

Review

Chemical Looping Strategy in Various Types of Carbon Capture Technologies

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Abstract: Considering the worsening of global warming, development of efficient strategies in carbon capture process is essential. The chemical looping process (CLP) is considered a promising method applicable in various carbon capture strategies. In pre-, post-, or oxy-fuel combustion strategies, the efficiency of CLP has been explored and tested. This review discusses the applied CLP in each type of carbon capture strategy. Chemical looping gasification and reforming are categorized in the pre-combustion system. On the other hand, the popularity of calcium looping and amine looping are recognized as post-combustion strategies. Additionally, numerous oxygen carrier materials have been determined to reach high efficiency in oxy-fuel combustion. The review of the characters and the principle of the method was complemented by justification for real-scale application. Nonetheless, the popularity of CLP's real implementation as a carbon capture strategy was still limited by several factors, including required cost for the facilities and energy demand. Thus, analysis on the prospect of CLP utilization was also included in this study.

Keywords: chemical looping process; carbon capture; oxygen carrier; pre-combustion; post-combustion; oxy-fuel combustion



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1. Introduction

Exaggerated usage of fossil fuels causes a massive reduction in the source sustainability and emission of carbon dioxide (CO₂). Emitted CO₂ remains in the atmosphere for a long time [1]. Moreover, the utilization of fossil fuels in various life sectors dominates CO₂ emission and leads to global warming, which is harmful to the environment [2,3]. Furthermore, domination of the greenhouse gas annual emissions by CO₂ reached 77%, or 35 billion tons [1]. It was previously reported by Olabi et al. [4] that the global carbon emission of 33.5 Gt-CO₂ in 2018 was reduced to 32.1 Gt-CO₂, which was caused by the effect of lockdown during the COVID-19.

One of the obvious effects of global warming is the increase in average temperature. The combustion of coal, which is mostly used for power plants, has had a great contribution in elevating the average temperature by 0.3 °C [5,6]. Moreover, the anticipation of 1.5 °C rise in global average temperature is predicted to occur in 2040 [5]. CO₂ also has been recognized as the major species in the carbon cycle [7]. Thus, concern about CO₂ mitigation has been drastically rising in recent years and has focused on the absorption of existing CO₂, the development of renewable energies, and CO₂ capture and storage (CCS) [2].

1.1. Carbon Capture Technologies: Types and Trend

A considerable amount of research has been developed around the topic of CCS, or carbon capture utilization and storage (CCUS). The developed strategies in CCS can be classified into pre-combustion, oxy-fuel combustion, and post-combustion based on the position of the CO₂ capture process [2]. Figure 1 illustrates the mechanism of carbon

capture in different CCS types. Pre-combustion and post-combustion are the technologies that are installed for CO₂ capture at the beginning and end of combustion, respectively. Pre-combustion strategy uses oxidation of hydrocarbon fuels into syngas (CO and H₂), which will be followed by a water–gas shift process for the production of CO₂ and H₂O [4]. In post-combustion strategy, carbon capture technology is installed at the end point of the process and is considered a simpler method to apply than pre- or oxy-fuel combustion [4]. Differently, oxy-fuel combustion creates high-purity oxygen during the combustion process for the production of CO₂ in high concentrations [5].

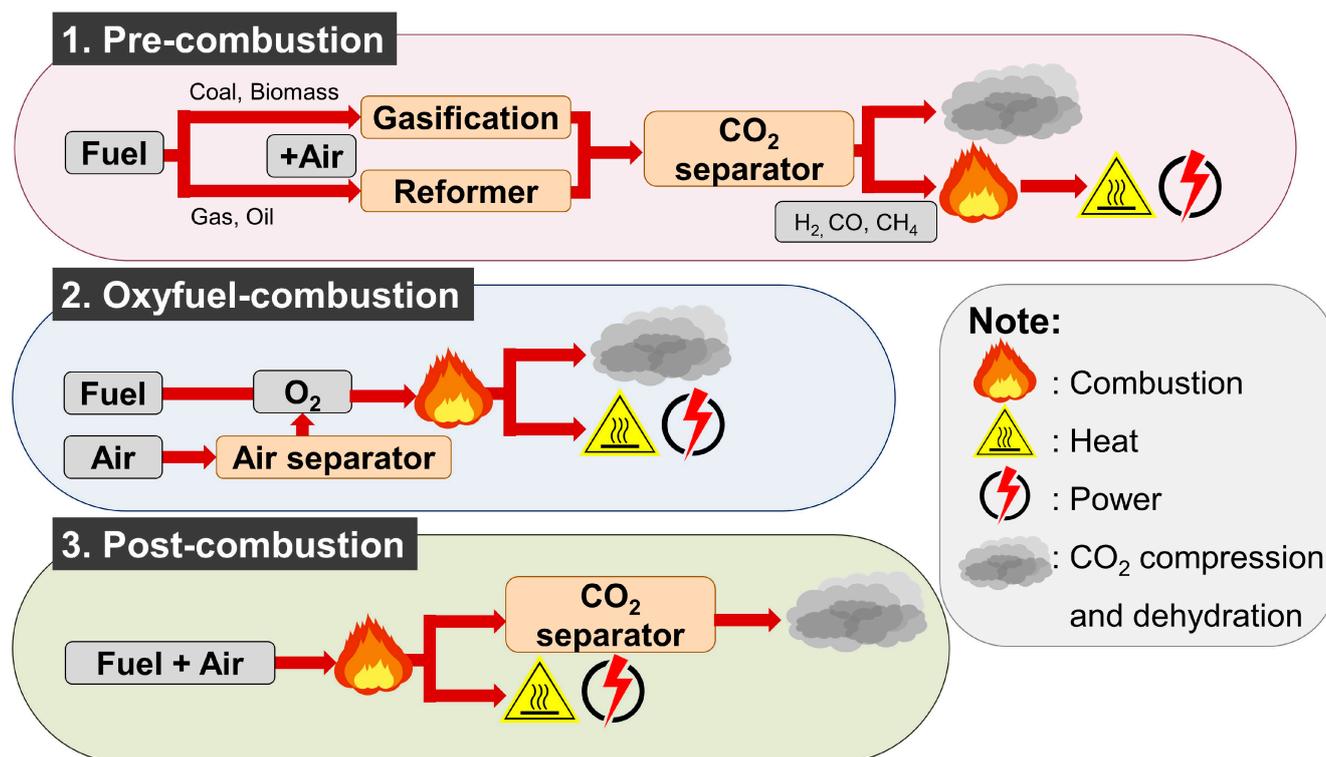


Figure 1. Comparison of CO₂ capture process according to the separation position.

For all of the strategies in CO₂ capture, several methods can be applied in the carbon capture process including absorption, adsorption, membrane technologies, cryogenic distillation [1,8], etc., as can be seen in Table 1.

Table 1. Feasible technologies in CO₂ capture.

No	Technologies	Working Principle	Consideration of Implementation	References
1	Adsorption	Applied several types of solid material (zeolites, clay, oxides, etc.) as selective adsorbent for CO ₂ .	Can be applied under low energy demand but highly influenced by the affinity of CO ₂ , along with the molar size, molar weight, and polarity of the sorbents.	[9–12]
2	Physical absorption	Implements high pressure and low temperature to improve solubility of CO ₂ into the sorption medium.	Unsuitable for low CO ₂ content. Further test on performance and stability are required.	[13,14]
3	Chemical absorption	Utilizes several types of chemicals (amines, potassium carbonate, calcium carbonate, amino acids, etc.) to absorb the CO ₂ gas stream.	Can be applied in low pressure condition, but regeneration of solvent needs to be maintained. Created the issue of corrosion and high regeneration energy demand.	[15–17]

Table 1. Cont.

No	Technologies	Working Principle	Consideration of Implementation	References
4	Hydrate-based	Deliver the CO ₂ containing flue gas using high pressure into water to form hydrate.	Applicable for pre- and post-combustion but highly depends on the rate of hydrate formation, solubility, and contact surface area.	[18–21]
5	Cryogenic separation	Use the difference in sublimation properties and high boiling points for physical separation of CO ₂ in gas.	High energy demand for conditioning of refrigeration cycle. High applicability for CO ₂ concentration > 50%.	[22,23]
6	Membrane separation	Supply the CO ₂ gas stream through membrane materials to	Membrane materials with high permeability, low cost, and high durability are required. Considered as an eco-friendly and low energy demand strategy but low partial pressure issue should be handled.	[24–27]
7	Molecular sieve	Gas separation strategy using permeable materials with suitable hole size of the CO ₂ gas molecule.	Simple process for adsorption or desorption, but the design is complicated, and the process is highly influenced by the thermal stability.	[28–30]
8	Metal organic frameworks	Capture CO ₂ by the open structure of porous solid of metal organic materials.	Maintenance of practical pressure, CO ₂ partial pressure, and temperature is essential to reach high efficiency. Adaptive to be combined with other capture methods.	[31,32]
9	Ionic liquids	CO ₂ sorption using the combination of anion and cation made of organic or inorganic liquids.	Non-corrosivity and low volatility are accompanied by high viscosity and cost during the process. High possibility to be combined with the membrane strategy.	[33–35]

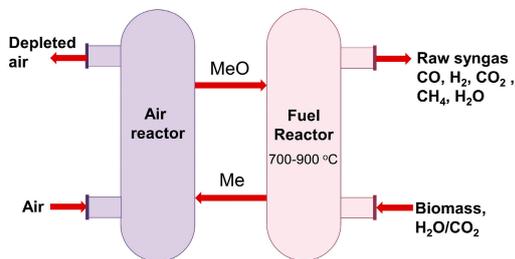
1.2. Chemical Looping Process in Improvement of Carbon Capture Strategy

The chemical looping process (CLP) for various carbon capture strategies has attracted the interest of researchers. In principle, CLP separates the conventional technique into more than one sub-reaction and applies the redox cycle [36]. Fundamentally, carbon capture technology using CLP utilizes metal-oxide-based oxygen carriers in conversion of carbonaceous fuels through two reactors for reduction and oxidation reactions in a redox loop [7]. Besides, reaction and regeneration in the CLP can involve the intermediate materials like metal oxides for oxidation of fuel known as the chemical looping full oxidation (CLFO) [37]. Application of CLP is favorable to be applied for gaseous fuels due to its great thermodynamic properties [7]. Several applied CLP methods for pre-, post-, and oxy-fuel combustion strategies are illustrated in Figure 2.

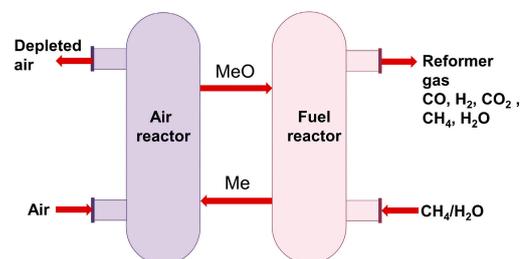
In the reducer reactor (commonly called a fuel reactor), the supplied fuel will meet the oxygen carrier under a temperature range of 850–900 °C for further reaction and result in reduced oxygen carrier material. Concentrated CO₂ and H₂O will be generated as the output of this reactor. Therefore, oxygen carrier with a high oxidation state will be beneficial for the full conversion of the fuel. Furthermore, when biomass was used as the fuel source, gasifying agents along with steam, CO₂, and/or H₂ were also involved in the reaction kinetics [7]. The reduced oxygen carrier was then transferred to the oxidizer reactor (commonly called an air reactor) to undergo hydrogen production. Combustion in oxidizer reactors is commonly conducted in the range of 700–900 °C [3,7].

1. Pre-combustion

Chemical Looping Gasification

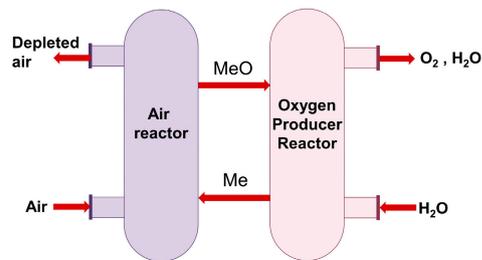


Chemical Looping Reforming

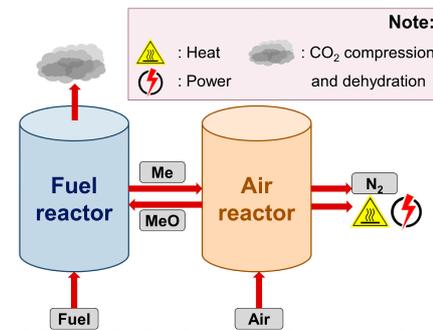


2. Oxyfuel-combustion

Chemical Looping Air separation

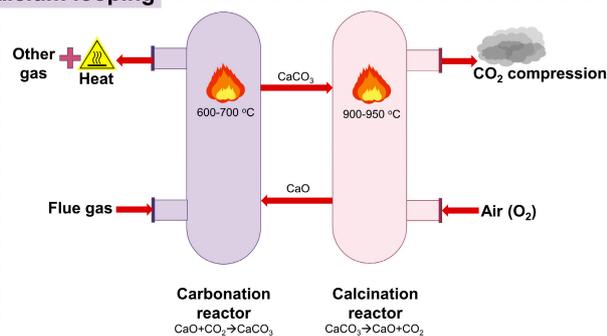


Chemical Looping Combustion



3. Post-combustion

Calcium looping



Amine looping

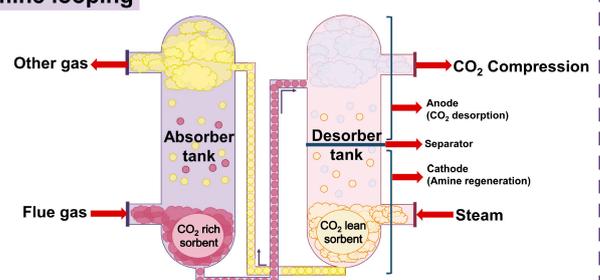


Figure 2. Working principle of chemical looping processes in carbon capture strategies.

As an emerging technology, the development of CLP has performed good stability and maturity to be implemented in various industries. It has been reported by Abuelgasim et al. [2] that the global application of CLP has exceeded 11,000 h in 2018 from 40 units. Compared to the conventional carbon capture methods, CLP offers lower energy penalty, especially for the separation process [2]. The major cost in carbon capture process comes from the energy penalty. For example in a coal fired power plant, CO₂ capture may increase 30% fuel need per unit of electricity, and application of CLP can reduce or even eliminate the energy penalty value [38]. A previous report by He et al. [39] discussed application of three stage Fe-based CLP for a power system using liquid fuel that even achieved zero-energy penalty in the carbon capture process. From the above-mentioned process, 98.46% CO₂

emission ratio was followed by 12.19% fuel energy savings due to the hydrogen generation in chemical looping. Integration of CLP in the carbon capture strategy may also reduce energy penalty from the steam generation in air reactor [40,41]. Additionally, through the application of CLP, gas emission from the fuel reactor emitted higher concentration of CO₂ compared to the conventional boiler technology [41]. The highly concentrated CO₂ will beneficially support the process of sequestration.

Overall, not only will benefits be derived from the energy penalty, reductions in the cost of processing can also be achieved from various aspects in CLP, including utilization of low-cost oxygen carrier, re-use of produced steam, and lifetime of installed instrument [42]. In the conventional carbon capture process, the required cost can reach the range of 63–150 USD/MWh [39]. The overall operational cost in conventional carbon capture strategy can be successfully reduced by application of CLP [43]. The lower cost in the range of 16–26 EUR/ton-CO₂ (17–28 USD/ton-CO₂) can be achieved by CLP in a carbon capture system compared to the conventional technologies [44]. Integration of CLP in carbon capture process of a power system using liquid fuel was reported to reduce the cost requirement and to reach 55.46 USD/MWh [39]. Additionally, implementation of CLP for carbon capture resulted high purity of CO₂ and further reduce the cost for downstream process [44].

2. Chemical Looping Process in Pre-Combustion Strategies

In the case of pre-combustion strategies, the process is commonly applied for the natural gas boilers and coal-fired power plants that combine the production of syngas (H₂ and CO) with further conversion of CO and H₂O into CO₂ and H₂ before the separation process [1].

2.1. Chemical Looping Gasification (CLG)

Compared to the conventional gasification process, CLG offers various advantages, especially for the gasification for biomass fuels. In the fuel reactor, limitation from slow gasification process due to the fuel conversion can be answered with the implementation of oxygen carrier [45]. Biomass CLG (BCLG) performs with higher efficiency (reached 10–25% higher) due to its circular process and supports in managing gas emissions, including of CO₂, along with extreme cost reduction [36].

BCLG circulates the oxygen carrier material between gasification reactors to steam-gasify the biomass fuels and the combustion reactor for combustion of the residual char and heat production for the next cycle of gasification [36]. Cost reduction with BCLG can be achieved via elimination of the air separation unit, which becomes a requirement in conventional gasification, and implementation of low-cost oxygen carrier [36]. Besides the cost reduction, implementation of BCLG also generates syngas with higher purity along with the minimum emissions of pollutants and lower loss in exergy value [46].

Modification of pressure in the CLG can be conducted for enhancement of energy efficiency, especially in the power plant [47]. Under the increasing pressure, elevation of reaction kinetics, product selectivity, fuel conversion, and rate of heat and mass transfer will be achieved. Pressurized CLG is highly dependent on Le Chatelier's principle to reach its optimum efficiency [47]. A combined cycle technology for BCLG process for power generation even has been reported to reach zero CO₂ emissions due to the improvement in efficiency of biomass utilization [48].

2.2. Chemical Looping Reforming (CLR)

The main purpose of chemical looping reforming (CLR) is the production of hydrogen [49]. CLR is efficient in reducing the thermal requirements during the process compared to the conventional steam reforming system [50]. CLR can be classified into several types according to the heating process, like autothermal chemical looping reforming (CLRa), chemical looping steam reforming (CLSR), and chemical looping dry reforming (CLDR) [37]. Supply of CO₂ or H₂O to the fuel reactor is conducted for CLDR or CLSR, respectively, along with the circulation of oxygen carrier material for source of oxygen [49].

For CLDR process, the flexibility of the fuel used is considered as a beneficial aspect since this method can be applied for various fuel types. However, coking phenomena and the selectivity of product are the main challenges to be dealt with [51].

3. Chemical Looping Process in Oxy-Fuel Combustion Strategies

According to the working mechanism, oxy-fuel combustion (OFC) has a higher impact in reducing the capture cost during CCS compared to pre-combustion and post-combustion [5]. Besides the creation of lower energy demand, OFC also has the capability to build a low-cost process which is suitable to be applied in industry. In oxy-fuel combustion, CLP is commonly applied in the air-separation process to produce high-purity O₂ for combustion processes. In this mechanism, the oxygen carrier plays an important role and is considered as the main parameter to transfer the oxygen between air and fuel reactors and in building a successful CLP [2]. Attraction of CLP in oxy-fuel combustion not only comes from the development of an oxygen carrier with great performance but also in other supporting process, like the air separation [52]. The combination of oxy-fuel combustion with chemical looping in air separation also can be investigated for its life cycle environmental and economic analysis to reach a great efficiency [53]. Additionally, oxy-fuel combustion has also gained high interest due to its flexibility in the integration with various processes, including those in oil refinery plants [54].

3.1. Oxygen Carrier Materials

Oxygen carrier materials contain reducible metal oxides (MOx) for the generation of oxygen (ion or vacancy), the formation of electron–hole pairs, the diffusion of the electron to the bulk phase, and providing active sites for surface reaction [37]. In choosing a feasible oxygen carrier material, several considerations need to be inserted into the account, including [2,3]:

- High capacity in oxygen transport;
- Good properties for thermodynamic and kinetic capacity for conversion of fuel;
- Great endurance in melting temperature;
- Good characteristics in fluidization and low chance of agglomeration;
- High mechanical strength;
- Low possibility of carbon deposition;
- Low-cost and eco-friendly materials.

Regarding the above-mentioned criteria, and since the combustion is carried out at high temperatures (600–1200 °C), several materials—including Cd, Zn, Ce, and MoO₃—have been avoided as oxygen carriers due to their low melting points. This is not limited to only the manufactured oxygen carrier materials—several natural ores also potentially present similar performances [3].

Moreover, the performance of oxygen carriers also depends on the character of the supporting materials and the preparation method. Al₂O₃, TiO₂, SiO₂, and MgAl₂O₄ are favorable to use as supporting materials for oxygen carriers [2]. Table 2 presents the popular oxygen carrier materials for carbon capture process. Oxygen carrier can be produced under various preparation methods, including precipitation, impregnation, freeze granulation, sol-gel, and spray-drying. However, in real-scale production of oxygen carrier, concerns of cost and lifetime feasibility must be considered [2]. Several key points are important to be monitored during the test of oxygen carriers, including mass transfer, heat balance, thermodynamic properties, and reaction kinetics [3].

Table 2. Performance of various oxygen carrier materials for CO₂ capture process.

No	Oxygen Carrier	Features	References
1	Cu-based mixed oxides from hydrotalcite derivation (CuAl ₂ O ₄ , CuAlO ₂ , etc.)	Improved oxygen uptake and release capacity.	[55]
2	Cu-based with silica and zirconia support	Improved stability during the cycle test.	[56]
3	Cu-doped Zn oxides (Cu-ZnO)	Improved the CO Faradaic efficiency and current density for the process of CO ₂ electrochemical reduction.	[57]
4	Cu-based with red mud support (Cu _{1.3,0} Red _{87.0} @C)	Improved capacity of carbon capture using low-cost material.	[58]
5	Ca-Cu-based oxygen carrier	Improved capacity and stability in simultaneous H ₂ production and CO ₂ capture from chemical looping system.	[59]
6	Cu-Al-based oxygen carrier	Promoted mechanical strength during chemical looping combustion process	[60]
7	Hematite- and copper-ore-based oxygen carrier	Improved selectivity, stability, and ability of oxygen release.	[61]
8	20NiO/MgAl ₂ O ₄ oxygen carrier	Improved the hydrogen selectivity and material stability in chemical looping steam reforming system.	[62]
9	LaFe _{2.9} Ni _{0.1} Al ₉ O ₁₉	Promoted the utilization of CO ₂ and separation of O ₂ impurities in chemical looping system	[63]
10	MnFe ₂ O ₄ oxygen carrier	Formation of spinel structure improved the migration of lattice oxygen	[64]
11	Ni-Ca-based co-loaded on ZrO ₂	Improved isothermal capture and release of CO ₂	[65]
12	Perovskite (CaMn _{0.775} Mg _{0.1} Ti _{0.125} O _{3-δ})- and Cu-based oxygen carrier	Promoted reduction of NO _x emission during CO ₂ capture	[66]
13	Ca-Fe-Mg oxygen carrier	Created a stable H ₂ /CO ratio due to the presence of Ca	[67]
14	Fe-based oxygen carrier (K _{0.85} Fe _{0.85} Ti _{0.15} O ₂ , K _{0.4} Fe _{0.4} Ti _{0.6} O ₂ , KTi ₈ O ₁₆ , and KTi ₈ O _{16.5})	Improved thermostability during CO ₂ capture in CLC system	[68]
15	Iron ore combined with alkaline earth and transition metal ions	Improved the reactivity with volatiles for production of higher CO ₂ content	[69]
16	LaFe _{1-x} Ni _x O _{3-δ} oxygen carrier	Formed simple tuning for syngas production and CO ₂ utilization	[70]
17	Ni and Co doping on SrFeO _{3-δ} oxygen carrier	Increased the migration of lattice oxygen for chemical looping dry reforming of methane	[71]
18	Combination of lignite with CaSO ₄ -CoO oxygen carrier	Improved reactivity and reduce sintering effect in chemical looping combustion	[72]
19	Cu-Mn oxygen carrier	Prolonged lifetime and increase mechanical resistance during chemical looping combustion system	[73]
20	Fe ₂ O ₃ -MnO ₂ on Ti support	Promoted physicochemical stability during the looping cycle	[74]

3.2. Metal-Oxide-Based Oxygen Carriers

3.2.1. Copper (Cu)

Cu-based oxygen carriers usually come in the form of CuO and Cu₂O and are acknowledged as materials with great transport capacity, high thermodynamic capability, and the ability to perform full fuel oxidation [2,75]. Additionally, the low cost of Cu-based oxygen carrier is also favorable for use on a larger scale [46]. However, application of Cu as oxygen carrier is suitable to be carried out in the average temperature of 900 °C due to its lower melting point (1085 °C) and its performance tends to decline after few

cycles usage [2]. Thus, combination with support material is necessary to improve the performance of Cu-based oxygen carrier but the side thermodynamic effect from its mixture need to be taken into account [2].

Although having a high price, copper ore is also considered as a potential oxygen carrier with less thermodynamic limitation due to the domination of CuO content. The composition of copper ore is usually accompanied by several impurities, including SiO₂, CaSO₄, and Al₂O₃. Nevertheless, lower melting points as found in manufactured Cu also result in agglomeration in the sintering process [2].

3.2.2. Nickel (Ni)

Exploration on Ni-based oxygen carrier is popular to be tested in continuous system compared to the oxygen carrier materials as reported by Abuelgasim et al. [2]. Due to its thermodynamic stability, Ni-based oxygen carrier is favorable for gaseous fuel. A high reactivity and followed by the great performance under temperature range of 900–1100 °C can be achieved by Ni-based oxygen carrier [75]. Even the high reactivity of Ni-based oxygen carriers also beneficially supports the cracking process of tar and char [46]. Furthermore, Ni-based oxygen carrier beneficially improves combustion when applied to CH₄ due to its high stability in reactive chemical bond cutting. Nevertheless, the developed efficiency is also followed by a major drawback—formation of Ni-aluminates [2]. Additionally, the risk in cost and health effect also presented by the application of Ni-based oxygen carrier [2]. The limitation from the particle formation also occurred in Ni-based oxygen carriers, especially those with the Al₂O₃ support material [75].

3.2.3. Cobalt (Co)

Co-based oxygen carriers commonly come in the forms of Co₃O₄, Co, or CoO, which display special characters in the oxygen transport and oxygen uncoupling processes to support the full conversion of gaseous fuel [2]. The best thermodynamic conversion of gaseous fuel is shown by CoO/Co materials, and exploration on their application for solid fuel in continuous systems is still rare [2].

3.2.4. Manganese (Mn)

Several types of Mn-based materials are commonly applied to perform oxygen carrier reaction, including Mn₂O₃ and Mn₃O₄. Meanwhile, MnO/Mn is unfavorable to be applied as oxygen carrier due to its limitation in reduction process in the fuel reactor. Like the other types of oxygen carriers, Mn-based materials improved through mixture with support materials and ZrO₂ or bentonite are preferable. However, several compounds—including SiO₂, TiO₂, Al₂O₃, MgAl₂O₄, and sepiolite—are avoided due to lower reactivity, tendency to agglomerate, or crack formation in the structure [2].

Besides the synthetic Mn oxygen carrier, manganese ore also has been acknowledged as a good oxygen carrier material. The high oxygen transport capacity, low tendency in agglomeration, and great reactivity with syngas of Mn ore are favorable. However, reaction of Mn ore for CH₄ is still limited [2]. Application of Mn ore materials as oxygen carriers was reported by Abuelgasim et al. [2]. Performance of manganese ore as an oxygen carrier is greater than that of iron ores. High resistance in the sintering process and stable conversion are presented by Mn ores. However, the risk of attrition and deactivation due to formation of Mn₃O₄ also become drawbacks in its application [2].

3.2.5. Iron (Fe)

Iron as the oxygen carrier materials come in several common forms, including Fe₃O₄, Fe₂O₃, and Fe. Various type of Fe-based oxygen carriers have been previously reported by Yu et al. [76], and several aspects need to be considered in choosing Fe-based oxygen carrier types. Application of Fe-based oxygen carriers in chemical looping combustion under various syngas conditions, including the presence of H₂S, have also been tested [77]. Despite its popularity as a low-cost and eco-friendly material, in the role of oxygen carrier,

Fe has lower reactivity, reaction rate dependent on the gaseous fuel type, and unsteady under application with solid fuel [2]. Moreover, the impurities in solid fuel, including phosphorus and sulfur, have the tendency to interact with Fe-based oxygen carrier, lowering its efficiency [76]. Additionally, with longer usage, heat management using Fe-based oxygen carrier needs to be maintained due to reduction of Fe_2O_3 to Fe by deposited carbon [2]. However, compared to other oxygen carrier materials, Fe is recognized for its lower tendency toward carbon formation [46,75].

Not only a synthetic Fe-based oxygen carrier, ilmenite—as a natural ore mainly composed of FeTiO_3 —is also favorable due to its low cost and eco-friendly properties along with similar performance to the manufactured material even under low pretreatment processes. Sources of ilmenite are highly available in China, Canada, Australia, and South Africa [3]. The wide application of ilmenite as an oxygen carrier was reported by Daneshmand-Jahromi et al. [3] and also previously tested in chemical looping combustion under various parameters [78]. Despite the good performance of ilmenite, most of the previous studies present low durability under the presence of CH_4 , and conversion of solid fuel is highly dependent on the operation setup and application of high temperature [2]. Additionally, the issue of reactivity declining during the multiple cycle implementation is due to segregation of Fe material from the TiO_2 portion. Nevertheless, pretreatments like low-temperature calcination [79] and the addition of calcium nitrate [80] have been reported to deal with the above-mentioned problem.

Another type of commonly used iron ore, hematite, is dominated by the presence of Fe_2O_3 , which is also found in Fe-based industrial byproducts. Implementation of hematite as an oxygen carrier is less favorable than ilmenite due to its lower stability and oxygen transfer capacity [3]. As also found in ilmenite, application of other types of iron ores is also limited by material loss due to high abrasion rate, small capacity in oxygen transport, and restriction in application with CH_4 [2].

3.3. Combined Metal Oxygen Carriers

Improvement of the oxygen carrier material can be carried out by mixing two or more oxide types via chemical or physical methods [46]. Combination of the oxides can be conducted in spinel or perovskite forms. Compounds from combination via physical methods are commonly called “mixed oxides”, while combined oxides are referred to as “products” after chemical mixing. The purpose of metal oxide combination is to promote several properties that might not be reached by single materials, including promotion of mechanical strength, reactivity, oxygen capacity, and even cost reduction [2].

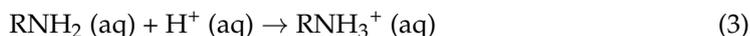
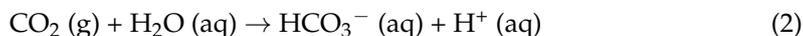
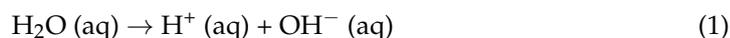
A combination of Fe, Mn, and SiO_3 produces improvement in oxygen release efficiency under higher temperatures along with magnetic behavior and lowers the loss of oxygen carrier [81]. Improvement of oxygen uncoupling process is performed via the combination of Fe/TiO_2 [82] and $\text{Cu}_{1.5}\text{Mn}_{1.5}\text{O}_4$ [83]. Combustion efficiency is also improved in the chemical looping process using $\text{Fe}_2\text{O}_3/\text{TiO}_2$ as oxygen carrier material [84]. In the case of oxygen coupling promotion, perovskite types from the combination of Ca, Mg, and Mn are preferable and offer high fuel conversion [2].

4. Chemical Looping Process for Post-Combustion Strategies

4.1. Amine Looping

Monoethanolamine (MEA) is the dominant amine species utilized in the amine looping process due to its high removal capacity that can reach 87.1–100%. Other types of primary amine compounds, like 2-(2-aminoethoxy) ethanol (DGA), 1-amino-2-propanol (1A2P), and 2-amino-1-butanol (2A1B), can also be used for the carbon capture process due to their high water solubility, low cost, and fast kinetics. However, primary amine commercialization is unfavorable due to their tendency toward solvent, thermal, and oxidative degradation, which further lead to issues like solvent loss, fouling, corrosion, and increases in viscosity [8]. In addition to primary amine compounds, secondary and tertiary amines also have the potential to be used as solvents. Carbon capture through amine looping is initiated by

ionization of water (Equation (1)), CO₂ hydrolysis and ionization (Equation (2)), protonation of alkanolamine (Equation (3)), and formation of carbamate (Equation (4)) [8].



Despite its simplicity in the carbon capture process, several issues related to solvent degradation, solvent loss, fouling, corrosion of instrument, and increasing of solvent viscosity also become drawbacks of amine looping [8].

The alkaline pH value from amine solvent will turn into acid condition after the carbon capture process. Discharge of protons in the amine-CO₂-H₂O system causes corrosive issues for the carbon capture facility as previously discussed by Zhao et al. [85].

4.2. Ca-Looping

The principal mechanism of Ca-looping utilizes reversible CO₂ gas absorption by Ca-based solid material to form Ca-carbonate, as explained in Equation (5) [86].



In the Ca-looping system, Ca-based solid material is circulated between the carbonator (600–700 °C) and calciner (>900 °C) parts of the plant [87]. Reaction in the carbonator is initially controlled by the rapid kinetic rate prior to the slower diffusion control phase [88]. Release of CO₂ is carried out in the calciner, which can be further purified, compressed, and stored [89].

The low processing cost from utilization of the calcium looping method for carbon capture is accompanied by high theoretical uptake [87]. However, the efficiency of the system is also influenced by the presence of other elements in the Ca-based materials. Nevertheless, due to the requirement of high operating temperature, Ca looping systems will commonly be combined with other technologies, including oxy-fuel combustion, to improve their efficiency [87]. Moreover, solar-driven calcium looping also has been tested for implementation in cement industry to significantly cut CO₂ emissions [90]. A previous study with combination of the CaO for the calcium looping process with the oxy-fuel combustion has also been tested to improve its energy utilization and CO₂ capture [53].

5. Application of Chemical Looping Process: Challenge and Alternative Solutions

5.1. Challenges

Application of carbon capture strategy is essential in industry considering the worsening of global warming. However, several limitations inhibit the development and popularity of applied carbon capture strategy in industry. The high efficiency of CLP in carbon capture is still haunted by the maintenance, control, and balancing processes during operation, which further inhibit the development of this strategy [38]. The issues of large-scale implementation and lowering energy demand and cost are the main problems in CCS [91]. In CLP used for carbon capture, one of the inhibitions to its development comes from consideration of the challenge in pressurization, which becomes a drawback in reaching energy efficiency [92]. Although numerous studies have been conducted on the topic of carbon capture, energy demand during the process is still considered the main drawback in most established technologies [2,3]. Another issue comes from the requirement of additional units in companies specially for CO₂ capture. Liu et al. [6] reported that post-combustion and pre-combustion technologies account for 10% and 5–9% reductions in plant efficiency, respectively.

Additional costs throughout the lifetimes of oxygen carrier materials were also considered as another challenge in the implementation of CLP [44]. Other material-related issues in CLP also reported by Arnaiz del Pozo et al. [38] included the requirement in circulation process, fuel slip due to the slow reaction rate, and unstable performance of oxygen carrier. Previous report by Huang et al. [93] discussed the tendency in declining of CLP for carbon capture due to the carbon deposition on the oxygen carrier surface that become a concern in application for industrial scale.

Besides the great investment cost for carbon capture facilities, the cost in providing compression process, steam energy, and solvent materials also need to be considered [91]. As was reported by Olabi et al. [94], high expenses and complicated separation of CO₂/H₂ limited the implementation of pre-combustion technologies. The ultimate cost of CO₂ capture for carbon capture technology can even account for 70–80% of the total cost [95]. However, the application of carbon capture strategies in high CO₂ concentration, such as natural gas, fertilizer, and chemical industries, will be lower compared to other types of industry due to the cost requirement [96]. Cost issues appear not only during the carbon capture process but also for the supply chain of the captured CO₂, as reported by Gabrielli et al. [97]. On the other hand, application of post-combustion technologies will be inefficient under low CO₂ input and, oxy-fuel combustion technologies are threatened by the corrosion issue [94].

Limited space for carbon capture facilities, great amounts of water resource utilization, and efficiency of capture depended on the flue gas composition, which also appeared as a limitation of its efficiency [91]. The growth in exploration and investigation in carbon capture technology also elevates the cost for initial investment and operation [4]. Additionally, assessment of the safety risk along and the monitoring process is also required in the carbon capture process [91]. The amine sorption process is still considered to be the most commonly applied carbon capture technology; however, the corrosion issue is still the drawback of the implementation [85,94].

5.2. Alternative Solutions

Modification of technology has been applied in the carbon capture process for optimization of performance. Bartocci et al. [98] designed the application of pressurized chemical looping combustion with a turbo expander for optimization of carbon capture and reduction of required cost. The promising advantages from the application of gas-switching combustion for the improvement of conventional CLP in carbon capture have also been discussed by Arnaiz del Pozo et al. [38].

The corrosive effect from the amine looping process can be reduced by controlling the amine solvent (type and concentration) or the process (temperature, CO₂ loading, SO₂ and O₂ concentrations) [85]. Additionally, application of internal coating for the facility along with the addition of corrosion inhibitors either with cathodic (Na₂SO₃, NaVO₃, etc.) or anodic (CuCO₃) character has also been reported to have positive effect in reducing corrosion [99,100].

In CLP for natural gas utilization, a technical issue in the configuration of the scaling-up process can come from the arrangement of the pressure condition. However, implementation of a reactor for internal circulation has been reported to efficiently deal with this issue [92].

To reduce the cost of oxygen carrier production, several industrial wastes are explored to be used as cheap alternative material [3]. Discharged slag from steel companies, especially from basic oxygen furnaces, has been explored to be applied for the CO₂ sorption under various conditions [101]. Moreover, the hybrid process with re-utilization of wasted heat as the energy source also significantly promotes the increment of carbon capture efficiency [4].

6. Chemical Looping Process: Future and Prospect in Industrial Application

Global growth of carbon capture technologies has reached a steady process. Nevertheless, to achieve the 2050 climate goal, a more enthusiastic action is needed [96]. The

application of carbon capture facilities in industries, especially those with high-intensity demands of heat and power, will effectively reduce CO₂ emission. Taking into account the cement, iron, steel, oil refinery, and chemical industries, cutting the emission of high CO₂ concentrations from these types of companies will provide a great contribution toward dealing with global warming [4].

However, implementation on a real industrial scale is still limited by several barriers, including the testing of new technologies, regulation, commercialization, and financial return [95]. Considerations of the cost of implementation of carbon capture technologies can be reviewed from the standpoints of required space. This is instrumental, along with expenses for process, especially in temperature adjustment and pumping [94]. Nevertheless, a higher possibility in reducing the cost issue can be achieved through implementation of CLP from utilization of low-cost oxygen carrier material without major performance change as well as cutting the price of CO₂ purification instrument [42].

Prospects in the implementation of carbon capture technologies for developed countries were reported by Shirmohammadi et al. [102], who discussed several insights, including market and social acceptance and the availability of regulation and law. Concerns of policy, planning, and action implementation are essential in development of carbon capture technologies. However, local capabilities of the country also provide great contributions in the implementation of carbon capture systems [102]. In Pakistan, the increasing trend in the growth of the BCLG process is promising for creating clean and efficient power sources [103].

It was previously reported by Hong [96] that America has been recognized as the country with the highest carbon capture implementation and that it even possessed 41 new carbon capture projects in 2021. Additionally, Europe and Asia–Pacific are also reported to be in the second and third ranks, respectively, for the number of implemented carbon capture technologies [96]. Installation of post-combustion technologies in power plants is not popular but has been applied in other types of industries (especially in the processing of natural gas) for decades [94,96]. However, the popularity of up-scaling CLP in carbon capture process is promising owing to its great cost reduction and high sustainability from lifetime instrument usage [42]. For example, a previous study by Cabello et al. [43] reported the technoeconomic aspect of CLC in power plants, and the improvement in cost could be achieved through the equipment, electricity needs, payback period, and capture process. Although the wide application of CLP is still limited by the higher initial instrument cost compared to conventional technology, the efficiency from the cut of downstream process of CO₂ purification, along with the long-lifetime oxygen carrier material, still has high possibility to attract its development in the future [104].

Several industries in the United States have been reported by Olabi et al. [94] for their implementation of commercial-scale carbon capture technologies along with some companies for supplying post-combustion systems. Potentially, cement industries, which have accounted for 6–7% of global CO₂ emissions, can be improved by implementing post- and oxy-fuel combustion strategies for their carbon capture processes [96,105]. Progressive results were also achieved by Sweden, which successfully created a carbon-neutral cement plant after achieving 1.8 Mt-CO₂/year from a cement plant in Slite [4]. Nevertheless, application of carbon capture in aluminum industries is limited by the low CO₂ concentration [96]. Agricultural industries can also be proposed as a suitable target for the implementation of carbon capture [106]. For the case of cement industry plants, it has been reported that Anhui Conch Group in China successfully captured 50 kt-CO₂ in 2017, while the implementation of a carbon capture facility for NORCEM in Norway was proposed to cut 400 kt-CO₂/year in 2020 [4]. The carbon capture process from intensive CO₂ emission in steel companies has also been reported to provide great contribution in reducing the global warming. Progress in the implementation of carbon capture from steel companies was also reported by Olabi et al. [4]. Additionally, the slag waste from this kind of company can also be beneficially applied as material in the calcium looping process [107]. Various

carbon capture technologies have been implemented for the oil refinery industries with 110–126 Mt-CO₂/year reduction [4].

Recently, increases in the global trend of the application of carbon capture technology in various industries can be observed. However, some implemented technologies are insufficient due to the high load of emitted CO₂. Steel-making industries contributed 2.6 Gt of emitted CO₂ in 2019, but only a few companies have been reported to have a carbon capture unit [96]. On the other side, application of CLP for air separation processes to support oxy-fuel combustion installation in several power plants in Australia also indicated efficient energy and thermal utilization and further led to cost reduction [108]. Carbon capture processes in power plants have also been assessed for their prospect in applications of CLP and indicated higher efficiencies and favorability for environmental protection [109].

Besides emissions from industrial flue gas, the exhausted gas of vehicles is also considered to contribute to increasing atmospheric CO₂. Shipping industries are also attractive targets for the net-zero carbon project. Several technologies are commonly applied for shipping companies, including molten carbonate fuel cells and amine or calcium capture [110]. Not only carbon capture from vehicle or industry emissions but also development of lower carbon emissions in household is also interesting to be explored. Utilization of concrete waste rather than natural gravel is one strategy for CO₂ emission [111]. The manufacturing process of natural gravel produces intense amounts of CO₂. Therefore, substitution of the concrete waste will create a significant impact in environmental protection.

The rapid development of CLP for carbon capture can also be supported by the generation of valuable products throughout the process. Hydrogen production from CLP in carbon capture for natural gas utilization has been reported to reach a cost avoidance of 19.46 EUR/tCO₂ for CO₂ emissions [112]. Additionally, the involvement of produced hydrogen in the energy system will also support environmental protection via the reduction in emissions of greenhouse gases [113]. Production of hydrogen-rich gas is also one of the favorable advantages from the Ca-based CLG process [114]. The captured CO₂ can be converted into several products, like methane, formate, methanol, and ethanol, through combination of other processes in the separated method [115]. Production of alkylammonium formate salts from amine-captured CO₂ has been used for synthesis of methanol and format [116]. In addition to the production of valuable byproducts during the carbon capture process itself, attraction has also been dragged into the potential conversion of CO₂ after sequestration using various methods, including electrochemical reduction [117] and plasma catalysis [118].

Although some drawbacks in the instrument installation and technical issues follow the application of CLP in carbon capture, its high efficiency along with the benefits in cost reduction will support the growth of this technology at an industrial scale. Additionally, the concerns regarding environmental protection also come from the consumer since the products from companies with lower carbon capture have also gained high interest recently. Therefore, CLP in carbon capture can be a promising idea for achieving both cost efficiency for industry and proper environmental protection.

According to the trend in recent studies related to the carbon capture topic, chemical looping processes in oxy-fuel combustion have greater potential to be up-scaled in industry. CLP in oxy-fuel combustion offers a simple process and promising efficiency in producing higher CO₂ content in the future. The high CO₂ production that can reach to >90% will further improve the simplicity of the capture process. Additionally, various materials, either natural or synthetic, can be used as the oxygen carrier in the process. Furthermore, oxy-fuel combustion can be applied in various temperatures. Therefore, management of the energy demand can be conducted in an easier manner when applied in industry. Compared to pre- and post-combustion, the regeneration of oxygen carrier in oxy-fuel combustion can be simultaneously conducted. Thus, a greater energy reduction can be achieved.

Indeed, for implementation in companies, several other considerations need to be discussed. In the technology aspect, installation of facilities for pre- or post-combustion systems will be simpler than that for oxy-fuel combustion. Companies do not need to

undertake a large task of re-structuring the blueprints of their plants to install new parts for pre- or post-combustion carbon capture. However, oxy-fuel combustion needs to be implemented in the middle of the process. Thus, reconstruction of the plant will be harder and even more costly.

Nevertheless, for the countries who implemented penalties to companies for their flue gas emissions, the high efficiency of oxy-fuel combustion is attractive for cutting costs. Additionally, recently, the concern of environmental issues has also been used by various companies to gain high interest in consumer attraction. The companies with the lowest CO₂ footprints will receive higher interest from consumers. Therefore, the CLP in oxy-fuel combustion systems is more potential to be applied at the company scale compared to pre-and post-combustion.

7. Conclusions

Implementation of CLP for carbon capture technology is a promising strategy for cutting energy demand and reaching high efficiency in reducing CO₂ emissions. Tests of CLP for pre-, post-, and oxy-fuel combustion performed with higher efficiency in energy utilization. Additionally, combined metals as oxygen carriers in oxy-fuel combustion offers greater advantages in dealing with the drawbacks of single-metal oxides. Although amine solvents have the issue of corrosion and regeneration processes, this method is still favorable in industry due to its simplicity. Several challenges need to be considered before the implementation of carbon capture process on a real industrial scale. Limitation by the issue of high cost for the maintenance, initial facilities, along with the safety and energy demand during the process, are the main considerations that need to be seriously highlighted. Regardless, the development and growth of the carbon capture implementation still need to be improved considering the quickly worsening pace of global warming. Application of CLP in oxy-fuel combustion has gained greater interest compared to pre- and post- combustion methods. Nevertheless, the overall CLP process is promising to be up-scaled for carbon capture strategy owing to its advantages in achieving high carbon capture efficiency along with lowering the cost and energy consumption during the process. Additionally, high consumer attraction to companies with lower carbon capture may also lead to voluntary action from industries to install carbon capture facilities. Thus, sustainable support for environmental protection action through the reduction of CO₂ emission can be achieved. Furthermore, in the future, implementation of CLP in oxy-fuel combustion technology has a higher possibility of being rapidly developed. The high concentration of CO₂ from oxy-fuel combustion processes can increase the efficiency in sequestration processes. Additionally, the availability of low-cost and stable oxygen carrier for CLP in oxy-fuel combustion technology can be another attractive side for its implementation at an industrial scale.

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