Combined Heat and Power System with Zero Carbon Emission by Integrating Catalytic Methane Pyrolysis and Carbon Conversion

Authors:

Tianyue Li, Jian Long, Wenli Du, Feng Qian, Vladimir Mahalec

Date Submitted: 2022-10-14

Keywords: Combined Heat and Power System, Methane Pyrolysis, Carbon capture and In-Situ Conversion

Abstract:

Many industrial plants require electricity and high temperature thermal energy which are typically generated by burning hydrocarbon fuels. This study proposes an energy system that produces electricity and thermal energy by burning hydrocarbons without emitting CO2 through integration of catalytic methane pyrolysis (CMP), carbon capture and in-situ conversion (CCISC), methanol synthesis as well as combined heat and power (CHP) system. The system can eliminate CO2 emissions by industrial plants and residential areas and produce methanol and carbon black as chemical by-products, in addition to producing electricity and thermal energy. Result shows that the maximum net electricity efficiency can reach 52%.

CSChE Systems & Control Transactions
Open Access | Original Research

Conference Proceedings
Canadian Chemical Engineering Conference 2022
October 23-26, Vancouver, BC, Canada

PSEcommunity.org/LAPSE:2022.0081

PSE PRESS

Combined Heat and Power System with Zero Carbon Emission by Integrating Catalytic Methane Pyrolysis and Carbon Conversion

Tianyue Li[a], Jian Long[a], Wenli Du[a], Feng Qian[a]*, Vladimir Mahalec[b]*

[a] East China University of Science and Technology, Key Laboratory of Smart Manufacturing in Energy Chemical Process, Shanghai, China
[b] McMaster University, Department of Chemical Engineering, Hamilton, ON, Canada
* Corresponding Author: mahalec@mcmaster.ca.

ABSTRACT

Many industrial plants require electricity and high temperature thermal energy which are typically generated by burning hydrocarbon fuels. This study proposes an energy system that produces electricity and thermal energy by burning hydrocarbons without emitting CO_2 through integration of catalytic methane pyrolysis (CMP), carbon capture and in-situ conversion (CCISC), methanol synthesis as well as combined heat and power (CHP) system. The system can eliminate CO_2 emissions by industrial plants and residential areas and produce methanol and carbon black as chemical by-products, in addition to producing electricity and thermal energy. Result shows that the maximum net electricity efficiency can reach 52%.

Keywords: Combined Heat and Power System, Methane Pyrolysis, Carbon capture and In-Situ Conversion

Date Record: Original manuscript received October 12, 2022. Published October 14, 2022.

INTRODUCTION

Climate change is a global issue and has received widespread attention [1]. At present, a basic consensus has been formed on the control of greenhouse gas (GHG) emissions. Non-energy industry is an enormous part of GHG emissions, takes 31% of CO_2 emissions, and basic materials production has presented for approximately 22% of CO_2 emissions [2]. Thus, it is important to control greenhouse gas emissions by the industry. Carbon capture and utilization is an effective way to control Green House Gas (GHG) emissions. In this study, a new energy system that burns natural gas with net-zero GHG emissions has been designed and analyzed. The proposed method integrates methane pyrolysis, carbon capture in-situ conversion, combing heat and power (CHP) system, and methanol synthesis process. The system is designed to export electricity and steam to the grid which is for the residential area. Moreover, methanol and carbon black are by-products of the system which is high value and can increase the competitiveness of the system.

BACKGROUND

Catalytic Methane Pyrolysis

Catalytic methane pyrolysis (CMP) is a process that can convert methane into hydrogen and solid carbon without CO_2 emissions [3,4]. The reaction of methane pyrolysis is shown in Equation (1).

$$CH_4 \rightarrow C_{(s)} + 2H_2 \quad \Delta H_{298} = 74.8\ kJ/mol \tag{1}$$

It works at high temperatures in the presence of metal or carbon catalyst. Methane pyrolysis is rapidly moving from the laboratory stage toward commercialization. BASF plans to use their moving bed reactor method to start large scale hydrogen production in 2030.

In the pyrolysis reactor, natural gas flow from bottom to top and carbon catalyst flow counter-current, where the heat transfer is enhanced. There are electrodes in the reactor, and the carbon is heated by the electric current and transfers heat to the natural gas.

Carbon capture and in-situ conversion

Carbon capture and in-situ conversion (CCISC) is a laboratory level technology. It integrates Calcium-Looping (CaL) and Reverse Water Gas Shift (RWGS) in one reactor to convert CO_2 into CO and produce syngas as the product by $Fe_5Co_5Mg_{10}CaO$ heterojunction-redox catalysts[1] [5].

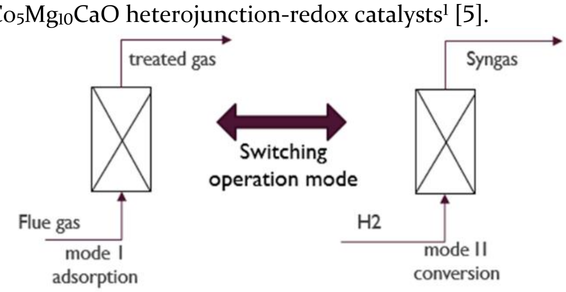

Figure 1. Operating modes and schematic of CaL/RWGS integrated reactor.

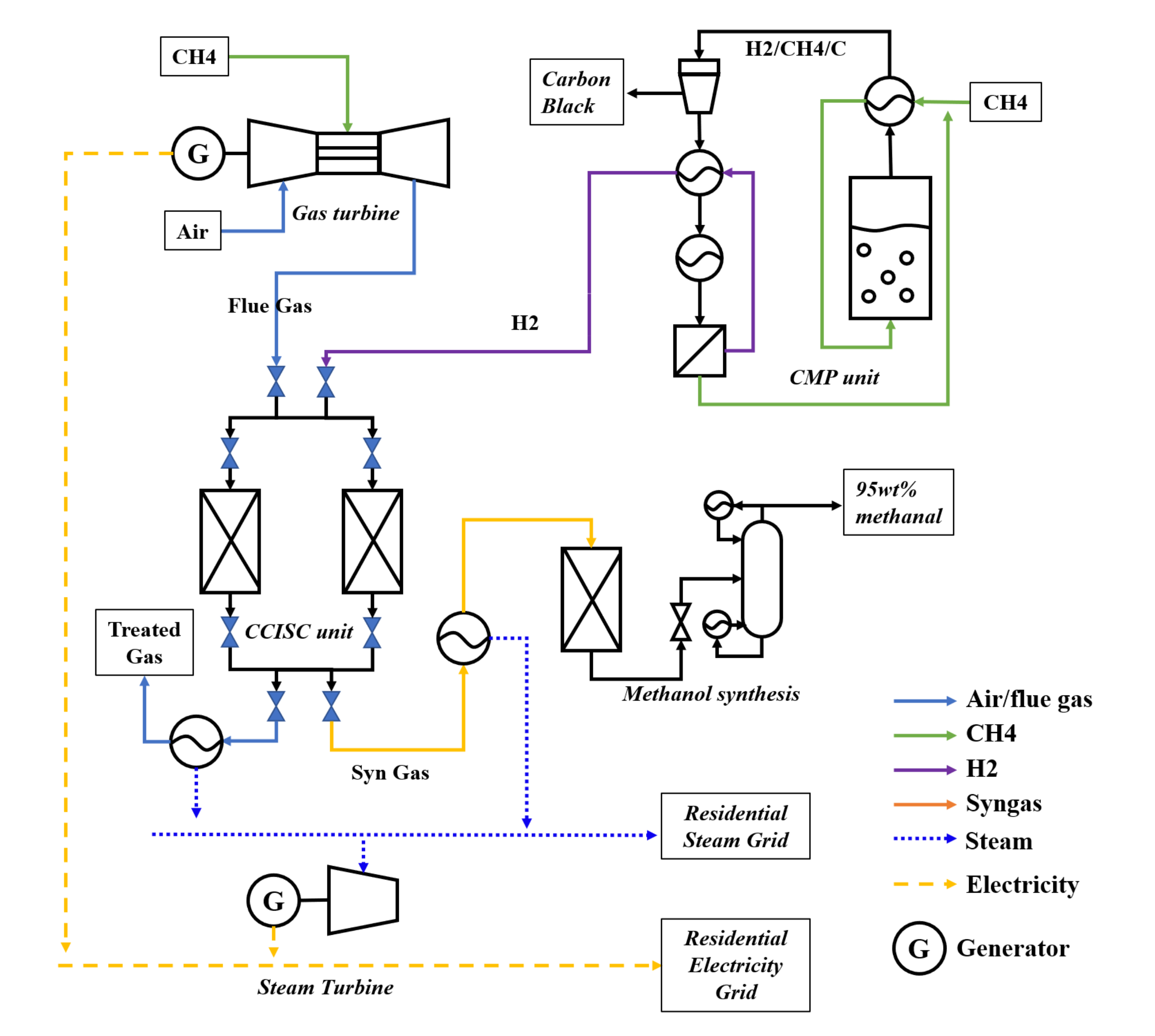

Figure 2. Simplified diagram for the net-zero GHG emission energy systems that integrates CMP, CCISC and Methanol

The system operates in two batch modes, as shown in Figure 1. In mode 1, the flue gas first passes through the bed where CO_2 is adsorbed by the catalyst and releases adsorption heat. After adsorption step, the reactor will switch from mode 1 to mode 2, the hydrogen will be added to the reactor and the reactor is heated to 650 ℃. RWGS reaction happens in mode 2, converting CO_2 into syngas. The reaction of RWGS is shown in Equation (2)

$$CO_2 + H_2 \rightarrow CO + H_2\,O_{(g)} \;\; \Delta H_{298} = 41.12\; kJ/mol \quad (2)$$

Since the process requires a large amount of heat and hydrogen, a good heat integration with some heat generation process and an eco-friendly hydrogen source are required.

PROCESS MODEL

The design of the proposed energy system is shown in Figure 2. Detailed model of the proposed system has been developed in Aspen HYSYS. The system contains five parts: Gas turbine, CMP unit, CCISC unit, Methanol synthesis and Steam turbine.

The Gas turbine is the heat source of the entire process. It produces electricity and hot flue gas; thermal energy from the flue gas is recovered in the heat recovery steam generator (HRSG). In this process, the flue first passes through the CCISC unit then through HRSG.

The CCISC unit is the key process in the system. It can remove the CO_2 in the flue gas of the Gas turbine by converting it into syngas which is the feedstock of the methanol synthesis. The CCISC is designed to use electricity to heat the reactor to 650°; the conversion rate can reach up to 85%.

The CMP unit is the hydrogen source of the process. This unit consumes electricity for heating. The hydrogen will be used for the CCISC unit and methanol synthesis. And the Carbon black produced by the CMP unit is valuable by-product.

The methanol synthesis process can convert syn gas into methanol, where the carbon in the syngas is converted from gas phase into liquid phase. Methanol is an important chemical material which can produce formaldehyde, methoxy methane, olefins or alkenes.

The steam turbine is used to generate more electricity from steam generated from the HRSG. There are three kinds of steam: High pressure (HP), Medium Pressure (MP) and low pressure (LP). HP and MP will be used to generator electricity and LP will be used to the Steam grid for residential heating demand.

RESULTS

Sensitivity analysis on Gas Turbine Fuel and Heat Output is introduced to the system.

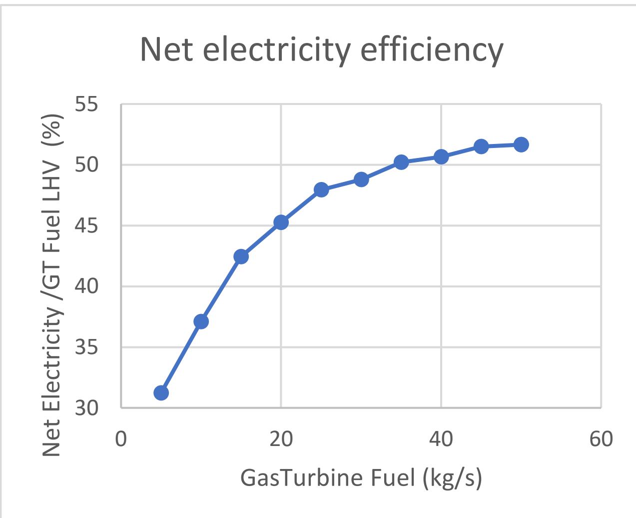

Figure 3. Realation between Gas Turbine Fuel and Net electricity efficiency.

As shown in Figure 3, the affect of Gas Turbine Fuel to Net electricity efficiency (Net electricity output/ Gas Turbine Fuel LHV) is tested. It is assumed there is a fixed heating demand of 100MW, and all the steam left is used to generated electricity. As GT fuel grows, the efficiency of the net electricity grows first quickly. As the GT fuel reaches 35 kg/s the efficiency will reach 50%.

As shown in Figure 4, the relation between Net electricity, Gas Turbine Fuel and Heat output is tested. The Heat output has higher impact to the Net electricity under low Gas turbine fuel.

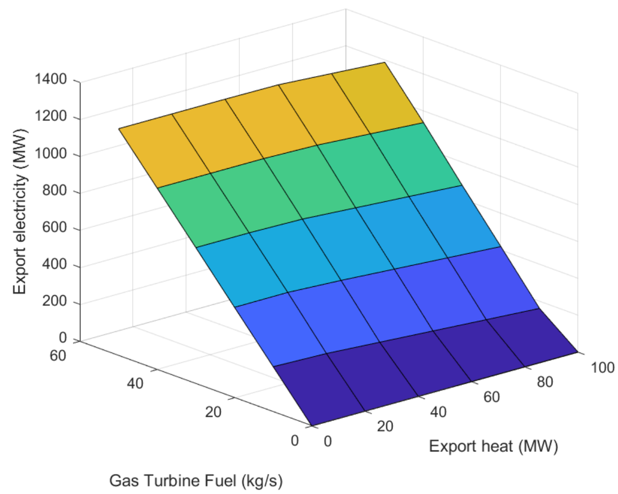

Figure 4. Relation between Net electricity, Gas Turbine Fuel and Heat output.

CONCLUSIONS

This work presents a novel energy system for providing electric and thermal energy with zero carbon emission by burning natural gas. By integrating catalytic methane pyrolysis (CMP), carbon capture and in-situ conversion (CCISC), methanol synthesis as well as gas turbine combined heat and power (CHP) system, the energy system can have high energy efficiency and output carbon free electricity as well as steam for residential areas. In summary, the proposed method can eliminate GHG emission associated with production of electricity and thermal energy for residential areas and also produce methanol and carbon black. Proposed method can provide a path for reducing or completely eliminating GHG emissions produced by energy generation via burning of natural gas.

ACKNOWLEDGEMENTS

The work has been supported by the National Natural Science Foundation of China (Basic Science Center Program: 61988101), National Natural Science Foundation of China (61725301, 61973124, 61873092), International (Regional) Cooperation and Exchange Project (61720106008). We thank McMaster University for hosting Tianyue Li from conception to completion of this work.

REFERENCES

1. Wang, C., Geng, L. & Rodríguez-Casallas, J. D. How and when higher climate change risk perception promotes less climate change inaction. *J. Clean. Prod.* 321:128952 (2021)
2. Wang, H. & Chen, W. Modelling deep decarbonization of industrial energy consumption under 2-degree target: Comparing China, India and Western Europe. *Appl. Energy* 238:1563–1572 (2019)
3. Sánchez-Bastardo, N., Schlögl, R. & Ruland, H. Methane Pyrolysis for Zero-Emission Hydrogen Production: A Potential Bridge Technology from Fossil Fuels to a

Renewable and Sustainable Hydrogen Economy. *Ind. Eng. Chem. Res.* 60:11855–11881 (2021)
4. Abbas, H. F. & Wan Daud, W. M. A. Hydrogen production by methane decomposition: A review. *Int. J. Hydrog. Energy* 35:1160–1190 (2010)
5. Shao, B. et al. Heterojunction-Redox Catalysts of Fex-CoyMg$_{10}$CaO for High-Temperature CO_2 Capture and In-situ Conversion in the Context of Green Manufacturing. Energy Environ. Sci. 14:2291–2301 (2021).