the original thickness of each original NPS, the modified thickness ($t_{\text{NPS}}$) is established. Plunging $t_{\text{NPS}}$ and corresponding OD$_{\text{NPS}}$ into $D_{\text{out}} = D_{\text{inner}} + 2t$, the modified inner diameter ($ID_{\text{NPS}}$) is obtained. Based on $ID_{\text{NPS}}$, the classified range of $D_{\text{inner}}$ is established. It can be seen that $D_{\text{inner}}$ should be in the range of $0 < D_{\text{inner}} \leq 898.55$.

### References


