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Review

Insight into catalytic reduction of CO_2: Catalysis and reactor design

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A B S T R A C T

Catalytic reduction of CO_2 to produce specialty chemicals or renewable energy sources has attracted immense attention because of the possibility of renewable, sustainable alternative energy, and safer environment. Utilization of CO_2 as an alternative feedstock for synthesis of biorenewable fuel is one of the numerous strategies essential for mitigation of the greenhouse gases emission into the atmosphere. CO_2 reduction occurs at temperature above 413 K and pressure above 1 MPa by using a suitable hydrogenation catalyst. This study investigates the recent advances in catalytic reduction of CO_2 via hydrogenation, focusing on catalysis, reactor, and process intensification. Several factors for the effective catalytic reduction of CO_2 and recent progress in the reactor design for the system are also highlighted.

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Nomenclature

GHG	Greenhouse gas
IPCC	International Panel on Climate Change
CCS	Carbon dioxide capture and storage
RWGS	Reverse water-gas-shift
GHSV	Gas hourly space velocity
DME	Dimethyl ether
TMC	Transitional metal carbide
PSA	Pressure swing adsorption
CNT	Carbon nanotube
KMC	Kinetics Monte Carlo
ZPE	Zero-point energy
DFT	Density functional theory
CO	Carbon monoxide
CO_2	Carbon dioxide
CH_3OH	Methanol
CuO	Copper oxide
Al_2O_3	Aluminum oxide
$\gamma-Al_2O_3$	Gamma alumina
ZrO_2	Zirconium oxide
ZnO	Zinc oxide
HCO_2^-	Formate
CH_4	Methane
CaO	Calcium oxide
WC	Tungsten carbide
Mo_2C	Molybdenum carbide
SiC	Silicon carbide
TaC	Tantalum carbide
Fe_3C	Iron carbide
MnO	Manganese oxide
Cr_2O_3	Chromium oxide
La_2O_3	Lanthanum oxide
Ga_2O_3	Gallium oxide
MCM-41	Mobil Composition of Matter No. 41
K_2O	Potassium oxide

1. Introduction

Global warming is currently the foremost environmental concern faced by mankind (Valipour, 2012a, 2012b; Yannopoulos et al., 2015). Carbon dioxide, extracted from combustion of fossil fuel, is the chief greenhouse gas (GHG) in the atmosphere that immensely contributes to global climate change (Budzianowski, 2012; McCollum et al., 2014; Roy et al., 2010). CO_2 capture from petrochemical process streams and flares is necessary for reduction of GHG emission into the atmosphere (Alaba, Sani and Daud, 2015b; Ravanchi and Sahebdelfar, 2014; Sani, Alaba, Raji-Yahya, Aziz and Daud, 2016b). The global temperature increase via absorption and re-emission of infrared light is due to the effect of GHG. The GHG effect has global and significant aspects including rising precipitation throughout the earth, ice melting on the Earth pole, and fast increasing sea level (Abnisa and Daud, 2015; Khatib, 2012). International Panel on Climate Change (IPCC) predicted that the level of release of CO_2 to the atmosphere may possibly increase to 590 ppm by 2100 and the average global temperature could increase by ~1.9 °C (Change, 2007). To avoid this, IPCC proposed 50%–85% reduction of global CO_2 emissions relative to 2000 levels by the year 2050 (McGlade and Ekins, 2015). Generation of energy via combustion of fossil fuel is the main source of CO_2 emission, thus depleting fossil fuel. The major challenge for adequate reduction of CO_2 emissions is disposing or utilizing the captured CO_2. A prospected and appealing method for utilizing captured CO_2 is CO_2 sequestration into biorenewable fuels or specialty chemicals (Jeong et al., 2012). Consequently, it is crucial to discover a renewable and sustainable energy source to alleviate the effect of global warming as well as meeting the rising energy need (Alaba, Sani and Daud, 2015a; Alaba et al., 2016a,b,c,d; Mikkelsen et al., 2010; Yui et al., 2011). Furthermore, researchers need to work extensively toward CO_2 storage and utilization to stabilize the atmospheric CO_2 level.

Theoretically, reduction of CO_2 emission in the atmosphere is mainly categorized into three routes, including CO_2 utilization, direct reduction of CO_2 emission, and CO_2 capture and storage (CCS) (Hurst et al., 2012; Windle and Perutz, 2012). Increasing industrialization (Alaba et al., 2016a,b,c,d; Bauer et al., 2013) combined with population growth cause the daily increase of fossil fuel consumption (Alaba et al., 2016a,b,c,d; Sani, Alaba, Raji-Yahya, Aziz and Daud, 2016a); therefore, the mitigation of CO_2 emission and the development of carbon-neutral renewable energy source appear unachievable. In addition, environmental hazard because of leakage, cost of gas compression, and transportation is the major disadvantage of the CCS (K. Li, An, Park, Khraisheh and Tang, 2014). Therefore, CO_2 reduction into fuels or specialty chemicals via major techniques, such as thermochemical, photochemical (Bai et al., 2015; Berardi et al., 2014; Qu and Duan, 2013), electrochemical (Back et al., 2015; Costentin et al., 2013; S. Ma and Kenis, 2013), inorganic transformation, (Sanna et al., 2014) and biological methods, is the growing concern of researchers since the past decade.

As commercially available CH_3OH from CO_2 technology uses Cu/Zn-based formulation and Cu/Zn/Al/Zr-based catalysts the catalysts should be improved. CO_2 is a stable compound and thus requires a substantial energy and highly stable and active catalyst for conversion into specialty chemicals. This finding requires developing suitable catalysts and intensifying CO_2 conversion for economical production. The techniques, prospects of the synthesis, and material and reactor design of using CO_2 as the main starting material for an economically viable renewable and sustainable energy source are investigated. The basic catalytic reduction of CO_2 is discussed first. The rational design of catalysts with remarkable activity as well as the critical factors for efficient catalytic reduction of CO_2 is emphasized. The progress in using CO_2 reduction catalytic reactors for clean fuel and specialty chemicals production is also discussed.

2. CO_2 reduction and its mechanism

In recent time, atmospheric CO_2 utilization engendered the replacement of CO with CO_2 as a feedstock for CH_3OH synthesis. The process is necessary to alleviate the GHG effect associated with considerable rise in the amount of CO_2 in the atmosphere (Olah, 2004; C. Yang et al., 2006). Catalytic reduction of CO_2 to CH_3OH is a remarkable approach toward green environment. Generally, CH_3OH synthesis from CO_2 starts in hydrogenation using suitable hydrogenation catalyst at temperature above 413 K and pressure above 1 MPa (J. Ma et al., 2009). When CO_2 is activated at high temperature and pressure for hydrogenation, the desired reaction