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Energy Efficiency Study of Waste Heat Recovery-Based Chemical Absorption Decarbonization and Liquefaction for Natural Gas

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Abstract

This study presents an integrated approach for biogas purification and liquefaction, combining methyldiethanolamine (MDEA)-piperazine (PZ) solvent absorption with waste heat recovery from gas turbine exhaust. Through Aspen HYSYS simulation of a high-CO_2 (10%) feed gas system, we demonstrate a cascading energy utilization scheme that achieves both effective decarbonization (reducing CO_2 to <0.5%) and enhanced energy efficiency. Key findings reveal optimal absorption pressure at 1.5 MPa, where specific power consumption reaches 0.584 kW·h/kg LNG. The waste heat recovery system delivers 84.9% utilization efficiency, fully meeting the regeneration heat demand (828.99 kJ/m^3) without external energy input. This configuration shows superior performance compared to conventional biogas treatment methods, particularly for CO_2-rich (⩾10%) feedstocks, offering significant energy savings for LNG production facilities.

Keywords

Biogas purification; MDEA-PZ solvent; CO_2 removal; Waste heat recovery; LNG production; Process simulation

1. Introduction

With the growing global demand for sustainable energy, biogas has gradu-ally garnered attention as a clean and efficient renewable energy source [1]. In 2019, the Guidelines on Promoting the Industrialized Development of Biomethane, jointly issued by several national ministries, aimed to acceler-ate rapid progress in this field, setting a target of achieving an annual bio-methane productio of 20 billion cubic meters by 2030—signaling significant growth for the industry. Although classified as an 'uncon-ventional natural gas' alongside shale gas and coalbed methane, biomethane's future development prospects are evi-dently superior to those of its counterparts from the perspective of sustainable resource utilization.China boasts abundant reserves of biomethane resources, with an annual exploitable potential of

approximately 230 billion cubic meters. Its most critical feature lies in its sustainable utilization, which lays a solid foundation for industrial ad-vancement. Meanwhile, the development and utilization of rural biogas, in line with national policies, will not only meet the energy demands of rural areas but also contribute to ecological conservation and the revitalization of the rural economy.

The carbon dioxide (CO_2) content in biogas typically ranges between 28% and 44%. These non-combustible gases not only degrade the quality and combustion efficiency of natural gas but also increase equipment maintenance and compression costs, ultimately limiting its application scope and overall efficiency. Consequently, the removal of CO_2 is a critical step in natural gas processing.Currently, the most commonly employed desulfurization and decarbonization technologies include chemical absorption [2], physical absorption [3], and membrane separation [4]. Among these, chemical absorption has emerged as the most widely adopted method in natural gas decarbonization due to its superior removal efficiency, cost-effectiveness, and reusability [5]. This technique is capable of reducing CO_2 concentrations to below 50 ml/m^3, meeting stringent industry standards.

In natural gas sweetening processes, chemical absorbents can be broadly categorized into two types: alkanolamines and carbonates, with the former currently being the most widely adopted option[6]. Among various alkanolamine-based absorbents, methyldiethanolamine (MDEA) has been selected as the optimal choice due to its superior performance in terms of chemical stability, relatively low corrosiveness, and reduced energy consumption.Within the field of desulfurization and decarbonization, acid gas removal systems utilizing MDEA as the primary component have achieved comprehensive application [7]. In China's natural gas purification processes, this technology also serves as the predominant approach. However, in practical applications, the rapid gas-liquid flow velocity of CO_2 within absorption towers coupled with the relatively slow reaction rate between MDEA and CO_2 often makes it difficult to achieve ideal decarbonization efficiency when relying solely on MDEA solutions.Current research focus has primarily concentrated on two approaches: blended amine systems combining MDEA with other alkanolamines, and the introduction of piperazine (PZ) as an activator in MDEA formulations [8]. Piperazine, demonstrating remarkable activation characteristics, has been shown in research to significantly enhance energy efficiency in composite absorbents compared to traditional mixed amine solutions. Consequently, PZ-MDEA formulations have become prevalent in decarbonization processes, where PZ is added in trace amounts (typically <5%) as an accelerator, substantially improving CO_2 capture efficiency.

This research focuses on process simulation and analysis of carbon dioxide removal from natural gas using alkanolamine solutions, integrating chemical absorption-based decarbonization with natural gas liquefaction processes. The study particularly investigates energy-saving strategies for solvent regeneration in chemical absorption systems through waste heat recovery from gas turbine-driven compres-

sor units.Taking as a case study the decarbonization system of a liquefied natural gas (LNG) plant processing high-CO_2-content feed gas, we employ Aspen HYSYS simulation software to conduct comprehensive analyses of two critical aspects:

Waste heat utilization from gas turbine exhaust gases powering the compression system

Energy transfer optimization via high-temperature heat pump integration

The research objectives are twofold:

To achieve effective CO_2 reduction meeting stringent LNG product specifications

To significantly enhance system energy efficiency

Preliminary results indicate that this integrated approach demonstrates superior energy performance compared to conventional biogas liquefaction treatment methods, with potential applications in energy-intensive natural gas processing facilities.

2. Process Simulation

2.1 Conditions and Assumptions

Assumptions and Conditions for HYSYS Process Simulation

1) Feedstock Composition

The simulation assumes the crude gas is composed of CH_4 and CO_2, with a CO_2 content of 10%. The feed gas is sourced from a low-pressure pipeline network with the following parameters:

- Delivery pressure: 120 kPa
- Flow rate: 2 kmol/s
- Temperature: 40°C

2) Simulation Setup Conditions

- The Peng-Robinson property package is employed for purified natural gas, refrigerants, and flue gas, while the Acid Gas-Chemical Solvent package is used for acid gases and their absorbents.
- Water cooler outlet temperature: 40°C
- Heat exchanger approach temperature: 3°C
- Isentropic efficiencies: 75% for pumps, 85% for compressors
- Natural gas liquefaction rate: 100%, with LNG storage pressure at 110 kPa
- Heat pump unit operates under steady-state conditions
- Condensation pressure is approximately equal to generation pressure
- Condenser outlet vapor is saturated
- Pressure drop losses across heat exchangers are neglected

3) Process Assumptions

- The natural gas is assumed to consist of pure methane for composition considerations
- An excess air coefficient of 1.1 is set to ensure complete combustion
- Air composition: 20% O_2 and 80% N_2
- The chemical reaction equation for all material streams:
  $CH_4 + 2.2O_2 + 8.8N_2 \rightarrow CO_2 + 2H_2O + 0.2O_2 + 8.8N_2$
- Gas turbine efficiency: 35%
- Methane consumption rate: 12.80 mol/h per kW of electricity generated
- Flue gas temperature: 600°C(based on thermodynamic calculations and literature references) [9]

4) Performance Parameters

- Natural gas consumption rate is defined as:

$$w = \frac{W_C + W_P}{M_{LNG}}$$

- System waste heat utilization efficiency is defined as:

$$\alpha = \frac{E_{in} - E_{out}}{E_{in}} \times 100\%$$

Where:
W_c = Total compressor power consumption (kW)
W_p = Circulating pump power consumption (kW)
E_{in} = LPG input to the system (kW)
Eout = Waste gas output (kW)
M_{LNG} = LNG mass flow rate (kg/h)

2.2 Process Description

This system integrates chemical absorption with waste heat recovery technology to achieve natural gas decarbonization and liquefaction. The process comprises three key modules: Purification, Liquefaction, and Waste Heat Recovery, as illustrated in Figure 1.

1) Purification Unit

In the purification unit, the feed gas is initially pressurized by compressor C-01, then cooled in water cooler WC-01 before being introduced at the bottom of absorption column A-01. Within the column, the feed gas undergoes mass transfer with lean amine solution fed from the top.

The purified natural gas exits from the column top and enters separator X-01 for moisture removal, after which it is directed to the liquefaction module. The CO_2-rich amine solution from the column bottom passes through throttle valve V-01 for

pressure reduction and enters flash drum S-01 for gas-liquid separation.

The amine-rich liquid phase first exchanges heat with regenerated lean amine in heat exchanger HE-01, then flows into regeneration column D-01 to complete the regeneration process. The regenerated lean amine is pre-cooled in HE-01, further cooled to 40°C in water cooler WC-02, and supplemented with make-up water. It is then pressurized by circulation pump P-01, cooled again in WC-04, and finally returned to the top of absorption column A-01, forming a closed-loop cycle.

2) Liquefaction Module

In the liquefaction unit, the purified natural gas undergoes preliminary cooling through two-stage heat exchangers HE-04 and HE-05, before entering LNG-100 for deep cooling to achieve liquefaction and subcooling. The liquefied natural gas, after compression and water cooling, is then depressurized to 110 kPa through throttle valve V-05, and finally stored in storage tank T-101.

Within heat exchanger HE-04, the mixed refrigerant is cooled to between -35°C and -30°C. The cooled liquid then enters separator S-02 for component separation. The liquid phase components are further processed in HE-05, where they are cooled to between -100°C and -90°C, then depressurized through throttle valve V-03 to provide the required cooling capacity for HE-05 and HE-04, subsequently warming back to 37°C. The vapor phase components are successively cooled through HE-05 and LNG-100 to approximately -145°C, then depressurized through throttle valve V-04 to supply the necessary cooling capacity for LNG-100 and HE-04, ultimately also warming back to 37°C.

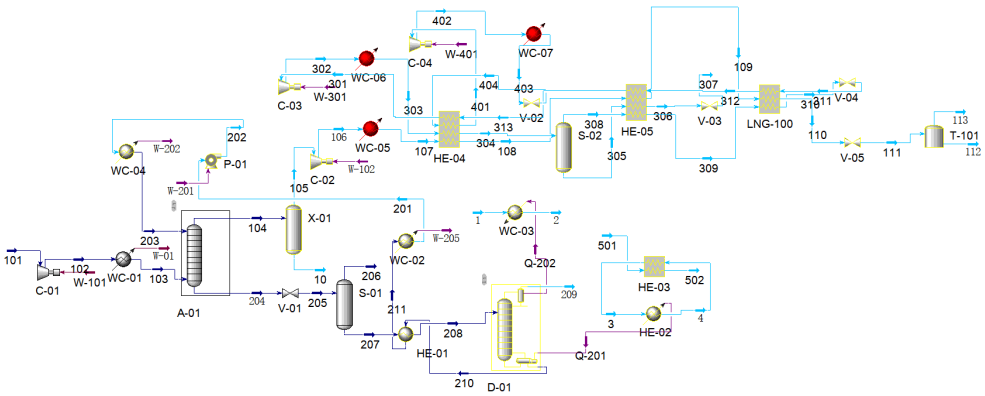
Additionally, the propane refrigerant is compressed in compressor C-04 and cooled in water cooler WC-07, then depressurized to 120 kPa through throttle valve V-02 before flowing into HE-04 to complete heat exchange and returning to the compressor, thereby forming a complete circulation process.

3) Waste Heat Recovery Module

The waste heat recovery system processes high-temperature exhaust gas (Stream 501) from the gas turbine through heat exchanger HE-03, where thermal energy is extracted before the gas is discharged from the system. The heated circulating thermal medium (Stream 3) then transfers to the reboiler (HE-02) at the base of the regeneration column, delivering the required thermal energy before returning to HE-03 after heat exchange, completing a closed-loop circulation.

The absorption heat pump recovers condensation heat from the gas turbine exhaust, elevating the primary heating network water temperature from 60°C to 90°C. Subsequent utilization of gas turbine extraction steam further raises the water temperature from 90°C to 120°C. The circulating water enters the heat pump at 25°C and exits at 20°C, then proceeds to the gas turbine condenser for heat absorption. This completes the thermal cycle by transferring the condenser's released heat to the heat pump. The system employs 0.4 MPa saturated steam as the energy source to drive the absorption heat pump.

Figure1. Process Flow Schematic of the System



A - Absorption Column C - Compressor D - Regeneration Column HE - Heat Exchanger P - Pump
Q - Heat (thermal energy transfer) S - Gas-Liquid Separator T - Storage Tank V - Valve
W - Work (power) WC - Water Chiller X - Component Separato

3. Results and Analysis

3.1 Simulation Results

During the purification process, the activated solvent used consists of 35% methyldiethanolamine (MDEA) and 3.5% piperazine (PZ). When the CO_2 concentration in the feed gas is 10%, the key operational parameters at critical nodes of the purification system are detailed in Table 1.

3.2 Results Analysis

3.2.1 Effect of Absorption Pressure on Specific Power Consumption

As shown in Figure 2, when the CO_2 concentration is set at 10%, the system's specific power consumption is significantly influenced by absorption pressure. Initially, the specific power consumption decreases with increasing absorption pressure, but subsequently rises as pressure continues to increase. The minimum specific power consumption is achieved at an operating pressure of 1.5 MPa.

At a CO_2 concentration of 10% and pressures below 1.5 MPa, increasing absorption pressure more substantially reduces amine circulation flow rate, leading to greater energy savings for pump operation.

3.2.2 System Energy Consumption Analysis

Table 2 presents the relationship between specific power consumption and regeneration heat demand under optimal absorption pressure conditions. When the CO_2 concentration in feed gas reaches 10%, the heat required for MDEA solution regeneration can be entirely supplied by other internal heat sources, achieving a waste heat utilization efficiency of 84.9%. These findings demonstrate that the proposed waste heat recovery scheme is particularly suitable for natural gas treatment systems with CO_2 concentrations exceeding 10%.

Table 1. Key Node Parameters of Purification Section

Flow	T/℃	Molar flow/（kmol/h）	CO_2 content/%	P/kPa	CH4 content/%
101	40	7200	10	101	90
103	40	7200	10	1500	90
104	40.03	6473	0	1440	99.56
201	40	16869	0.01	150	0
203	40	16869	0.01	1440	0
204	67.95	17564	4.03	1500	0.03
205	67.91	17564	4.03	200	0.03
208	85	17549	4.02	200	0
210	113.2	16790	0.01	150	0
211	89	16790	0.01	150	0

Figure 2. Variation Curve of Specific Power Consumption with Absorption Pressure

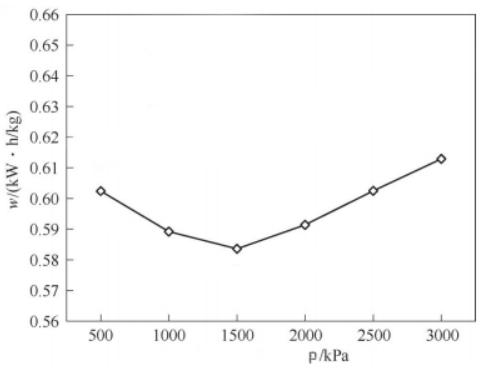


Table 2. System Energy Consumption

CO_2 content/%	Regeneration heat load /(kJ/m3）	Net regeneration heat load/(kJ/m3)	Purification power consumption /(kW·h/m3)	w/(kW·h/kg)	α/%
10	828.99	0	0.087	0.584	84.9

4. Summary

This study designs a decarbonization process for natural gas liquefaction that utilizes a coupled MDEA-activated solvent system and achieves waste heat recovery from high-temperature exhaust gases generated by gas turbines through cascade energy utilization. Based on in-depth analysis of system energy consumption and thermodynamics, the following key conclusions are drawn:

(1)The integration of natural gas liquefaction with an MDEA solvent absorption system, incorporating waste heat recovery from gas turbine exhaust gases, significantly enhances energy reuse efficiency and improves the overall energy utilization rate of the natural gas purification process.

(2)At a CO_2 concentration of 10%, the thermal energy required for MDEA solvent regeneration can be entirely supplied by waste heat from gas turbine emissions, with the system achieving a waste heat utilization efficiency of 84.9%.

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