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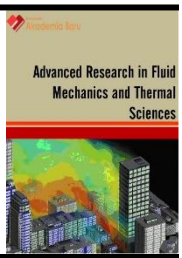

Comparative Study and Optimization of CO_2 Capture and Storage in LNG-fired Power Plant

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ABSTRACT

In the trends of sustainable development and environmental protection, reducing greenhouse gas emissions and utilizing energy sources are feasible solutions. In this study, Aspen HYSYS-based performance simulations for LNG-fired power plants with CO_2 capture and storage using cryogenic and amine technologies were conducted to compare and evaluate. LNG cold energy is employed in liquefied CO_2 process. Waste heat from exhaust gas of a gas turbine was powered for steam cycle or stripper column. The results showed that the thermal power generation efficiency of the amine system is lower than that of the cryogenic system, however the excessive gasification of LNG in the MEA system is much lower than that of a cryogenic system. The CO_2 mass fraction in recovered liquid of the amine system is also higher than the other one. Multi-objective optimization using genetic algorithm (GA) is then carried out providing a set of optimum solution for investors and operators in balance of the excessive gasification of LNG and CO_2 recovery rate.

1. Introduction

Facing a dramatic climate change throughout the world, mitigation of greenhouse gas emission has been put in place [1]. In which, greenhouse gas CO_2 emitting a large amount from thermal power plants are deeply concerned. Clean energy sources from liquefied natural gas (LNG) are gradually being used more and more in power plants as a fuel. That also resulted in a large amount of CO_2 emitted from LNG-fired power plants. Therefore, CO_2 recovery in LNG-based power plants is an issue for extensive researches in recent years. Babar *et al.,* [2] performed a review study on cryogenic CO_2 capture in presence of natural gas. The related diagrams and equation of states were depicted and compared for the purpose of more efficient, economical, and sustainable CCS design. The integration

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of Kalina cycle system, organic Rankine cycle and CO_2 capture with heat recovery of LNG cold energy was proposed [3]. The feasible thermal efficiency of 53% can be finalized from the analysis. Chang carried out thermodynamic analysis of refrigeration systems to liquify natural gas [4]. Several cycles and parameter in details were presented as design plots to facilitate cycle selection and evaluation. Tan *et al.,* [5] employed refrigeration during expansion process to liquefy natural gas. The process flow diagram and the optimal operating condition were obtained from the study.

There are several CO_2 recovery technologies from flue gas. CO_2 capture and storage (CCS) are generally so much high energy consumption. Therefore, appropriate technology selection is necessary and pays attention. Pires *et al.,* [6] presented an overview of CO_2 capture technologies. Plaza *et al.,* [7] confirmed that amine-based CO_2 capture was the most feasible selection for coal- and natural gas-fired power plants. Alabdulkarem *et al.,* [8] integrated many cycles into LNG plant in order to raise overall performance. The integration results in 11.17% more power than the conventional system.

In LNG-fired power plants, LNG cold energy is often discarded in vain [9,10]. However, this cold energy is redundant because LNG is usually stored at the relatively low temperature of -160°C and converted to natural gas (NG) before combustion. Therefore, the recovery of LNG cold energy in power plants is being considered and exploited. Lee *et al.,* [9] studied suitable fluid for Organic Rankine Cycle (ORC) using LNG cold energy as a heat sink. Results showed that binary mixture of R14-C_3H_8 can be the pertinent working fluid. Kanbur *et al.,* [11] performed cryogenic CO_2 capture for the small scale power generation systems by adopting LNG cold energy utilization. Models with less than 200 kW microturbines is found applicable. Bao *et al.,* [12] integrated LNG-fired power plant with CO_2 capture to increase the power generation efficiency by taking advantage of low-temperature waste heat. By the integration, the efficiency could be enhanced nearly 1%. Lee and Ro [13] examined use of LNG cold energy to liquify exhaust gas of submarine diesel engine. Results showed that the ratio for compressor power consumption to the net power engine is remarkedly low up to 6.3%. Lee [14] used LNG cold and hot energy in a gas turbine cycle to remarkably reduce compression power consumption in comparison with conventional cascade ammonia cooling system. The thermal efficiency and exergetic performance for a combination of CO_2 solidification and an absorption chiller were analyzed and optimized [15]. The results showed that the power consumption for compressors of solidification cycle significantly decreases when comparing the combined cycle with a multi-stage compression cycle. Chen *et al.,* [16] exploited energy of liquified natural gas and liquid oxygen to reduce power consumption of compressors. The mixed cycle can get higher net efficiency than that of conventional coal-fired power plant.

On the contrary, the use of LNG cold energy to sufficiently dissipate heat of hot fluid probably leads to an excessive gasification of LNG. Han *et al.,* [17] numerically investigated oxy-NG combustion technology for CO_2 capture. The thermal efficiency of their system is 7.8% higher than other related systems. Mass flow rate of LNG excessive gasification is 28.5 times that of LNG as a fuel. Xu and Lin [10] proposed the new CO_2 cryogenic capture system which does require excessive gasification of LNG. The new system used expansion of CO_2-removed flue gas to supply extra cold energy for CO_2 liquefaction. Ahmad *et al.,* [18] used a cryogenic technique to liquefy CO_2 from raw biogas. The CO_2 purity of 99% can be reached with the optimal energy consumption.

To the best of our knowledge, research on the entire system of LNG-fired power plants with CCS, waste heat recovery and cold energy use of LNG has not been comparatively studied and evaluated the excessive gasification of LNG. This paper aims to appraise the performance parameters of LNG-fired power plants with CCS using cryogenic and chemical absorption technologies. LNG cold energy is recovered to liquefy CO_2. The waste heat from flue gas of gas turbine is supplied to the steam cycle for cryogenic CCS method or for reboiler of stripper column of the absorption CCS method. The NG flow rate for combustion was choice to be 1 kg/s to assess the excessive LNG gasification. System simulations were implemented in Aspen HYSYS v2006 software due to its highly accurate prediction [19]. Besides, multi-objective optimization of minimum excessive LNG gasification and maximum CO_2 recovery rate was presented using genetic algorithm in MATLAB toolbox R2018a. A set of optimum solution and Pareto optimal front were shown.

2. System Description

2.1 CO_2 Cryogenic Capture System

Process flow diagrams were setup in Aspen HYSYS software. The Peng-Robinson equation of state was used in simulations. Convergence criteria for the relative residuals were 1e-4. The steady state simulation was used for systems. Schematic diagram of CO_2 cryogenic recovery system in LNG-fired power plant is described in Figure 1. Liquefied natural gas (stream LNG1) with the parameters as shown in Table 1 [17] is pumped into heat exchanger to vaporize at the pressure of 30 bar.

The heat released from the gasification is used to liquefy CO_2 in the CO_2 cryogenic capture cycle. Natural gas (stream NG4) with mass flow rate of 1 kg/s enters the combustion chamber (COMB) together with the compressed air (stream Air3). The air entering the air compressor (C_air) has the parameters as shown in Table 1. The stream Air4 is to cool the gas turbine. Flow rate of this stream is adjusted so that the flue gas temperature (stream FG2) leaving the gas turbine (GT) is 611°C [8]. The high-temperature flue gas leaving gas turbine enters the heat recovery steam generator (HRSG) of steam turbine cycle. After that, the flue gas is cooled by FG cooler to separate water (SEP) before liquefaction.

In cryogenic CO_2 liquefaction cycle, the flue gas (stream FG6) is compressed by the compressor C_FG. The compressed flue gas is preliminarily cooled in the regenerator (E-101). It then enters a cooler (HX_CO2_LNG_h) to liquefy by LNG cold energy. The stream FG9 is sent to separator (V-100) to remove non-condensable gases. The rich CO_2 liquid (CO2_1) is pumped to the pressure of 110 bar [17] for storage purpose. The stream of non-condensable gases with high pressure and low temperature is recovered to cool the compressed flue gas in E-101 and generate power in a gas turbine (GT2) before removal to environment.

2.2 CO_2 MEA-based Capture System

The schematic diagram of the LNG-fired power plant with MEA-based CO_2 capture is shown in Figure 2. One more amine fluid package was added in this system due to the limited temperature of the amine package. To change the fluid package, the cutters are used as seen in Figure 2. LNG gasification and gas turbine cycle are similar to the system described above. Most of the exhaust heat of flue gas (stream FG2) is used to supply the reboiler of the stripper column of the CO_2 capture cycle using MEA (monoethanolamine). Therefore, the remaining heat is recovered to power organic boiler (HRSG) in the organic Rankine cycle. Organic fluid was selected to be N-pentane because of its thermal efficiency [8]. The operating principle of the CO_2 capture cycle using MEA can be seen in the literature [20,21]. The number of stages in the absorber (Abs) and the stripper were 19 and 24, respectively [22]. The CO_2 (stream CO2-/CO2+) is sent to compressor (C_CO2). It then enters a cooler (HX_CO2_LNG_h) to become CO_2 liquid by LNG cold energy. The CO_2 liquid (CO2_2) is pumped to the pressure of 110 bar for storage purpose. The excessive LNG gasification is flow rate of stream NG5 in Figure 1 and Figure 2. That means that a redundant LNG must release heat in the heat exchanger HX_LNG_CO2_c in order to liquify the captured CO_2. In other words, flow rate of stream NG5 of zero is desirable and this study aims to minimize the flow rate. Table 2 reported necessary parameters for the process modeling.

The thermal power generation efficiency of the systems can be estimated as follows:

$$\eta = \frac{W_{net}}{m_{NG4}LHV} \tag{1}$$

where m_{NG4} is mass flow rate of fuel entering combustion chamber (COMB). m_{NG4} =1 kg/s was selected in this study. LHV is the lower heating value of LNG. W_{net} is defined as:

$$W_{net} = \sum W_{turbines} - \sum W_{pumps} - \sum W_{compressors} \tag{2}$$

in which W represents power.

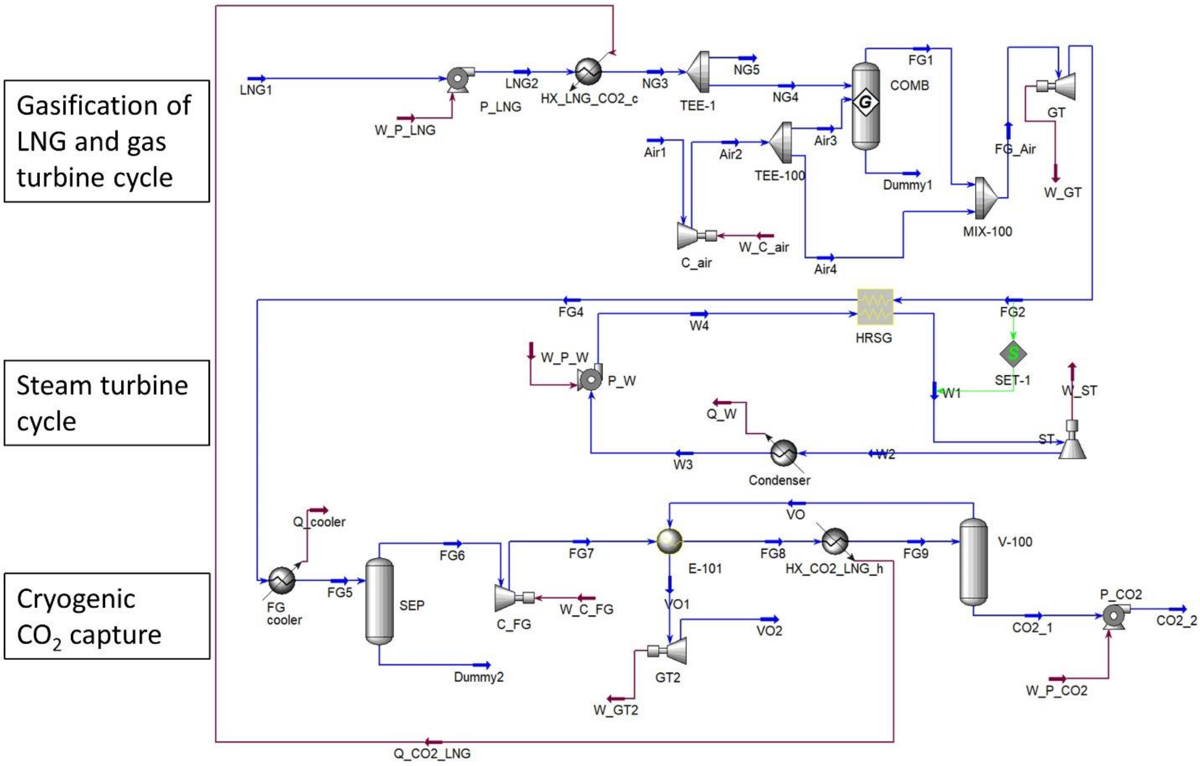

Fig. 1. LNG-fired power plant with CO_2 cryogenic capture

Table 1
Molar fraction and properties of LNG1 and Air1

	LNG1	Air1
CH_4 (%)	90.82	/
C_2H_6 (%)	4.97	/
C_3H_8 (%)	2.93	/
C_4H_{10} (%)	1.01	/
N_2 (%)	0.27	0.79
O_2 (%)	/	0.21
Temperature (°C)	-164.2	30
Pressure (bar)	1	1
Lower heating value (kJ/kg)	49200	/

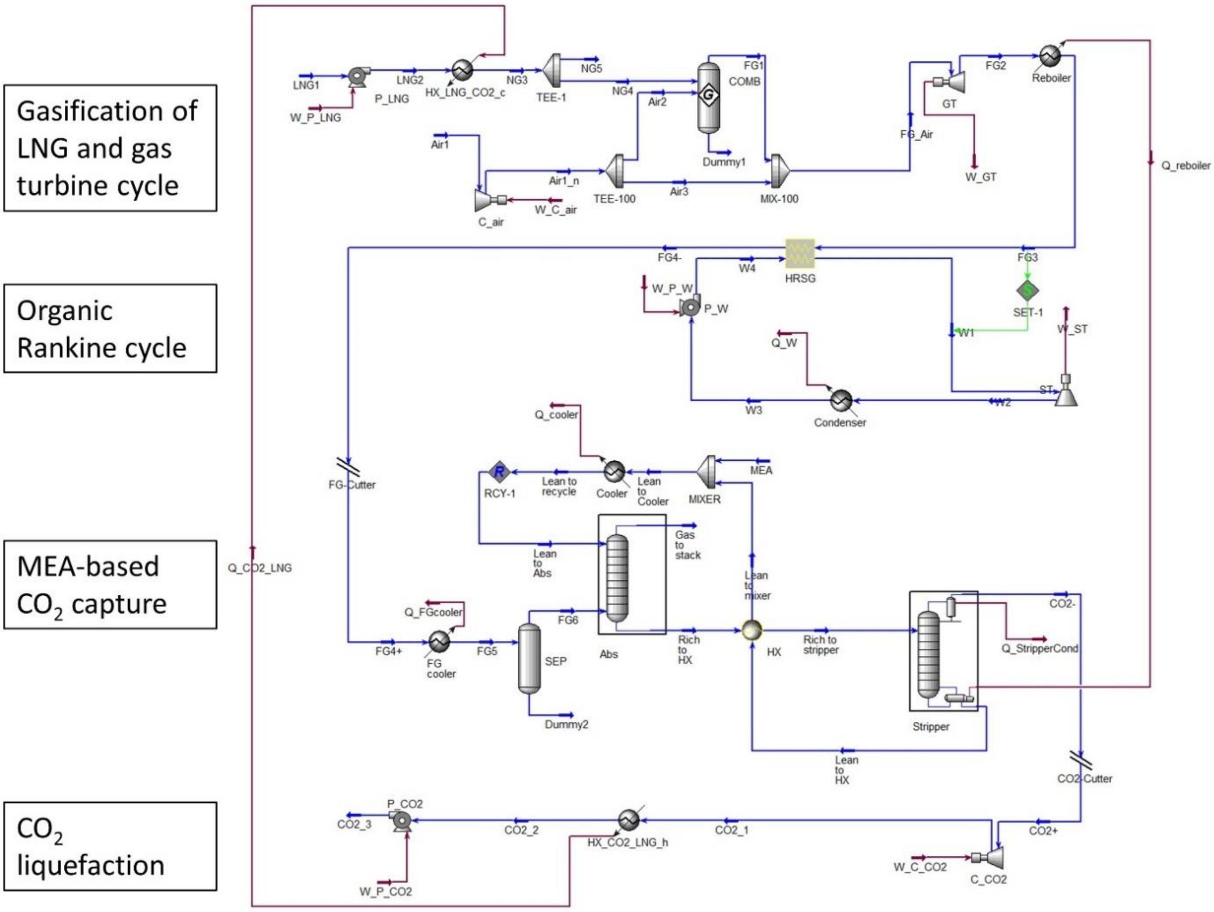

Fig. 2. LNG-fired power plant with CO_2 MEA-based capture

Table 2
Main assumptions in HYSYS simulations

	Parameters	Value	Refs.
Heat exchanger	Pressure loss	0	Xu and Wensheng [10]
	Temperature difference (°C)	10	Han *et al.* [17]
Pump	Isentropic efficiency (%)	90	Han *et al.* [17]
Compressor	Isentropic efficiency (%)	88	Han *et al.* [17]
Turbine	Isentropic efficiency (%)	92	Han *et al.* [17]
Reference	Temperature (°C)	25	Han *et al.* [17]
conditions	Pressure (bar)	1	Han *et al.* [17]

3. Results and Discussion

Because CCS in two systems proposed above use LNG cold energy and waste heat from flue gas to power reboiler. Therefore, the effect of CO_2 recovery parameters on system performance is examined. For the cryogenic system, the recovery temperature (i.e. temperature of stream FG9) and pressure of the pressured flue gas FG7 were assigned to be key parameters. For the MEA-based system, reboiler duty and pressure of the pressured CO_2 (stream CO2_1) were independent parameters. Effect of the parameters on CO_2 recovery rate, thermal power generation efficiency, CO_2 mass fraction in captured liquid streams (i.e. stream CO2_2 in Figure 1 and stream CO2_3 in Figure 2), and excessive gasification of LNG (mass flow rate of stream NG5) are presented in Figure 3 to Figure 6. The CO_2 recovery rate is defined as the amount of CO_2 at the captured liquid stream in the total incoming amount of CO_2 at stream FG2 as:

$$CO_2 \text{ recovery rate } = \frac{a\ mount\ of\ CO_2\ at\ state\ CO2\_2}{total\ incoming\ amount\ of\ CO_2\ at\ state\ FG2} \tag{3}$$

Figure 3 showed the effect of recovery temperature on the dependent parameters at the recovery pressure of 7.2 bar. When recovery temperature increases from -152 to -122°C, thermal efficiency increases slightly by 1.2%, CO_2 recovery rate decreases by 12.2%, CO_2 mass fraction in stream CO2_2 significantly increases to 34.9% and excessive LNG gasification reduced to 19.3%, as expected. When increasing recovery temperature, the captured CO_2 decreased which causes decrease in the power consumption for CO_2 pump (P_CO2), thus increasing the thermal efficiency. It can be seen that the higher recovery temperature resulted in the lower amount of other gases (N_2 and O_2) in the captured liquid, this caused increase in CO_2 mass fraction.

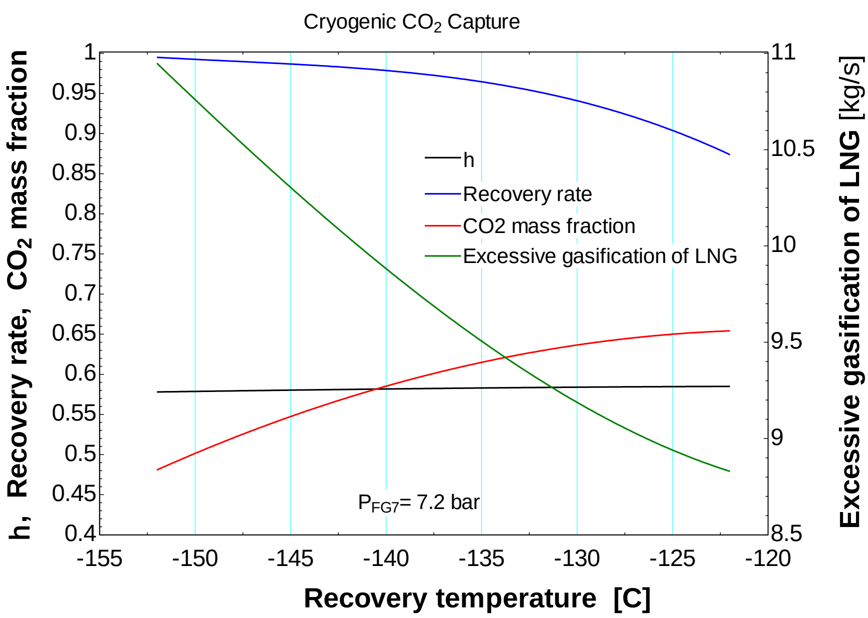

Fig. 3. Effect of T_{FG9} on cryogenic system

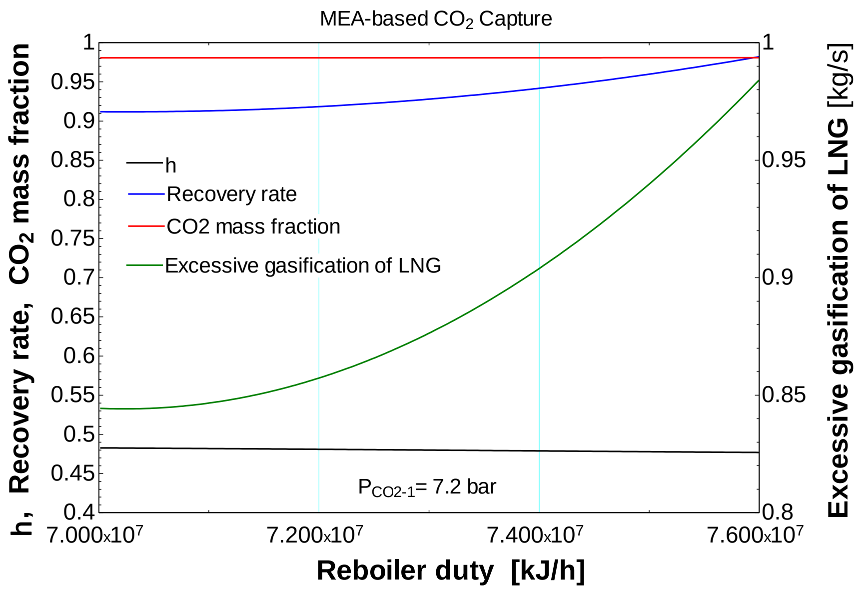

Fig. 4. Effect of reboiler duty on MEA-based system

Figure 4 showed the impact of reboiler duty on dependent parameters. It can be seen that the thermal efficiency of the system with MEA is much lower than that of the cryogenic system. This is because the heat from the exhaust flue gas is supplied to the stripper reboiler instead of the steam power cycle. However, excessive LNG gasification is only one-tenth that of the cryogenic system. CO_2 recovery rate is nearly the same for both systems, but CO_2 mass fraction in the captured liquid by the MEA system is much higher than that of the cryogenic system (e.g. 0.98 vs. 0.6). This proves that CO_2 capture by amine absorption is more effective than cryogenic system.

Figure 5 and Figure 6 show the effect of CO_2 recovery pressure on the parameters surveyed. For the cryogenic system, when the pressure increases, the thermal efficiency decreases because of the increased power consumption of the flue gas compressor (C_FG). The temperature of stream FG7 also increases with increase in the pressure. Therefore, the capacity of the heat exchanger (HX_CO2_LNG_h) increases. This leads to increase in excessive LNG gasification. When the pressure increases, the other gases are easily liquefied and presented in the recovered liquid, thus the mass fraction of CO_2 in the liquid is reduced. These trends are also observed for the MEA system. However, effect of the pressure is not pronounced. This is because the CO_2 liquefaction section of the MEA system contains most of the CO_2, other gases have been removed in the MEA-base CO_2 capture section.

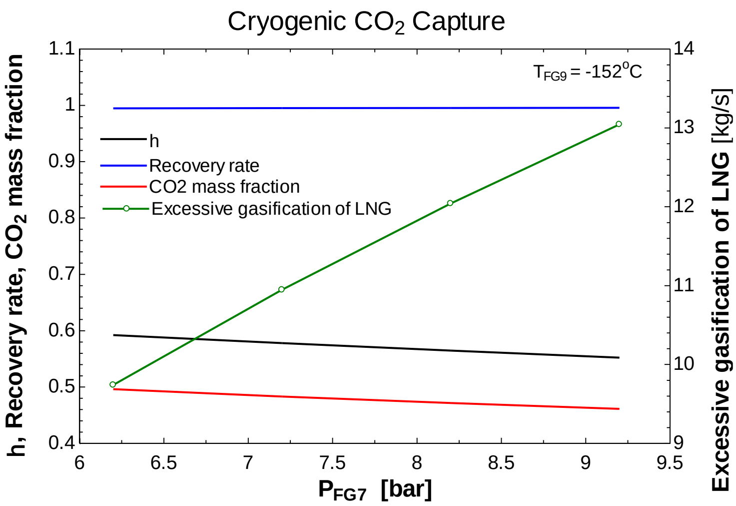

Fig. 5. Effect of CO_2 recovery pressure on cryogenic system

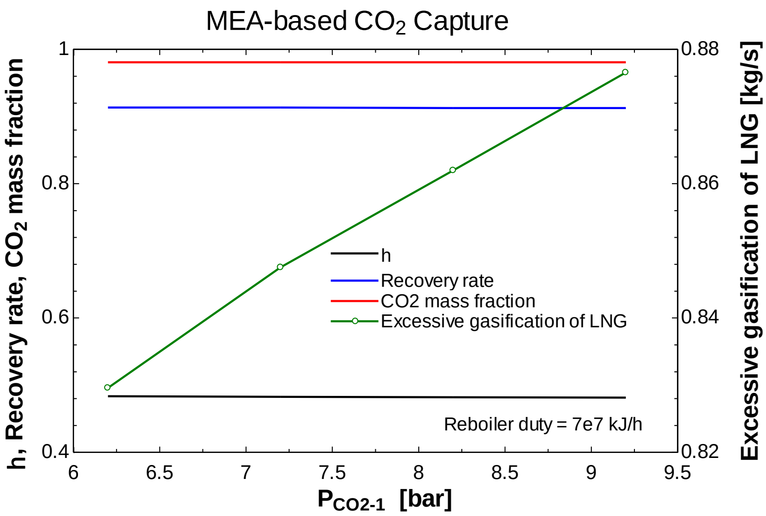

Fig. 6. Effect of CO_2 recovery pressure on MEA-based system

4. Optimization

CO_2 recovery rate is a parameter to be maximized in CO_2 capture technologies. In addition, this study also minimizes the amount of excessive LNG gasification because too much gasification can lead to redundancy in other users. Therefore, this section is to search for independent parameters so that CO_2 recovery rate is the highest and the LNG gasification are the smallest. To make a minimum problem, the objective function of CO_2 recovery rate is multiplied by negative one (-1). Multi-objective optimization was stated as follows:

For cryogenic system:

$$\min(x) = \begin{cases} \max recovery\ rate\ (T_{FG9}, P_{FG7}) \\ \min excessive\ gasification\ (T_{FG9}, P_{FG7}) \\ -155^oC \leq T_{FG9} \leq -120^oC \\ 6.2\ bar \leq P_{FG7} \leq 9.2\ bar \end{cases}$$

For MEA-based system:

$$\min(x) = \begin{cases} \max recovery\ rate\ (Q\_reboiler, P_{CO2\_1}) \\ \min excessive\ gasification\ (Q\_reboiler, P_{CO2\_1}) \\ 7e7\ kJ/h \leq Q\_reboiler \leq 7.6e7\ kJ/h \\ 6.2\ bar \leq P_{CO2\_1} \leq 9.2\ bar \end{cases}$$

These two objective functions are contradictory, i.e. when increasing the recovery rate, the excessive LNG gasification also increases, and vice-versa. Therefore, it is necessary to find a set of optimal solution that are called Pareto front solution. The Pareto front can be generated using the genetic algorithm implemented in MATLAB optimization toolboxTM R2018a (The MathWorks, Inc., Natick, MA, US). The parameters for setting GA were selected and listed in Table 3. The GA optimization algorithm flowchart can be seen in the literature [23-26]. The optimization converged to Pareto optimal set after 123 genetic algorithm generations. The Pareto optimal set is presented in Table 4. Twenty-four design points created Pareto set. To illustrate the non-dominated points constituting Pareto front, the Pareto front solution was indicated in Figure 7 and Figure 8.

Table 3
Parameters of multi-objective optimization genetic algorithm

Parameters	Value
Population size	60
Crossover fraction	0.8
Maximum number of generations	200 × number of variables
Mutation function	Adaptive feasible
Selection type	Tournament
Crossover function	Intermediate
Population type	Double vector

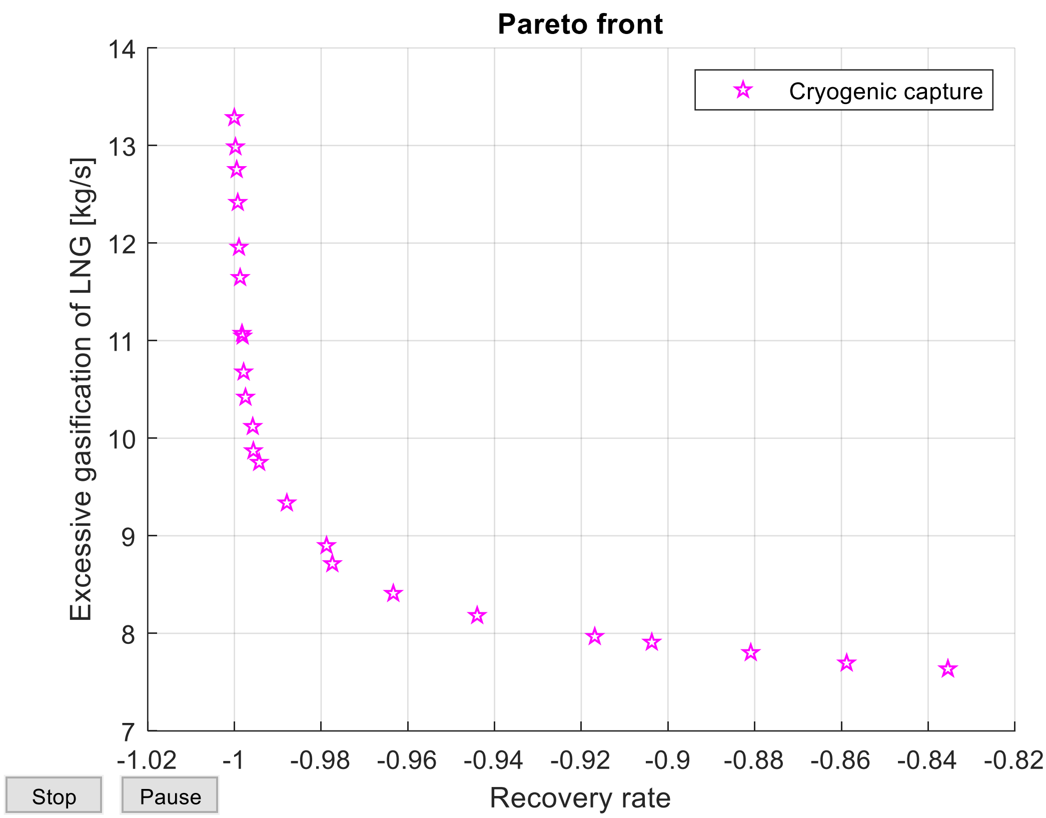

Fig. 7. Pareto front for optimization of cryogenic system

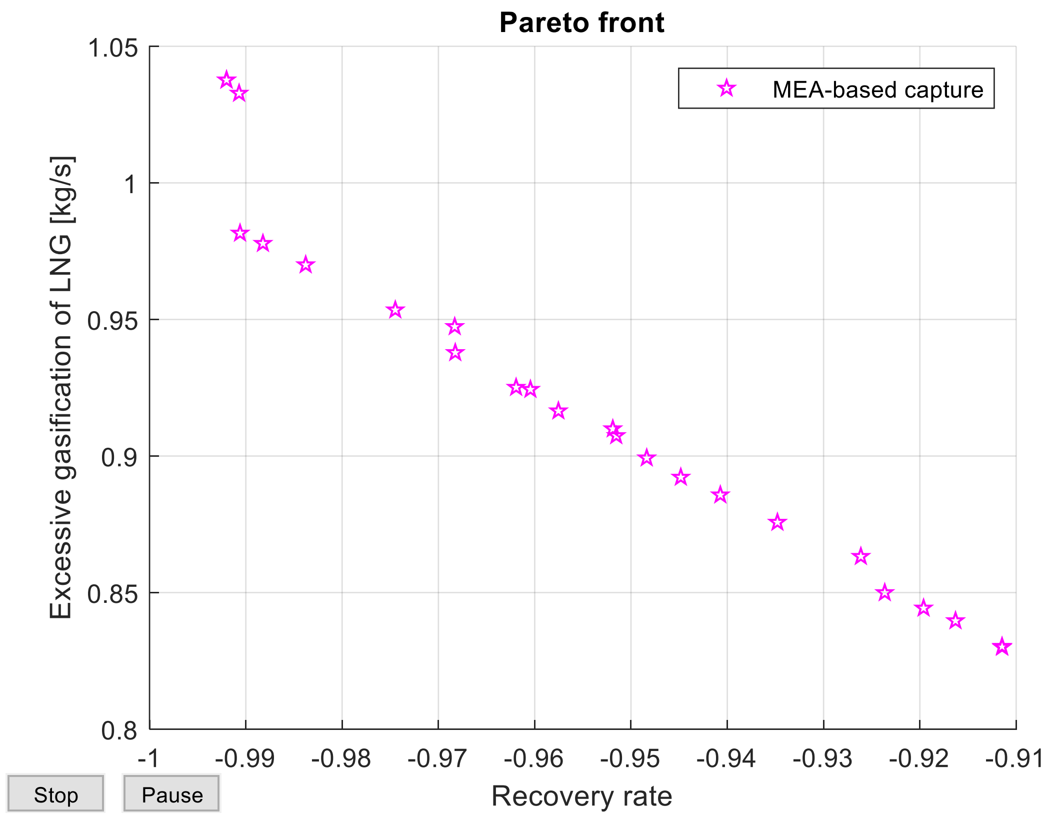

Fig. 8. Pareto front for optimization of MEA-based system

Table 4
Optimum Solution of CCS in LNG-fired power plant

Cryogenic capture				MEA-based capture			
Recovery temperature, C	Recovery pressure, bar	CO_2 Recovery rate	Excessive LNG gasification, kg/s	Reboiler duty, 10^7 kJ/h	Recovery pressure, bar	CO_2 Recovery rate	Excessive LNG gasification, kg/s
-120	6.2	0.8354	7.636	7	6.4264	0.9115	0.83
-154.9999	9.1986	1.0012	13.3511	7.4612	6.2999	0.9838	0.97
-154.9999	9.1986	1.0012	13.3511	7.0735	6.2237	0.9236	0.85
-120	6.2	0.8354	7.636	7.4969	6.2092	0.9906	0.9816
-154.9805	7.0587	0.9992	11.0631	7.4611	6.7074	0.9683	0.9474
-125.1581	6.2499	0.8959	7.8596	7.2774	6.2108	0.9619	0.9251
-154.9191	7.4286	0.9995	11.4853	7.3171	6.2239	0.9683	0.9378
-154.828	6.6157	0.9984	10.5148	7.5354	9.0615	0.9907	1.0328
-131.2888	6.267	0.9431	8.19	7.5387	9.2	0.992	1.0376
-151.4967	6.2746	0.9939	9.7862	7.5387	9.2	0.992	1.0376
-154.6332	6.8493	0.9984	10.7814	7.308	6.3249	0.9604	0.9244
-137.7011	6.277	0.9714	8.6331	7.42	6.3939	0.9745	0.9535
-145.6165	6.2881	0.9876	9.2848	7.1966	6.4316	0.9348	0.8757
-154.8447	6.4134	0.9981	10.2641	7.0697	6.4467	0.9163	0.8397
-154.9787	8.4334	1.0005	12.5802	7.0035	6.4416	0.9115	0.8303
-133.7407	6.2068	0.9558	8.2704	7.2995	6.4545	0.9519	0.9099
-154.9999	8.9486	1.0010	13.105	7.222	6.2599	0.9484	0.8993
-151.8577	6.5598	0.9945	10.1741	7.2022	6.2561	0.9448	0.8922
-154.9723	7.5463	0.9997	11.6234	7.2049	6.6823	0.9261	0.8632
-128.8275	6.2376	0.9267	8.0166	7.2699	6.3607	0.9515	0.9074
-140.1906	6.2894	0.9781	8.8386	7.0735	6.3448	0.9196	0.8443
-141.8804	6.2625	0.9817	8.9407	7.2551	6.2135	0.9575	0.9165
-154.9116	7.9407	0.9999	12.0522	7.2052	6.3414	0.9407	0.8857
-154.998	8.1179	1.0003	12.2508	7.4918	6.2548	0.9882	0.9778

5. Conclusions

In this study, thermal efficiency, recovered CO_2 rate, CO_2 fraction in recovered liquid and excessive LNG gasification of the two systems were evaluated and compared. Process flow diagram calculations are made with 1 kg/s LNG as fuel. Systems were simulated in the process simulation tool Aspen HYSYS. The main results are drawn as follows. The excessive LNG gasification in the cryogenic system is more than 10 times the MEA-based system. The CO_2 recovery rate of the two systems is close to each other but the amount of CO_2 in captured liquid of the MEA-based system is much higher than that of the cryogenic system. In other words, cryogenic technology captures a lot of CO_2 but the purity of CO_2 is not high compared to MEA technology. The thermal efficiencies of MEA-based and cryogenic systems are about 0.48 and 0.57, respectively. Multi-objective optimization based on GA and Pareto optimization has been applied for objective functions of maximum CO_2 recovery rate and minimum excessive LNG gasification. Optimal results are looking forward as design-maps for engineers who determine the appropriate parameters in a compromise between LNG gasification reduction and CO_2 recovery rate reduction, and vice versa.

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