

# Optimization of CO<sub>2</sub> separation technologies for Chinese refineries based on a fuzzy comprehensive evaluation model

Qian-Qian Song · Qing-Zhe Jiang · Zhao-Zheng Song

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**Abstract** This study aims at determining the optimal CO<sub>2</sub> separation technology for Chinese refineries, based on current available technologies, by the method of comprehensive evaluation. Firstly, according to the characteristics of flue gas from Chinese refineries, three feasible CO<sub>2</sub> separation technologies are selected. These are pressure swing adsorption (PSA), chemical absorption (CA), and membrane absorption (MA). Secondly, an economic assessment of these three techniques is carried out in accordance with cash flow analysis. The results show that these three techniques all have economic feasibility and the PSA technique is the best. Finally, to further optimize the three techniques, a two-level fuzzy comprehensive evaluation model is established, including economic, technological, and environmental factors. Considering all the factors, PSA is optimal for Chinese refineries, followed by CA and MA. Therefore, to reduce Chinese refineries carbon emission, it is suggested that CO<sub>2</sub> should be captured from off-gases using PSA.

**Keywords** Chinese refineries · CO<sub>2</sub> emission · Separation technique · Economic evaluation · AHP-entropy method · Fuzzy comprehensive evaluation model

## 1 Introduction

It is well accepted that carbon dioxide (CO<sub>2</sub>), which is considered as the leading source of greenhouse gas (GHG) emissions, results in the climate change. Direct emissions of CO<sub>2</sub> from industry account for approximately 20 % of global CO<sub>2</sub> emissions (IEA 2010). Globally, the petroleum refining industry is one of the largest contributors to anthropogenic CO<sub>2</sub> emissions (IEA 2009; de Mello et al. 2009; Kuramochi et al. 2012). CO<sub>2</sub> emissions from refineries account for about 4 % of the global CO<sub>2</sub> emissions, close to 1 billion metric tons of CO<sub>2</sub> per year (Van Straelen et al. 2010).

China has surpassed U.S. as the world's largest emitter of CO<sub>2</sub>. In 2012, China contributed 26.1 % of total world CO<sub>2</sub> emissions, equal to 8,254 million metric tons (Mt) (EIA 2013). On the other hand, the overall goal of the Chinese government is to reduce the CO<sub>2</sub> emissions per unit of GDP by 40–45 % by 2020 from 2005 levels. Nevertheless, with the ever-increasing enlargement of refining scale, the rising demand for high-quality products and the restricted supply of light and sweet crudes, CO<sub>2</sub> emissions of Chinese refineries have increased significantly. In 2012, Chinese crude oil refining reached 468 Mt. Consequently, it was estimated that CO<sub>2</sub> emissions would be around 133 Mt according to the CO<sub>2</sub> emission factor of 0.284 t/t crude oil (Ma et al. 2011). In this paper, a proper mitigation strategy for the Chinese oil refining sector is badly needed to enable China to appropriately implement its climate change policy with consideration of its socio-economic features.

At present, CO<sub>2</sub> emissions of oil refineries can be reduced in three ways. The first option requires energy conservation. The second option requires energy consumption switching to non-fossil fuels such as hydrogen,

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Q.-Q. Song · Q.-Z. Jiang (✉) · Z.-Z. Song (✉)  
State Key Laboratory of Heavy Oil Processing, China University  
of Petroleum, Beijing 102249, China  
e-mail: [jiangqz@cup.edu.cn](mailto:jiangqz@cup.edu.cn)

Z.-Z. Song  
e-mail: [song@cup.edu.cn](mailto:song@cup.edu.cn)

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nuclear, biomass, and solar energy. The third option involves CO<sub>2</sub> capture and storage (CCS). However, the nature of oil refining implies that even if a refinery is highly energy efficient, it will consume considerable amounts of energy, and therefore produce considerable amounts of CO<sub>2</sub>. The first two measures could reduce the current CO<sub>2</sub> emissions by 9–20 Mt/year, yet a 13–80 % reduction of CO<sub>2</sub> emissions could be achieved by implementing carbon capture (Johansson et al. 2012). Thus, to meet mid- to long-term CO<sub>2</sub> reduction, cost-effective CO<sub>2</sub> separation technologies are the key issue for oil refineries.

Most of the reported studies have focused on technical and economic performance of CO<sub>2</sub> capture technology for power generation, and only a very few studies are about CO<sub>2</sub> capture for the petroleum refining industry (IEA-GHG 2000; Van Straelen et al. 2010; de Mello et al. 2009; Kuramochi et al. 2012; Ho et al. 2011). Specifically, no studies have been reported on Chinese refineries.

The objective of this study is to optimize CO<sub>2</sub> separation technologies for Chinese refineries. Section 2 of this paper reviews CO<sub>2</sub> separation technologies and initially selects available technologies for Chinese refineries. Section 3 introduces the method of economic evaluation and fuzzy comprehensive evaluation. Section 4 presents the results. Section 5 gives the conclusions. The general frame of this study is shown in Fig. 1.

## 2 Preliminary selections of CO<sub>2</sub> separation technologies

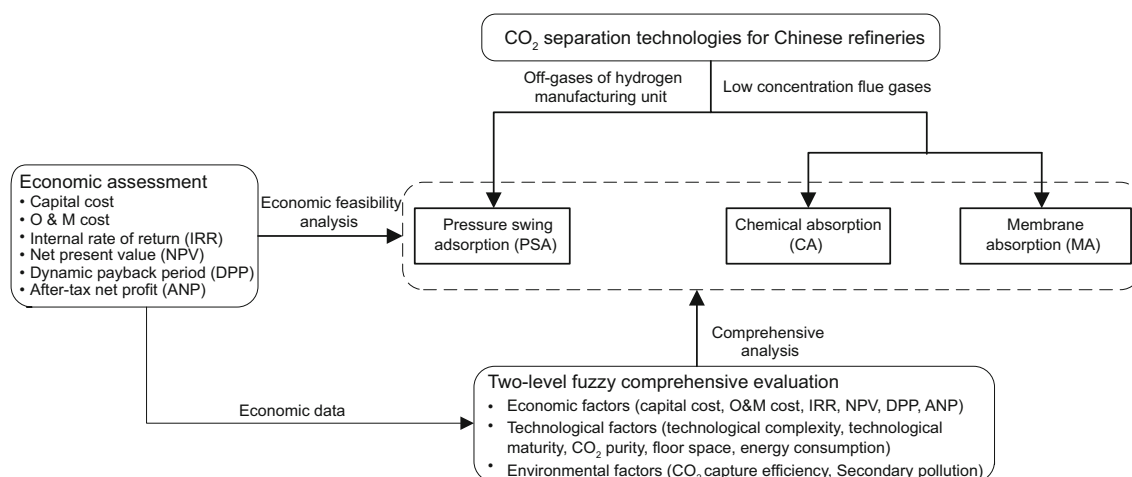
Currently, the technologies for separating CO<sub>2</sub> from a flue gas include absorption, adsorption, use of membranes, cryogenics, and chemical-looping combustion (CLC) (Figuroa et al. 2008; Yang et al. 2008; Olajire 2010; Mondal et al. 2012). Choosing a suitable technology

depends on the characteristics of the flue gas stream and its separation requirements.

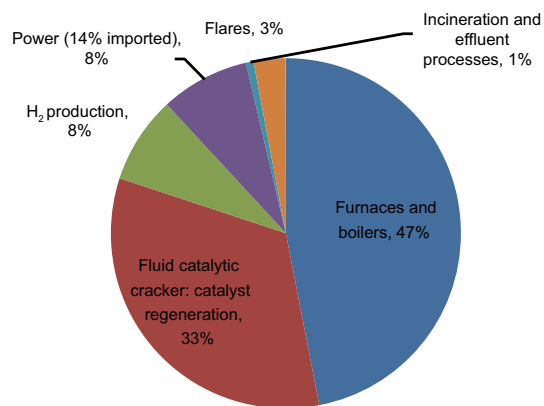
CO<sub>2</sub> may be emitted from a variety of sources at a refinery, even over 20 sources of emissions for a complex refinery. The main CO<sub>2</sub> emission sources include furnaces, boilers, catalyst regeneration, and hydrogen manufacturing. Figure 2 shows the CO<sub>2</sub> emissions of a typical Chinese refinery with 12 Mt/year of crude processing capacity (Jiang et al. 2013). The CO<sub>2</sub> concentration of flue gases changes in a wide range. For example, it is 10–20 vol% for catalyst regeneration in fluid catalytic cracking (FCC) (de Mello et al. 2009), and 50–55 vol% for hydrogen manufacturing units (Reddy and Vyas 2009). Table 1 shows the composition of some CO<sub>2</sub> emission sources for the typical Chinese refineries. Table 2 provides a summary of the pros and cons of CO<sub>2</sub> separation techniques. Based on the characteristics of the flue gases, three available CO<sub>2</sub> separation technologies are initially selected for Chinese refineries, as follows:

### 2.1 Pressure swing adsorption (PSA)

The PSA for CO<sub>2</sub> separation is based on the preferential or selective adsorption of CO<sub>2</sub> on a solid adsorbent at a relatively high pressure by contacting hot gas with solid adsorbent in a packed column. The adsorbed component (CO<sub>2</sub>) is then desorbed from the solid by lowering the gas-phase partial pressures inside the column so that the adsorbent can be re-used. From the point of view of technology, PSA can capture CO<sub>2</sub> of almost all concentrations from flue gases. But some studies have proved that at the present commercial development state, PSA is not a suitable technology for bulk capture of CO<sub>2</sub> from postcombustion power plant flue gas (Reiner et al. 1994; Liu et al. 2012). However, due to relatively low energy consumption and easy operation, PSA is a promising technology



**Fig. 1** The general frame diagram of this study



**Fig. 2** CO<sub>2</sub> emissions of a Chinese refinery (Jiang et al. 2013)

**Table 1** Compositions of some CO<sub>2</sub> emission sources for the typical Chinese refineries

Compositions, vol%	FCC	Hydrogen manufacturing
CO <sub>2</sub>	16.6	50
N <sub>2</sub>	82	–
O <sub>2</sub>	0.8	–
H <sub>2</sub>	–	30
CO	0.6	–
SO <sub>x</sub> , ppmv	20	–
Other combustible gas (e.g., methane, light alkanes & alkenes)	–	20

for capturing CO<sub>2</sub> of high concentration (20–80 vol%) (Ho et al. 2008; Martunus et al. 2012). In oil refineries, most hydrogen manufacturing units use a PSA to recover H<sub>2</sub> from the syngas. PSA can only recover 75–90 % of the overall H<sub>2</sub> in the syngas. PSA off-gas containing CO<sub>2</sub>, unrecovered H<sub>2</sub>, and combustible gas is usually burned as fuel gas (shown in Table 1). The direct combustion of off-gases would lead to not only energy waste, but also the emission of large quantities of CO<sub>2</sub>. Therefore, to maximize overall production and profitability, oil refineries should recover the CO<sub>2</sub> and remaining valuable H<sub>2</sub> in PSA off gas. Reddy and Vyas (2009) have investigated the recovery of CO<sub>2</sub> and H<sub>2</sub> from PSA off gas using the CO<sub>2</sub>LDSep<sup>SM</sup> plant. Beijing Yanshan Petrochemical Company (China) has constructed a PSA unit recovering hydrogen manufacturing off-gases, with which 0.2 Mt food-grade CO<sub>2</sub>, 64.8 Mm<sup>3</sup> combustible gases and 36 Mm<sup>3</sup> H<sub>2</sub> can be produced annually. In the study, some relevant data of the PSA is determined based on this industrial application.

## 2.2 Chemical absorption (CA)

The chemical absorption process, using amine solutions, is a commercialized technology and has been used in natural gas

industry for 60 years. It is regarded as a mature process. The most commonly used solvent is monoethanolamine (MEA). Many studies have been reported about CO<sub>2</sub> capture from an existing coal-fired power plant using chemical absorption method based on MEA (Singh et al. 2003; Alie et al. 2005; Aroonwilas and Veawab 2007; Rubin et al. 2007; Abu-Zahra et al. 2007). They all have indicated that CO<sub>2</sub> capture using MEA is the only feasible option in the short term for flue gases with low concentration CO<sub>2</sub>. Therefore, in this study, random packed columns and ordinary carbon steel are used to act as the absorber and stripper with anticorrosive fluororubbers and stainless steel internals. Furthermore, 20 wt% MEA is selected to absorb CO<sub>2</sub>, and the CO<sub>2</sub> loadings of lean and rich solution are, respectively, set to 0.20 mol-CO<sub>2</sub>/mol-MEA and 0.45 mol-CO<sub>2</sub>/mol-MEA (Alie et al. 2005). An absorption temperature of 40 °C is used and the average pressure is around 0.01 MPa. The regeneration temperature is 110 °C and pressure is 0.025 MPa. Therefore, based on these operating conditions, the size of absorber and stripper needed can be determined using the model provided by Abu-Zahra et al. (2007).

## 2.3 Membrane absorption (MA)

MA, that is using a membrane in conjunction with chemical absorption, is considered as a suitable alternative to chemical absorption by many researchers, due to its unique advantages including large interfacial area, good device-modularity, good operational flexibility, and high mass transfer coefficient (Rangwala 1996; Falk-Pedersen and Dannström 1997; Feron and Jansen 2002; deMontigny et al. 2005; Yeon et al. 2005; Yan et al. 2007, 2008, 2011). In addition, membrane CO<sub>2</sub> absorption technology can also solve the operating problems, successfully including entrainment, flooding, and foaming. It means that solvent losses can be reduced substantially, thereby reducing the absorbent makeup cost. However, the barriers in coal-fired power plants are membrane wetting and plugging which degrade CO<sub>2</sub> separation performance. In order to maintain constant CO<sub>2</sub> removal efficiency, membrane modules need to be replaced again and again, and hence the cost of captured CO<sub>2</sub> will be increased (Mavroudi et al. 2003; Wang et al. 2005; Yan et al. 2008, 2011). Because there are no particles in the flue gas of refineries, membrane plugging will not occur. So, in the assessment of MA in this study, only the membrane wetting problem is considered. With higher specific surface area than packings, hydrophobic hollow fiber membrane contactor is used as the permeable barrier between gas and liquid phase, and the CO<sub>2</sub> can be captured by solvents (e.g., MEA) (Li and Chen 2005). Therefore, hydrophobic polypropylene membranes are selected owing to their relatively low price and commercial availability, with an assumption that the working life of the membranes is 5 years. In addition, the only difference between MA technique and CA technique is the

**Table 2** Pros and cons of CO<sub>2</sub> separation technologies

Separation technologies	Applicable situations	Pros	Cons
Chemical absorption (CA)	Lower or medium CO <sub>2</sub> pressure	High selectivity Wide application Reproducible solvent Quick reaction velocity	Large loss of absorbent High energy consumption of regeneration Strong corrosiveness
Membrane absorption (MA)	Lower CO <sub>2</sub> pressure	Large contact area No problems of bubbling, flooding and entrainment Better permeability and selectivity Low energy consumption Good modularity	Porous membrane easily wetted or blocked Under research
Pressure swing adsorption (PSA)	Higher CO <sub>2</sub> pressure	Easy process Low energy consumption No pollution and corrosion High adaptability and product purity	Low recovery Big investment Large floor area
Physical absorption	Higher CO <sub>2</sub> and total pressure	Low energy consumption and corrosiveness Easy regeneration and lower dosage of adsorbent	Low selectivity and separation efficiency Higher pressure
Cryogenics	High CO <sub>2</sub> pressure (concentration, ~60 vol%)	Higher separation efficiency and purity	High cost and energy consumption
Membrane technology	Higher CO <sub>2</sub> pressure	Simple device No pollution Low energy consumption High separation efficiency	High selectivity but not high permeability Not high CO <sub>2</sub> purity Not resistant to high temperature Not easily cleaned
Chemical-looping combustion (CLC)	Under research	No NO <sub>x</sub> Low energy consumption Low operation cost	No large commercial application

type of absorber. Others are designed as same as CA technique. Because of the constant liquid–gas contact area, the total membrane contact area can be easily scaled-up linearly based on some successful projects or even the experimental results. According to literature (Yeon et al. 2005; Yan et al. 2007, 2008, 2011), the total membrane contact area could be calculated.

### 3 Methods

#### 3.1 Method for economic evaluation

Many studies on economic evaluation of CO<sub>2</sub> capture from industrial sources have been reported (Abu-Zahra et al. 2007; de Mello et al. 2009; Yan et al. 2011; Meerman et al. 2012). For Chinese refineries, the economic assessments are subject to two generally accepted guidelines: the Economic Assessment Method and Parameters for Capital Construction Projects (NDRC and MOC 2006), the

Economic Assessment Method and Parameters for Oil Construction Projects (MOHURD 2010). Although the economic indicators are not the same due to geographic differences, the methodology is similar.

In the study, the economic assessment using cash flow analysis are made up of the following six key economic categories: capital cost, operating and maintenance (O & M) cost, internal rate of return (IRR), net present value (NPV), dynamic payback period (DPP), and after-tax net profit (ANP). The cost model developed in the present study is based on the China-specific guidelines, and the methods for calculating the costs of each category and the data are drawn from the two guidelines (Table 3).

#### 3.2 Method for fuzzy comprehensive evaluation

The evaluation of the optimal CO<sub>2</sub> separation technology for Chinese refineries is influenced by a number of factors, such as economic benefits, environmental policy, technological level, and social impact. However, because of the

**Table 3** Cost estimation of CO<sub>2</sub> separation technologies

1	Capital cost	Formulas
1.1	Engineering	$C_1 + C_2 + C_3$
1.2	Miscellaneous	$1.1 \times C_4$
1.3	Budgetary reserves	$(1.1 + 1.2) \times C_5$
1.4	Annual interest	$(1.1 + 1.2 + 1.3)/C_6 \times (1 - C_7)/C_6 \times C_8$
1.5	Liquidity	
	Capital cost	$1.1 + 1.2 + 1.3 + 1.4 \times C_6 + 1.5$
2	Operating and maintenance (O & M) cost	Formulas
2.1	Materials	
2.2	Fuels & power	
2.3	Wage & Welfare	
2.4	Depreciation	Straight-line depreciation
2.5	Maintenance	
2.6	Miscellaneous	
2.7	Administration	
2.8	Financial	Straight-line amortization
2.9	Sales	
	Annual O & M cost	$\sum 2.i$ (where 2.i is 2.1–2.9)
3	Annual cash flow	Formulas
3.1	Income	
3.2	Cash inflow	3.1
3.3	Construction investment	$(1.1 + 1.2 + 1.3)/C_6$
3.4	Operating cost	$2.1 + 2.2 + 2.3 + 2.5 + 2.6 + 2.9$
3.5	Tax and extra charges	
3.6	Income tax	When $(3.1 - 3.7 - 3.6) > 0$ , $(3.1 - 3.7 - 3.6) \times C_9$
3.7	Cash outflow	$3.3 + 3.4 + 3.5 + 3.6$
3.8	Net cash flow	$3.2 - 3.7$

$C_1$ – $C_9$  are the parameters extracted from the China-specific Guidelines stated above.  $C_1$  is the equipment procurement cost ( $10^4$  Yuan);  $C_2$  is the installation cost ( $10^4$  Yuan);  $C_3$  is the construction cost ( $10^4$  Yuan);  $C_4$  is the miscellaneous fixed asset cost in the proportion of engineering cost, 0.12;  $C_5$  is the budgetary reserves ratio, 0.1;  $C_6$  is the construction period (years);  $C_7$  is the owner’s capital–capital cost ratio;  $C_8$  is the loan interest rate; and  $C_9$  is the income tax rate

complexity and uncertainty involved in evaluation, a decision maker must consider these factors in a comprehensive evaluation to avoid one-sidedness. Fuzzy comprehensive evaluation is the process of evaluating an objective utilizing fuzzy set theory. When evaluating an objective, multiple related factors must be considered comprehensively in order to give an appropriate, non-contradicting, and logically consistent judgment (Jorge et al. 2000; Chen et al. 2002; Liang et al. 2006).

In this study, a two-level fuzzy comprehensive evaluation is used as follows.

- Assuming that the objective being evaluated contains  $n$  factors, i.e., the factor set is  $U = \{U_1, U_2, U_3, \dots, U_n\}$
- First-level fuzzy evaluation is carried out for each factor  $U_k (k = 1, 2, \dots, n)$   $A_k = (a_{k1}, a_{k2}, \dots, a_{kp})$  is the fuzzy weight vector of each sub-factor in  $U_k$ , where  $a_{kl}$  is the relative importance of factor  $l$ , and  $\sum_{l=1}^p a_{kl} = 1$ .

The fuzzy appraisal matrix of all  $p$  sub-factors:

$$R_k = \begin{bmatrix} r_{k11} & r_{k12} & \dots & r_{k1m} \\ r_{k21} & r_{k22} & \dots & r_{k2m} \\ \dots & \dots & \dots & \dots \\ r_{kp1} & r_{kp2} & \dots & r_{kpm} \end{bmatrix} \tag{1}$$

where  $r_{kij}$  is referred to the fuzzy membership degree of appraisal of factor  $i$ . In the study, based on the type of factor  $i$ ,  $r_{kij}$  is defined as (Xie et al. 2012):

For benefit factors:

$$r_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{2}$$

For cost factors:

$$r_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}}, \tag{3}$$

where  $x_{ij}$  is the eigenvalue of factor  $i$ ,  $\max x_{ij}$  and  $\min x_{ij}$  is, respectively, the maximum, the minimum.

The first-level appraisal result,  $B_k$ , can be obtained:

$$B_k = (b_{k1}, b_{k2}, \dots, b_{km}) = A_k \times R_k \tag{4}$$

- Second-level fuzzy evaluation is implemented for  $U$ . According to the aforementioned results, the comprehensive appraisal result,  $B$ , is calculated as:

$$\begin{aligned}
 B &= (b_1, b_2, \dots, b_m) = A \times R \\
 &= (a_1, a_2, \dots, a_n) \times \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1m} \\ b_{21} & b_{22} & \dots & b_{2m} \\ \dots & \dots & \dots & \dots \\ b_{n1} & b_{n2} & \dots & b_{nm} \end{bmatrix}
 \end{aligned}
 \tag{5}$$

- The priority of evaluated objects can be obtained, and the optimal separation technology for Chinese refineries can finally be determined based on different scenarios.

## 4 Results

### 4.1 Economic evaluation

Three CO<sub>2</sub> separation technologies without considering CO<sub>2</sub> compression and transportation can recover 0.1 Mt/year liquid CO<sub>2</sub>. Faced with the restricted downstream demand, CO<sub>2</sub> is usually consumed nearby. Hence, it is assumed for the boundary of the economic evaluation model that around oil refineries there are enough market demands and CO<sub>2</sub> can be completely sold as a commodity. Additionally, Chinese government has established 7 CO<sub>2</sub> pilot emission trading markets in Beijing, Shanghai, Tianjin, Shenzhen etc., and will establish a China national CO<sub>2</sub> emission trading market in the 13th Five-Year Plan. Therefore, some mandatory measures, such as CO<sub>2</sub> emissions taxation, must be taken in the near future in China for refineries as large emission sources. Considering the carbon emissions taxation, CO<sub>2</sub> capture can obtain additional economic benefit. Due to many uncertainties in the pilot carbon market, the CO<sub>2</sub> price may fluctuate greatly, for example, the lowest CO<sub>2</sub> price is 28 Yuan/t and the highest CO<sub>2</sub> price can reach 140 Yuan/t in Shenzhen carbon market. So, in the economic evaluation in this work, a CO<sub>2</sub> price of 140 Yuan/t is used. However, it is worth noting that with the PSA technique, 18 Mm<sup>3</sup>/year of H<sub>2</sub> can be recovered simultaneously, and can be sold at a price of 2.0 Yuan/m<sup>3</sup>. The common basis for the three techniques is shown in Table 4.

The cost of major equipment for the PSA technique is estimated in terms of investment per unit capacity. Based on the PSA unit of Beijing Yanshan Petrochemical Company (China), the major equipment investment for the PSA technique is estimated to be 243.6 Yuan/t, accounting for

**Table 4** Assumptions for economic evaluation with PSA, MA and CA techniques

Items	Value
CO <sub>2</sub> capture efficiency, %	90
CO <sub>2</sub> purity, %	>99
Project working life, years	15
Construction period, years	1
Plant operating time, h/year	8000
Discount rate, %	12
CO <sub>2</sub> sale price, Yuan/t	260
CO <sub>2</sub> transaction price, Yuan/t	140
Owner’s capital/capital cost	0.3
Loan interest rate, %	6.55
Income tax rate, %	25

**Table 5** Economic evaluation results for the three techniques

Items	CA	MA	PSA
Capital cost, 10 <sup>4</sup> Yuan	3453.3	3613.9	3671.3
O & M cost, 10 <sup>4</sup> Yuan/year	3407.1	3397.0	3348.3
IRR, %	17.55	17.75	86.05

approximately 72 % of total construction investment. For the CA and MA techniques, the cost of the absorber and stripper is firstly calculated from the above designs of CA and MA. Then, other costs are estimated in terms of certain proportions. The economic evaluation results for the three CO<sub>2</sub> separation techniques are shown in Table 5.

Table 5 shows that the capital cost of the PSA technique is the highest, but its other economic indicators are optimal. The reason is that it can simultaneously recover CO<sub>2</sub> and by-product H<sub>2</sub>. The capital cost of the MA technique is higher than that of CA. That is because the membrane price is high (about 13 Yuan/m<sup>2</sup>), and the membrane needs to be replaced about every 5 years. However, the O & M cost of CA is higher than that of MA, because of lower CO<sub>2</sub> loading capacity, higher solvent losses, and regeneration heat consumption, meaning that using membrane gas absorption process can save the O & M cost in capture of CO<sub>2</sub>.

### 4.2 Fuzzy comprehensive evaluation

#### 4.2.1 Establishment of the factor set

A factor set consists of various factors affecting the evaluation objective. The evaluation objective of this study is to optimize CO<sub>2</sub> separation technologies. Combining experts’ knowledge and experience with the actual production condition of Chinese refineries, the factor set

**Table 6** Factors for CO<sub>2</sub> separation technologies

Items	Types	Attributes
Economy (C <sub>1</sub> )		
IRR (I <sub>1</sub> )	Benefit	Quantitative
NPV (I <sub>2</sub> )	Benefit	Quantitative
DPP (I <sub>3</sub> )	Cost	Quantitative
Capital cost (I <sub>4</sub> )	Cost	Quantitative
O&M cost (I <sub>5</sub> )	Cost	Quantitative
ANP (I <sub>6</sub> )	Benefit	Quantitative
Technology (C <sub>2</sub> )		
Technological complexity (I <sub>7</sub> )	Cost	Qualitative
Technological maturity (I <sub>8</sub> )	Benefit	Qualitative
CO <sub>2</sub> purity (I <sub>9</sub> )	Benefit	Quantitative
Floor space (I <sub>10</sub> )	Cost	Qualitative
Energy consumption (I <sub>11</sub> )	Cost	Qualitative
Environment (C <sub>3</sub> )		
CO <sub>2</sub> capture efficiency (I <sub>12</sub> )	Benefit	Quantitative
Secondary pollution (I <sub>13</sub> )	Cost	Qualitative

involving economic, technological, and environmental factors has been established (Table 6).

4.2.2 Determination of the weight vector

There are dozens of methods to determine a weight, including Delphi (Ma et al. 2003), AHP (Saaty and Shang 2011; Jiang et al. 2012) and entropy (Lai et al. 2012; Khan and Bhuiyan 2014) methods. Each method has its background, significance, merits, shortcomings, and specific areas of application. Combination of different methods can offset the shortcomings of each, integrate their various advantages, and result in an advanced evaluation method (Refat et al. 2011). In this study, the weight of factors is determined by a combination of subjective (AHP) and objective (entropy) methods, that is, the AHP-entropy method takes into account the data and the subjective preferences of decision-makers to achieve a synthesis of subjective and objective and to make the results more realistic and reliable.

4.2.2.1 Determination of the weight vector by AHP method

AHP, originally developed by Saaty (1977, 1990, 1994), is a mathematical method for analyzing complex decision problems with multiple criteria and through combination of quantitative analysis with qualitative ones. In this paper, the model is based on the combination of qualitative opinions from experts and references and quantitative analysis from aforementioned economic evaluation, and the results are listed in Table 7.

**Table 7** Results of the weight vector by AHP

C	C <sub>1</sub>	C <sub>2</sub>	C <sub>3</sub>	W <sub>i</sub>
	0.4000	0.2000	0.4000	
I <sub>1</sub>	0.4149	0	0	0.1660
I <sub>2</sub>	0.2592	0	0	0.1037
I <sub>3</sub>	0.0501	0	0	0.0200
I <sub>4</sub>	0.0848	0	0	0.0339
I <sub>5</sub>	0.1609	0	0	0.0644
I <sub>6</sub>	0.0300	0	0	0.0120
I <sub>7</sub>	0	0.0732	0	0.0146
I <sub>8</sub>	0	0.4269	0	0.0854
I <sub>9</sub>	0	0.1824	0	0.0365
I <sub>10</sub>	0	0.0413	0	0.0083
I <sub>11</sub>	0	0.2762	0	0.0552
I <sub>12</sub>	0	0	0.5000	0.2000
I <sub>13</sub>	0	0	0.5000	0.2000

C is the optimization of CO<sub>2</sub> separation technologies for Chinese refineries; W<sub>i</sub> is the weight of the factor set

**Table 8** Results of the weight vector by entropy method

Items		E <sub>i</sub>	d <sub>i</sub>	W <sub>i</sub> <sup>''</sup>
Benefit				
I <sub>1</sub>	IRR	0.0181	0.9819	0.1212
I <sub>2</sub>	NPV	0.0337	0.9663	0.1192
I <sub>5</sub>	ANP	0.0022	0.9978	0.1231
I <sub>8</sub>	Technological maturity	0.5119	0.4881	0.0602
I <sub>9</sub>	CO <sub>2</sub> purity	0.6219	0.3781	0.0467
I <sub>12</sub>	CO <sub>2</sub> capture efficiency	0.6072	0.3928	0.0485
Cost				
I <sub>3</sub>	DPP	0.0960	0.9040	0.1116
I <sub>4</sub>	Capital cost	0.4659	0.5341	0.0659
I <sub>6</sub>	O & M cost	0.3793	0.6207	0.0766
I <sub>7</sub>	Technological complexity	0.5119	0.4881	0.0602
I <sub>10</sub>	Floor space	0.4555	0.5445	0.0672
I <sub>11</sub>	Energy consumption	0.5794	0.4206	0.0519
I <sub>13</sub>	Secondary pollution	0.6126	0.3874	0.0478

E<sub>i</sub> is the entropy; d<sub>i</sub> is the diversity; W<sub>i</sub><sup>''</sup> is the entropy weight

4.2.2.2 Determination of the weight vector by entropy method

Entropy, first proposed by Shannon, is a concept originating from information theory (Chen et al. 2012). It can calculate the amount of information in the message, which consists of a countable length of character combination. By computing the total probabilities of all the characters in the message, the information entropy of the message is obtained. Generally, the smaller the entropy of a certain factor is acquired, the more weight the factor is given, and vice versa. Table 8 presents the results of the weight vector by the entropy method.

**Table 9** Results of the weight vector by AHP-entropy method

Items	AHP	Entropy	AHP-entropy
Economy ( $C_1$ )			
$I_1$	0.4149	0.1962	0.4392
$I_2$	0.2592	0.1931	0.2700
$I_3$	0.0501	0.1806	0.0488
$I_4$	0.0848	0.1067	0.0488
$I_5$	0.1609	0.1994	0.1731
$I_6$	0.0300	0.1240	0.0201
Technology ( $C_2$ )			
$I_7$	0.0732	0.2105	0.0791
$I_8$	0.4269	0.2105	0.4614
$I_9$	0.1824	0.1630	0.1526
$I_{10}$	0.0413	0.2348	0.0498
$I_{11}$	0.2762	0.1813	0.2571
Environment ( $C_3$ )			
$I_{12}$	0.5000	0.5035	0.5035
$I_{13}$	0.5000	0.4965	0.4965

4.2.2.3 *Determination of the weight vector by AHP-entropy method* The combined weights are determined by Eq. (6), and the results are shown in Table 9.

$$a_i = \frac{(\omega'_i \times \omega''_i)}{\left(\sum_{i=1}^m \omega'_i \times \omega''_i\right)} \tag{6}$$

4.2.3 *Determination of the fuzzy appraisal matrix*

Based on Eqs. (1), (2), and (3), the fuzzy appraisal matrix for the economic, technological, and environmental factors is obtained as follows:

$$R_{C1} = \begin{bmatrix} 0.0000 & 0.0029 & 1.0000 \\ 0.0000 & 0.0061 & 1.0000 \\ 0.0000 & 0.0224 & 1.0000 \\ 1.0000 & 0.2633 & 0.0000 \\ 0.0003 & 0.0000 & 1.0000 \\ 0.0000 & 0.1718 & 1.0000 \end{bmatrix},$$

$$R_{C2} = \begin{bmatrix} 1.0000 & 0.0000 & 0.3333 \\ 1.0000 & 0.0000 & 0.3333 \\ 1.0000 & 0.0000 & 0.7538 \\ 0.0000 & 1.0000 & 0.2500 \\ 0.5000 & 1.0000 & 0.0000 \end{bmatrix},$$

$$R_{C3} = \begin{bmatrix} 1.0000 & 0.6296 & 0.0000 \\ 0.0000 & 0.6667 & 1.0000 \end{bmatrix}$$

4.2.4 *Results and analysis*

- (1) Results of first-level fuzzy comprehensive evaluation According to Eq. (4), the following results of the single-level fuzzy evaluation are obtained:

- For the economic factors,  $B_1 = [0.0489 \ 0.0203 \ 0.9512]$ . The order of the economic benefit of the three techniques is PSA>CA>MA.
- For the technological factors,  $B_2 = [0.8217 \ 0.3069 \ 0.3076]$ . The order of the technological level is CA>PSA>MA.
- For the environmental factors,  $B_3 = [0.5035 \ 0.6480 \ 0.4965]$ . The order of the environmental benefit is MA>CA>PSA.

- (2) Results of two-level fuzzy comprehensive evaluation The  $B_1$ ,  $B_2$ , and  $B_3$  constitute the fuzzy appraisal matrix of second-level factor, that is,

$$R_C = \begin{bmatrix} 0.0489 & 0.0203 & 0.9512 \\ 0.8217 & 0.3069 & 0.3076 \\ 0.5035 & 0.6480 & 0.4965 \end{bmatrix}.$$

The economic, technological, and environmental factors all belong to benefit attribute, and based on the AHP-entropy method, the weigh vector is  $A = [0.3247 \ 0.3664 \ 0.3089]$ . The overall fuzzy comprehensive evaluation is  $B = A \times R_C = [0.3942 \ 0.3220 \ 0.6349]$ . The order of the three separation technologies is PSA>CA>MA.

5 **Conclusions and implications**

Chinese refineries should prefer PSA, due to its unique advantage of recovering both CO<sub>2</sub> and H<sub>2</sub>. With the increasing amounts of heavy and high-sulfur crude oils to be processed, demand for H<sub>2</sub> in Chinese refineries is rising. The recovery of hydrogen from manufacturing off-gases with PSA can not only reduce total emissions from refineries, but also expand their production and profitability. On the other hand, MA, if the obstacle of the membrane wetting is overcome, will be the most promising alternative to chemical absorption to capture CO<sub>2</sub> from oil refinery flue gas in the future. In addition, the methodology presented might be beneficial to decision-making for CO<sub>2</sub> capture projects in oil refineries in other countries. The result is important for evaluating the deployment of CCS in Chinese refining sector.

Utilization of technological options for separation and/or capture of CO<sub>2</sub> from flue gases will make Chinese refining industry realize their target of emission reduction in the future. However, without mandatory cuts, incentives, and a major technological break-through, the high costs impose restrictions on the implementation of carbon capture at Chinese refineries. There are a lot of uncertainties about which technologies could lead to real improvements and which have no real prospects for reducing the cost of



capture. On the other hand, the use of the captured CO<sub>2</sub> as a secondary product appears to be attractive. The utilization includes producing chemical substances through the application of organic chemistry, biofuels, etc., or injecting pure captured CO<sub>2</sub> underground for enhanced oil recovery (EOR), enhanced gas recovery (EGR), and enhanced coal-bed methane (ECBM), although this is not mentioned in the paper.

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