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Utilization of LNG cryogenic energy in a proposed method for inlet air cooling to improve the performance of a combined cycle

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Abstract
In this study a cold production process was proposed for inlet air cooling in which cryogenic energy from liquefied natural gas (LNG) was sufficiently converted to cold energy. The effect of using the cold production process for inlet air cooling on the off-design performance of a gas turbine combined cycle was analyzed under different ambient conditions. The cold output of the proposed process was increased by about 38.1% to 42.5% compared to that of the conventional cold production process that involves direct LNG evaporation. Furthermore for the inlet air cooling, the proposed method increased the relative power increment from 2.2% to 14.4% and the relative efficiency increment from 0.7% to 2.2%, mainly depending on the variations in the relative humidity, compared to cold production without air cooling. The relative power and relative efficiency of the proposed air cooling were increased by 0.6% to 3.1% and 0.3% to 0.5%, respectively, above those of the traditional air cooling.

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Key Words: Inlet air cooling, CO₂ working medium, LNG cryogenic energy utilization, Combined cycle

1. Introduction
Ambient temperature significantly affects the performance of gas turbines. If, say, the ambient temperature is 40 °C, exceeding the designed point of 15 °C, the power output of the turbines can decrease by as much as 16%. Therefore, various types of inlet air cooling, such as absorption chiller air cooling, mechanical chiller air cooling, high-pressure fogging, and water evaporation air cooling, have been widely studied to augment power output. Cryogenic energy from liquefied natural gas (LNG) is one of the cold sources used in air cooling. An advanced combined cycle that integrates cryogenic energy from LNG utilization, air inlet cooling, and inter-cooling [1] was proposed and studied, in which LNG cryogenic energy is used in both air cooling and exhaust steam condensation. Reference [2] analysed the performance of a combined power cycle in which inlet air cooling using the cold energy of LNG, and the natural gas evaporated in the cold production process is totally used in the combined cycle. In this study, the cold production process is proposed with the use of LNG cryogenic energy for inlet air cooling. The

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effect of the air cooling on the performance of the gas turbine combined cycle fuelled with the cold energy of LNG is also analysed.

2. Proposed cold production process driven by LNG cryogenic energy for inlet air cooling

In the traditional cold production process in which LNG is used in inlet air cooling, LNG is pumped through and directly vaporized in a heat exchanger and a heating medium (HM, usually a glycol-water solution) is cooled to near 5 °C to prevent moisture in air from freezing. However, LNG cryogenic energy cannot be efficiently utilised because of the large temperature difference between LNG and the glycol-water solution. In this study, the LNG cryogenic energy is therefore used first in a Rankine cycle with CO₂ as the working fluid, after which the power from the CO₂ turbine drives a CO₂ compression–refrigeration process to augment the cold output. A flow diagram of the proposed cold production process for inlet air cooling is shown in Fig. 1, which depicts that the cold production process combines the characteristics of power production using LNG and the mechanical chiller air cooling process. The main merits of the proposed process are as follows: (1) The working medium of CO₂ in the Rankine cycle is vaporized at about 0 °C, and the cold produced by vaporization is used to cool the air-cooling medium. (2) The indirect vaporization of LNG by the Rankine cycle results in an increase in the cold output compared to the direct LNG vaporization. (3) The CO₂ compression–refrigeration system further increases the cold output of the entire cold production process. Fig. 2 shows that the HM is used in a combined power cycle for air cooling. The heat recovery steam generator (HRSG) is a pattern of double pressure with reheating.

3. Methodology and main assumptions

The proposed cold production process is simulated with the use of the commercial software Aspen Plus using the property method of PENG-ROB. The LNG and the working fluid of CO₂ are considered pure substances. Tables 1 and 2 list the main assumptions. The off-design performance of the gas turbine cycle is simulated with keeping both the turbine swallowing capacity (\( \dot{m} \sqrt{T} / P \), where \( \dot{m} \) is the mass flow rate, \( T \) is the inlet temperature, and \( P \) is the inlet pressure) and the turbine inlet temperature unchanged. The relation of the compressor capacity with ambient temperature is described in Reference [2]. Turbine blade cooling is simply considered as 9% of the compressed air bled, 80% of which is fed to the gas turbine, with the other 20% being mixed with the flue from the

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### Table 1. Gas turbine cycle at designed point

| Parameters/variable                | Value | Unit |
|-----------------------------------|-------|------|
| Ambient temperature               | 15    | °C   |
| Ambient pressure                  | 1.01  | bar  |
| Air mass flow rate                | 420.83| kg/s |
| Natural gas/LNG flow rate (pure CH₄) | 8.69  | kg/s |
| Gas turbine exhaust gas temperature | 600   | °C   |
| HRSG exhaust flue gas temperature | 146.3 | °C   |
| Gas turbine power output          | 150.00| MW   |
| Steam turbine power output        | 81.94 | MW   |
| Net efficiency (LHV based)        | 53.34 | %    |
turbine. A rough HRSG off-design model is considered in this study. As for the characteristics of the exhaust flue gas from the gas turbine, the steam inlet temperature is considered constant, while the steam mass flow rate is set to be proportional to the mass flow rate of the exhaust flue gas. The sliding pressure operation of the steam cycle is considered. The parameters obtained are then used as the input parameters in the modelling of the combined cycle with the use of Aspen Plus, and performance is calculated. The air cooler and the compressor are simulated with the UNIQUAC property method, whereas other processes are simulated with the PENG-ROB property method. The air-side pressure drop in the air cooler is set at 1% of the inlet air pressure.

4. Results and discussion

The cold output of the proposed system is 38.1% to 42.5% higher than that of the traditional method (LNG direct evaporation). The CO₂ turbine inlet temperature significantly affects the CO₂ turbine work output. However, the increase in the CO₂ turbine inlet temperature negatively affects the cold output. Therefore, a near-ambient inlet temperature is recommended for the CO₂ turbine.

Given the reliability of the current calculations, the simulation results of the gas turbine off-design without air cooling match the average variations in the power and efficiency of the current high-performance gas turbines [2, 3]. The simulation results of the steam turbine off-design are compared with those in Reference [2]; the variation tendency is the same, with slightly changed variation ranges for the different pressure levels and assumptions.

| Table 2 Basic assumptions for simulation |
|------------------------------------------|
| **Cold production process**              |
| Pressure loss, heat exchanger (%)        | 5 |
| Pinch temperature difference of Condenser (°C ) | 15 |
| Cooling water temperature at 28/40 °C (°C ) | 20.2/25 |
| Isentropic efficiency, turbine (%)       | 90 |
| Isentropic efficiency, compressor (%)    | 85 |
| Mechanical efficiency, turbine & compressor (%) | 99 |
| **Combined cycle**                       |
| Pressure loss, gas turbine combustor (%) | 3 |
| Gas turbine inlet temperature (°C)       | 1260 |
| Compressor pressure ratio                | 13.5 |
| Mechanical efficiency, gas turbine (%)   | 99 |
| Isentropic efficiency, gas turbine (%)   | 89 |
| Isentropic efficiency, air compressor (%)| 86 |
| Power generator efficiency (%)           | 98.62 |
| Pinch temperature Difference of HRSG (°C ) | 15 |
| Pressure loss of HRSG (%)                | 3 |
| Steam turbine inlet temperature (°C)     | 535 |
| Isentropic efficiency, steam turbine, HP, M-L (%) | 88, 85 |
| Condensation pressure, bar               | 0.035 |

Fig. 3 shows that the drops in air temperature resulting from the proposed cold production process are about 1.1 °C to 2.3 °C at a relative humidity of 90%, and 4.4 °C to 4.5 °C at a relative humidity 30%, higher than that of the traditional cold production process. The heat duty in the air cooler is more significantly affected by the LNG consumption change due to the ambient temperature change compared to that due to the humidity change. The heat duty is also partially affected by the cooling water...
temperature as assumed in Table 1. The relative humidity more significantly affects the air temperature drop than ambient temperature.

The results in Fig. 4 and Fig.5 show that, by the proposed air cooling process, the relative gas turbine power and relative combined cycle power are augmented by 2.4% to 17.3% and 2.2% to 14.4%, respectively, compared to those without air cooling, and are about 0.7% to 3.8% and 0.6% to 3.1% higher, respectively, than those by traditional air cooling. The proposed cold production process is very suitable for the ambient conditions of relatively high temperatures with a low relative humidity.

Fig. 4 Relative efficiency comparison between the proposed and traditional air cooling methods.

![Fig. 5 Relative power output of traditional air cooling.](image-url)

Fig. 5 Relative power output of traditional air cooling.

Fig. 6 depicts air cooling driven by the LNG cryogenic energy increase in efficiency as compared with the cold production without air cooling. The relative efficiency of the proposed air cooling method is about 0.7% to 2.2% higher than that of the cold production without air cooling, and about 0.3% to 0.5% higher than that of the traditional air cooling, depending mainly on the relative humidity.

5. Conclusions

A novel cold production process for inlet air cooling in a combined cycle fuelled with LNG has been analysed in this study. The cold output of the proposed process is shown to be higher by about 38.1% to 42.5% than that of the traditional cold production process. Compared to a combine cycle power plant without air cooling, the relative power output increase resulting from the proposed air cooling method varies from 2.2% to 14.4%, and its relative efficiency increases by 0.7% to 2.2%, depending on differences in the relative humidity. The relative power output and relative efficiency of the proposed air cooling method are 0.6% to 3.1% and 0.3% to 0.5% higher, respectively, than those of the traditional air cooling. The proposed method for the air cooling is very suitable for an ambient condition of relatively high temperatures with a low relative humidity.

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