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Preliminary study of a new CO_2 resource utilization system that combines waste heat recovery and cold energy utilization[#]

Fulu Lu [1, 2], Chuhan Pan [1, 2], Hongguang Zhu [1, 2*], Qi Wu [1, 2], Yanan Liao [1, 2]
[1] School of Mechanical Engineering, Tongji University, Shanghai 201804, China
[2] Bio-Energy Research Center, Institute of New Rural Development, Tongji University, Shanghai, 201804, China

(Corresponding author: zhuhg@tongji.edu.cn)

ABSTRACT

The bio-natural gas (BNG) industry, which utilizes organic waste to produce biogas and purify it into BNG, has gained rapid development because it is in line with global carbon neutrality targets and sustainable development strategies. However, the difficulty in utilizing the carbon dioxide separated by the purification system restricts the green development of the BNG industry. Liquid CO_2 is easier to store and transport compared to gaseous state, but liquefaction not only consumes power but also requires a high-grade cold source. In this research, based on a BNG station with a daily production of 5000 m^3, a novel CO_2 resource utilization system is proposed, which combines the waste heat recovery of CO_2 compression heat with the utilization of cold energy from liquid natural gas (LNG) gasification to achieve energy saving and consumption reduction. The system consists of a two-stage CO_2 cascade compression system, an organic Rankine cycle system and an LNG gasification system. A thermodynamic analysis was conducted on the system, and the results show that the ORC system effectively recover the waste heat of the CO_2 cascade compression system, reducing the power output by 12.8%. When the evaporation and condensation temperatures of the ORC system are 368.15 K and 303.15 K, respectively, the cold energy recovery rate of LNG gasification reaches 62.6%. The pressurization ratio of the CO_2 cascade compression system and the evaporation temperature of the ORC system have a large impact on the combined system, and the exergy analysis and parameter optimization design will be carried out subsequently. This study will provide theoretical guidance for CO_2 resource utilization in BNG industry.

Keywords: CO_2 resource utilization; Waste heat recovery; Cold energy utilization; System analysis

NONMENCLATURE

Abbreviations	
AD	Anaerobic digestion
BNG	Bio-natural gas
LNG	Liquid natural gas
Symbols	
a	Ambient

1. INTRODUCTION

The unsustainability of fossil energy and greenhouse effect caused by CO_2 excessive emission push people around the world to develop renewable energy [1]. Bioenergy has been accepted widely attention because of its significant potential in CO_2 emission reduction [2]. Anaerobic digestion technology (AD) become the main method in bioenergy utilization because it can utilize organic waste like straw and sewage to produce biogas. And biogas can be further purified to generate bio-natural gas (BNG) instead of combustion for fuel. BNG is an important substitute of natural gas which is non-renewable. The natural gas used in China is highly dependent on imports, and more than 30% natural gas is import [3]. Thus, BNG industry has gained rapidly developed in China since it can provide clean natural gas. The target of BNG production is 10 billion m^3 per year in 2025. However, there exist a prominent problem in BNG industry with its booming development. That is, the CO_2 produced in purification process, which realize the transformation of biogas to BNG, is not obtained effectively management.

The biogas produced by AD process mainly contain 55%-60% CH_4 and 40%-45%CO_2 [4]. Only by improving the content of CH_4 up to 95%, biogas can become BNG[3]. Therefore, BNG station produce large CO_2 when it generates BNG. It should be noted that the CO_2 produced by biogas purification is not regarded as CO_2 emission because it is from nature. In the past, those CO_2 was usually discharged into the atmosphere, which

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reduced the CO_2 utilization rate. Therefore, to develop an effective CO_2 utilization way is an urgent task for BNG industry.

The importance of CO_2 utilization and storage technologies increases day by day because of carbon emission reduction policy and energy safety [5]. CO_2 storage technology includes underground storage, deep sea storage, CO2 mineral hydration, et al [6]. Research [7] indicated that CO_2 recycling utilization is better than simple storage. The premise of CO_2 utilization is CO_2 storage and transportation in BNG station. The main stream ways of CO_2 storage and transportation are high pressure gaseous storage and low temperature liquid storage. Liquid CO_2 is easier to store and transport compared to gaseous state. However, CO_2 liquefaction may consume large power and cold source. A strategy that can reduce energy consumption and improve cold energy utilization rate may contribute to the CO_2 liquefaction technology in BNG station. CO_2 usually is compressed to a high level before liquefaction process and the compressed process may release large waste heat. A system that can recover those waste heat while simultaneously utilize cold energy is helpful to realize CO_2 storage and transportation.

Organic Rankine cycle (ORC) is widely used in waste heat recovery [8] and cold energy utilization system [9]. Aryanfar et al. [10] investigated the energy and exergy performance of a two-stage ORC system in waste heat recovery and LNG cold energy. Results showed that the energy efficiency increased from 20.23% to 38.36% using two-stage ORC system. Xu et al. [11] designed a new ORC system combined with air separation system and LNG regasification. Resulted showed that the combined system improved the total power output ratio from 0.03 to 0.5. Lu et al. [12] utilized ORC to improve the energy efficiency of air energy storage system that used LNG as cold source. Results showed that the proposed system had larger electrical round-trip efficiency compared to exist system. Bruno et al. [13] proposed a novel ORC system to recover cold energy during LNG regasification process. Results showed that the system generated 7.02 MW/year and produced 137.5 kg/s freshwater.

Literature reviews above show that ORC system can be utilized in both waste heat recovery and LNG cold energy utilization situation. Therefore, based on a daily production of 5000 m^3 BNG station, a new ORC system used in CO_2 compressed waste heat recovery and LNG cold energy utilization is developed in this study. The system consists of a two-stage CO_2 cascade compression system, an organic Rankine cycle system and an LNG gasification system. Energy and exergy analysis are performed to investigated the efficiency of system and exergy destruction of each system component. Finally, multiple objectives optimization is carried out to figure out the optimal system parameters.

2. SYSTEM DESCRIBTION

The flow chart of proposed system is shown in Figure 1. CO_2 undergoes two-stage compression before liquefaction. CO_2 is first compressed to middle pressure through compressor P1. Then it transfers heat to the medium of ORC system in heat exchanger 1 (HE1) (stream 1-2). HE1 is also the super-heat heat exchanger of ORC system. Subsequently, CO_2 is further compressed by compressor P2 after temperature reduction (stream 3-4). The waste heat of CO_2 is absorbed in heat exchanger 2 (HE2). HE2 is regarded as the heater of ORC system. The high-temperature waste heat produced by compressed process of CO_2 is recovered by ORC system. Then, the low-temperature waste heat of CO_2 is used to heat LNG in heat exchanger 3 (HE3). HE3 is the first regasification heat exchanger of LNG. The remain cold energy of LNG after HE3 is further used to cooled the organic fluid in the ORC condenser. The ORC system both utilizes the waste heat of CO_2 compress process and the cold energy of LNG regasification, realizing power generation and cold energy utilization. The power output by the turbine (Tur) of ORC can reduce the power consumption of total system, which is regarded as energy conservation efficiency.

3. MATHEMATICAL MODEL

This section may display the establishment process of mathematical model. MATLAB 2020a and REFPROP 9.1 are utilized for model development and data acquisition. Some assumptions are set to simplify the mathematical model and reduce the computing resource. (a) the system runs in steady state. (b) both pressure and mass loss in the component and pipeline can be ignored. (c) the isentropic efficiencies of turbine and compressor are 0.85.

3.1 Energy and exergy analysis

Energy analysis is performed to investigate the energy efficiency of the combined system. Energy analysis is based on mass and energy conservation law [14]. The basic equations of energy analysis are showed as follow.

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

$$\dot{Q}+\sum \dot{m}_{in}h_{in} = \dot{W}+\sum \dot{m}_{out}h_{out} \tag{2}$$

Where *m* is the mass flow rate. *Q* and *W* are heat transfer and power. *h* is specific enthalpy.

Exergy analysis is utilized to investigate the exergy efficiency of system and figure out the exergy destruction each system component. Exergy analysis is based on the second law of thermodynamics [14]. The basic equations of exergy analysis are showed as equation (4) to equation (6).

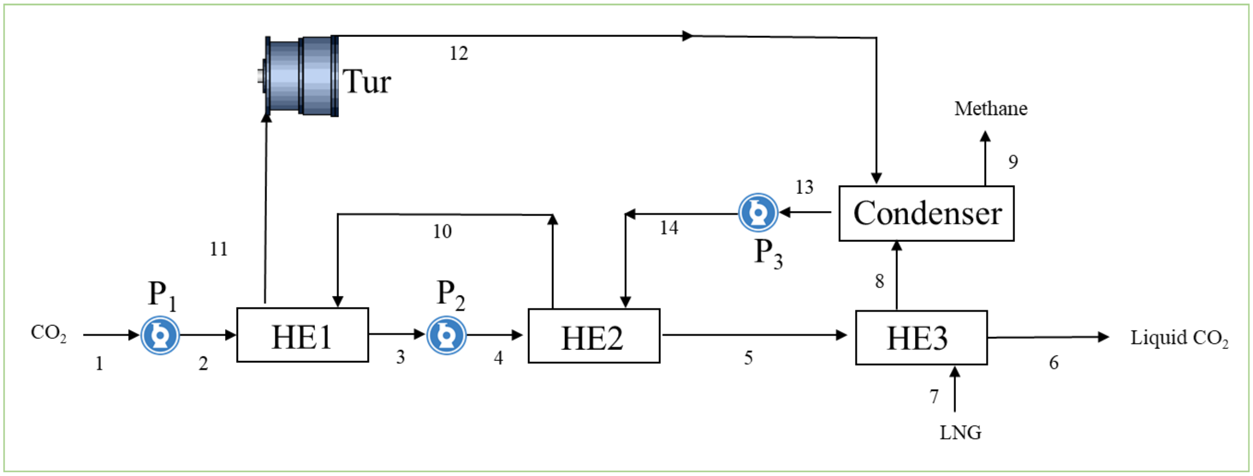


Fig. 1 Flow chart of proposed system

$$e = (h_{\text{state}} - h_a)\text{-}T_o(s_{\text{state}} - s_a) \quad (4)$$

$$\dot{E}_q + \sum \dot{m}_{in} e_{in} = \dot{E}_w + \sum \dot{m}_{out} e_{out} + \dot{E}_D \quad (5)$$

$$\dot{E}_D = \dot{E}_{in} - \dot{E}_{out} \quad (6)$$

Where e is the specific physical exergy. h_a is the specific enthalpy in ambient condition. E is the exergy with kW as unit. $\dot{E}_D$ is the exergy destruction.

The energy and exergy balance equations are summarized in Table 1 and Table 2.

Table 1. Energy balance equations of system components.

Components	Equations
P1	$\dot{W}_{P1} = \dot{m}_1(h_2\text{-}h_1), \eta_{P1} = \frac{h_{2s}-h_1}{h_2-h_1}$
HE1	$\dot{m}_2(h_2\text{-}h_3) = \dot{m}_{10}(h_{11}\text{-}h_{10})$
P2	$\dot{W}_{P2} = \dot{m}_3(h_4\text{-}h_3), \eta_{P2} = \frac{h_{4s}-h_3}{h_4-h_3}$
HE2	$\dot{m}_4(h_4\text{-}h_5) = \dot{m}_{10}(h_{10}\text{-}h_{14})$
P3	$\dot{W}_{P3} = \dot{m}_{13}(h_{14}\text{-}h_{13}), \eta_{P3} = \frac{h_{14s}-h_{13}}{h_{14}-h_{13}}$
HE3	$\dot{m}_5(h_5\text{-}h_6) = \dot{m}_7(h_8\text{-}h_7)$
Condenser	$\dot{m}_8(h_9\text{-}h_8) = \dot{m}_{12}(h_{12}\text{-}h_{13})$
Tur	$\dot{W}_{Tur} = \dot{m}_{11}(h_{11}\text{-}h_{12}), \eta_{Tur} = \frac{h_{11}-h_{12}}{h_{11}-h_{12s}}$

Table 2. Exergy balance equations of system components.

Components	Equations
P1	$E_D = W_{P1}\text{-}(E_2\text{-}E_1)$
HE1	$E_D = (E_2\text{-}E_3)\text{-}(E_{11}\text{-}E_{10})$
P2	$E_D = W_{P2}\text{-}(E_4\text{-}E_3)$
HE2	$E_D = (E_4\text{-}E_5)\text{-}(E_{10}\text{-}E_{14})$
P3	$E_D = W_{P3}\text{-}(E_{14}\text{-}E_{13})$
HE3	$E_D = (E_5\text{-}E_6)\text{-}(E_8\text{-}E_7)$
Condenser	$E_D = (E_{12}\text{-}E_{13})\text{-}(E_9\text{-}E_8)$
Tur	$E_D = (E_{11}\text{-}E_{12})\text{-}W_{Tur}$

The energy conservation efficiency is calculated as equation (7). Energy conservation efficiency represents the power save from ORC system which utilize the waste heat to generate power.

$$Efficiency = \frac{(\dot{W}_{Tur}\text{-}\dot{W}_{P3})}{(\dot{W}_{P1}+\dot{W}_{P2})} \quad (7)$$

The cold energy utilization efficiency of LNG is calculated as equation (8). The low temperature cold energy of LNG that is used to liquefy CO_2 is regarded as the useful cold energy in this article. The rest cold energy is used to cool ORC organic in condenser.

$$Efficiency = \frac{(h_8\text{-}h_7)}{(h_9\text{-}h_7)} \quad (8)$$

3.2 Multiple objectives optimization

Non-dominated sorting genetic algorithm-II (NSGA-II) [15] is used to performed multiple objectives optimization in this study. The objectives of the optimization include the energy conservation efficiency, the cold energy utilization efficiency of LNG and the total exergy destruction of all system component. Among them, the energy conservation efficiency and the cold energy utilization efficiency of LNG are expected to obtain the maximum value. The total exergy destruction of all system component is expected to obtain the minimum value.

4. RESULTS AND DISCUSSION

4.1 Model validation

The ORC system proposed in this study is validated by the results of Ref. [16]. *With the same input parameters, the maximum difference occurs in the thermal efficiency* *and the value is 6.25%. The validation result show that the model is of good agreement with the reference.*

4.2 *Parameter analysis*

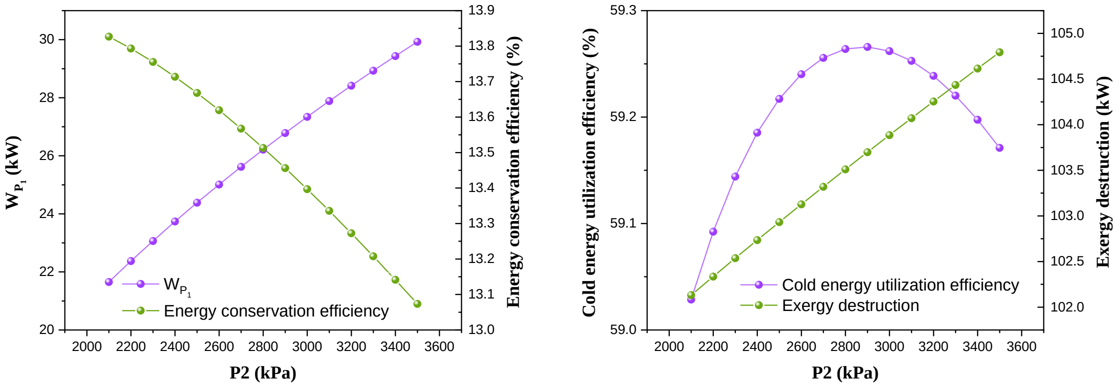
Some parameters that have prominent effect on the system performance are investigated in this section to figure out the optimal parameter value. These parameters include the pressure of stream 2 (P2), the pressure of stream 4 (P4) and the temperature of stream 13 (T13).

4.2.1 Effect of P2

The effects of P2 on system performance are showed in Fig. 2. The power consumption by P1 increases with the increment of P2. However, the energy conservation efficiency decreases as the P2 increasing. On the other hand, the cold energy utilization efficiency increases first then decreases with the increase of P2. The maximum value is 59.27% when P2 equals to 2900 kPa. The exergy destruction increases with the increase of P2. Results indicate that the power consumption is proportional to pressure and the irreversible loss increases as the pressure increasing. Therefore, the exergy destruction increases. The energy conservation efficiency decreases because the net power output of the system decreases. As to the cold energy utilization efficiency, the mass flow of ORC decreases while the temperature of steam 12 increases with the increment of P2. Thus, the heat transfer in ORC condenser first increases then decreases as the increasing of P2. The specific enthalpy of steam 9 decreases first then increases with the increment of P2. The trend of cold energy utilization efficiency indicates that the value of P2 should not be too large.

4.2.2 Effect of P4

The effects of P4 on system performance are showed in Fig. 3. Both the power consumption by P2 and the energy conservation efficiency increase with the increment of P2. However, both the cold energy utilization efficiency and the exergy destruction decrease as P2 increasing. The power output of ORC turbine increases with the increment of P4. And the net power of ORC system increases although the power consumption by P3 increases. That is the reason for the energy conservation efficiency increases when the power consumption by P2 increases. The cold energy utilization efficiency decreases from 66.68% to 58.95% because the specific enthalpy of steam 9 increases with the increment of P4. On the other hand, the mass flow of LNG decreases as P4 increasing. Therefore, the amount of LNG regasification decreases when P4 increases. Irreversible loss mainly occurs in HE3. As a result, the



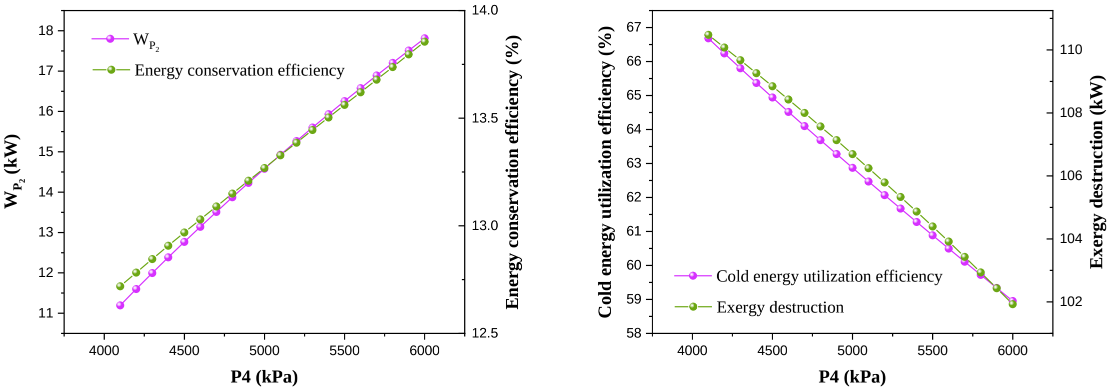


Fig. 3 Effect of P4

total exergy destruction decreases as P4 increasing since the exergy destruction in HE3 decreases with the decrement of the mass flow of LNG.

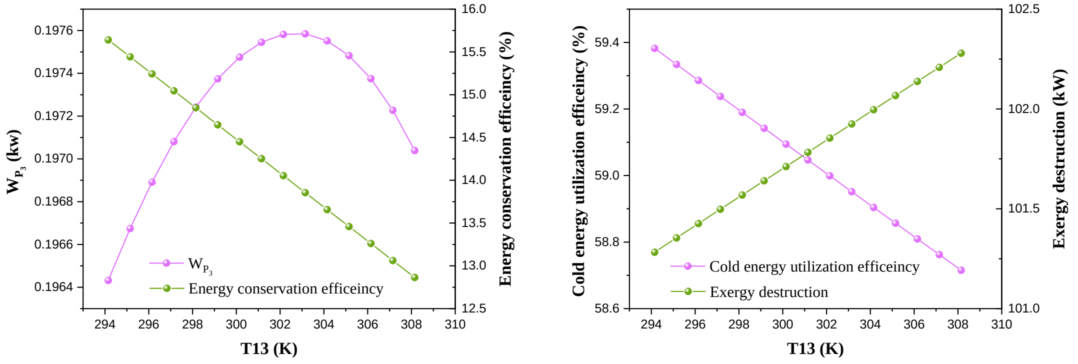


Fig. 4 Effect of T13

4.2.3 Effect of T13

The effects of T13 on system performance are showed in Fig. 4. The power consumption by P3 increases first then decreases with the increment of T13. However, the variation of power consumption by P3 is little. The energy conservation efficiency decreases as T13 increasing. The cold energy utilization efficiency decreases while the exergy destruction increases with the increment of T13. The energy conservation efficiency shows the most significant change with the increment of T13, from 15.64% to 12.89%. The reason is the power output of ORC decreases with the increment of T13. Therefore, results indicate that the value of T13 should be smaller to obtain a higher system efficiency.

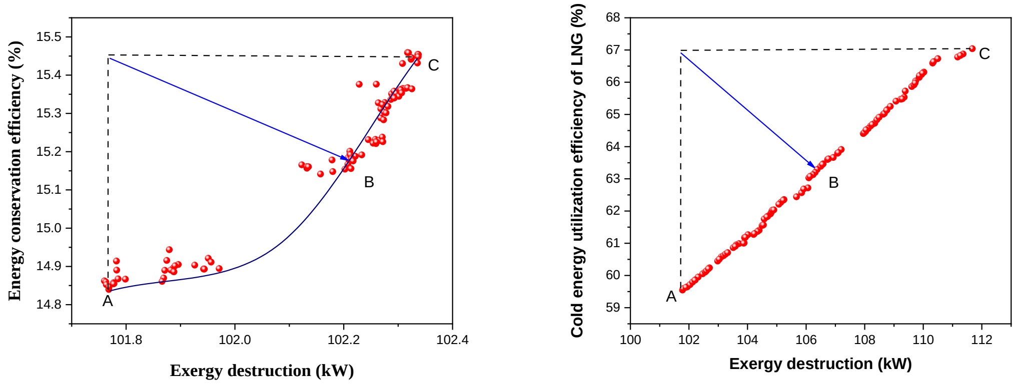


Fig. 5 Results of multiple objectives optimization

4.3 Multiple objectives optimization analysis

The results of multiple objectives optimization are shown in Fig. 5. The population and generation number of NSGA-II are 400 and 10, respectively for the objectives of energy conservation efficiency and exergy destruction. That value for the cold energy utilization efficiency and exergy destruction objectives are 100 and 10, respectively. Results show that point B is the optimal parameter for both objectives. The parameter used in optimization include P2, P4 and T13. The variation of these parameters is 2100-3500 kPa, 4100-6000 kPa and 294.15-308.15 K, respectively. The values of P2, P4 and T13 for the objectives of energy conservation efficiency

Pa and 295.85 K, respectively. That for the objectives of cold

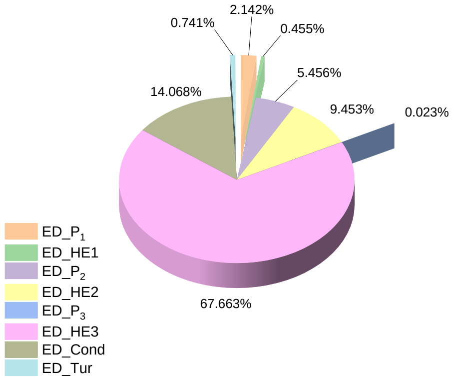


Fig. 6 Exergy destruction distribution

energy utilization efficiency and exergy destruction are 2203.5 kPa, 5025.4 kPa and 294.15 K, respectively.

The exergy destruction analysis is carried out based on multiple objectives optimization results, as shown in Fig. 6. The exergy destruction in HE3 is the largest, following by the exergy destruction in ORC condenser. The irreversible loss in P3 is the minimal.

5. CONCLUSIONS

A novel system used for recovering both waste heat and cold energy of LNG regasification is developed in this study. Detail thermodynamic analysis was conducted on the system, and multiple objectives optimization is carried out to figure out the optimal parameter. Results show that the developed system decreases the power consumption in CO_2 liquification and increase the cold energy utilization efficiency of LNG regasification. The main conclusions are summarized as follow.

(a) When the evaporation and condensation temperatures of the ORC system are 368.15 K and 303.15 K, respectively, the cold energy recovery rate of LNG gasification reaches 62.6%.

(b) multiple objectives optimization results show that the value of P2, P4 and T13 for the objectives of cold energy utilization efficiency and exergy destruction are 2203.5 kPa, 5025.4 kPa and 294.15 K, respectively.

(c) The exergy destruction in HE3 is the largest and the irreversible loss in P3 is the minimal.

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