Journal of Cleaner Production 266 (2020) 121994

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

Carbon dioxide transport via pipelines: A systematic review

Hongfang Lu [a, c, e, *], Xin Ma [b], Kun Huang [a], Lingdi Fu [d], Mohammadamin Azimi [e]

[a] State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, 610500, China
[b] School of Science, Southwest University of Science and Technology, Mianyang, 621010, China
[c] Division of Construction Engineering and Management, Purdue University, West Lafayette, IN, 47907, United States
[d] Safety, Environment and Technology Supervision Research Institute of PetroChina Southwest Oil & Gasfield Company, Chengdu, 610041, China
[e] Trenchless Technology Center, Louisiana Tech University, Ruston, LA, 71270, United States

A R T I C L E I N F O

Article history:
Received 16 December 2019
Received in revised form
11 April 2020
Accepted 29 April 2020
Available online 4 May 2020

Handling Editor: Prof. Jiri Jaromir Klemeš

Keywords:
Carbon capture and storage
Carbon dioxide pipeline
CO_2 pipeline design
CO_2 transport process
CO_2 transport risk

A B S T R A C T

Carbon dioxide transport plays a crucial role in carbon capture and storage systems. As an economical and convenient carrier, pipelines have huge advantages in the transport of carbon dioxide. In this paper, the development of carbon dioxide transport via pipeline is systematically reviewed from four aspects: pipeline design, process, risk and safety, standard and specification. The results reveal that there are many similarities between the carbon dioxide pipeline and the natural gas pipeline, but due to different gas compositions and transportation destinations, the transport process, design, and construction considerations are quite different. Especially in terms of management, the specifications and standards for carbon dioxide pipelines are still minimal, the techno-economic framework and integrity management system are still immature. In addition, this paper summaries the challenges and future directions of carbon dioxide transport via pipeline. It is concluded that the studies on the influence of impurities on phase equilibrium and corrosion mechanisms in carbon dioxide pipeline are challenges, and the new construction and detection technologies are also crucial. With the rapid development of computer science, some interdisciplinary applications such as artificial intelligence and digital twin will promote the development of carbon dioxide pipeline.

Contents

* Corresponding author. State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, 610500, China.
E-mail address: [redacted]@126.com (H. Lu).

https://doi.org/10.1016/j.jclepro.2020.121994
0959-6526/

1. Introduction

1.1. Background

Carbon dioxide (CO_2) is one of the leading greenhouse gases (GHGs) that cause global warming (Jacobson et al., 2019; Zhang et al., 2015; Lu et al., 2020c,d). It is mainly derived from industrial production and power generation (Lu et al., 2020; Akbostancı et al., 2018). In recent years, a growing number of countries begin to pay attention to the increasingly severe problem of global warming (Carey, 2012; King et al., 2017), and many research institutions and enterprises such as BP and Shell (Lu et al., 2019a) are also committed to the research of carbon capture and storage (CCS) technologies (Tapia et al., 2018; Wang et al., 2017). CCS is one of the critical technologies to control global warming (Metz et al., 2005). In this technical system, CO_2 transport is a momentous link between carbon capture and storage (Leung et al., 2014). As shown in Fig. 1, the captured CO_2 is transported to the storage point or buffer storage through the pipeline, and part of the CO_2 continues to be transported to the ocean and stored in the geological storage. The transportation system can be divided into onshore transport and offshore transport. Among them, highway, railway, and pipeline can be used for onshore transport, while offshore transport carrier includes pipeline and ship. The advantages and disadvantages of these transport methods are shown in Fig. 2. Technically speaking, it is feasible to transport liquefied gas by road and railway tanker, but this method is not the choice of a large CCS project. Despite all this, China's onshore CO_2 transport is mainly based on highway cryogenic storage tanks because related research has just started in China. The significance of the CO_2 pipeline to CCS lies in: (1) it is the key to the effective operation of the CCS system; (2) it guarantees the safety of CO_2 transport; and (3) it guarantees the economical operation of the CCS system.

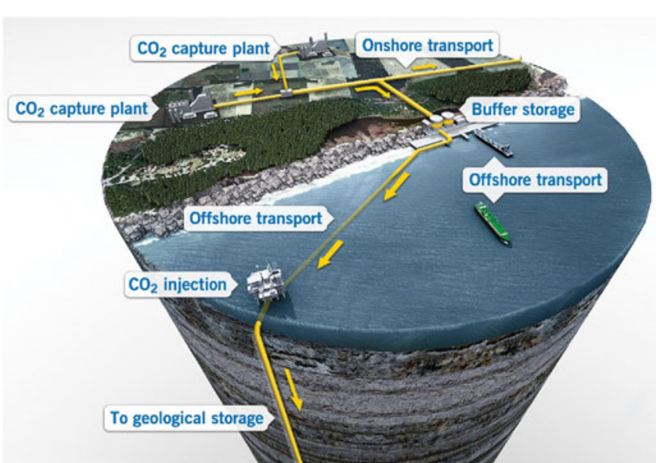

Fig. 1. CO_2 transport system (Source: Global CCS Institute, 2019).

Based on the above description, the pipeline is the primary way to transport CO_2. In addition to the driving force of CCS project, enhanced oil recovery, enhanced gas recovery, global emission reduction action, and enhanced coal bed metal recovery are the main driving factors of CO_2 pipeline construction (Noothout et al., 2014). According to statistics, the length of the global CO_2 pipeline has exceeded 8000 km in 2015, of which the United States has the largest share (over 7200 km in 2015) (Peletiri et al., 2018; IEA Environmental Projects Ltd, 2014; Chandel et al., 2010; Morbee et al., 2010). Fig. 3 reveals that the CO_2 pipelines in the United States are mostly distributed in the central and southern regions with the developed natural gas industry. Table 1 lists some parameters of typical CO_2 pipeline projects. It indicates that the CO_2 pipeline is not a new development, it has existed as early as the 1970s.

After many countries signed the Paris Agreement in 2016 (Bataille et al., 2018), research on CCS and energy transformation have entered a new phase. The agreement sets a common goal to control the global average temperature rise in this century within 2 °C. In this context, the demand for CO_2 pipeline construction will also increase greatly. Experts estimate that by 2050, it will take 200 thousand kilometers of pipelines to transport 10 billion tons of CO_2 (Edwards and Celia, 2018; Spinelli et al., 2014; Newcome and Apt, 2008).

1.2. Brief description of CO_2 and CO_2 pipeline

The fundamental reason for the particularity of the CO_2 pipeline is the medium. It is necessary to describe the main physical and chemical properties of CO_2. Some of the main properties and some implications are shown in Table 2.

CO_2 pipeline is similar to the natural gas pipeline, which can reach thousands of kilometers and can cross mountains, cities, and oceans. However, the differences between CO_2 pipeline and gas pipeline are as follows: (1) transmission medium; (2) operation; (3) pipe material strength.

1.2.1. Transmission medium

CO_2 is similar to natural gas in color, odor, and transportation form, but CO_2 is non-toxic and non-flammable. When a pipeline leaks, it diffuses much slower than natural gas since it is heavier than air, and it accumulates in low-lying areas. Although the frequency of leakage failure of the CO_2 pipeline is low, its leakage and diffusion law are still worthy of further study.

1.2.2. Operation

As the physical properties of CO_2 are quite different from those of natural gas (Liu et al., 2019), its transportation form is greatly affected by temperature, pressure, and impurities, so it is elementary to have phase transformation in the transportation process. In

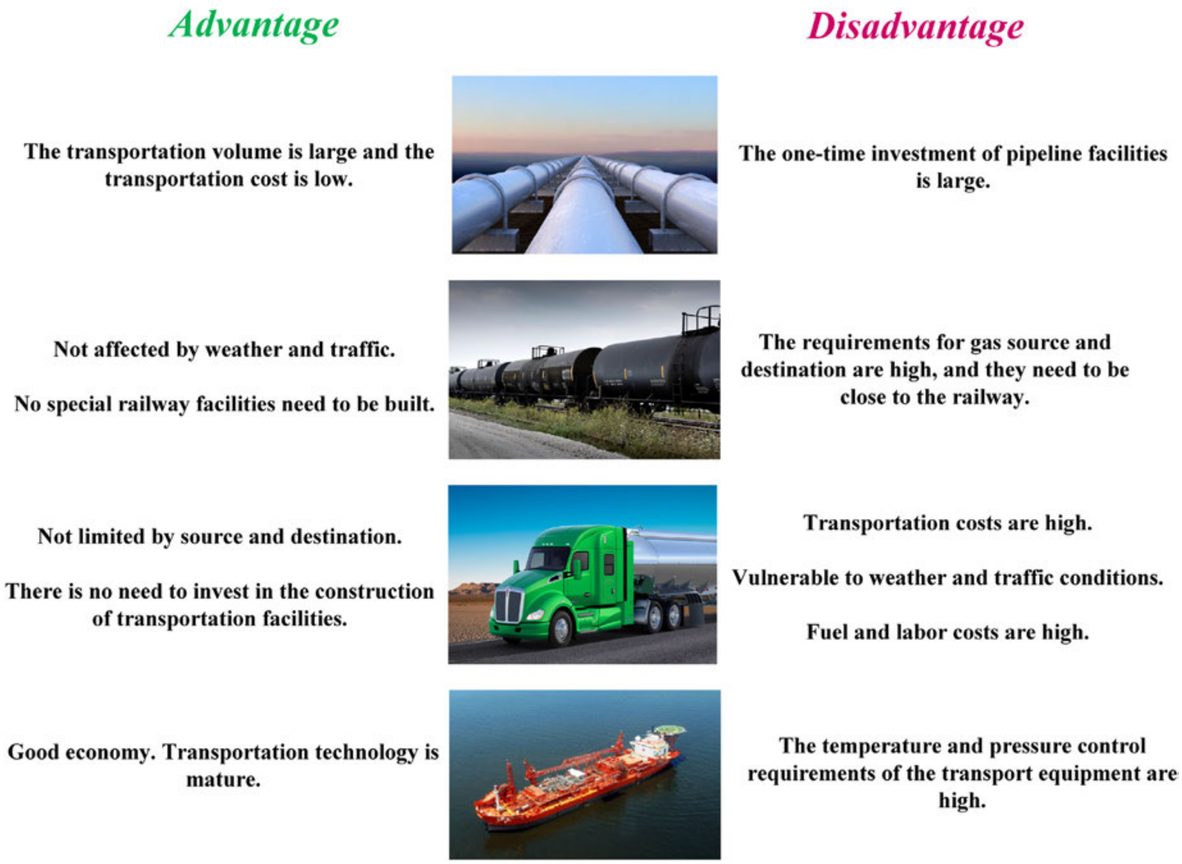

Fig. 2. Pros and cons of the four CO_2 transport methods.

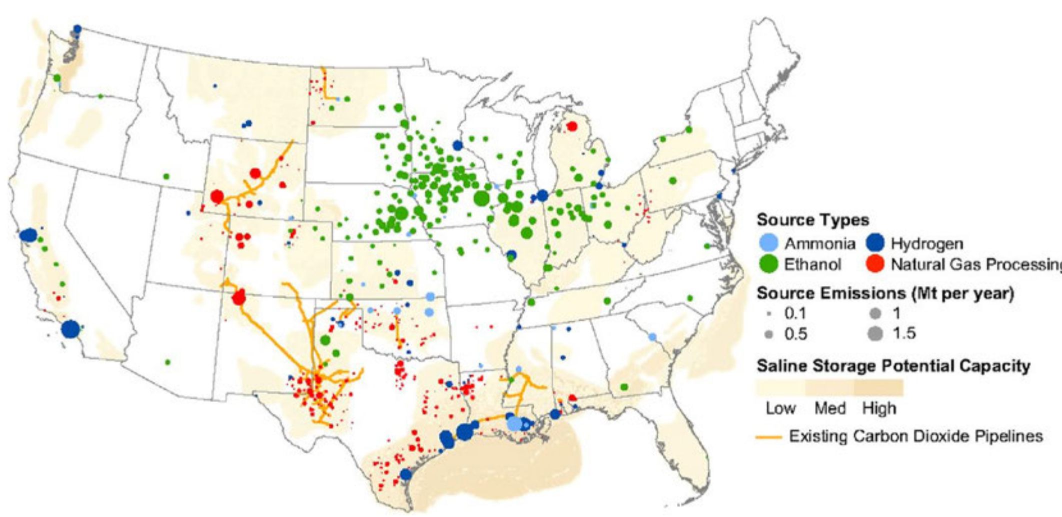

Fig. 3. Existing CO_2 pipeline in the United States (Source: Edwards and Celia, 2018).

Table 1
General situation of some typical CO_2 pipeline projects (Peletiri et al., 2018; IEA Environmental Projects Ltd, 2014).

Project name	Length (km)	Year	Onshore/offshore	Country
Canyon Reef Carriers	225	1971	Onshore	USA
Quest	84	2012	Onshore	Canada
Qinshui	116	2006	Onshore	China
Weyburn	330	2008	Onshore	Canada
ROAD	25	2010	Onshore and offshore	The Netherlands
Gorgon	9	2011	Onshore	Australia

Table 2
Properties of CO_2 (Wang et al., 2016).

Property	Revelation
It is denser than air.	The diffusion speed and law of CO_2 in the air are different from other gases.
The critical temperature is 31.4 °C, the critical pressure is 7.38 MPa, and the triple point is (0.52 MPa, 56.6 °C).	Temperature and pressure are very important for the mode of transportation.
It has strong corrosiveness when encountering water.	The anti-corrosion measures of the transport vessel are essential.
The delivered CO_2 usually contains impurities.	The pressure and temperature requirements of the transport may be changed due to changes in the property of the gas.

the process of natural gas transportation, special attention should be paid to the temperature and pressure to control the formation of the hydrate. For CO_2, the impurity limit should also be considered.

1.2.3. Pipe material strength

CO_2 pipes are more prone to ductile fracture. Because of low-temperature transportation and decompression waves, the material properties of CO_2 pipes have higher requirements.

1.3. Motivations, contributions, and article organization

The purpose of this paper is to provide a basis for decision-makers, designers, and managers by collecting information about CO_2 pipelines. It can not only provide support for the operation and management of the completed CO_2 pipelines, but also give a reference for the future CO_2 pipeline design.

Through a systematic review of the reports and articles on CO_2 pipeline, the contributions of this paper mainly include: (1) The relevant technologies and research of the CO_2 pipeline are introduced and reviewed; (2) relevant standards and specifications are collected; (2) the future challenges and research directions are summarized.

The rest of the paper is organized as follows: Section 2 introduces the methodology of literature review. Section 3 introduces the related technologies and research of the CO_2 pipeline from four aspects. Section 4 summarizes the challenges and future directions of the CO_2 transport technologies via pipeline. Section 5 lists the primary conclusions of this paper.

2. Review methodology

The following steps are followed during the literature review:

- **Step 1: Keyword-based search**
  Although the quality of articles in the Web of Science database can be guaranteed, due to the delay of indexing, we have combined the search results of multiple databases. The key information of the search is as follows:
  Objective: carbon dioxide pipe
  Database: Google Scholar, Web of Science, Scopus, Ei Compendex, ScienceDirect, CNKI
  Keywords: carbon dioxide pipe transport OR CO_2 pipe transport;
  Language: English and Chinese
  Considering that some organizations or companies may have some key information in their reports, Google and Bing are used as regular search tools.
- **Step 2: Extraction of related references**
  The references of some documents may contain some useful information, the references of the documents in Step 1 are further extracted.
- **Step 3: Screening**
  The contents of some documents may not be consistent with the review objectives. In this step, the collected literature is screened by reading the title and abstract. The screening principle is as follows: the research content needs to be related to the design, operation, maintenance, standard, and other aspects of the CO_2 pipeline. In this step, four topics for review are clarified: (1) pipeline design; (2) process; (3) safety and risk; (4) code or standard.
- **Step 4: Reviewing**
  Read each document and extract valuable information from it.

3. Carbon dioxide pipeline transport

This section reviews the research of CO_2 transport via pipeline from the following four aspects: process, pipeline design, risk and safety, standard and specification.

3.1. Process

According to the literature review, the research of the CO_2 transport process can be divided into three aspects: state equation, transport process, and thermodynamic analysis.

3.1.1. State equation

The phase behavior of CO_2 is the basis of transport research. At different temperatures and pressures, CO_2 will have different phase states (Mazzoccoli et al., 2014; Laboureur et al., 2015). In the study of phase states, the determination of state equation is the most important. At present, scholars from various countries have not formed a unified opinion on the selection of CO_2 state equation (Li and Yan, 2009; Stang et al., 2013). King (1982a) proposed to consider the impact of impurities and to verify the reliability of the state equation for specific impurity components in the design of CO_2 pipelines. Farris (1983) proposed Benedict-Webb-Rubin-Starling (BWRS) equation as the state equation for CO_2. Through the CO_2 pipeline project in Rocky Mountain, the economy of supercritical transport is proved. Hein used Peng-Robinson (PR) equation (Peng and Robinson, 1976) and Soave Redlich Kwong (SRK) equation to calculate the thermodynamics of CO_2. Zhang et al. (2006) adopted the Boston-Mathias modified PR equation (PRBM) as the basis of CO_2 thermodynamic calculation. Li and Yan (2006) proposed that the reliability of the state equation needs to be verified experimentally because the choice of the state equation has a significant influence on the pipeline design. Huh et al. (2009) investigated the reliability of SRK, PR, BWRS, and other state equations through experiments, and concluded that PR and PRBM equations are more suitable for CO_2 pipeline transport. Seevam et al. (2008) used PR equation to analyze the influence of impurities on CO_2 pipeline transport, and determined that impurities may affect pipeline design, compressor or pump power. Through the comparison of the experimental and theoretical results, Chen (2016) concluded that PR equation is more practical to calculate the physical parameters of CO_2. It can be implied from the review that in different case studies, many scholars have obtained inconsistent results and recommended different state equations, which shows that the gas quality analysis is necessary before conducting phase analysis. It can be also concluded that the PR-based state equation (PR equation or its improved form) is more suitable for CO_2 pipeline.

3.1.2. Transport process

The forms of CO_2 transport include gaseous transport, liquid transport, dense-phase transport, supercritical transport, and solid transport. In terms of feasibility, the first four methods are more suitable for long-distance and large-scale transportation. Fig. 4 shows the process flow chart of these four transport methods. Table 3 lists the transport features and applications of different methods. Through the summary of practice, gaseous transport and liquid transport can be used for short-distance pipelines, and dense-phase transport and supercritical transport can be utilized for long-distance pipelines. Among them, supercritical transport and dense-phase transport are more economical.

Some scholars or institutions have conducted some basic research regarding CO_2 transport. Zhang et al. (2006) studied the pressure drop of pipelines during CO_2 transportation. They concluded that the pressure along the pipeline continued to drop until the CO_2 evaporated, and the pipeline may eventually be blocked, thus inferring that the CO_2 transportation has the largest safe transportation distance. Yu et al. (2009) studied CO_2 transportation technology and concluded that the pressure drop of supercritical transport is greater than that of liquid transport and dense-phase transport, while that of liquid transport is greater than that of dense-phase transport. Wang et al. (2016) simulated the processes of different transport methods and performed a sensitivity analysis. Under gaseous transport conditions, the lower the temperature of the CO_2 pipeline inlet, the higher the pressure drop (Wang, 2017). Ambient temperature has a more significant impact on the pressure drop of the pipeline. The higher the ambient temperature, the greater the pressure drop. Moreover, compared with the natural gas pipeline, if the operating conditions are the same, the CO_2 pipeline will have a smaller pressure drop than the natural gas pipeline, but the temperature drop is greater, and CO_2 is more likely to generate hydrates than natural gas. Therefore, the gaseous transport of CO_2 has high requirements for the control of temperature and pressure. When dense-phase transportation is adopted, the effect of the pipeline inlet temperature on the pressure drop is small and the effect on the temperature drop is substantial. With the increase of the transport distance, the influence of the ambient temperature on the pressure of the pipeline increases. The higher the ambient temperature, the greater the pressure drop of the pipeline. If supercritical transport is used, the influence of pipeline inlet temperature on pressure is small. However, during the transportation process, the temperature decreases rapidly, so that the phase transition will occur under a shorter transportation distance. Ambient temperature has less effect on the pressure drop of the pipeline, but has a greater effect on the temperature drop. In addition, the author compared dense-phase transport with supercritical transport. Under the same conditions, the pressure drop of supercritical transportation is more considerable. In dense-phase transport, the temperature of the pipeline will drop to ambient temperature, but no phase change will occur. However, supercritical transport may require additional heating stations to maintain temperature. Sinopec also did some basic research on the physical properties of CO_2 to provide a basis for the transport process. They obtained the relationship curves between different parameters, including temperature-density, pressure-density, temperature-viscosity, pressure-viscosity (Chen, 2016). Moreover, some design companies are also carrying out relevant research, such as Project Consulting Services, ® Inc in the United States, which has obtained the influence of impurities on pressure loss at different positions of pipelines (Istre, 2019).

From the above review, it reveals that temperature and pressure control is the key technologies in CO_2 pipeline transport, and the presence of impurities will have a high impact on transportation. Therefore, some scholars have studied the optimization of CO_2 pipeline transport. Zhang and Feng (2005) performed numerical simulations on the processes of supercritical transport and liquid transport for CO_2. It was concluded that under appropriate climate conditions, the use of liquid transport could reduce operating energy consumption, and the use of pumps as pressurizing equipment can also lower the cost. Zhang et al. (2006) compared the supercritical transport with the subcooled fluid transport of CO_2. Through numerical simulation, they concluded that the subcooled fluid transport method could effectively improve the energy efficiency, reduce the cost under the conditions of isothermal and adiabatic transports, and concluded that the scheme is more suitable for cold areas. Di (2013) conducted simulation and optimization studies on CO_2 pipelines, and concluded that the presence of nitrogen and methane has little effect on the temperature and pressure drop of supercritical transport, but has a greater impact on liquid transport, and the impact of nitrogen is greater than methane. By optimizing the actual project, it is concluded that low-

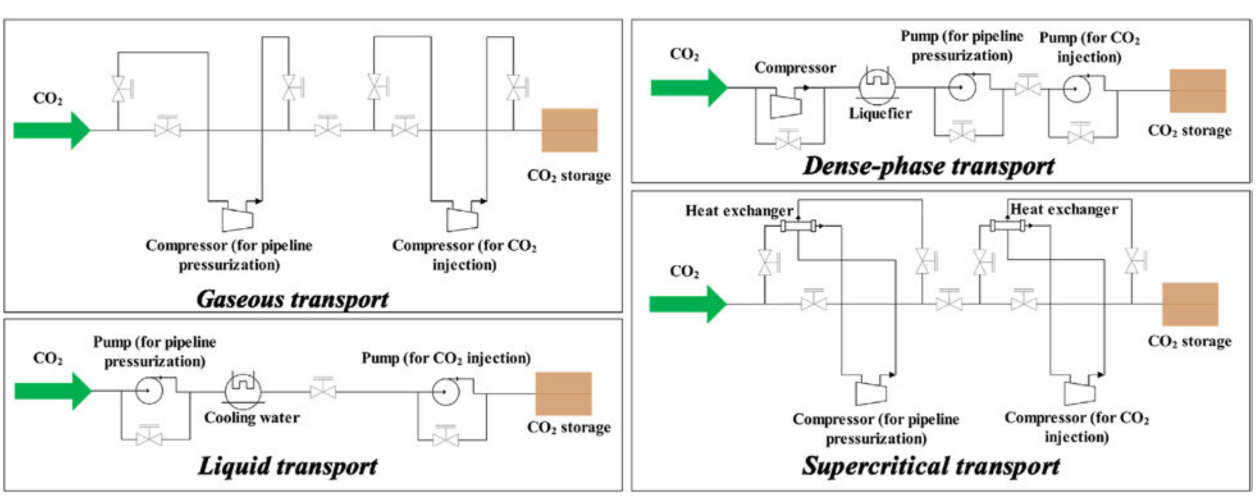

Fig. 4. Four process flow diagrams suitable for large-scale CO_2 pipeline transport (Zheng et al., 2018).

Table 3
Characteristics of the four CO_2 transport methods (Zheng et al., 2018; Gao and Liu, 2017; Li, 2013).

Transport method	Description	Requirement	Advantage	Disadvantage	Applications
Gaseous transport	CO_2 is always gaseous during transportation.	CO_2 needs to be throttled and depressurized before entering the pipeline. The pressurization during the transport process must not exceed the critical pressure to avoid the phase change of CO_2. No insulation required for the pipeline.	The requirements of pipeline materials for gaseous transport are relatively low.	In the same situation, the transport volume is small, and the economy is poor. Poor adaptability to high-pressure transport.	Small capacity, short distance pipeline, densely populated area.
Liquid transport	CO_2 is always liquid during transport.	Temperature control needs to be very strict to prevent CO_2 from becoming gaseous or solid.	The friction during the transport is small, the viscosity is small, and the density is small, which is convenient for transportation.	High vapor pressure may affect regular transport.	Small capacity, short distance pipeline, densely populated area. Suitable for use in oil fields.
Dense-phase transport	CO_2 is always in dense-phase during transportation.	The transport temperature should be slightly lower than that of supercritical transport, and the whole pressure range should not be changed	The investment cost of dense-phase transport is much lower than gaseous transport and liquid transport, but closer to supercritical transport.	Only applicable to areas with relatively small populations.	Pipeline with large capacity and long-distance. Less densely populated areas.
Supercritical state transport	CO_2 is always in a supercritical state during transportation.	The transport temperature and pressure are both above the critical value.	Good economy.	Due to changes in temperature and pressure, many impurities may precipitate from the CO_2 and form a gas phase.	Pipeline with large capacity and long-distance. Less densely populated areas.

pressure supercritical pressure boosting at the gas gathering station and the use of low-pressure supercritical transport can improve the economics of operation. Mohammadi et al. (2019) proposed an optimization framework to minimize the cost of CO_2 transport via pipeline, and they used genetic algorithms to find the solution with the lowest total cost. The results show that the pipe elevation and pipe diameter are the most critical parameters affecting cost. From the literature review, it indicates that dense-phase transport and supercritical transport have more advantages in long-distance, large-scale CO_2 pipeline engineering, and temperature and pressure control are still the key content in the transportation process. In recent years, some scholars have started research on transportation optimization, mainly considering the economics of pipeline operation.

3.1.3. *Thermodynamic analysis*

For CO_2 pipelines, temperature control is particularly important. The temperature of the pipeline is not only related to the inlet temperature, but also the ambient temperature. Therefore, many researchers have analyzed the thermodynamics of pipelines. Brown et al. (1996) proposed a computational model for tube bundle heat transfer. Zabaras and Zhang (1998) analyzed the transient cooling performance of six different tube bundle structures. Jackson et al. (2005) analyzed the effect of seawater around submarine pipelines on the adiabatic layer. Xie et al. (2014) analyzed the leakage of the CO_2 pipeline using supercritical transport method. The results show that the thermal boundary layer in the pipeline is constantly changing when CO_2 leaks, and the convection intensity near the leakage point is the largest. Witkowski et al. (2014a) proposed that the design of the CO_2 pipeline needs to consider the extreme conditions of the ambient temperature, and through the analysis of the example, the maximum transmission distance at 35 °C is 310 km. Li et al. (2014) studied the flow and heat transfer characteristics of CO_2 pipelines in case of leakage. They concluded that the mass flow rate and Nusselt number can be used for the leakage detection of CO_2 pipelines using supercritical transport method. Yu et al. (2017) experimentally studied the thermodynamic characteristics of the supercritical transport of CO_2 during decompression. The results show that the release of CO_2 will lead to the decrease of pressure, temperature and pipe wall temperature, and then tend to be stable, and the temperature drop in the initial stage is the largest. Wang (2017) performed a sensitivity analysis on the total heat transfer coefficient of CO_2 pipelines with different transport processes, and concluded that when CO_2 is transported in a gaseous state, if the total heat transfer coefficient is in the range of 0.84–3.02 ($W \cdot m^{-2} \cdot {}^\circ C^{-1}$), the total heat transfer coefficient has a small effect on the pressure drop. When transported in the liquid phase, if the total heat transfer coefficient is in the range of 0.84–1.9 ($W \cdot m^{-2} \cdot {}^\circ C^{-1}$), the total heat transfer coefficient has a small effect on the pressure drop. When dense-phase transport is adopted, the thermal insulation performance of the pipeline is not high. When supercritical transport is used, the total heat transfer coefficient has a small effect on the pressure drop. The review of thermodynamic analysis indicates that the analysis of thermal insulation and pressure drop during the CO_2 transport process is critical to the regular pipeline operation. At the same time, this is also the focus of flow assurance research.

3.2. *Pipeline design*

As with other pipelines, the design of CO_2 pipelines also needs to consider length, pipe diameter, wall thickness, pressure, and construction (Gao et al., 2011; Roussanaly et al., 2013, 2014).

3.2.1. *Length, capacity, and initial booster power*

The CO_2 pipeline can be divided into large-scale and small-scale according to the length. According to statistics of a total of 65 CO_2 pipelines in two important reports (IEA Environmental Projects Ltd, 2014; Wallace et al., 2015), the pipeline length ranges from 1.9 to 808 km, which is relatively broad. The shortest and longest pipelines are in the United States, the Decatur pipeline project (1.9 km) in Illinois and the Cortez pipeline project (808 km) in Texas. The longer the pipeline, the higher the designed transport capacity (see Fig. 5). Although there is no direct relationship between transport capacity and length, operating companies usually do so to maximize utilization. Since the longer the pipeline, the greater the pressure to be provided, the power of the initial booster is usually positively related to the length of the pipeline. If CO_2 is in the gas phase, compressors are used for pressurization. If CO_2 is in liquid or dense phase, pumps are used. For a long-distance pipeline, it is usually necessary to adopt a stepwise pressurization method, and multiple booster stations will be established along the way. The calculation method of design power of compressor station and pump station is given in the literature (Ikeh et al., 2011). Based on the collected data of CO_2 pipeline projects, the Global CCS Institute divides it into three categories according to the transport scale (IEA Environmental Projects Ltd, 2014), and their length, capacity, and initial booster power range are shown in Table 4.

Table 4
Length, capacity, and initial booster power range of different categories of CO_2 pipeline.

Design parameter	High	Medium	Low
Length (km)	657–808	116–380	1.9–97
Transport capacity (Mt/y)	10–37	2.8–7.2	0.06–2
Initial booster power (MW)	43–68	15–17	0.2–8

3.2.2. Diameter and wall thickness

In the design of CO_2 pipeline, the calculation of pipe diameter is the most important because it not only directly determines the transportation capacity, but also determines the investment. Generally, the larger the pipe diameter, the greater the investment. Therefore, the most reasonable pipe diameter is to minimize the pipe diameter on the basis of meeting the transmission requirements (Chen and Zhang, 2011). In the design of pipe diameter, in addition to the above factors, pressure, flow rate, and fluid flow should also be considered. After many years, many scholars have proposed various pipe diameter design or optimization formulas based on different considerations, as shown in Table 5. These formulas do not apply only to CO_2 pipelines, but to natural gas pipelines. Most of these formulas are based on the principle of hydraulic calculation, and some are based on economic considerations. In addition, different formulas have different advantages and disadvantages. For example, number 3 is convenient for calculation, but the average flow rate needs to be assumed and the pressure drop is not considered. Vandeginste and Piessens (2008) summarized the applicability of some pipe diameter calculation formulas. Peletiri et al. (2018) obtained the results from different pipe diameter calculation formulas through an example. They assumed that the length of the pipe is 200 km and the total pressure drop is 5 MPa. The calculation was completed in the gPROMS software. The results show that the calculation result of formula 7 is the most conservative, while the calculation result of formula 1 is the smallest.

The pipe wall is used to bear the internal and external pressure on the pipe. The larger the wall thickness, the higher the pressure bearing capacity of the pipeline, but at the same time, the investment will increase. Table 6 lists several mainstream formulas for the design of pipe wall thickness. Among them, the ideas of formulas A and B are the same, but the expressions are different. Equation C considers the corrosion allowance in the wall thickness design. Equation D considers the effects of temperature. Because CO_2 may be transported in different ways, the phase state should be considered in the design of wall thickness. Teh et al. (2015) proposed that if other conditions are the same, the wall thickness required for liquid transport is smaller than that for supercritical transport. Similarly, the Global CCS Institute divides the existing CO_2 pipeline projects into three grades according to pipe diameter and wall thickness (IEA Environmental Projects Ltd, 2014), as shown in Table 7. It can be obtained that the design of pipe diameter and wall thickness of CO_2 pipeline is based on the results of hydraulic analysis and stress analysis, just like that of natural gas pipeline. This means that the wall thickness needs to be determined according to the material of the pipeline under the premise of satisfying the transportation conditions. Under the same conditions, the higher the steel grade, the smaller the wall thickness required for the material, and it also means that the cost will be higher. Table 8 lists the characteristics of some common materials. As the transport pressure level of CO_2 may be higher than that of natural gas, a more conservative scheme is recommended for the design of wall thickness.

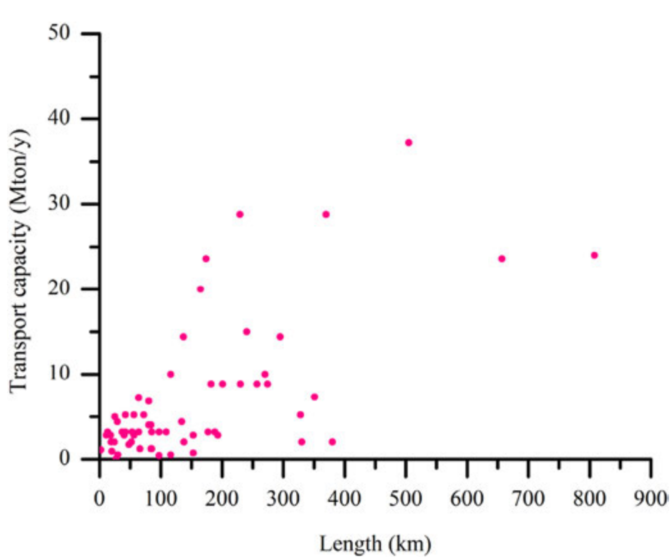

Fig. 5. Pipe length and transport capacity.

Note: t represents pipe wall thickness; p_{max} represents maximum pressure; S represents yield strength; D_o represents outer diameter of the pipeline; D_i represents inner diameter of the pipeline; F represents design factor; E represents longitudinal joint factor; T represents temperature factor; L_f represents location factor; CA represents corrosion allowance.

3.2.3. Pressure and temperature

Temperature and pressure directly determine the CO_2 transport state in the pipeline. A report states that for CO_2 to be transported under supercritical conditions, the temperature and pressure ranges should be 12–44 °C and 8.5–15 MPa, respectively (Serpa et al., 2011). The temperature and pressure during CO_2 transport are not constant, and both fluctuate within a certain range. Among them, the lower pressure limit is based on the consideration of CO_2 supercritical transport, and the upper-pressure limit is based on economy and risk. For example, an offshore CO_2 pipeline can have a maximum pressure of 30 MPa because it is far away from populated areas. The lower temperature limit is based on the ambient temperature in winter, and the upper-temperature limit is determined based on the outlet temperature of the booster station and the temperature limit of the outer casing material. Another report pointed out that if CO_2 is transported in a low-pressure gas phase, the maximum pressure is 4.8 MPa. If the pressure is greater than 9.6 MPa, it can ensure that CO_2 can be transported in the dense phase at any temperature. The Global CCS Institute divides the pressure levels of CO_2 pipelines into three categories according to the minimum and maximum pressures (IEA Environmental Projects Ltd, 2014), as shown in Table 9.

3.2.4. Pipeline route and construction considerations

The pipeline route is determined by the source and destination of CO_2. It will not only determine the length of the pipeline, but also affect the design of the pressure, temperature, and material of the pipeline. The long-distance CO_2 pipeline may pass through different areas, the pipeline design and construction in different areas will also have different considerations, such as economy (McCoy and Rubin, 2008; Luo et al., 2014) and special areas, as shown in Table 10. One of the preconditions of construction is to obtain the right of way (ROW) (see Fig. 6). Therefore, before

Table 5
Pipe diameter design formulas for the gas pipeline.

Number	Equation	Reference(s)
1	$D = \sqrt[5]{\frac{2.252 L f \rho Q_m^2}{\Delta p}}$	IEA GHG (2002)
2	$D = \sqrt[5]{\frac{32 f_F Q_m^2 L}{\rho \pi^2 \Delta p}}$	Hamelinck et al. (2002); Heddle et al., 2003
3	$D = \sqrt{\frac{4Q_m}{\upsilon \pi \rho}}$	Tian et al. (2017); GHG, 2005; Chandel et al. (2010)
4	$D = 0.363\rho^{0.13}\upsilon^{0.025}\left(\frac{Q_m}{\rho}\right)^{0.45}$	Zhang et al. (2006)
5	$D = \left(\frac{8fQ_m^2 L}{\rho\pi^2[\rho g\Delta h + (p_1 \quad p_2)]}\right)^{0.2}$	Vandeginste and Piessens (2008)
6	$D = \left(\frac{64 Z_{ave}^2 R^2 T_{ave}^2 f_F Q_m^2 L}{\pi^2[M Z_{ave} R T_{ave}(p_2^2 \quad p_1^2) + 2gP_{ave}^2 M^2 \Delta h]}\right)^{0.2}$	Vandeginste and Piessens (2008); McCoy and Rubin (2008); Mohitpour et al. (2003)
7	$D = \left[\frac{4^{10/3} n^2 Q_m^2 L}{\pi^2\rho^2[\Delta h + (p_1 \quad p_2)/\rho g]}\right]^{3/16}$	Vandeginste and Piessens (2008)
8	$D = \frac{\rho f \upsilon^2 L}{2\Delta p}$	Chandel et al. (2010)
9	$D = \left(\frac{8fLQ_m^2}{\rho\pi^2\Delta p}\right)^{0.2}$	Energy (2010)
10	$D = \frac{fLM_f^2}{2\Delta p \rho}$	Tian et al. (2017)
11	$D = \frac{1}{Q_v} C_1 f^{-0.5} E \left[\frac{p_1 \quad p_2 \quad C_2\left(G\Delta h \frac{P_{ave}^2}{Z_{ave}T_{ave}}\right)}{G T_{ave} Z_{ave} L}\right]^{0.5}$	Johnson and Ogden (2010)

Note: D represents pipe diameter; f represents friction factor; L represents pipe length; p_1 represents inlet pressure of the pipeline; p_2 represents output pressure of the pipeline; Q_m represents mass flow rate; Q_v represents volume flow rate; T_{ave} represents average temperature; P_{ave} represents average pressure; Z_{ave} represents compressibility factor at P_{ave} and T_{ave}; M represents molecular weight; R represents gas constant; ρ represents fluid density; v represents viscosity; Δp represent pressure drop; Δh represent evaluation change; M_f represents mass flux; G represents specific gravity; C_1 and C_2 represent two constants; E represents pipeline efficiency; f_F represents fanning friction factor; n represents manning factor.

Table 6
Pipe wall thickness design formulas for the gas pipeline.

Number	Equation	Reference(s)
A	$t = \frac{p_{\max} D_o}{2SEF}$	McCoy and Rubin (2008); Witkowski et al. (2014b)
B	$t = \frac{p_{\max} D_i}{2(SFE \quad p)}$	Lazic et al. (2014); Chandel et al. (2010)
C	$t = \frac{D_o + p_{\max}}{2SFE} + CA$	Knoope et al. (2014)
D	$t = \frac{p_{\max} D_o}{2SFL_f ET}$	Kang et al. (2015)

Table 7
Diameter and wall thickness range of different categories of CO_2 pipeline.

Design parameter	High	Medium	Low
Diameter (mm)	600–921	305–508	152–270
Wall thickness (mm)	19–27	10–13	5.2–9.5

Table 9
Maximum and minimum pressure range of different categories of CO_2 pipeline.

Design parameter	High	Medium	Low
Maximum pressure (MPa)	15.1–20.0	9.8–14.5	2.1–4.0
Minimum pressure (MPa)	7.2–15.1	3.1–3.5	0.3–1.0

Table 8
Properties of some common pipeline steels.

Steel grade (API 5L X grade)	Minimum yield strength (MPa)	Minimum tensile strength (MPa)
X52	359	455
X56	386	490
X60	414	517
X65	448	531
X70	483	565
X80	552	621

determining the route, it is usually necessary to give multiple schemes because the optimal scheme (less investment, short distance) is not necessarily feasible in law. According to the research, the acquisition of ROW may account for 4%–25% of the total construction cost (Peletiri et al., 2018), and ROW in suburban areas is easier to obtain than that in cities because there are fewer infrastructures.

The construction of a CO_2 pipeline is similar to that of the oil and gas pipeline. For an onshore pipeline, three steps are required: installation and cleaning, connection with the compressor station (or pump station), air tightness test (or pressure test). For offshore pipelines, a pipelay vessel is usually required (Serpa et al., 2011). In addition, trenchless technology has great potential in pipeline installation, not only has excellent advantages in urban and crossing projects, but also has faster speed and lower cost than traditional methods in offshore pipe laying. Note that the carbon footprint of trenchless technology is also much lower than that of traditional methods, and the more common trenchless installation technology is shown in Fig. 7. In May 2018, the Hong Kong International Airport completed the laying of two submarine pipelines using horizontal directional drilling (HDD) technology. Due to the long distance (5.2 km), the constructor used the method of laying from opposite ends and then splicing, as shown in Fig. 8. It can be seen that the construction consideration of CO_2 pipeline is similar to that of natural gas pipeline, and new construction technology can be considered more in the future construction (Lu et al., 2020f,g).

3.2.5. Techno-economic analysis

The purpose of techno-economic analysis is to evaluate the economy of CO_2 transport and play an important role in decision-making. Knoope et al. (2013) systematically reviewed some important techno-economic models for CO_2 transport. In this review, they divided all models into five categories: models based on flow rates, Carnegie Mellon University (CMU) models, quadratic equations, linear cost models, and models based on the weight of the pipeline. They introduced the parameters and applicable conditions of each model in detail, and made a detailed comparison. In these models, some major costs include materials, construction, ROW, labor, etc. Among them, pipe diameter and length are two important variables. Table 11 lists some major techno-economic models. Note that different methods have different reference periods of economic data, and different factors are considered.

3.3. Safety and risk

Like oil (Liu et al., 2019), natural gas (Peng et al., 2020; Su et al., 2019), and water pipelines, risk and safety studies are indispensable in the operation of CO_2 pipelines (Kaufmann, 2011). As it stands now, although the accident rate of CO_2 pipeline is relatively low, because its accident consequences may be severe, the United States has implemented strict CO_2 pipeline management regulations. Especially in densely populated areas, if the CO_2 pipeline leaks, since the density of CO_2 is higher than that of air, it will pose a massive threat to people and animals. Fig. 9 shows the harm degree of different concentrations of CO_2 to human health. Therefore, the safety of the pipeline is an essential consideration during the route section. The risk and safety research of CO_2 pipeline mainly includes two aspects, one is the transport safety caused by impurities in CO_2, the other is the safety related to pipeline materials.

Porter et al. (2015) proposed the composition of CO_2 produced in different industries and the concentration range of impurities. They summarized that oxygen, water, nitrogen, hydrogen sulfide (H_2S) and other impurities might be mixed in the captured CO_2. As early as 2009, Bilio et al. (2009) proposed that these impurities in CO_2 would threaten the integrity of the pipeline and cause problems such as hydrogen embrittlement, corrosion, rapid brittleness or tough fracture. Hydrogen molecules in the gas will reduce the tensile strength and ductility of the material, but this problem can be overcome by adding the sulfur element to the material, meanwhile, the cost of the material will increase. In addition, it is difficult to ensure that there is no water in the gas. When CO_2 meets water, it will produce carbonation to corrode the steel pipe. If there are impurities such as H_2S and oxygen, the corrosion of the pipeline will be accelerated. Research shows that even if there is a small amount of H_2S, it will also affect the corrosion rate of CO_2. Most scholars know that H_2S will lead to sulfide stress cracking, but they know little about the corrosion mechanism of the H_2S and CO_2 coexisting environment. In a review of CO_2 pipeline materials, the authors comprehensively reviewed the existing H_2S/CO_2 corrosion mechanism and found that the relevant research always presents the opposite results. Some researchers think that H_2S will slow down the corrosion rate of CO_2, while some researches show that H_2S will increase the corrosion rate of CO_2. Some other relevant studies are listed in Table 12. Some studies have shown that supercritical transport is an effective solution to the corrosion problem. Due to the existence of water, hydrate may also appear in the CO_2 pipeline during operation, which may block the pipeline in serious cases. Research on hydrates has been abundant in natural gas pipelines, and for CO_2 pipelines, the principle is similar (Barrie et al., 2005). Therefore, in addition to strict control of temperature and pressure, there are also relevant regulations for the quality of CO_2 before transportation. Intergovernmental Panel on Climate Change (IPCC) regulated the gas quality of CO_2 pipelines, including the minimum content of CO_2 and water content, as shown in Table 13.

The safety issue of CO_2 pipeline materials mainly focuses on crack propagation. In fact, the problem of crack propagation is a common problem in all high-pressure pipelines, and it has been studied most in natural gas pipelines. As early as the 1970s, full-scale blasting tests have been carried out in the natural gas

Table 10
Route selection considerations for different areas (Serpa et al., 2011).

Area	Considerations
Urban area	The urban area should be avoided as much as possible because it will increase the construction cost, increase the construction period and increase the risk of the operation. However, the consideration of trenchless technology in pipeline installation can reduce the damage to urban pavement to a certain extent without affecting the traffic.
Land covered area	Some areas with steep slopes and unstable soil layers need to be avoided, such as landslides and seismic zones.
Pipeline colligate alure	Use existing facilities whenever possible.
Sensitive area	Sensitive areas such as nature reserves need to be avoided in principle.
Linear features	Linear features such as rivers, highways, and railways, trenchless technology can be considered for crossing.
Deepwater	Generally, it is necessary to select the areas with the flat seabed and deep seabed, so that the impact of wave load on the pipeline will be relatively small. However, this will also increase the construction cost. According to the existing engineering data, the depth of the CO_2 pipeline can exceed 2000 m (Metz et al., 2005).

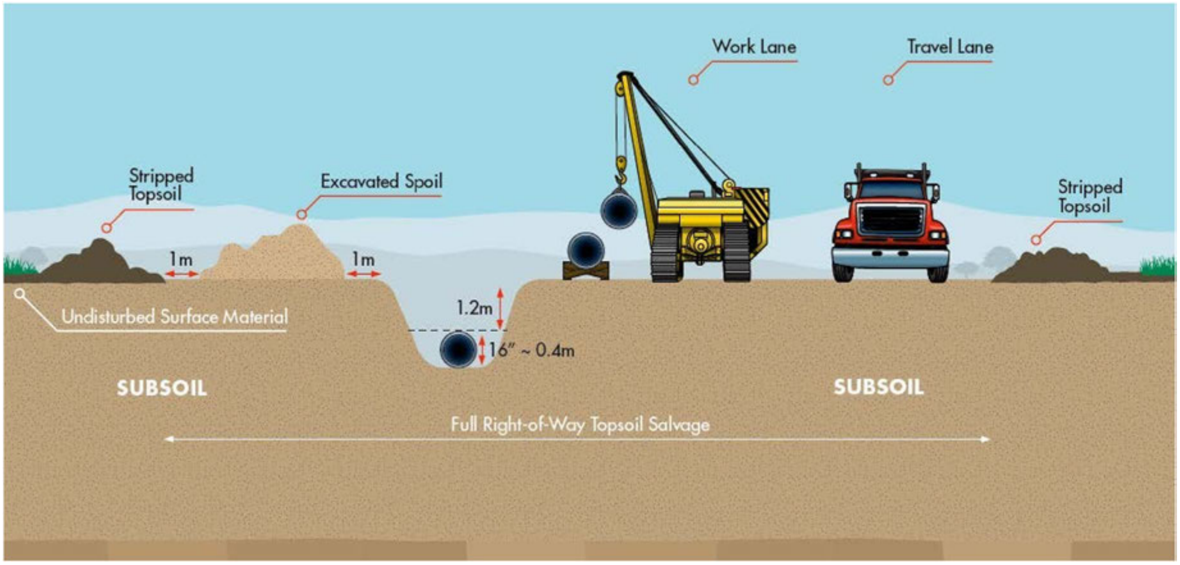

Fig. 6. ROW in CO_2 pipeline construction (Source: IEA Environmental Projects Ltd, 2014).

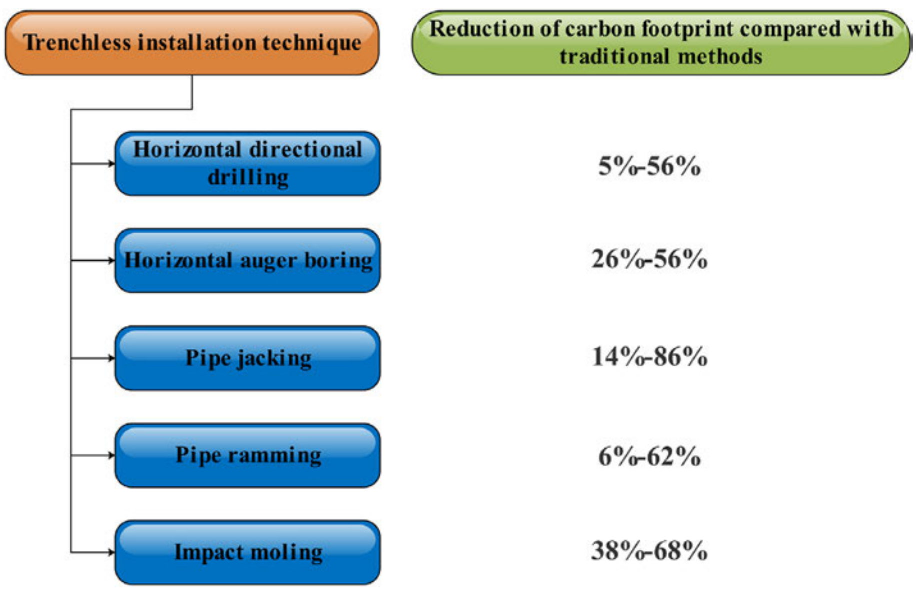

Fig. 7. Common trenchless installation technologies and their carbon footprint reduction ratio (Lu et al., 2020f).

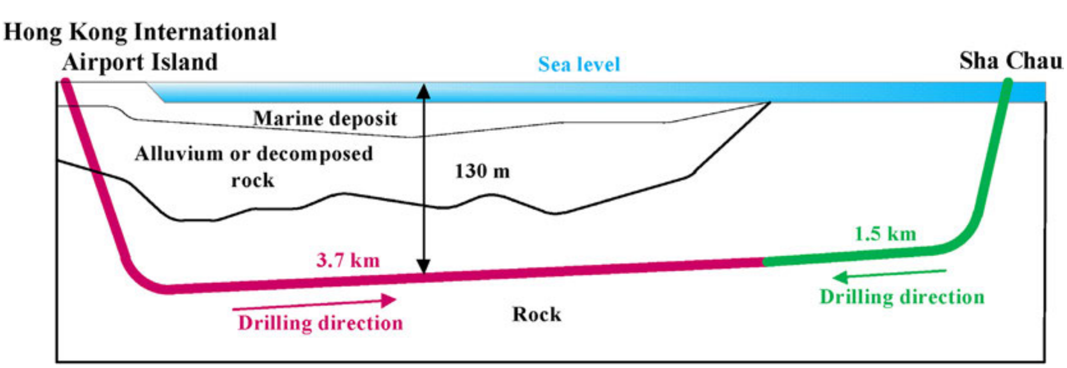

Fig. 8. Schematic diagram of the Hong Kong International Airport HDD pipeline project (Lu et al., 2020a).

Table 11
Major techno-economic models for CO_2 transport.

Reference	Description
IEA GHG (2002)	A model for CO_2 transport cost and performance estimation
McCoy and Rubin (2008)	A model for estimating transportation cost per ton of carbon dioxide
Heddle et al. (2003)	An estimation method based on the cost of natural gas pipeline project.
Skaugen et al. (2016)	A model for pipeline transportation cost over 500 km
McCollum and Ogden (2006)	A model to calculate transportation cost based on flow and length.

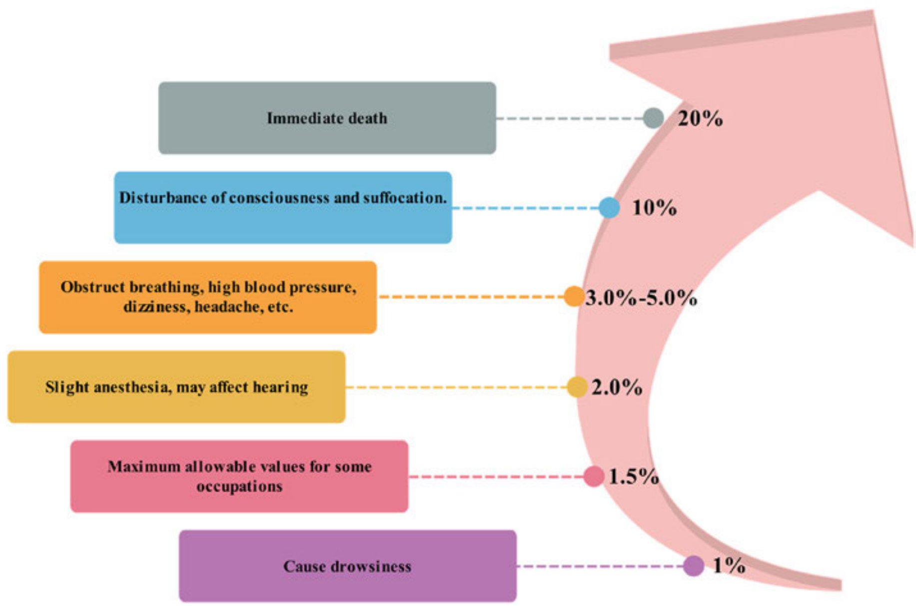

Fig. 9. The harm of different CO_2 concentrations to human health (Witkowski et al., 2013).

Table 12
Typical studies on corrosion of CO_2 pipeline in different environments.

Reference	Environment	Material	Conclusion
Xiang et al. (2012)	$CO_2/SO_2/O_2/H_2O$	X70 steel	The critical relative humidity of the upper limit of X70 steel corrosion is 50%–60%
Choi et al. (2010)	$CO_2/SO_2/O_2/H_2O$	X65 steel	SO_2 can promote the formation of iron sulfite hydrate on the steel surface. In the CO_2 saturated water environment containing O_2, the corrosion rate of 13Cr steel is lower than that of carbon steel.
Dugstad et al. (2011)	$CO_2/SO_2/O_2/H_2O/H_2S$	X65 steel	The existence of SO_2, O_2 and H_2S will accelerate the corrosion of carbon steel.
Russick et al. (1996)	CO_2/Methanol tetrahydrofurfuryl alcohol	Stainless steel, aluminum, carbon steel, copper	The corrosion effect of the medium on different materials is obtained.

Table 13
Gas quality regulations for CO_2 pipeline (Metz et al., 2005).

Component	Content requirements
CO_2	Mole percentage higher than 95%.
Water	No free water, no more than 30 lb/mmcf in the gas phase.
Total sulfur	No more than 35 ppm.
Nitrogen	The mole percentage does not exceed 4%.
Hydrogen sulfide	No more than 20 ppm.
Hydrocarbons	The mole percentage shall not exceed 5%, and the dew point temperature shall not exceed - 28.9 °C.
Oxygen	No more than 10 ppm.
Glycol	No more than 4×10^{5} L/m^3.

domain (Makino et al., 2001; Demofonti et al., 2004; Inoue et al., 2003). After the 21st century, more and more researchers began to carry out relevant research, they carried out full-scale blasting tests, pipeline ductile fracture propagation tests, decompression wave velocity tests (Botros et al., 2004; Chen and Shuai, 2006; Chen et al., 2009). Not only some theoretical models have been established, but more and more scholars have adopted the finite element method to obtain the dynamic fracture process of the pipeline (Nouri and Ziaeirad, 2010). Maxey (1986) did a fracture propagation test of an underwater nitrogen pipeline and found that water can reduce hoop stress and help suppress ductile fracture. Yang et al. (2006) used a finite element method to simulate the dynamic fracture process of natural gas pipelines and combined the full-scale experiments to obtain the relationship between the crack propagation speed and the material's dynamic fracture parameters. Shim et al. (2008) used ABAQUS software to analyze the dynamic fracture propagation process of the pipeline and combined with experiments to obtain the fracture velocity equation. Bilio et al. (2009) reviewed the research on pipeline crack, and concluded that the failure of CO_2 pipeline has two forms: fracture and ductile fracture, their failure modes are shown in Fig. 10. Some studies on fracture control are also carried out, King (1982b), Cosham and Eiber (2008) et al. explored the fracture control method of natural gas pipelines or CO_2 pipelines. It is concluded that crack arrestors can be added (Wilkowski et al., 2006), or the toughness of pipeline material can be increased to prevent ductile fracture. Aursand et al. (2016) used computational fluid dynamics to simulate the ductile fracture of CO_2 pipeline. They compared the numerical simulation results with the experimental results and found that they have a high consistency. In addition, they concluded that the pressure level at the opening fracture flap of the CO_2 pipeline is higher than that of the natural gas pipeline. Gruben et al. (2018) conducted a full-scale numerical simulation and experiment of CO_2 pipeline, and after comparison, it is found that the two agree well. Moreover, there are few studies on fracture control of the subsea CO_2 pipeline, but there are still some studies on the subsea natural gas pipeline. From the review of related research, it turns out that the research on CO_2 pipeline crack arrest is still in the pilot stage, and many scholars are comparing the difference between CO_2 pipeline and natural gas pipeline through full-scale experiments.

In recent years, some scholars have studied the leakage and diffusion of CO_2 pipeline. Witkowski et al. (2013) analyzed the hazards and risks of CO_2 pipeline leakage, provided the schematic diagram of gas leakage, and analyzed the impact scope of CO_2 leakage with PHAST software. The results show that when the CO_2 pipeline leaks, the influence range of concentration up to 20% reaches nearly 100 m, as shown in Fig. 11. Lankadasu et al. (2015) used a computational fluid dynamics method to calculate the leakage rate of CO_2 using the supercritical transport method. Li et al. (2019) numerically simulated the leakage law of high-pressure CO_2 pipeline with small leaks and verified the reliability of the numerical simulation through experiments. Summarizing the research on risk and safety, it can be obtained that the fracture and fracture control technology of materials is the hot research topics in recent years, and progress is slow. In addition, the leakage consequence analysis of CO_2 pipeline is helpful to improve the emergency repair technology and risk assessment system.

On the other hand, pipeline leakage inspection is also one of the important ways to monitor pipeline safety. However, according to the literature review, there are few related studies (Cui et al., 2016). The leakage detection technology for CO_2 pipeline has certain connectivity with the natural gas pipeline. According to the literature (Lu et al., 2020b), the leakage detection technology of the natural gas pipeline can be divided into hardware-based methods and software-based methods. Among them, hardware-based methods include optical method, acoustic method, tracer method, cable method, dynamic pressure transmitter method, ultrasonic flowmeter method, chemical composition analysis-based method and so on. Software-based methods include signal processing-based method, real time model-based method, neural network method, statistical method, harmonic analysis and so on. Among these technologies, some of them are currently widely used in water pipelines, the applicability of oil and gas pipelines is still in the practical stage, and some technologies have great potential in the inspection and monitoring of CO_2 pipelines.

With the rapid development of digital and intelligent technology, some technologies can be used for pipeline safety monitoring, such as digital pipeline and digital twin technology. The intelligent pipeline combines technologies such as the Internet of Things, cloud computing, big data, and automation, and can perform comprehensive maintenance on the pipeline based on the pipeline's life cycle data and the surrounding environment. Digital twin technology can use physical models and sensors to acquire pipeline data and complete mapping in virtual space to reflect the life cycle process of the pipeline. Technical details can be found in literature

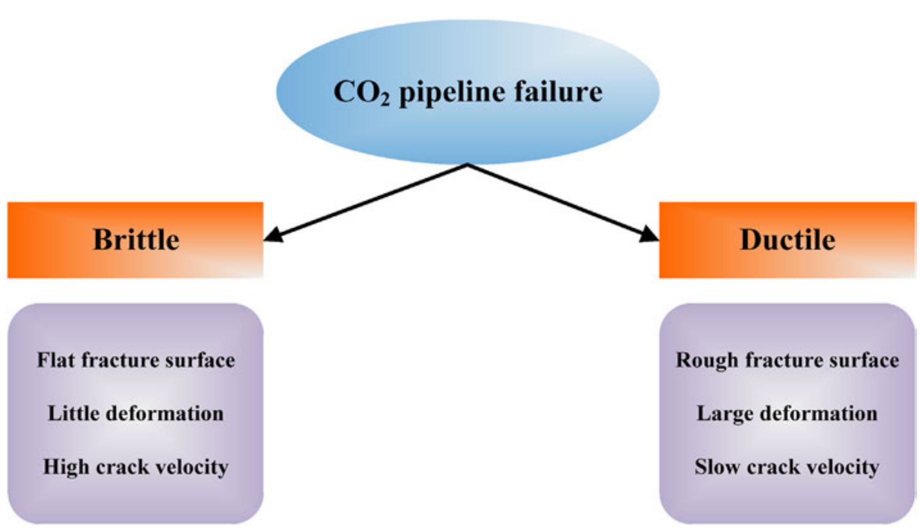

Fig. 10. Two failure modes of CO_2 pipeline.

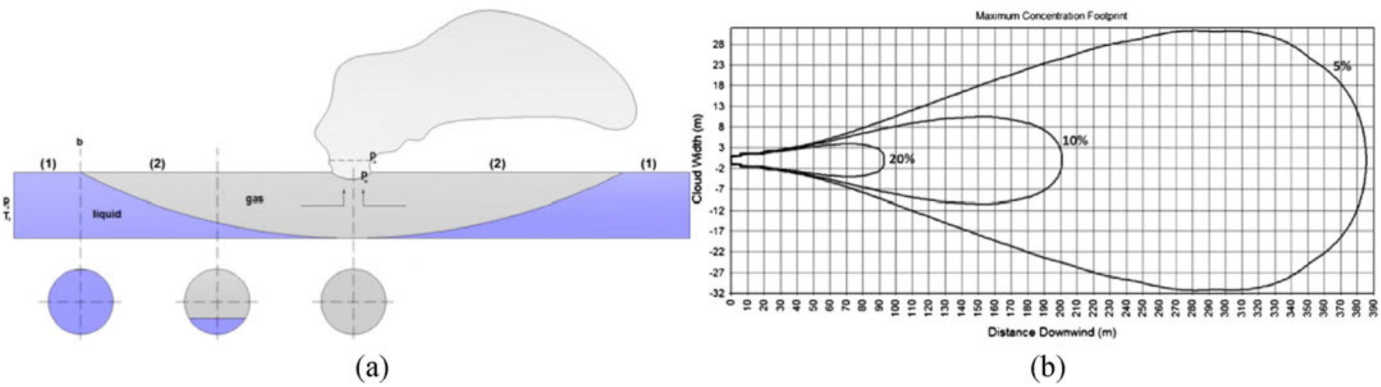

Fig. 11. Schematic diagram of gas pipeline leakage and the influence scope of CO_2 leakage (Witkowski et al., 2013). (a) Schematic diagram of gas pipeline leakage; (b) influence scope of CO_2 leakage in PHAST software.

(Lu et al., 2019b). However, these two technologies, especially digital twin technology, have not been widely used. The digital pipeline began to practice in the field of oil and gas.

3.4. Standard and specification

The formulation of standards and specifications in engineering is usually the most challenging part because it requires a lot of practice and research. Because CO_2 pipelines have relatively few practices compared to oil and gas pipelines, there are not many standards and specifications specifically for CO_2 pipelines, and many of them exist in some common standards, such as liquid pipelines and submarine pipeline. As of December 2019, through literature review and search, a total of 15 standards and specifications related to CO_2 pipelines have been collected worldwide (see Table 14). It reveals that the standards for CO_2 pipelines developed by different agencies focus on design, operation, and management, and most of the codes contain oil and gas pipelines. It can be implied from Fig. 12 that DNV and ISO are the primary formulator of CO_2 pipeline standards. Only MIIT in China and DNV in Norway have formulated standards specifically for CO_2 pipelines. The standards specific to CO_2 pipelines are still minimal, and the knowledge system needs to be further improved in the future.

Note: "Multiple aspects" refers to the design, operation, maintenance, and other aspects. DNV represents Det Norske Veritas; ISO represents International Organization for Standardization; ASME represents American Society of Mechanical Engineers; CFR represents Code of Federal Regulations (USA); MIIT represents Ministry of Industry and Information Technology (China); API represents American Petroleum Institute.

4. Challenges and future works

Through the review of CO_2 pipeline transport technology, the current challenges and technical gaps are clarified. In terms of transport technology, it reveals that impurities in CO_2 have a great impact on the regular transportation of pipelines. However, there is still no systematic methodology for the impact of different impurities on the phase equilibrium and corrosion of CO_2 pipelines. In the field of pipeline safety, although there are many related researches in the oil and gas pipeline, the risk assessment and safety control of CO_2 pipeline still have not formed a system. Especially, the ductile fracture index and fracture control technology of the CO_2 pipeline are still developing slowly. In the field of CO_2 pipeline

Table 14
Primary standards and specifications related to the CO_2 pipeline.

Standard (specification) number	Latest version	Formulator	Content of CO_2 pipeline	Remarks
DNVGL-RP-J202 (DNV, 2017a)	2017	DNV	Design and operation	
API RP 1160 (API, 2019)	2019	API	Management	
DNV-RP-C203 (DNV, 2014)	2014	DNV	Design	
DNVGL-RP-F107 (DNV, 2019)	2019	DNV	Management	
DNV-RP-F116 (DNV, 2015)	2015	DNV	Management	
ISO13623 (ISO, 2017b)	2017	ISO	Design and operation	Mainly for oil and gas pipelines, the content of CO_2 pipelines is added in this version.
DNVGL-ST-F101 (DNV, 2017b)	2017	DNV	Multiple aspects	
ASME B31.4 (ASME, 2019)	2019	ASME	Design	
ISO 27913 (ISO, 2016)	2016	ISO	Multiple aspects	
CSA Z662 (CSA, 2019)	2019	CSA Group	Management	
49 CFR 195 (CFR, 2019)	2019	CFR	Multiple aspects	Oil and gas pipelines are covered in this regulation.
SH/T 3202 (MIIT, 2018)	2018	MIIT	Design	
ISO/TR 27915 (ISO, 2017a)	2017	ISO	CO_2 leakage	
/	2010	Energy Institute (Energy Institute, 2010)	Design and operation	
ASME B31.8 (ASME, 2018)	2018	ASME	Design	

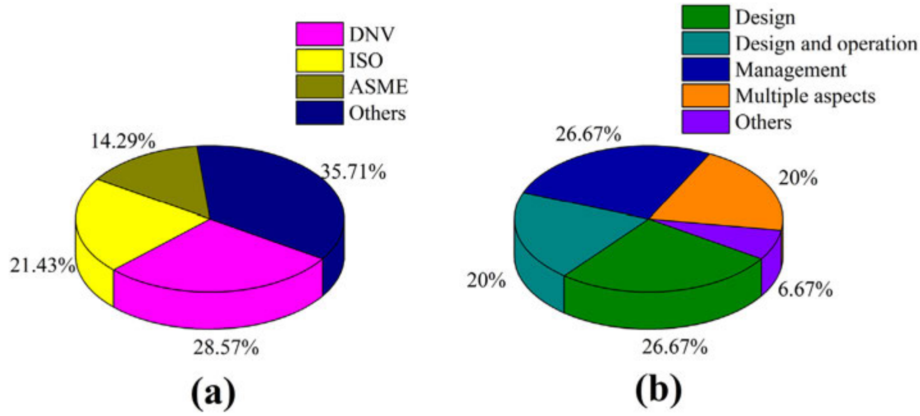

Fig. 12. Statistics of CO_2 pipeline related standards (or specifications) from different aspects. (a) Formulator; (b) Content.

material research, the study of failure mechanisms and the development of corrosion-resistant and high-grade materials are also a major challenge. In terms of management, it is necessary to establish a techno-economic framework for the CO_2 pipeline, which will affect not only regulatory issues, but also guide related policies. In addition, from the literature review, the establishment of a pipeline maintenance system (such as detection, monitoring, emergency repair, etc.) is also quite weak, and standards for CO_2 pipelines are quite limited.

While facing challenges, it also brings more opportunities. In this paper, some future research hotspots are summarized. These hotspots focus not only on the CO_2 pipeline itself, but also on some interdisciplinary subjects, as shown in Table 15.

5. Conclusions

The purpose of this review is to provide systematic information and reference about CO_2 pipeline for the designers and researchers. The literature review collected more than 100 critical academic papers and industry reports. The scope includes four aspects: process, pipeline design, safety and risk, standard and specification. The primary findings are as follows:

a) Regarding the CO_2 pipeline process, the control of temperature and pressure has always been the focus of pipeline operation since the phase equilibrium of CO_2 containing impurities is complex. Further research is needed due to the relevant knowledge system is not perfect.

b) For the design of the pipeline, based on the existing projects, this paper summarizes the scope and design points of various parameters. Although the CO_2 pipeline and natural gas pipeline are similar, their design considerations are still different. The control of temperature and pressure is more strict than that of natural gas pipeline. In addition to the formation of hydrate, the phase state also needs to be considered. Construction considerations are similar to those of natural gas pipelines, however, some new construction technologies are recommended.

c) In the field of safety and risk, the failure form of the CO_2 pipeline is the leading research direction. Although there have been many related researches in the field of natural gas pipeline, such as full-scale blasting test and conductive fracture propagation test, however, people still have insufficient understanding of the ductile fracture and fracture control methods for CO_2 pipeline. The consequence analysis and inspection of CO_2 pipeline leakage is also a research hotspot in recent years because it can help improve the risk assessment system.

d) In terms of CO_2 pipeline management, most of the relevant standards are related to oil and gas pipelines or hazardous liquids. There are not many standards or specifications for CO_2 pipelines, and the related integrity management system is also not perfect.

Based on the literature review, this article puts forward the challenges and future development directions of CO_2 pipeline

Table 15
Future research directions of CO_2 pipelines.

Research area	Future directions
Pipeline design	Effect of impurities on phase equilibrium
	Techno-economic framework for different CO_2 pipelines (Onyebuchi et al., 2018)
	Optimization of transport scheme, especially from the perspective of energy consumption and safety
Pipeline material	Ductile fracture index
	Corrosion mechanism of CO_2 pipeline in different environments
	Development of high-strength, corrosion-resistant steel
Pipeline construction	New construction technology, such as trenchless installation method
	Submarine pipeline construction
Safety and maintenance	Risk assessment system and method for CO_2 pipeline
	CO_2 leakage and diffusion mechanism
	Detection, monitoring, and emergency repair technologies for CO_2 pipeline
Management	Formulation of specifications and standards specifically for CO_2 pipelines
	Application of intelligent pipeline in transport deployment and monitoring
	Application of digital twin technology in safety management and early warning of CO_2 pipeline
	Establishment of CO_2 pipeline integrity system

transportation technology. In addition to continuing in-depth research on weak links, it is also necessary to learn from the relevant experience of natural gas pipelines to establish a relatively independent knowledge system for CO_2 pipelines. Moreover, the research directions are proposed in this paper, these also include some interdisciplinary areas, such as the application of artificial intelligence and digital twin in the CO_2 pipeline.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This article is funded by the National Natural Science Foundation of China (71901184), Humanities and Social Science Fund of Ministry of Education of China (19YJCZH119), and China Scholarship Council (201708030006).

References

Akbostancı, E., Tunç, G.İ., Türüt-Aşık, S., 2018. Drivers of fuel based carbon dioxide emissions: the case of Turkey. Renew. Sustain. Energy Rev. 81, 2599–2608.
API, 2019. API RP 1160: Managing System Integrity for Hazardous Liquid Pipelines.
ASME, 2018. ASME B31.8: Gas Transmission and Distribution Piping Systems.
ASME, 2019. ASME B31.4: Pipeline Transportation Systems for Liquids and Slurries.
Aursand, E., Dumoulin, S., Hammer, M., Lange, H.I., Morin, A., Munkejord, S.T., Nordhagen, H.O., 2016. Fracture propagation control in CO2 pipelines: validation of a coupled fluid–structure model. Eng. Struct. 123, 192–212.
Barrie, J., Brown, K., Hatcher, P.R., Schellhase, H.U., 2005. Carbon dioxide pipelines: a preliminary review of design and risks. In: Greenhouse Gas Control Technologies, vol. 7. Elsevier Science Ltd, pp. 315–320.
Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L.J., Fischedick, M., Lechtenböhmer, S., et al., 2018. A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. J. Clean. Prod. 187, 960–973.
Bilio, M., Brown, S., Fairweather, M., Mahgerefteh, H., 2009. CO2 pipelines material and safety considerations. In: Hazards XXI: Process Safety and Environmental Protection in a Changing World, vol. 155. Institution of Chemical Engineers, pp. 423–429, 155.
Botros, K.K., Studzinski, W., Geerligs, J., Glover, A., 2004. Determination of decompression wave speed in rich gas mixtures. Can. J. Chem. Eng. 82 (5), 880–891.
Brown, T.S., Clapham, J., Danielson, T.J., Harris, R.G., Erickson, D.D., 1996. January). Application of a transient heat transfer model for bundled, multiphase pipelines. In: SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers.
Carey, John, 2019. Global warming: faster than expected? Sci. Am. 307 (5), 50–55.
CFR, 2019. 49 CFR 195: Transportation of Hazardous Liquids by Pipeline.
Chandel, M.K., Pratson, L.F., Williams, E., 2010. Potential economies of scale in CO2 transport through use of a trunk pipeline. Energy Convers. Manag. 51 (12), 2825–2834.
Chen, F., Shuai, J., 2006. Research discussion of decompression behavior of high-pressure natural gas during pipeline fracture. Nat. Gas. Ind. 26 (11), 136–139.
Chen, F., Shuai, J., Feng, Y., Zhuang, C., 2009. Calculation of high-pressure natural gas decompression wave velocity during pipeline fracture. Journal of China University of Petroleum (Edition of Natural Science) 33 (4), 130–135.
Chen, L., 2016. Transmission technology of CO2 pipeline and practice in sinopec. Pet. Eng. Constr. 42 (4), 7–10.
Chen, L., Zhang, X.R., 2011. Simulation of heat transfer and system behavior in a supercritical CO2 based thermosyphon: effect of pipe diameter. J. Heat Tran. 133 (12), 122505.
Choi, Y.S., Nesic, S., Young, D., 2010. Effect of impurities on the corrosion behavior of CO2 transmission pipeline steel in supercritical CO2 water environments. Environ. Sci. Technol. 44 (23), 9233–9238.
Cosham, A., Eiber, R.J., 2008. January). Fracture control in carbon dioxide pipelines: the effect of impurities. In: 2008 7th International Pipeline Conference. American Society of Mechanical Engineers Digital Collection, pp. 229–240.
CSA, 2019. CSA Z662: Oil and Gas Pipeline Systems.
Cui, X., Yan, Y., Ma, Y., Ma, L., Han, X., 2016. Localization of CO2 leakage from transportation pipelines through low frequency acoustic emission detection. Sensor Actuator Phys. 237, 107–118.
Demofonti, G., Mannucci, G., Hillenbrand, H.G., Harris, D., 2004. January). Evaluation of the suitability of X100 steel pipes for high pressure gas transportation pipelines by full scale tests. In: 2004 International Pipeline Conference. American Society of Mechanical Engineers Digital Collection, pp. 1685–1692.
Di, X., 2013. The Process Research on Carbon Dioxide Gathering and Transportation. Master thesis. Northeast Petroleum University.
DNV, 2014. DNV-RP-C203: Fatigue Design of Offshore Steel Structures.
DNV, 2015. DNV-RP-F116: Integrity Management of Submarine Pipeline Systems.
DNV, 2017a. DNVGL-RP-J202: Design and Operation of Carbon Dioxide Pipelines.
DNV, 2017b. DNVGL-ST-F101: Submarine Pipeline Systems.
DNV, 2019. DNVGL-RP-F107: Risk Assessment of Pipeline Protection.
Dugstad, A., Morland, B., Clausen, S., 2011. Corrosion of transport pipelines for CO2–effect of water ingress. Energy Procedia 4, 3063–3070.
Edwards, R.W., Celia, M.A., 2018. Infrastructure to enable deployment of carbon capture, utilization, and storage in the United States. Proc. Natl. Acad. Sci. Unit. States Am. 115 (38), E8815–E8824.
Energy Institute, 2010. Good Plant Design and Operation for Onshore Carbon Capture Installations and Onshore Pipelines.
Energy, E., 2010. CO2 Pipeline Infrastructure: An Analysis Of Global Challenges and Opportunities. Tech. Rep., Final Report for IEA Greenhouse Gas Programme.
Farris, C.B., 1983. Unusual design factors for supercritical CO2 pipelines. Energy Prog 3 (3).
Gao, L., Fang, M., Li, H., Hetland, J., 2011. Cost analysis of CO2 transportation: case study in China. Energy Procedia 4, 5974–5981.
Gao, S., Liu, H., 2017. Research and application of key technologies for carbon dioxide pipeline transportation. Petrochemical Industry Technology 24 (9), 57.
Ghg, I., 2005. Building the Cost Curves for CO2 Storage: European Sector. International Energy Agency Greenhouse Gas R&D Programme, Cheltenham.
Global CCS Institute, 2019. Carbon capture and storage images. https://www.globalccsinstitute.com/resources/ccs-image-library/ accessed 13 December 2019.
Gruben, G., Dumoulin, S., Nordhagen, H., Hammer, M., Munkejord, S.T., 2018. Simulation of a full-scale CO2 fracture propagation test. In: 2018 12th International Pipeline Conference. American Society of Mechanical Engineers Digital Collection.
Hamelinck, C.N., Faaij, A.P.C., Turkenburg, W.C., Van Bergen, F., Pagnier, H.J.M., Barzandji, O.H.M., et al., 2002. CO2 enhanced coalbed methane production in The Netherlands. Energy 27 (7), 647–674.
Heddle, G., Herzog, H., Klett, M., 2003. The Economics of CO2 Storage. MIT LFEE 2003-003 RP, pp. 1–115. https://www.projectconsulting.com/pcs-insights/design-of-co2-transmission-pipeline-systems-part-1.
Huh, C., Kang, S.G., Hong, S., Choi, J.S., Moon, I.S., Lee, C.J., et al., 2009. January). Onshore and offshore transport process design for carbon dioxide sequestration in a marine geological structure. In: ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering. American Society of Mechanical Engineers Digital Collection, pp. 1503–1512.
IEA Environmental Projects Ltd, 2014. CO2 Pipeline Infrastructure. Cheltenham, UK.
Iea, G.H.G., 2002. Transmission of CO2 and Energy; PH4/6. IEA Environmental Projects Ltd, Cheltenham, UK.
Ikeh, L., Race, J.M., Aminu, A.G., 2011. January). Comparing the effects of pipe diameter on flow capacity of a CO2 pipeline. In: Nigeria Annual International Conference and Exhibition. Society of Petroleum Engineers.
Inoue, T., Makino, H., Endo, S., Kubo, T., Matsumoto, T., 2003. January). Simulation method for shear fracture propagation in natural gas transmission pipelines. In: The Thirteenth International Offshore and Polar Engineering Conference. International Society of Offshore and Polar Engineers.
ISO, 2016. ISO 27913: CO2 Capture, Transportation and Geological Storage-Pipeline Transportation Systems.
ISO, 2017a. ISO/TR 27915: Carbon Dioxide Capture, Transportation and Geological Storage-Quantification and Verification.
ISO, 2017b. ISO13623: Petroleum and Natural Gas Industries-Pipeline Transportation Systems.
Istre, M., 2019. Design of CO2 transmission pipeline systems. https://www.projectconsulting.com/pcs-insights/design-of-co2-transmission-pipeline-systems-part-1 accessed 13 December 2019.
Jackson, A., Johnsen, E., Kopystynski, A., Simonsen, E., Boye-Hansen, A., 2005. October). Design parametel for single pipe thermal insulation systems for offshore flow assurance. In: Proceedings of Rio-Pipeline Conference & Exposition, Rio de Janeiro, Brazil.
Jacobson, T.A., Kler, J.S., Hernke, M.T., Braun, R.K., Meyer, K.C., Funk, W.E., 2019. Direct human health risks of increased atmospheric carbon dioxide. Nature Sustainability 2 (8), 691–701.
Johnson, N., Ogden, J., 2010. Conceptual Design of Optimized Fossil Energy Systems with Capture and Sequestration of Carbon Dioxide. Regents Of The University Of California.
Kang, K., Seo, Y., Chang, D., Kang, S.G., Huh, C., 2015. Estimation of co2 transport costs in South Korea using a techno-economic model. Energies 8 (3), 2176–2196.
Kaufmann, K.D., 2011. June). Carbon dioxide transport in pipelines-under special consideration of safety-related aspects. In: 3rd Pipeline Technology Conference 2008. EITEP Institute.
King, A.D., Karoly, D.J., Henley, B.J., 2017. Australian climate extremes at 1.5 C and 2 C of global warming. Nat. Clim. Change 7 (6), 412.
King, G., 1982a. CO2 pipeline design: here are key design considerations for CO2 pipelines. Oil Gas J. 80 (39), 219–222.
King, G., 1982b. Propagating fractures, pipe sizing probed for high-operating-pressure CO2 pipelines. Oil Gas J. 80 (40), 100–102.
Knoope, M.M.J., Guijt, W., Ramírez, A., Faaij, A.P.C., 2014. Improved cost models for optimizing CO2 pipeline configuration for point-to-point pipelines and simple networks. International Journal of Greenhouse Gas Control 22, 25–46.

Knoope, M.M.J., Ramírez, A., Faaij, A.P.C., 2013. A state-of-the-art review of techno-economic models predicting the costs of CO2 pipeline transport. International journal of greenhouse gas control 16, 241–270.
Laboureur, L., Ollero, M., Touboul, D., 2015. Lipidomics by supercritical fluid chromatography. Int. J. Mol. Sci. 16 (6), 13868–13884.
Lankadasu, A., Tripathi, A., Saysset, S., Yackow, A., De La Roussiere, B., 2015. Numerical modeling of supercritical CO2 leaks and its subsequent dispersion in the ambient air. Procedia IUTAM 15, 49–56.
Lazic, T., Oko, E., Wang, M., 2014. Case study on CO2 transport pipeline network design for Humber region in the UK. Proc. IME E J. Process Mech. Eng. 228 (3), 210–225.
Leung, D.Y., Caramanna, G., Maroto-Valer, M.M., 2014. An overview of current status of carbon dioxide capture and storage technologies. Renew. Sustain. Energy Rev. 39, 426–443.
Li, H., Yan, J., 2006. June). Comparative study of equations of state for predicting phase equilibrium and volume properties of CO2 and CO2 mixtures. In: Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies, Trondheim, Norway.
Li, H., Yan, J., 2009. Evaluating cubic equations of state for calculation of vapor–liquid equilibrium of CO2 and CO2-mixtures for CO2 capture and storage processes. Appl. Energy 86 (6), 826–836.
Li, K., Zhou, X., Tu, R., Tu, H., Fang, Y., Su, L., 2019. Investigation of flow characteristics in small-scale highly pressurized leaked CO2 jet plume from pipeline. Int. J. Therm. Sci. 141, 160–170.
Li, K., Zhou, X., Tu, R., Xie, Q., Jiang, X., 2014. The flow and heat transfer characteristics of supercritical CO2 leakage from a pipeline. Energy 71, 665–672.
Li, X., 2013. Status of key technology research on carbon dioxide pipeline. Oil Gas Storage Transp. 32 (4), 343–348.
Liu, E., Li, W., Cai, H., Peng, S., 2019. Formation mechanism of trailing oil in product oil pipeline. Processes 7 (1), 7.
Liu, E., Lv, L., Yi, Y., Xie, P., 2019. Research on the steady operation optimization model of natural gas pipeline considering the combined operation of air coolers and compressors. IEEE Access. 7, 83251–83265.
Lu, H., Behbahani, S., Azimi, M., Matthews, J.C., Han, S., Iseley, T., 2020a. Trenchless construction technologies for oil and gas pipelines: state-of-the-art review. J. Construct. Eng. Manag. 146 (6), 03120001.
Lu, H., Guo, L., Zhang, Y., 2019a. Oil and gas companies' low-carbon emission transition to integrated energy companies. Sci. Total Environ. 686, 1202–1209.
Lu, H., Guo, L., Azimi, M., Huang, K., 2019b. Oil and Gas 4.0 era: a systematic review and outlook. Comput. Ind. 111, 68–90.
Lu, H., Iseley, T., Behbahani, S., Fu, L., 2020b. Leakage detection techniques for oil and gas pipelines: state-of-the-art. Tunn. Undergr. Space Technol. 98, 103249.
Lu, H., Ma, X., Azimi, M., 2020c. US natural gas consumption prediction using an improved kernel-based nonlinear extension of the Arps decline model. Energy 194, 116905.
Lu, H., Ma, X., Huang, K., Azimi, M., 2020d. Carbon trading volume and price forecasting in China using multiple machine learning models. J. Clean. Prod. 249, 119386.
Lu, H., Ma, X., Huang, K., Azimi, M., 2020e. Prediction of offshore wind farm power using a novel two-stage model combining kernel-based nonlinear extension of the Arps decline model with a multi-objective grey wolf optimizer. Renew. Sustain. Energy Rev. 127, 109856.
Lu, H., Matthews, J., Iseley, T., 2020f. How does trenchless technology make pipeline construction greener? A comprehensive carbon footprint and energy consumption analysis. J. Clean. Prod. 261, 121215.
Lu, H., Wu, X., Ni, H., Azimi, M., Yan, X., Niu, Y., 2020g. Stress analysis of urban gas pipeline repaired by inserted hose lining method. Compos. B Eng. 183, 107657.
Luo, X., Wang, M., Oko, E., Okezue, C., 2014. Simulation-based techno-economic evaluation for optimal design of CO2 transport pipeline network. Appl. Energy 132, 610–620.
Makino, H., Kubo, T., Shiwaku, T., Endo, S., Inoue, T., Kawaguchi, Y., et al., 2001. Prediction for crack propagation and arrest of shear fracture in ultra-high pressure natural gas pipelines. ISIJ Int. 41 (4), 381–388.
Maxey, W.A., 1986. Fracture propagation in underwater gas pipelines. J. Energy Resour. Technol. 108 (1), 29–34.
Mazzoccoli, M., Bosio, B., Arato, E., Brandani, S., 2014. Comparison of equations-of-state with P–ρ–T experimental data of binary mixtures rich in CO2 under the conditions of pipeline transport. J. Supercrit. Fluids 95, 474–490.
McCollum, D.L., Ogden, J.M., 2006. Techno-economic models for carbon dioxide compression, transport, and storage & correlations for estimating carbon dioxide density and viscosity. UCD-ITS-RR-06-14 1–87.
McCoy, S.T., Rubin, E.S., 2008. An engineering-economic model of pipeline transport of CO2 with application to carbon capture and storage. International Journal of Greenhouse Gas Control 2 (2), 219–229.
Metz, B., Davidson, O., De Coninck, H., Loos, M., Meyer, L., 2005. IPCC Special Report on Carbon Dioxide Capture and Storage. Intergovernmental Panel on Climate Change, Geneva (Switzerland) (Working Group III).
MIIT, 2018. SH/T 3202: Specifications for Engineering of Carbon Dioxide Pipeline Transportation.
Mohammadi, M., Hourfar, F., Elkamel, A., Leonenko, Y., 2019. Economic optimization design of CO2 pipeline transportation with booster stations. Ind. Eng. Chem. Res. 58 (36), 16730–16742.
Mohitpour, M., Golshan, H., Murray, A., 2003. Pipeline Design & Construction, first ed. ASME Press, New York, NY, USA.
Morbee, J., Serpa, J., Tzimas, E., 2010. The Evolution of the Extent and the Investment Requirements of a Trans-European CO2 Transport Network. EC and JRC.
Newcomer, A., Apt, J., 2008. Implications of generator siting for CO2 pipeline infrastructure. Energy Pol. 36 (5), 1776–1787.
Noothout, P., Wiersma, F., Hurtado, O., Macdonald, D., Kemper, J., van Alphen, K., 2014. CO2 Pipeline infrastructure–lessons learnt. Energy Procedia 63, 2481–2492.
Nouri, B.A., Ziaeirad, M., 2010. Numerical modeling of transient turbulent gas flow in a pipe following a rupture. Sci. Iran. 17 (2), 108–120.
Onyebuchi, V.E., Kolios, A., Hanak, D.P., Biliyok, C., Manovic, V., 2018. A systematic review of key challenges of CO2 transport via pipelines. Renew. Sustain. Energy Rev. 81, 2563–2583.
Peletiri, S.P., Rahmanian, N., Mujtaba, I.M., 2018. CO2 pipeline design: a review. Energies 11 (9), 2184.
Peng, S., Chen, Q., Zheng, C., Liu, E., 2020. Analysis of particle deposition in a new-type rectifying plate system during shale gas extraction. Energy Sci. Eng. 8 (3), 702–717.
Peng, D.Y., Robinson, D.B., 1976. A new two-constant equation of state. Ind. Eng. Chem. Fundam. 15 (1), 59–64.
Porter, R.T., Fairweather, M., Pourkashanian, M., Woolley, R.M., 2015. The range and level of impurities in CO2 streams from different carbon capture sources. International Journal of Greenhouse Gas Control 36, 161–174.
Roussanaly, S., Brunsvold, A.L., Hognes, E.S., 2014. Benchmarking of CO2 transport technologies: Part II–Offshore pipeline and shipping to an offshore site. International Journal of Greenhouse Gas Control 28, 283–299.
Roussanaly, S., Jakobsen, J.P., Hognes, E.H., Brunsvold, A.L., 2013. Benchmarking of CO2 transport technologies: Part I—onshore pipeline and shipping between two onshore areas. International Journal of Greenhouse Gas Control 19, 584–594.
Russick, E.M., Poulter, G.A., Adkins, C.L., Sorensen, N.R., 1996. Corrosive effects of supercritical carbon dioxide and cosolvents on metals. J. Supercrit. Fluids 9 (1), 43–50.
Seevam, P.N., Race, J.M., Downie, M.J., Hopkins, P., 2008. January). Transporting the next generation of CO2 for carbon, capture and storage: the impact of impurities on supercritical CO2 pipelines. In: 2008 7th International Pipeline Conference. American Society of Mechanical Engineers Digital Collection, pp. 39–51.
Serpa, J., Morbee, J., Tzimas, E., 2011. Technical and economic characteristics of a CO2 transmission pipeline infrastructure, JRC62502, 1–43.
Shim, D.J., Wilkowski, G., Rudland, D., Rothwell, B., Merritt, J., 2008, January. Numerical simulation of dynamic ductile fracture propagation using cohesive zone modeling. In: 2008 7th International Pipeline Conference. American Society of Mechanical Engineers Digital Collection, pp. 21–28.
Skaugen, G., Roussanaly, S., Jakobsen, J., Brunsvold, A., 2016. Techno-economic evaluation of the effects of impurities on conditioning and transport of CO2 by pipeline. International Journal of Greenhouse Gas Control 54, 627–639.
Spinelli, C.M., Demofonti, G., Lucci, A., Di Biagio, M., Ahmad, M., 2014, August. CO2 pipeline transportation new needs. In: The Twenty-Fourth International Ocean and Polar Engineering Conference. International Society of Offshore and Polar Engineers.
Stang, H.J., Løvseth, S.W., Størset, S.Ø., Malvik, B., Rekstad, H., 2013. Accurate measurements of CO2 rich mixture phase equilibria relevant for CCS transport and conditioning. Energy Procedia 37, 2897–2903.
Su, Z., Liu, E., Xu, Y., Xie, P., Shang, C., Zhu, Q., 2019. Flow field and noise characteristics of manifold in natural gas transportation station. Oil Gas Sci. Technol.–Revue d'IFP Energies nouvelles 74, 70.
Tapia, J.F.D., Lee, J.Y., Ooi, R.E., Foo, D.C., Tan, R.R., 2018. A review of optimization and decision-making models for the planning of CO2 capture, utilization and storage (CCUS) systems. Sustainable Production and Consumption 13, 1–15.
Teh, C., Barifcani, A., Pack, D., Tade, M.O., 2015. The importance of ground temperature to a liquid carbon dioxide pipeline. International Journal of Greenhouse Gas Control 39, 463–469.
Tian, Q., Zhao, D., Li, Z., Zhu, Q., 2017. Robust and stepwise optimization design for CO2 pipeline transportation. International Journal of Greenhouse Gas Control 58, 10–18.
Vandeginste, V., Piessens, K., 2008. Pipeline design for a least-cost router application for CO2 transport in the CO2 sequestration cycle. International Journal of Greenhouse Gas Control 2 (4), 571–581.
Wallace, M., Goudarzi, L., Callahan, K., Wallace, R., 2015. A Review of the CO2 Pipeline Infrastructure in the US. Doe/Netl-2014, p. 1681.
Wang, D., 2017. Research on Liquefaction, Transportation and Storage Technology of CO2. Master thesis. Yangtze University.
Wang, D., Zhang, Y.D., Adu, E., Yang, J.P., Shen, Q.W., Tian, L., Wu, L.J., 2016. Influence of dense phase CO2 pipeline transportation parameters. International Journal of Heat and Technology 34 (3), 479–484.
Wang, X., Zeng, F., Gao, R., Zhao, X., Hao, S., Liang, Q., Jiang, S., 2017. Cleaner coal and greener oil production: an integrated CCUS approach in Yanchang Petroleum Group. International Journal of Greenhouse Gas Control 62, 13–22.
Wilkowski, G., Rudland, D., Rothwell, B., 2006. January). How to optimize the design of mechanical crack arrestors. In: 2006 International Pipeline Conference. American Society of Mechanical Engineers Digital Collection, pp. 393–405.
Witkowski, A., Majkut, M., Rulik, S., 2014a. Analysis of pipeline transportation systems for carbon dioxide sequestration. Arch. Therm. 35 (1), 117–140.
Witkowski, A., Rusin, A., Majkut, M., Stolecka, K., 2014b. The analysis of pipeline transportation process for CO2 captured from reference coal-fired 900 MW

power plant to sequestration region. Chem. Process Eng. 35 (4), 497–514.
Witkowski, A., Rusin, A., Majkut, M., Rulik, S., Stolecka, K., 2013. Comprehensive analysis of pipeline transportation systems for CO2 sequestration. Thermodynamics and safety problems. Energy Convers. Manag. 76, 665–673.
Xiang, Y., Wang, Z., Yang, X., Li, Z., Ni, W., 2012. The upper limit of moisture content for supercritical CO2 pipeline transport. J. Supercrit. Fluids 67, 14–21.
Xie, Q., Tu, R., Jiang, X., Li, K., Zhou, X., 2014. The leakage behavior of supercritical CO2 flow in an experimental pipeline system. Applied energy 130, 574–580.
Yang, X., Zhuang, Z., Julaiti, M., 2006. Study on the relationship between dynamic fracture parameters and crack propagation velocity in gas pipelines. Eng. Mech. 23 (S1), 145–150.
Yu, J., Zhu, H., Guo, X., Yan, X., Cao, Q., Liu, S., 2017. Thermodynamic properties during depressurization process of supercritical CO2 pipeline. CIESC Journal 68 (9), 3350–3357.
Yu, X., Li, Z., Pan, X., Li, Y., Zheng, X., Wang, Y., 2009. Research on CO2 supercritical transportation technology. Nat. Gas. Ind. 29 (12), 83–86.
Zabaras, G.J., Zhang, J.J., 1998. Bundle-flowline thermal analysis. SPE J. 3, 363–372, 04.
Zhang, J., Luo, C.Y., Curtis, Z., Deng, S.H., Wu, Y., Li, Y.W., 2015. Carbon dioxide emission accounting for small hydropower plants—a case study in southwest China. Renew. Sustain. Energy Rev. 47, 755–761.
Zhang, Z.X., Wang, G.X., Massarotto, P., Rudolph, V., 2006. Optimization of pipeline transport for CO2 sequestration. Energy Convers. Manag. 47 (6), 702–715.
Zhang, Z., Feng, X., 2005. Optimization of CO2 transmission processes. Journal of Xi'an Jiaotong University 39 (3), 274–277.
Zheng, J., Shi, J., Liu, Z., Jiang, S., Liu, C., 2018. Recent advances in pipeline transportation technology of carbon dioxide. Sino-Global Energy 23 (6), 87–94.