A new stepwise and piecewise optimization approach for CO_2 pipeline

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Abstract: The process of CO_2 capture, transportation, enhanced oil recovery (EOR) and storage is one of the best ways for CO_2 emission reduction, which is also named as Carbon Capture, Utilization and Storage (CCUS). It has been noted that CO_2 transportation cost is an important component of the total investment of CCUS. In this paper, a novel stepwise and piecewise optimization is proposed for CO_2 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: CO_2 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 CO_2 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 CO_2 capture is far away from EOR and storage site. There are two main manners to transport CO_2, 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 CO_2 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).

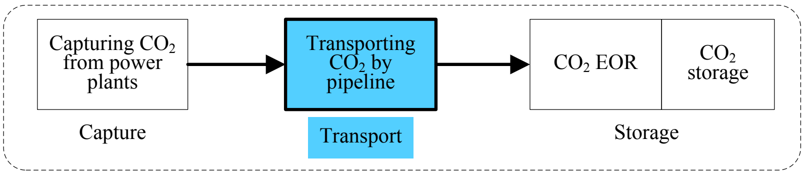

Figure 1. The flowsheet of CCUS

In general, there are two types of construction of CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 ℃

and 17 $^{\circ}C$, respectively. Note that the seasonal temperature still can affect the design of buried pipeline with thermal insulating layer, CO_2 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 CO_2 transportation. Therefore, it's necessary to optimize the operational pressure to minimize the levelized cost of CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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).

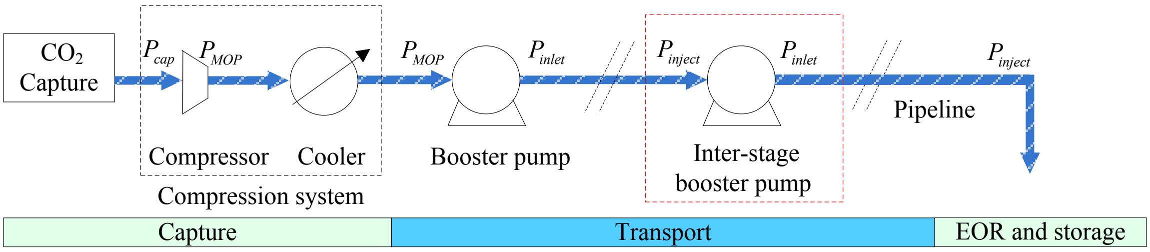

Figure 2. The process of CO_2 transportation

3 Stepwise and piecewise optimization approach

3.1 The optimization model

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

$$\begin{aligned} \min \quad & LC(P_{inlet}, T_{ave}) \\ \text{s.t.} \quad & P_{cap} < P_{inlet} \\ & P_{min} \le P_{inlet} \le P_{max} \\ & t_{cal} \le t_{design} \le t_{NPS} \\ & P_{out} < P_{intlet} \\ & T_{minop} \le T_{ave} \le T_{maxop} \\ & V < V_{max} \\ & 0 \le N_{pump} \\ & P_{out} = P_{inlet} - \Delta P_{act} L / (N_{pump} + 1) \end{aligned} \tag{1}$$

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

$$LC(P_{inlet}, T_{ave}) = \frac{CRF_1 \times C_{P\_cap} + CRF_2 \times C_{C\_cap} + CRF_3 \times C_{B\_cap} + C_{T\_OM} + C_{T\_energy}}{Q_m \times 10^{-3} \times H_{ope} \times 3600} \tag{2}$$

$$CRF_x = \frac{r}{1-(1+\mathrm{r})^{-z_x}} \tag{3}$$

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_{ope} is the operation time of the transportation ($hour/year$). P_{min} is the minimum operational pressure. P_{max} is the maximum operational pressure. t_{cal} is the calculated thickness, t_{design} is the designing thickness, t_{NPS} is the final selected thickness of NPS. T_{minop}, T_{maxop} are minimum and maximum operational temperature for liquid CO_2 transport, respectively. $V_{\max}$ is a certain velocity. The detail models can be found in the related literatures (Table 1).

Table 1 Detail models and the related literatures

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

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. ΔP_{inlet} and ΔT_{ave} are the increment of temperature and inlet pressure respectively, the smaller ΔP_{inlet} and ΔT_{ave}, the more accurate optimized results. The readers can find the required parameters, such as OD_{NPS}, $t_{\max}$, t_{NPS}, ID_{NPS}, range of D_{inner} in Appendix B.

Algorithm 1: The first step optimization (FSP)

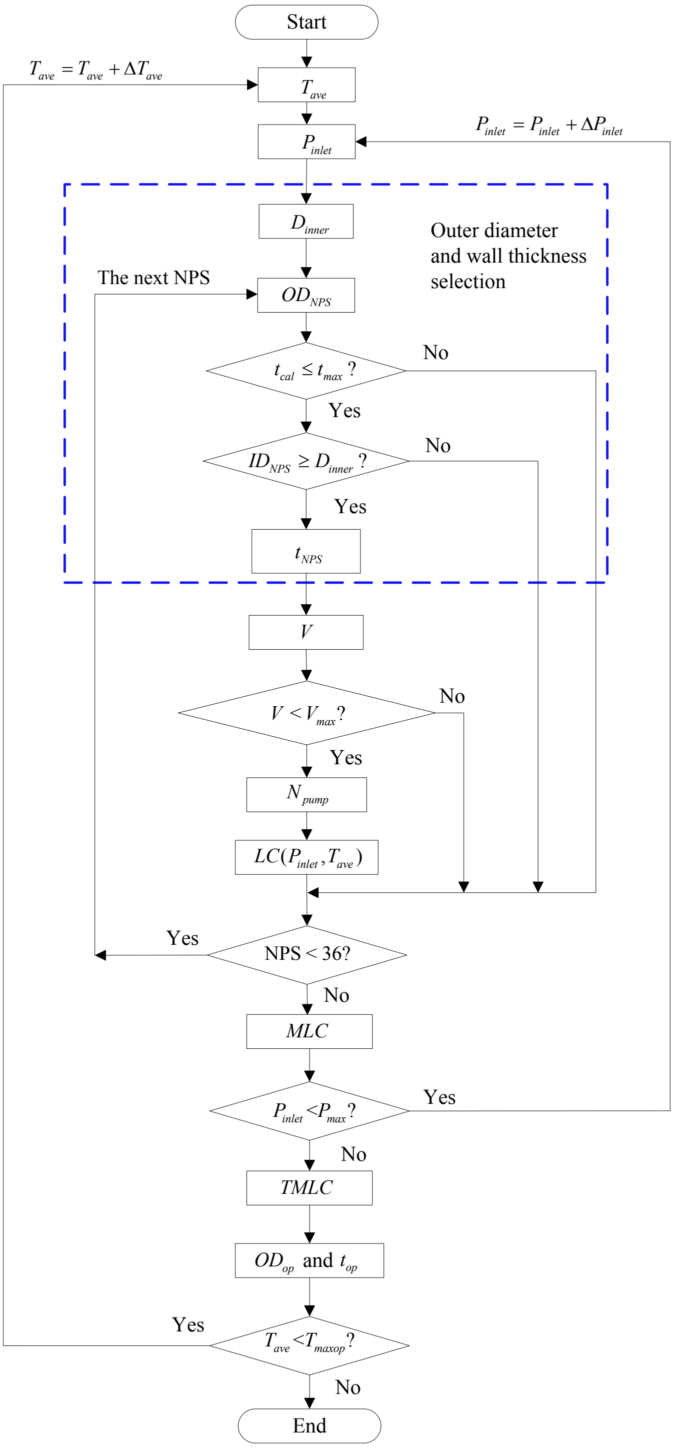

Figure 3. Flow diagram of the first step optimization

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 $OD_{NPS} > 1m$ 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:

$$
\begin{aligned}
&\min LC(P_{inlet}, T_{ave}) \\
&\text{s.t. } P_{min} \le P_{inlet} \le P_{cmax} \\
&\quad T_{minop} \le T_{ave} \le T_{maxop} \\
&\quad V < V_{max} \\
&\quad 0 \le N_{pump} \\
&\quad P_{out} = P_{inlet} - \Delta P_{act} L / (N_{pump} + 1)
\end{aligned}
\tag{4}
$$

where the decision variable of P_{inlet} satisfies the first optimization result of diameter and wall thickness. P_{cmax} is the maximum pressure, which is calculated by $t = P_{max} \times D_{out} / 2 \times S \times F \times E$ 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_{inlet} and the numbers of boosting pump stations N_{pump}. Figure 4 shows flow diagram of the second step optimization.

Algorithm 2: The second step optimization (SSP)

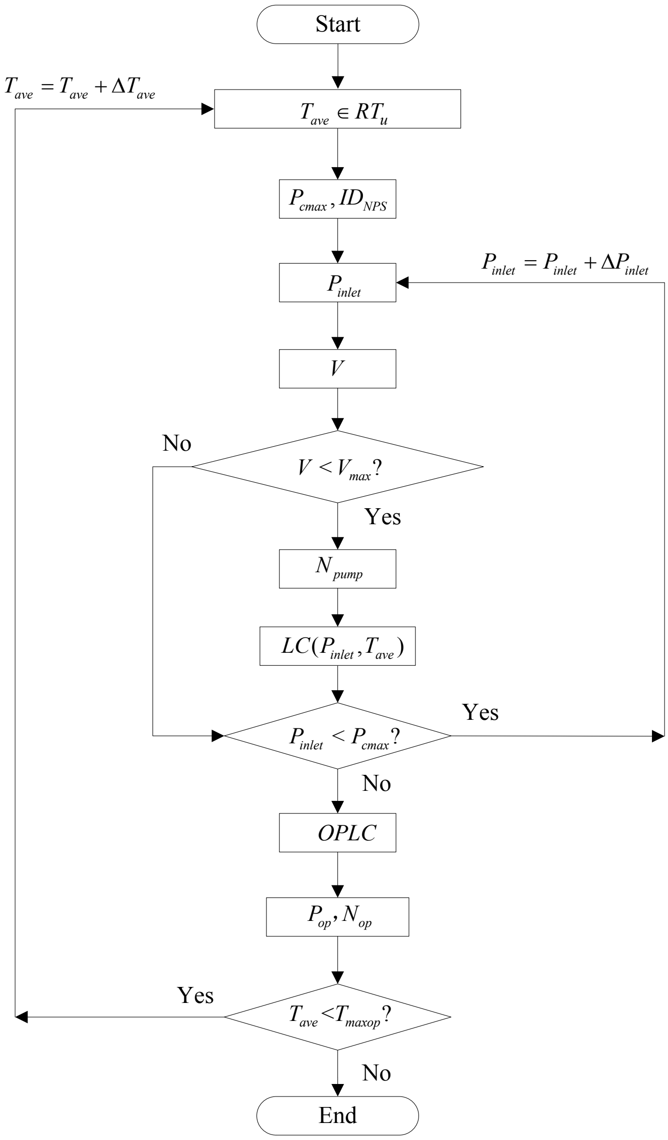

Figure 4. Flow diagram of the second optimization

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 $t = P_{max} \times D_{out} / 2 \times S \times F \times E$, 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:

$$
\begin{aligned}
& \min LC(P_{inlet}, T_{ave}) \\
& \text{s.t.} \quad P_{min} \le P_{inlet} \le P_{cmax} \\
& \qquad V < V_{max} \\
& \qquad 0 \le N_{pump} \\
& \qquad T_{ave} \in RT_u (u = 1, 2, 3 ... U) \\
& \qquad P_{out} = P_{inlet} - \Delta P_{act} L / (N_{pump} + 1)
\end{aligned} \tag{5}
$$

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

	RT_1	RT_2	$RT_{...}$	RT_U
t_H	rt_1	rt_2	$rt_{...}$	rt_U
$LC(t_H)$	$LC(rt_1)$	$LC(rt_2)$	$LC(rt_{...})$	$LC(rt_U)$
Condition	$LC(t_H) < LC(rt_1)$	$LC(t_H) < LC(rt_2)$	$LC(t_H) < LC(rt_{...})$	$LC(t_H) < LC(rt_U)$
Changing temperature of RT_H in	RT_1	RT_2	…	RT_U

where: t_H is the maximum T_{ave} in the area; RT_H is the interval which includes t_H , $H \in u$; $rt_u \in RT_u$ and $rt_u \notin RT_H$.

Algorithm 3: piecewise optimization

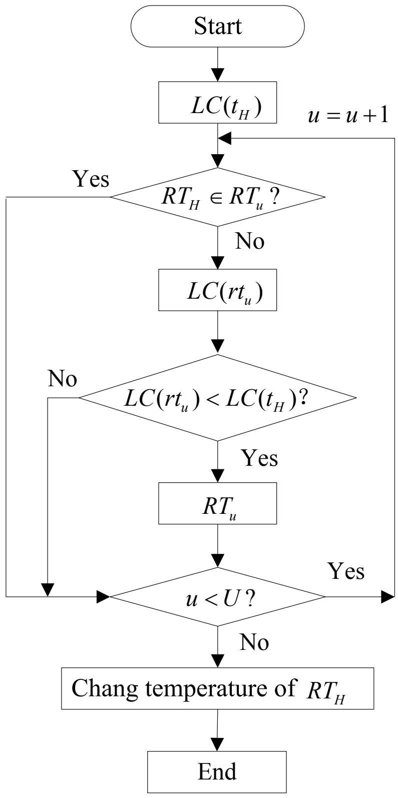

Figure 5. The flow diagram of piecewise optimization

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)

Parameter	Symbol	Value
Typical operational temperature (°C)	T_{ope}	-20~35
District temperature (°C)	T_{soil}	2~17
CO_2 inlet pressure (MPa)	P_{inlet}	8.6~15.3
Altitude difference (m)	$H_1 - H_2$	0
Pipeline length (km)	L	150
CO_2 mass flow rate (kg/s)	Q_m	252
Injection pressure (MPa)	P_{inject}	10
Operation time (hour)	H_{ope}	8760

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

Parameter	Symbol	Value

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	$f_{PO\&M}$	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)

Parameter	Symbol	Value
CO_2 compressibility factor (1.013 bar , 15 °C)	Z	0.9942
Universal gas constant($J/mol\ K$)	R	8.3145
Suction temperature (K)	T_1	313.15
Specific heat ratio (c_p/c_v)	γ	1.294
Molar mass (g/mol)	M	44.01
Number of stages for compression system	N	4
Isentropic efficiency	η_{iso}	80%
Mechanical efficiency	η_{mech}	99%
Suction pressure (MPa)	$P_1(P_{cap})$	0.101
Discharge pressure (MPa)	$P_2(P_{MOP})$	8.6
Base costs for calculating the compressor capital cost ($M€$)	I_0	21.9
Base scale of the compressor (MWe)	$W_{comp,0}$	13
Scaling factor	y	0.67
Multiplication exponent	n	0.9
Percentage of the capital cost for boosting pump stations	$f_{BO\&M}$	0.04
Efficiency booster pump	$\eta_{booster}$	0.5
Dollar- Euro exchange rate	r_D	0.7230
Operation time of compressor (hour)	T_C	8760
Operation time of boosting pump stations (hour)	T_B	8760
Price of electricity ($€/per\ kilowatt\ hour$)	C_{PE}	0.0584

Table 6. Parameter values of the levelized cost model (Knoope et al. 2013; Knoope et al. 2014)

Parameter	Symbol	Value
Interest rate (%)	r	15
Design lifetime of the pipeline (years)	z_1	50
Design lifetime of compressors (years)	z_2	25
Design lifetime of the boosting pump stations (years)	z_3	25

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_{ave} is 15 °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

Q_m (kg/s)		150	200	250	300	350
T_{ave} (°C)		15	-10	17	30	-10
P_{inlet} (MPa)	FSP	11.8550	11.7384	10.6042	10.8215	10.63070
	SSP	10.1855	10.1908	10.1325	10.1060	10.11660
D_{out} (m)	FSP	0.32385	0.3556	0.4064	0.45720	0.45720
	SSP	0.32385	0.3556	0.4064	0.45720	0.45720
t (m)	FSP	0.00635	0.00635	0.00635	0.007925	0.007925
	SSP	0.00635	0.00635	0.00635	0.007925	0.007925
LC (€/t CO_2)	FSP	7.5560	7.0981	6.8231	6.8814	6.6009
	SSP	7.4919	7.0446	6.8062	6.8508	6.5846
Total cost (€) (25 years)	FSP	893572560	1119228408	1344833010	1627588728	1821452346
	SSP	885992094	1110792528	1341502020	1620351216	1816954524
Total saving	%	0.85	0.75	0.25	0.45	0.25
	cost (€)	7580466	8435880	3330990	7237512	4497822

Table 8. Results of the first step optimization

Range of operational temperature (°C)	D_{out} (m)	t (m)
RT_1 (-20 ~ 15.255)	0.4064	0.00635

RT_2 (15.31 ~ 35)	0.4572	0.007925

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 be 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 ℃, the levelized cost is 6.7928 €/t CO_2. That is, reducing the temperature not more than 1.745 ℃, 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.

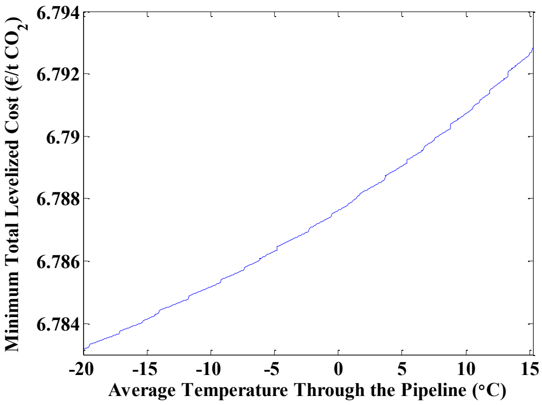

Figure 6(a). Minimum levelized cost over RT_1

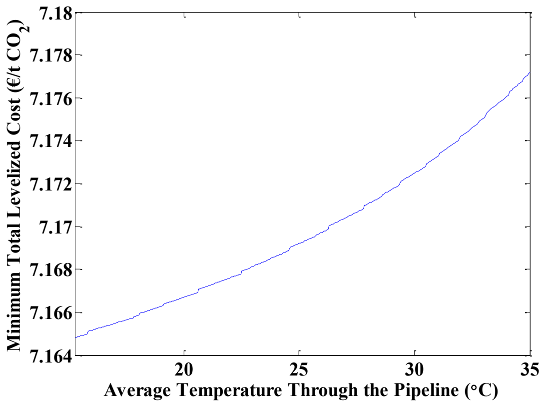

Figure 6(b). Minimum levelized cost over RT_2

Table 9. Piecewise optimization rules

	RT_1	RT_2	RT_H
Temperature (℃)	-20~15.255	15.31~35	15.31~17
LC (€/t CO_2)	6.7832~6.7928	7.1648~7.1772	7.1648~7.1655

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 ℃.

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

Method	Q_m (kg/s)	P_{inlet} (MPa)	D_{out} (m)	t (m)	LC ($€/t\ CO_2$)
(Zhang et al. 2012)	100	13.8	0.27305	0.00635	10.4371
(Knoope et al. 2014)	250	10.6201	0.4064	0.00635	8.1002
The proposed approach	100	10.3710	0.27305	0.004191	9.0660
	250	10.1908	0.4064	0.00635	8.0876

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)

Cost	IC	BC	AC	EC
Total saving /(€) 25 years	9903882	9837436	9881446	10204212

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).

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

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_{out}=10MPa is the minimum injection pressure (Zhang, D et al. 2012). For example, if Q_m=120kg/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_{out} decreases from 10 to 9.7702MPa as the temperature increases. Therefore, if the optimization design is applied based on the minimum temperature, P_{out} is smaller than 10MPa at higher temperatures, this lead to the design unsuitable.

Based on the proposed approach, P_{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

Method \ Q_m (kg/s)		120	130	140	145
Optimization design based on the minimum temperature	D_{out} (m)	0.32385	0.32385	0.32385	0.32385
	t (m)	0.00635	0.00635	0.008382	0.008382
	P_{inlet} (MPa)	13.0276	13.5480	14.3985	14.7137
	P_{out} (MPa)	10~9.7702	10~9.7352	10~9.6781	10~9.6578
The proposed method	D_{out} (m)	0.32385	0.32385	0.32385	0.32385
	t (m)	0.00635	0.00635	0.008382	0.008382
	P_{inlet} (MPa)	13.2537	13.8080	14.7134	15.0479
	P_{out} (MPa)	10.2283~10	10.2636~10	10.31920~10	10.3388~10

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.

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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):

$$D_{inner} = 0.363 Q_m^{\ 0.45} [f_\rho (P_{ave}, T_{ave})]^{-0.32} [f_\mu (P_{ave}, T_{ave})]^{0.025} \tag{6}$$

where P_{ave} is the average pressure along the pipeline (MPa); T_{ave} is the soil temperature around the pipeline ($^{\circ}C$). $f_\rho(P_{ave}, T_{ave})$ is the function of density that depends on the P_{ave} and T_{ave} (kg/m^3); $f_\mu(P_{ave}, T_{ave})$ 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:

$$f_\rho (P_{ave}, T_{ave}) = (BT)^T P \tag{7}$$

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

$$f_\mu (P_{ave}, T_{ave}) = (DT)^T P \tag{8}$$

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}.

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

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

$$D_{inner} = 0.363 Q_m^{\ 0.45} \left((BT)^T P \right)^{-0.32} \left((DT)^T P \right)^{0.025} \tag{9}$$

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 ~ 15.3 MPa) and temperature (-20 $^{\circ}C$ ~ 35 $^{\circ}C$). The ranges of pressure and temperature are detialed in the text.

Table 12. Value of b_{ij} coefficients in (7)

	b_{i5}	b_{i4}	b_{i3}
$i=5$	3.41303419112014E-09	-6.27606343131403E-08	-1.83750350897551E-06
$i=4$	-2.1479352541565E-07	3.93076652279199E-06	0.000115547578911259
$i=3$	5.38395520369261E-06	-0.0000979614237758237	-0.00289271196485396
$i=2$	-0.0000672108836203396	0.00121424647915507	0.0360416517323296
$i=1$	0.000418099646923243	-0.00748487070134038	-0.223492778776728
$i=0$	-0.0010377856097512	0.0183499072848713	0.551534176694391

	b_{i2}	b_{i1}	b_{i0}
$i=5$	0.0000230230930909667	0.000224944614768009	-0.000852920610610217
$i=4$	-0.00144458113956358	-0.0141687690130181	0.0532381024649439
$i=3$	0.0360950459842883	0.355697287851562	-1.31850338708515
$i=2$	-0.449221125789696	-4.45600334239692	16.081925864937
$i=1$	2.78940873199454	28.0357205366994	-90.7523009464699
$i=0$	-6.95671353509922	-76.2734885162019	1144.8428039407

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

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

	d_{i5}	d_{i4}	d_{i3}
$i=5$	2.96979983755421E-16	-5.11790363405514E-15	-1.61341423050057E-13
$i=4$	-1.87118491886111E-14	3.2115785053841E-13	1.01460065638067E-11
$i=3$	4.69554059206441E-13	-8.0183431311157E-12	-2.53958254359596E-10
$i=2$	-5.86762907841313E-12	9.95470125149012E-11	3.16249472186625E-09
$i=1$	3.65292223605669E-11	-6.14360261245057E-10	-1.95888466031802E-08
$i=0$	-9.07040455852916E-11	1.50745813211555E-09	4.81654629878995E-08

	d_{i2}	d_{i1}	d_{i0}
$i=5$	2.96979983755421E-17	-5.11790363405514E-16	-1.61341423050057E-14
$i=4$	-1.87118491886111E-15	3.2115785053841E-14	1.01460065638067E-12
$i=3$	4.69554059206441E-14	-8.0183431311157E-13	-2.53958254359596E-11
$i=2$	-5.86762907841313E-13	9.95470125149012E-12	3.16249472186625E-10
$i=1$	3.65292223605669E-12	-6.14360261245057E-11	-1.95888466031802E-09
$i=0$	-9.07040455852916E-12	1.50745813211555E-10	4.81654629878995E-09

Appendix B. The modified nominal pipe size

Table 14. The modified NPS

NPS	OD_{NPS} (mm)	t_{maxNPS} (mm)	t_{maxOP} (mm)	t_{max} (mm)	t_{NPS} (mm)	ID_{NPS} (mm)	Classified range (mm)
1/8	10.26	2.413	0.2257	0.889	0.889	8.4812	$0 < D_{inner} \leq 8.4812$
1/4	13.72	3.023	0.3018	1.245	1.245	11.23	$8.4812 < D_{inner} \leq 11.23$

3/8	17.15	3.200	0.3773	1.245	1.245	14.66	$11.23 < D_{inner} \leq 14.66$
…	…	…	…	……	……	…..	……
34	863.6	17.475	18.9974	17.475	7.925 9.525 12.7 15.875 17.475	847.75 844.55 838.2 831.85 828.65	$796.95 < D_{inner} \leq 847.75$
36	914.4	12.7	20.1149	12.7	7.925 9.525 12.7	898.55 895.35 889	$847.75 < D_{inner} \leq 898.55$

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

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