Innovative Structure of a Liquefied Natural Gas (LNG) Process by Mixed Fluid Cascade Using Solar Renewable Energy, Photovoltaic Panels (PV), and Absorption Refrigeration System

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Abstract

Among the principal industrial approaches for conveying natural gas, aside from pipeline transportation, is the liquefaction of natural gas (LNG). In recent years, a significant portion of natural gas imports has been done through the transportation of LNG. The economic viability of an LNG venture is substantially influenced by the pivotal role of the liquefaction procedure in determining its financial returns. Conversely, a paramount concern within LNG plants revolves around enhancing the energy efficiency of the liquefaction procedures. In this research, an Innovative structure of a liquefied natural gas process by mixed fluid cascade using solar renewable energy, photovoltaic panels (PV), and absorption refrigeration system is presented and evaluated. This structure relies on substituting the vapor compression refrigeration cycle with the absorption refrigeration system. The required power of the cycle is 19.37 MW and is provided by renewable solar energy and PV, and the absorption refrigeration system derives its necessary heat load from the existing surplus heat within the facility. Aspen HYSYS V12.1 software, a conventional chemical process simulator, performs process simulation. Also, the design and simulation of PV were performed using the PVsyst 7.3.1 software, with the weather conditions in Rafsanjan City, Kerman Province, in Iran. To supply the part of cycle power, out of 3 modules of AXITEC AC-550MBT and 157 inverters Canadian Solar CS-125KTL have been used. The highest and lowest of performance ratio (PR) were 89.6 % in January and 78.9 % in July, respectively. Also, the highest and lowest of available energy were 3,726.8 in September and 3,304.6 MWh in February, respectively. Additionally, the maximum and minimum losses due to mismatch were recorded in September and February in the amount of 83.79 and 72.77 MWh, respectively. The ammonia-water cycle has a coefficient of performance (COP) at a value of 0.48. As well as the presented innovative structure displays a specific energy consumption (SEC) of 0.172 kWh/kgLNG, illustrating a 30 % decrease in energy usage. Also, the presented novel system offers the potential to achieve a reduction of up to 31 % in the necessary heat transfer area.

**Keywords**: Process integration, liquefied natural gas, solar energy, photovoltaic panels (PV), absorption refrigeration system.

* 1. Introduction

The exponential surge in energy and environmental challenges over recent decades can be attributed to the swift expansion of commercial domains and the global economy (Ebrahimi et al., 2021). Environmentalists have expressed profound concern for decades regarding the substantial threats posed to global ecosystem sustainability by climate change and ozone layer degradation (Ghorbani et al., 2021 and Taghavi and Lee, 2024). LNG transportation, comprising 32 % of natural gas imports in 2012, stands as a pivotal industrial approach for natural gas conveyance, distinct from the predominant pipeline mode (Mehrpooya et al., 2016). The economic viability of an LNG project hinges significantly on the efficacy of the liquefaction process. Enhancing energy efficiency is paramount within LNG plants, given the substantial energy consumption inherent in liquefying and sub-cooling natural gas to temperatures below -160 °C. The predominant contributor to this energy demand lies in the compression refrigeration cycles (CRCs). The utilization of the Mixed Fluid Cascade (MFC) process is prevalent in high-capacity LNG plants. The Linde and Statoil MFC methodology incorporates three refrigeration cycles employing a blend of methane, ethane, propane, or nitrogen as refrigerants. These cycles facilitate pre-cooling (around -25 °C), liquefaction (approximately -86 °C), and sub-cooling (about -160 °C) stages in the natural gas processing (Ghorbani et al., 2018). In this paper, a novel structure of a LNG process is presented, employing a mixed fluid cascade using solar renewable energy, PV, and an absorption refrigeration system. The process is simulated using Aspen HYSYS V12.1 software and Peng Robinson thermodynamic equation of states, while photovoltaic panels are simulated using PVsyst 7.3.1 software.

* 1. Process description

Ammonia-water emerges as an efficient working fluid, reaching -60 °C in the Absorption Refrigeration Cycle (ARC). In the ARC, a pump elevates solution pressure, aiding the refrigerant's separation (Chen et al., 2021). Essential cooling in the condenser utilizes ambient air or cooling water (Hunt et al., 2023). Waste heat from turbines and boilers, including gas discharge, drives the energy-intensive separation process. This waste heat is used to generate low-pressure steam (T=180 °C and P=4.5 bar), fueling the separation of ammonia from water in the generator. Effectively utilizing waste heat in an ARC proves practical and feasible for low to medium temperature heat sources (Táboas et al., 2014). Table 1 presents the molar composition data for the input streams used in simulating the developed structure. Also, the process flow diagram (PFD) of the mixed fluid cascade cycle illustrated in Fig. 1.

**Table 1.** Molar composition for the integrated structure.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Str.** | **N2** | **CH4** | **C2H6** | **C3H8** | **n-Butane** | **i-Butane** | **i-Pentane** | **H2O** | **NH3** |
| A1 | 0.040 | 0.875 | 0.055 | 0.021 | 0.005 | 0.003 | 0.001 | 0 | 0 |
| A6 | 0.370 | 0.629 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| A7 | 0.015 | 0.893 | 0.059 | 0.022 | 0.005 | 0.003 | 0.001 | 0 | 0 |
| A9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.750 | 0.250 |
| A11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.933 | 0.066 |
| A14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.001 | 0.999 |
| A16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.233 | 0.766 |
| A17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.001 | 0.999 |
| A22 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.739 | 0.260 |
| A24 | 0 | 0.126 | 0.329 | 0.277 | 0.266 | 0 | 0 | 0 | 0 |



**Fig. 1.** The process flow diagram (PFD) of the mixed fluid cascade cycle. Modified from reference (Mehrpooya et al., 2016).

The thermodynamic details of compressors (C) and pump (P) utilized in the mixed fluid cascade cycle is detailed in Table 2.

**Table 2.** Operational specifications the thermodynamic details of compressors (C) and pump (P) in the mixed fluid cascade cycle.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Equipment** | **Adiabatic Efficiency (%)** | **Power (kW)** | **ΔP (kPa)** | **Pressure Ratio (−)** |
| C1 | 80.00 | 7,149.75 | 3,037 | 9.603 |
| C2 | 80.00 | 11,977.6 | 2,481 | 9.015 |
| P1 | 90.00 | 243.3 | 1,180 | 10.83 |

* 1. Simulation and design of photovoltaic panels (PV)

Amidst rising global energy needs, solar power, especially photovoltaic cells, emerges as a crucial player in harnessing renewable energy through the photovoltaic effect (Soonmin & Taghavi, 2022). The International Energy Agency (IEA) prescribes key performance parameters, crucial for on-grid PV system assessment (Ebrahimi et al., 2022). A vital metric, the final system yield (YF), gauges on-grid energy production over a specified period, computed by dividing the AC energy by the PV unit's maximum power under standard test conditions (STC) and presented in Eq. 1 (Afrouzy & Taghavi, 2021). The PV system's performance is gauged by crucial metrics: YF (final yield) in kWh/kWp, EAC (energy yield) in kWh/kWp, PPV (peak power output) under STC, and YR (reference yield) by Eq. 2 (Taghavi et al., 2023). YA represents DC energy per kWh of nominal power per kWp under STC. PR gauges final yield against reference yield. Total energy loss is calculated using Eq. 5. Array absorber loss, obtained by Eq. 6, is the deviation between reference and array yield. Inverter efficiency (Eq. 7) is AC power produced divided by PV array's DC power output. PV system efficiency (Eq. 8) is the product of PV module and inverter efficiency (Taghavi et al., 2021).

|  |  |
| --- | --- |
|  | (1) |
|  | (2) |
|  | (3) |
|  | (4) |
|  | (5) |
|  | (6) |
|  | (7) |
|  | (8) |

* 1. Result and discussion

PVsyst 7.3.1 software modelled photovoltaic panels for Rafsanjan City, Iran (latitude 30.4015, longitude 55.9945, altitude 1,519 m), considering local weather conditions. It shares borders with Bafgh to the north, Shahrebabak to the west, Sirjan to the south, and Kerman to the east. Fig. 2 contrasts monthly yield and energy output between the reference (Afrouzy & Taghavi, 2021) and proposed models.

**Fig. 2.** Presents monthly yield and energy production for reference (Afrouzy & Taghavi, 2021) and proposed models.

Analyse location specifics and meteorological data for precise modelling. The study used fixed-tilt panels with a 32º slope angle in the PV system. According to the photovoltaic simulations, Rafsanjan's monthly average global radiation spans 117.5 kWh/m² (December) to 253.4 kWh/m² (June). In July, the hottest month, the temperature averages 41.77 °C, while January, the coldest, sees 2.566 °C. Rafsanjan's annual average environmental temperature is 29.43 °C. Table 3 outlines the details of the examined PV system. Fig. 3 illustrates the performance ratio (PR), array energy output, and grid-injected energy.

**Table 3.** Characteristics of investigated PV system.

|  |  |
| --- | --- |
| **PV module characteristics** | |
| Length × Width × Thickness (mm) ; Weight (kg) | 2,278 × 1,134 × 35 ; 28.5 |
| Number of Module | 3 |
| Manufacturer | Axitec Energy |
| Description and details | AXITEC AC-550MBT/144 |
| **PV inverter characteristics** | |
| Length × Width × Thickness (mm) ; Weight (kg) | 714 × 1,176 × 315 ; 84 |
| Number of Inverter | 157 |
| Manufacturer | Canadian Solar Inc. |
| Description and details | CS-125KTL-GI-E |

**Fig. 3.** Monthly array energy production and energy injected into the grid and PR.

Fig. 3 showcases monthly solar energy injection for various systems throughout the year. The highest PR was 89.6 % in January, while July recorded the lowest at 78.9 %. Fig. 4 shows losses of PV system during the year based on simulations.

**Fig. 4.** Schematic illustrates system losses throughout the entire year in Rafsanjan.

In September, the mismatch loss peaked at 83.79 MWh, while it reached its lowest point in February at 72.77 MWh.

* 1. Conclusions

Incorporating absorption refrigeration cycles in the mixed fluid cascade LNG process aims to reduce electrical power consumption by utilizing plant waste heat. In this research, the ARC replaced the pre-cooling compression refrigeration cycle. Also, renewable solar energy was used to supply the electricity required for the cycle the amount of 19.37 MW using PV. The main results of the developed process analysis are presented as follows:

* Specific energy consumption was 0.172 kWh/kgLNG, signaling a 30 % consumption reduction; modified process reduces heat transfer area by up to 31 %.
* Coefficient of performance (COP) of NH3-H2O was 0.48, revealing cycle efficiency.
* Achieving a peak PR of 89.6 % in January and minimizing losses to 72.78 MWh in February, the system demonstrates robust efficiency.
* The highest available energy was in September (3,726.8 MWh) and the lowest was (3,304.6 MWh) in February, which showed that the power generation is sufficient for the cycle.

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