Energy Proceedings
Vol 52, 2025
ISSN 2004-2965

# Thermodynamic Analysis of Combined Cycle Power Plant Fired with Ammonia[#]

Karpilov I[2,1], Papkov V[2,1], Pashchenko D[1,2,3*]

1 Department of Mechanical Engineering (Robotics), Guangdong Technion–Israel Institute of Technology, 241 Daxue Road, Guangdong, Shantou, 515063, China

2 Faculty of Mechanical Engineering, Technion - Israel Institute of Technology, Technion City, Haifa 3200003, Israel

3 Guangdong Provincial Key Laboratory of Materials and Technologies for Energy Conversion, Guangdong Technion–Israel Institute of Technology, 241 Daxue Road, Guangdong, Shantou, 515063, China

(Corresponding Author: dmitry.pashchenko@gtiit.edu.cn)

**ABSTRACT**

Ammonia is a perspective carbon-free fuel that can be used in gas turbines. In this paper, the concept of ammonia fed combined cycle power plant (CCPP) with chemically recuperated gas turbine (CRGT) is provided. The effect of operating parameters such as temperature, pressure and pressure ratio on the efficiency of combined cycle power plant is determined. The comparative analysis of CCPP with traditional gas turbine and chemically recuperated gas turbine is provided. The results of the thermodynamic analysis show that efficiency of CCPP with CRGT is significantly higher (up to 5.5%) than efficiency of CCPP with a conventional gas turbine without thermochemical exhaust heat recuperation. The ratio between the work output from steam turbine and gas turbine is determined to show that in CCPP with CRGT the higher amount of heat is used in gas turbine cycle. This ratio is 2-7% higher than for CCPP with simple gas turbine without exhaust heat recuperation.

**Keywords:** ammonia, gas turbine, thermochemical recuperation, hydrogen-rich fuel, thermodynamic analysis

## 1. INTRODUCTION

Transition to zero carbon energy and industry is crucial for mitigating the impacts of climate change and reducing greenhouse gas emissions [1]. It involves a shift towards renewable energy sources such as wind, solar, and hydropower, as well as implementing energy-efficient technologies, utilization of carbon-free fuels in industries. China is the largest producer of renewable energy in the world and has set a target to achieve carbon neutrality by 2060 [2].

However, despite the progress made in the use of renewable energy sources such as solar and wind, their share in the energy balance remains relatively small. The production of electricity through thermal power plants by burning fossil fuels is still dominant. Ammonia has the potential to be a way to zero carbon energy because it can be produced from renewable sources such as wind and solar power [3]. In addition, ammonia can be used as a fuel for power generation [4]. It has a moderate high energy density, which makes it a viable alternative to fossil fuels such as natural gas and diesel. Additionally, ammonia does not produce greenhouse gas emissions when burned, making it a zero carbon fuel. Another advantage of ammonia is that it can be easily transported and stored in comparing with hydrogen [5].

The use of ammonia as a fuel in gas turbines is promising in order to reduce carbon dioxide emissions and achieve carbon-free generation of electricity. The use of ammonia as a fuel for gas turbines is still in the early stages of development, but there has been some promising progress in recent years. Despite researcher's and engineer's efforts, there are still some challenges that need to be addressed in order to make ammonia-fed gas turbines a viable option for commercial use. One of the main challenges is the development of effective schematic diagrams, reducing the emissions of nitrogen oxides ($NO_x$), which can be produced when ammonia is burned, and low combustion efficiency due to the low flame speed and long quenching distance of the fuel. This paper aims to provide the thermodynamic analysis of ammonia fed combined cycle power plant with chemically recuperated turbine.

## 2. SCHEMATIC DIAGRAM AND METHODOLOGY

Recently, the thermochemical exhaust heat recuperation systems found a wide discussion for application in the different fuel consuming equipment such as industrial furnaces, internal combustion

# This is a paper for the 16th International Conference on Applied Energy (ICAE2024), Sep. 1-5, 2024, Niigata, Japan.

engines, etc. The concept of chemically recuperated gas turbines was firstly reported in 1970s by Olmsted and Grimes [6].

Generally, the concept of thermochemical recuperation is based on the use of exhaust heat for the endothermic fuel transformation before its combustion [7-9]. As a result of this transformation, the new gas fuel is produced and the lower heating value of this mew fuel is higher than the lower heating value of the original fuel.

parameters. This analysis showed the overall efficiency of CCPP with CRGT as a function of operating parameters [10].

A share of exhaust heat used in a reformer is depending on the enthalpy of ammonia decomposition reaction. In parallel, the enthalpy of ammonia decomposition reaction is depending on process variables such as temperature and pressure. Moreover, these variables are also affecting on product distributions after a reformer.

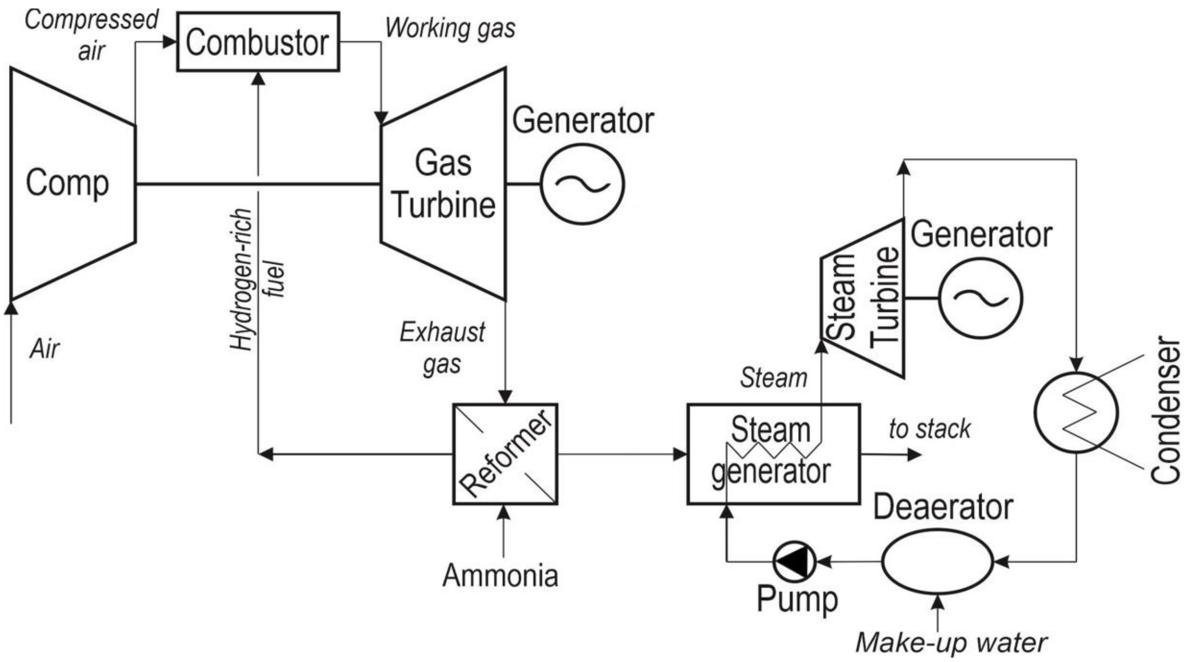


*Fig. 1 The schematic diagram of ammonia fed combined cycle power plant with chemically recuperated gas turbine*

The schematic diagram of ammonia fed combined cycle power plant with chemically recuperated gas turbine is presented in Fig.1. Exhaust heat after gas turbine is used as heat sources for the endothermic reaction of ammonia decomposition:

$2NH_3 = N_2 + 3H_2$; $\Delta H_{298} = 46.19$ kJ/mol (1)

The products of ammonia decomposition – hydrogen-rich gas are fed to the combustion chamber for the combustion process.

In addition, in this paper, ammonia fed combined cycle power plant with traditional gas turbine when exhaust heat is used for steam generation is analyzed.

The thermodynamic analysis of the ammonia fed combined cycle power plant with chemically recuperated gas turbine has been performed with the help of Aspen HYSYS. This software is a widely used process simulator for the modeling of the different schemes including the schemes with chemical reactions. Aspen HYSYS makes it possible to model compression and expansion, combustion, chemical reaction, etc. Based on the developed model, the thermodynamic analysis was conducted for a wide range of operating

The equilibrium conditions of the ammonia decomposition system are calculated by using the Gibbs free energy minimization method with using the Peng-Robinson equation of state. The detailed algorithm and governing equations were presented in author's previous papers [11, 12]. The thermodynamic analyses of ammonia decomposition under various operating variables were conducted via Aspen HYSYS software.

The thermodynamic analysis makes it possible to calculate the equilibrium concentration of the reforming products at the given operating parameters such as temperature and pressure.

In order to make a comprehensive comparative analysis, the working fluid temperature at the gas turbine inlet has been set as constant for all analyzed schemes (CCPP with CRGT and CCPP with traditional gas turbine). The temperature range of working fluid at the gas turbine inlet is from 800 to 1200℃. Other initial conditions and turbine parameters for a parametric analysis are presented in Table 1.

*Table 1 – Stream properties and efficiency parameters of gas turbine and compressor*

| Parameter | Value |
|---|---|
| Ammonia mass flow rate | 100 kg/h |
| Turbine isentropic efficiency | 0.90 |
| Compressor isentropic efficiency | 0.85 |
| Inlet temperature of ammonia | 20°C |
| Temperature of atmospheric air | 20°C |
| Pressure ratio | 5-20 |

## 3. RESULTS AND DISCUSSION

The efficiency of ammonia-fed chemically recuperated gas turbine in combined cycle power plant depends on operational parameters such as temperature and pressure.

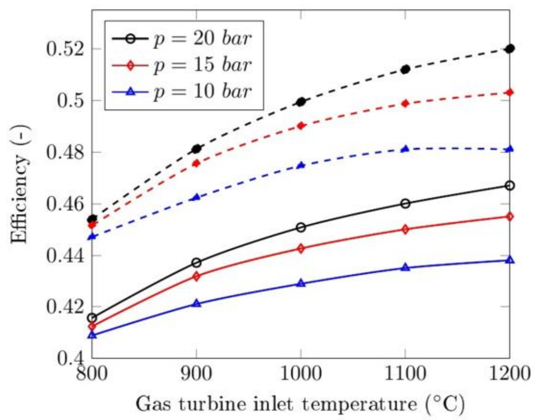


*Fig. 2 Efficiency of ammonia fed CCPP with CGRT (dashed lines) and CCPP with simple gas turbine (solid lines)*

Fig. 2 shows the effect of temperature and pressure on the efficiency of a combined cycle power plant (CCPP) with chemically recuperated gas turbine (CRGT) (dashed line) and CCPP with a simple gas turbine (solid line). The pressure in Fig. 2 corresponds to the pressure ratio and pressure for the ammonia decomposition process.

Fig. 2 clearly demonstrates that the use of a chemically recuperated gas turbine for an ammonia-fed CCPP significantly increases the efficiency compared to a CCPP with a simple gas turbine without recuperation. An increase in pressure (pressure ratio) has different effects on the efficiency. For low-pressure CRGT, an increase in the turbine inlet temperature above 1000°C leads to an insignificant increase in efficiency. However, for high-pressure CRGT, an increase in the turbine inlet temperature leads to a notable increase in efficiency. This can be explained by the fact that for a CCPP with CRGT, the exhaust heat is recuperated and then used in the gas turbine cycle. The thermal efficiency of the gas turbine cycle is higher than the thermal efficiency of the steam turbine cycle. Therefore, more heat is used in the gas turbine cycle and less heat is used in the steam turbine cycle. The maximum increase in the efficiency of CCPP is observed in the temperature range below 1000°C. This is because the temperature of the exhaust gas after the gas turbine is higher than the temperature of the ammonia decomposition process required for full ammonia decomposition.

To further understand the effect of using a chemically recuperated gas turbine on the work output in a combined cycle power plant, the energy balance for a pressure of 20 bar as a function of turbine inlet temperature is shown in Fig.3. Fig.3a shows that the ratio of work output for the steam turbine and gas turbine in a CCPP with CRGT decreases with an increase in temperature. This is due to the fact that in this case, a larger amount of heat is used in the gas turbine cycle, which has a higher thermal efficiency than the steam

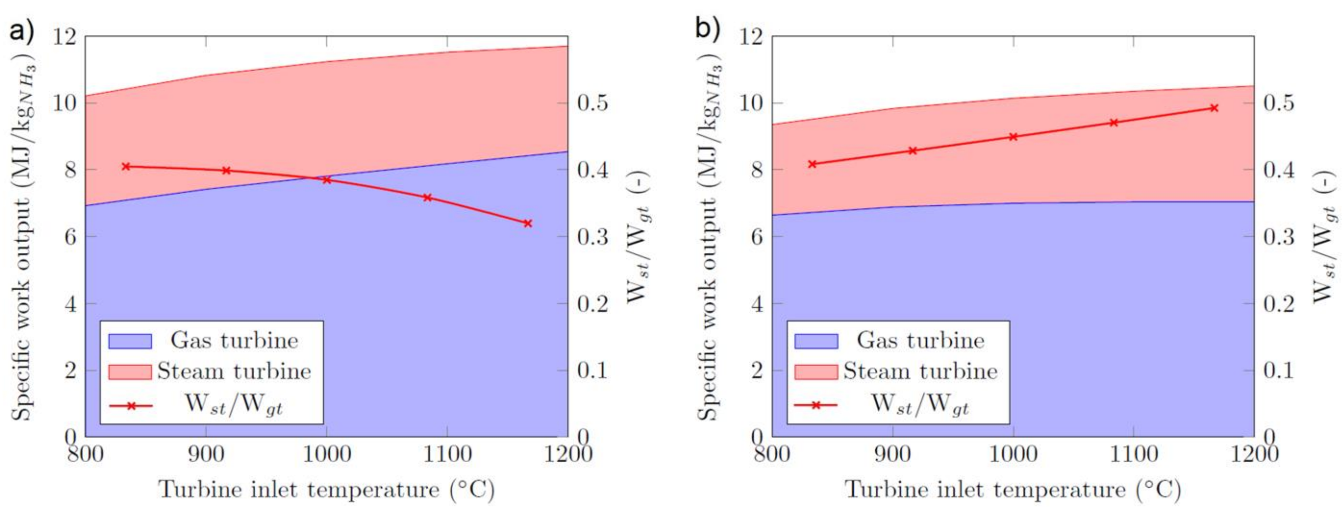


*Fig. 3 Specific work output and ratio of work output in steam turbine and gas turbine of CCPP with CRGT (a) and CCPP with simple gas turbine (b)*

turbine cycle. On the other hand, Fig. 4b shows the work output for a CCPP with a simple gas turbine. Fig.4b demonstrates that an increase in turbine inlet temperature leads to an increase in the ratio of steam and gas turbine work output because in this case, an increase in turbine inlet temperature leads to an increase in the exhaust gas temperature.

The results from Fig. 2 and Fig. 3 demonstrate that the use of a chemically recuperated gas turbine in an ammonia-fed combined cycle power plant increases the efficiency by utilizing more heat in the gas turbine cycle. This is due to the higher thermal efficiency of the gas turbine cycle compared to the steam turbine cycle. Additionally, the thermochemical transformation of ammonia produces a hydrogen-rich gas that improves combustion stability in the gas turbine. The combustion stability of ammonia is lower and its flame speed is slower compared to hydrogen. Therefore, the use of a chemically recuperated gas turbine not only increases thermal efficiency but also enhances combustion stability in an ammonia-fed CCPP.

In addition, it should be noted that the thermochemical ammonia transformation leads to generation of hydrogen rich gas. This hydrogen rich gas is used as a fuel in gas turbine. It is well known that the combustion stability of ammonia is notable lower than combustion stability of hydrogen. Moreover, the flame speed of ammonia is more than 10 times less than the flame speed of hydrogen [13]. Therefore, it should be expected that the use of chemically recuperated gas turbine in CCPP fueled with ammonia will lead not only to an increase of thermal efficiency but also to an increase of the combustion stability.

## 4. CONCLUSION

In this paper, the concept of ammonia fed combined cycle power plant with chemically recuperated gas turbine is investigated. The thermodynamic analysis of the cycle and recuperation system of an ammonia-fed CCPP is performed. The thermochemical exhaust heat recuperation system is based on the endothermic reaction of ammonia decomposition. The analysis is performed for a wide range of operating parameters: turbine inlet temperature of 800-1200°C, the pressure of 10-20 bar. The comparison of the efficiency of CCPP with CRGT and CCPP with simple gas turbine shows that the addition of the thermochemical exhaust heat recuperation system leads to a significant increase in the thermal efficiency of CCPP up to 5%. The main reason for an increase in the thermal efficiency is an increase of amount of heat that used in the gas turbine cycle that has higher thermal efficiency than steam turbine cycle.

Furthermore, in an ammonia-fed CCPP with a CRGT, the thermochemical transformation of ammonia produces a hydrogen-rich gas. This hydrogen-rich gas improves combustion stability in the gas turbine. It is important to note that the combustion stability of ammonia is lower and its flame speed is lower compared to hydrogen. Therefore, the use of a chemically recuperated gas turbine not only increases thermal efficiency but also enhances combustion stability in an ammonia-fed CCPP.

## REFERENCE

[1] Chien F, Vu TL, Phan TT, Van Nguyen S, Anh NH, Ngo TQ. Zero-carbon energy transition in ASEAN countries: The role of carbon finance, carbon taxes, and sustainable energy technologies. Renewable Energy 2023;212:561-9.

[2] Wang Y, Zhang D, Ji Q, Shi X. Regional renewable energy development in China: A multidimensional assessment. Renewable and Sustainable Energy Reviews. 2020;124:109797.

[3] Frattini D, Cinti G, Bidini G, Desideri U, Cioffi R, Jannelli E. A system approach in energy evaluation of different renewable energies sources integration in ammonia production plants. Renewable Energy. 2016;99:472-82.

[4] Valera-Medina A, Xiao H, Owen-Jones M, David WI, Bowen PJ. Ammonia for power. Progress in Energy and combustion science. 2018;69:63-102.

[5] Wan Z, Tao Y, Shao J, Zhang Y, You H. Ammonia as an effective hydrogen carrier and a clean fuel for solid oxide fuel cells. Energy Conversion and Management. 2021;228:113729.

[6] Olmsted JH, Grimes PG. Heat engine efficiency enhancement through chemical recovery of waste heat. In7th intersociety energy conversion engineering conference 1972;2:42-53.

[7] Tartakovsky L, Sheintuch M. Fuel reforming in internal combustion engines. Progress in Energy and Combustion Science. 2018;67:88-114.

[8] Popov SK, Svistunov IN, Garyaev AB, Serikov EA, Temyrkanova EK. The use of thermochemical recuperation in industrial plant. Energy. 2017;127:44-51.

[9] Mardani M, Tsolakis A, Nozari H, Herreros JM, Wahbi A, Sittichompoo S. Synergies in renewable fuels and exhaust heat thermochemical recovery in low carbon vehicles. Applied Energy. 2021;302:117491.

[10] Pashchenko D, Mustafin R, Karpilov I. Efficiency of chemically recuperated gas turbine fed with methane: Effect of operating parameters. Applied Thermal Engineering. 2022;212:118578.

[11] Pashchenko D. Thermochemical waste-heat recuperation as on-board hydrogen production technology. International Journal of Hydrogen Energy. 2021;46(57):28961-8.
[12] Pashchenko D, Mustafin R. Ammonia decomposition in the thermochemical waste-heat recuperation systems: A view from low and high heating value. Energy Conversion and Management (2022);251:114959.
[13] Xiao H, Valera-Medina A, Bowen PJ. Modeling combustion of ammonia/hydrogen fuel blends under gas turbine conditions. Energy & Fuels. 2017;31(8):8631-42.