Energy Conversion and Management 106 (2015) 466–478

Contents lists available at ScienceDirect

Energy Conversion and Management

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

A polygeneration from a dual-gas partial catalytic oxidation coupling with an oxygen-permeable membrane reactor

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ARTICLE INFO

Article history:
Received 24 July 2015
Accepted 22 September 2015

Keywords:
Polygeneration
Coke oven gas
Coal gasified gas
Partial oxidation
Oxygen-permeable membrane

ABSTRACT

Polygeneration system, typically involving chemicals/fuels and electricity co-production, is a promising technology for the sustainable development of energy and environment. In this study, a new polygeneration system based on coal and coke oven gas (COG) inputs for co-production of dimethyl ether (DME)/methanol and electricity is proposed. In the new system, an appropriate syngas for the synthesis of DME is from coal gasified gas (CGG) reforming of COG coupled with an oxygen-permeable membrane reactor, in which both COG and CGG reforming process and fuel combustion process are incorporated, which reduces exergy destruction in the whole reforming process. In order to obtain the best performance of CO_2 reduction, energy saving and economic benefit, the key operation parameters of the proposed process are analyzed and optimized. The new system is compared with the process based on CH_4/CO_2 dry reforming, in terms of exergy efficiency, exergy cost and CO_2 emissions. Through the new system, the exergy efficiency can be increased by 7.8%, the exergy cost can be reduced by 0.88 USD/GJ and the CO_2 emission can be reduced by 0.023 kg/MJ. These results suggest that the polygeneration system from CGG and COG partial catalytic oxidation coupling with an oxygen-permeable membrane reactor (PL-PCO-OPMR) would be a more attractive way for highly efficient and clean use of CGG and COG.

1. Introduction

As one of the most promising technologies for clean and efficient use of energy today, polygeneration system synergistically integrating the chemical engineering and power generation systems can realize cascade utilization of both chemical and thermal energies, and step-by-step conversion of effective components [1]. In addition, polygeneration system is a highly flexible and cross-sector integrated system of resources, energy and environment, which can simultaneously make two or more marketable products, such as chemicals, fuels and electricity from a mix of different energy resources with element and energy efficiencies and pollution emission reduction, all of which are potentially higher than current standalone practices [2–4]. Base on these advantages, a number of polygeneration systems on the basis of different energy resources types (such as coal, natural gas, solar and biomass) with various configurations and products (eg. methanol (MeOH), dimethyl ether (DME), dimethyl carbonate (DMC), Fischer–Tropsch oil and electricity) are proposed and investigated [5–10].

As the biggest coke production country, nowadays China produces about 500 million tons of coke, with the resulting by-product of about 210 billion m^3 of coke oven gas (COG, 6 vol% CO, 59 vol% H_2, 26 vol% CH_4, 3 vol% CO_2, and 6 vol% N_2) which is a presently underutilized hydrogen-rich product [11]. Except for about 50% of that is COG recycled to provide energy for coking process, most of the rest is discharged into the air after combustion, leading to a waste of potential energy resources and also causing serious air pollution. Hence, it is necessary to find a suitable way for high efficient and clean utilization of COG resources. Since COG is rich in hydrogen and methane, we can use COG to reform with carbon-rich gas such as CO_2, CGG (coal gasified gas) and flue gas etc. via CH_4/CO_2 dry reforming to produce syngas at a proper ratio of C/H for downstream production [12–14], and syngas is an indispensable medium for the synthesis of chemicals and liquid fuels in energy chemical engineering.

Bermúdez et al. [14,15] investigated CO_2 reforming of COG over Ni-based catalysts to produce syngas for methanol synthesis, and

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http://dx.doi.org/10.1016/j.enconman.2015.09.058
0196-8904/

Nomenclature

Capital letters

BCFNO $BaCo_{0.7}Fe_{0.2}Nb_{0.1}O_{3-\delta}$
C_{DME} concentration of DME, mol/m^3
C_{H_2O} concentration of H_2O, mol/m^3
C_{MeOH} concentration of methanol, mol/m^3
C_Q the cost of heat transfer, USD/GJ
C_w the cost of power input, USD/GJ
$E_{k_{in}}$ the exergy of input of the stream k, MW
$E_{k_{out}}$ the exergy of output of the stream k, MW
EX^{in}_{fuel} the total exergy of input fuel, MW
EX^{out}_{ch} exergy of the chemical product, MW
EX^{out}_{p} exergy of the output work, MW
F_{CH_3OH} methanol outflow rate of products, kmol/h
F_{DME} dimethyl ether outflow rate of products, kmol/h
$(F_{CO}+F_{CO_2}+F_{CH_4})_{in}$ the total CO, CO_2 and CH_4 inflow rate of system, kmol/h
$(F_{CH_4}+F_{CO_2})_{out}$ CO_2 and CH_4 outflow rate of synthesis unit, kmol/h
I_k the investment of the unit k, USD
K_{CO} adsorption constant of CO, bar^{-1}
K_{CO_2} adsorption constant of CO_2, bar^{-1}
K_{H_2} adsorption constant of H_2, bar^{-1}
K_{H_2O} adsorption constant of H_2O, bar^{-1}
K_{MeOH} adsorption constant of methanol, bar^{-1}
K^0_3, K^0_4, K^0_5, K^0_6 thermodynamic equilibrium constant of the reaction (1–4)
N plant life, year
PL-DR polygeneration system from CGG and COG based on CH_4/CO_2 dry reforming
PL-PCO-OPMR polygeneration system from CGG and COG partial catalytic oxidation coupling with an oxygen-permeable membrane reactor
PV_f remanent value of equipment
S_r purchase cost of facility in the reference scale, USD
X the scale of proposed plant
X_r scale of facility in the reference scale,
U_C carbon element utilization of system
$U_{CH_4+CO_2}$ $CO_2 + CH_4$ conversion efficiency of system

Lowercase letters

$c_{k_{in}}$ exergy cost per unit of input fuel, USD/GJ
f_{CO} fugacity of CO in gas phase, bar
f_{CO_2} fugacity of CO_2 in gas phase, bar
f_{H_2} fugacity of H_2 in gas phase, bar
f_{H_2O} fugacity of H_2O in gas phase, bar
f_{MeOH} fugacity of methanol in gas phase, bar
i the discount rate, %
k_1, k_2, k_3, k_4 reaction rate constant of the reaction (1–4), mol/(s kg bar)
r_1, r_2, r_3, r_4 reaction rate of the reaction (1–4), mol/(s kg)
t tonne
y year

Greek letters

α scale factor of facility in the present scale
ω the circulation ratio of unreacted gas
λ the ratio of coke oven gas to coal gasified gas
η the exergy efficiency of system
μ the cost coefficient of operation & maintenance
τ operation time

Acronyms

AAFBG ash-agglomerated fluidized bed gasifier
ASU air separation unit
BWRS method Benedict–Webb–Rubin–Starling equation of state
CGG coal gasified gas
Compr model compressor/turbine
USD United States dollar
COG coke oven gas
COS carbonyl sulfur
DMC dimethyl carbonate
DME dimethyl ether
Flash model flash vessel
GTL gas-to-liquid
Heater model heater/cooler
Heatx model two-stream heat exchanger
HRSG heat recovery steam generator
IGCC integrated gasification combined cycle
JOGMEC Japan Oil, Gas and Metals Corporation
LHV low heat value
M million
Mcompr model multistage compressor/turbine
MeOH methanol
MIEC mixed ionic and electronic conductor
O&M operation & maintenance
PR-BM method Peng–Robinson equation of state with Boston–Mathias modifications
Radfrac columns rigorous distillation tower
RAU reforming auxiliary unit
Rcstr continuous-stirred tank reactor
RStoic stoichiometric reactor
Sep model multi-outlet component separator

proposed a new process for producing methanol from COG by means of CO_2 reforming. Compared with a conventional process of methanol synthesis from natural gas, the new process has been proved to be superior to the conventional process from the perspective of environment, raw material exploitation and purification costs, and also consumes less energy than conventional production. Yi et al. [16,17] designed and estimated a polygeneration system for producing MeOH/DME/electricity from COG reforming with CGG, and it is found that the polygeneration system shows better performance in terms of energy efficiency, economy and CO_2 emission compared with the stand-alone production. Similarly, Lin et al. [18] proposed a new polygeneration system for methanol and power production based on COG reforming of CGG with CO_2 recovery, and the new system presents good thermal performance and CO_2 is also avoided with less energy penalty. Qian et al. [19,20] demonstrated a conceptual design of COG assisted coal to olefins process, and the two co-feed systems ensure great reduction of CO_2 emissions and significantly improve energy efficiency compared with coal-to-olefins process. Generally, Ni-based catalysts are widely used for CH_4/COG reforming due to its properties of low cost and high activity. However, carbon deposition on nickel catalysts is a fatal problem for CH_4/CO_2 dry reforming and is the main reason for not industrialization of this technology [21,22].

In order to solve the carbon deposition problem in CH_4/CO_2 dry reforming, another approach, $CH_4/CO_2/O_2$ partial catalytic