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Analysis and simulating recuperator impact on the thermodynamic performance of the combined water-ammonia cycle

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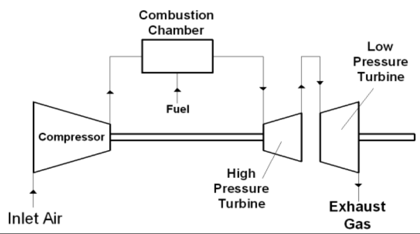
GRAPHICAL ABSTRACT



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ABSTRACT

In this study Analysis and simulating recuperator impact on the thermodynamic performance of the combined water-ammonia cycle will be investigated. Due to the importance of power generation cycles including double cycles, many studies have been conducted in recent years in this field and many researchers have tried to optimize these cycles using existing methods. In this study, the water-ammonia cycle has been studied. The aim of this paper is to examine the recuperator on the thermodynamic performance of the combined water-ammonia cycle. First, the water-ammonia power generation cycle has been modeled in the current study then, in order to study and compare, the combined Gas-Rankine cycle has been simulated thermodynamically and have been studied from the perspective of the first and second laws of thermodynamics. Finally, the effect of the recuperator on thermodynamic performance has been investigated.

INTRODUCTION

In the combined water-ammonia cycle, the double-ammonia mixture is used as the operating fluid. This cycle enables using resources such as waste energy, normal power cycle or an independent heat source that uses solar energy or global warming. Gas turbines have many uses, the most important of which is in the propulsion of various types of aircraft however, in industries, gas turbines are also used to operate mechanical devices such as pumps, compressors and small generators of electricity, and especially to provide peak loads and intermediate loads and sometimes basic loads [1]. Gas turbines are also increasingly used in combined power stations cycle. These power stations are made of a combination of vapor and gas turbines and there are several types of heat

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recovery devices depending on the type of turbine [2]. Gas turbines used in power stations and industries has many advantages. The size of a gas turbine power station in compared to a vapor power station is smaller, lighter and its initial cost per power unit of generation is less than the cost of a vapor power station. The required time to deliver gas turbine is relatively short and it can be installed and used quickly [3]. The operation of turbine power stations is fast and often through remote control. By using gas turbine, in addition to generating electricity, some side needs can be met, such as compressed air production. A variety of liquid and gaseous fuels, including new synthetic fuels such as low-value gases can be used in gas turbines. Gas turbines have fewer environmental limitations in compared to other major production devices [4]. By using gas turbines in combined cycles, its efficiency can be reduced and as a result, it was used as a power station. At the same time, its other benefits, such as fast start-up and its functional flexibility have been widely used. Gas turbines may have single-axis or two-axis arrangement (Fig. 1). In the recent type of arrangement, two axes are used that rotate at different speeds. On one axis of the compressor and the turbine that feeds the compressor, while on the other axis of the turbine are the external power and load. There may also be high pressure on one compressor and turbine axis, and low pressure and external load on the other compressor and turbine axis. In any arrangement, the part of the system that includes the compressor, combustion chamber and high-pressure turbine is called the generator. In two-axis arrangement, it is possible that the load velocity varies and this is appropriate for several cases of industrial applications [5-8].

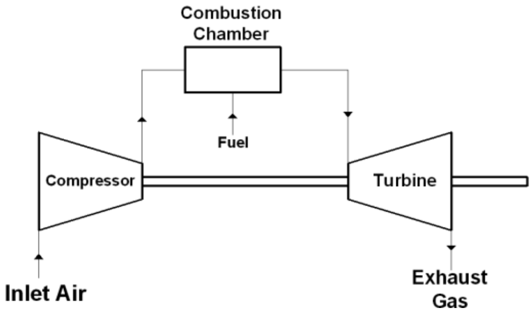

Fig.1. Single-axis open and direct gas turbine cycle

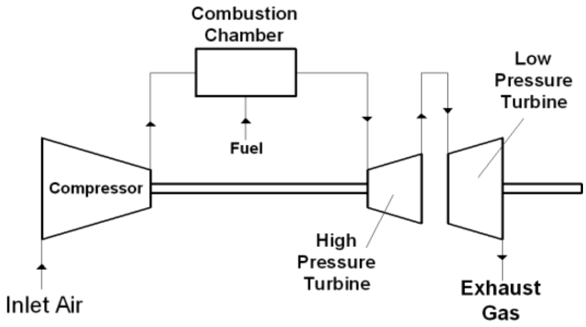

Fig. 2. Two-axis open and direct gas turbine cycle

Sometimes gas turbines designed for aircraft propulsion are used to make improvements to industrial applications. In single-axis turbines, the compressor, turbine and load are placed on a single axis that rotates at a constant speed. This type of arrangement is used to run small generators as well as large power generators in power stations [9].

Simulation and analysis of combined cycles

To simulate thermal cycles, equations must be written separately for each component, and then these materials must be dissolved together in one device and the temperature, pressure, flow, etc. must be obtained at each point. In this study, the combined gas-ammonia water cycle (Fig. 3) and for better comparison of the combined Gas-Rankin cycle (Fig. 4) have been studied. It should be noted that the indexes used in this season's relations are as follows.

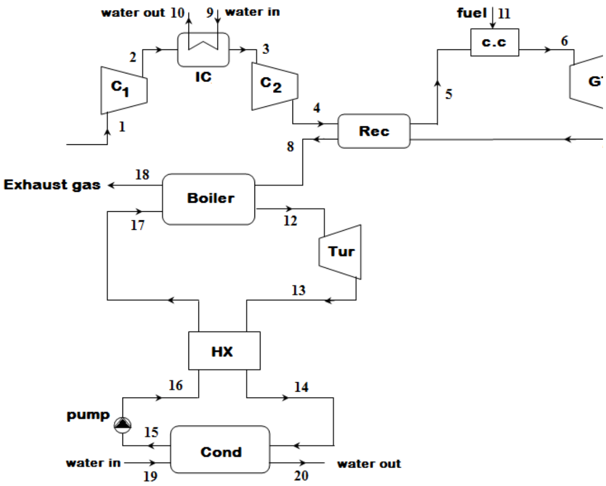

Fig. 3. Combined gas-ammonia water cycle

In general, the energy equation for each component is assumed to be the control volume and will be written as follows:

$$\dot{Q} + \dot{n}_i \bar{h}_i = \dot{W} + \dot{n}_e \bar{h}_e \quad (1)$$

The energy balance equation in each component is shown as follows:

$$\dot{E}_{in} + \sum \dot{Q}_i \left(1 - \frac{T_0}{T_i}\right) = \dot{E}_{out} + \dot{W} + \dot{E}_D \quad (2)$$

$\dot{\mathbf{E}}$ represents the total energy at any point, which includes the sum of the physical and chemical exorcisms of the components at the desired point.

Physical energy in a thermodynamic system consists of two parts: mechanical and thermal energy.

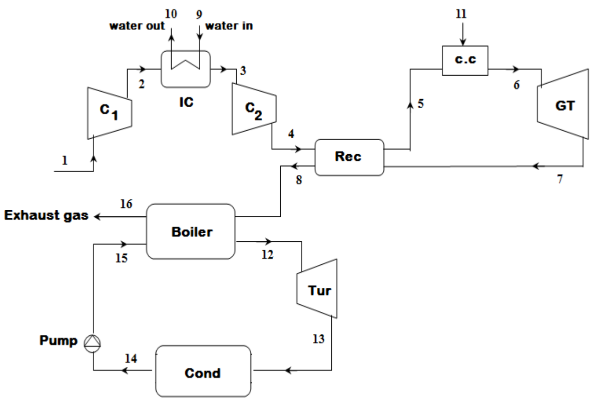

Fig. 4. Combined Gas-Rankin cycle

Mechanical is a function of the thermodynamic pressure system and thermal energy is a function of the thermodynamic temperature system [10-13]. Therefore, physical energy in a thermodynamic system can be shown as follows:

$$\dot{E}x^{ph} = \sum \{n_i [(h - h_0) - T_0(s - s_0)]\} \quad (3)$$

The chemical energy is equal to the maximum work produced when the chemical species of the thermodynamic system enables to mix and react chemically with the species in the environment. These reactions produce additional work called the system's chemical energy. Chemical energy is obtained by the following relation:

$$\dot{E}x^{ch} = \sum_i n_i \sum_i (x_i \,.\, ex_i^{ch} + RT_0\, x_i . \ln(x_i)) \quad (4)$$

$\mathbf{ex_i^{ch}}$ is a chemical energy specific to each system component and $\mathbf{X_k}$ is the molecular fraction of each thermodynamic system component. The general energy of the system is obtained from the following relation:

$$\dot{E}x^{tot} = \dot{E}x^{ph} + \dot{E}x^{ch} \quad (5)$$

The main destruction and production mechanisms of energy Entropy

Heat transmission:

Heat transmission reduces the ability to work because no work has been done between a higher and lower temperature object. Therefore, it is important to minimize the temperature difference between the sources among a heat exchanger to minimize the irreversibility of heat transmission.

Mixing:

Mixing is an irreversible process that reduces efficiency. Mixing is inevitable in many processes, such as combustion [14].

Friction:

Fluid friction is similar to mechanical friction. Internal friction in the components of the thermodynamic system wastes some of energy and prevents it from becoming useful [15].

Suppression:

In the process of suppression, the fluid is converted from a higher pressure to a lower pressure fluid. No work or heat is transferred during this process. The process of suppression is an irreversible process in which the ability to work is reduced [16].

Enthalpy and entropy of different components

The currents in the combined cycles have different components, so for each point the enthalpy and entropy must be calculated by separate equations. Enthalpy is obtained from any of the following relations:

$$h = \sum_i x_i \bar{h}_i \quad (6)$$

That $\mathbf{x_i}$ is the molar fraction of each point components and $\bar{\mathbf{h}}$ is the specific molar enthalpy of each point components.

The entropy of each point is obtained in the following equation:

$$s = \sum_i x_i \ s_i \quad (7)$$

That $\mathbf{x_i}$ is the molar fraction of each point components and $\mathbf{s_i}$ is the molar enthalpy of each point components.

For each component, the corresponding equations can be found in the following way [4, 17-19].

Compressor

The compressor function is to compress and raise the air pressure and input fuel to the cycle. By defining the Isentropic efficiency for the compressor and also by determining the input temperature and pressure to the turbine, it is possible to calculate the temperature and pressure at the compressor output using the equations under temperature [10, 20].

To calculate the optimal intermediate pressure of the two compressors, we use the following equation:

$$PR_c = \frac{P_4}{P_1} \quad (8)$$

In the compressor, the low pressure is calculated by using the known temperature and pressure at the compressor input and by using the relation between temperature and pressure at the compressor output.

By writing the energy balance equation for the low pressure compressor, the required power by the low pressure compressor is obtained:

$$P_2 = \sqrt{P_1 \ P_4} \quad (9)$$

Also, by writing the energy balance, the energy destruction in the low pressure compressor is obtained:

$$s_1 = s_{2s} \quad (10)$$

$$\eta_{c1} = \frac{h_1 - h_{2s}}{h_1 - h_2} \quad (11)$$

The same process will be repeated for the high pressure compressor and the following relations will be obtained:

$$\dot{W}_{c1} = \dot{n}_2 \bar{h}_2 - \dot{n}_1 \bar{h}_1 \quad (12)$$

And the energy destruction in the high pressure compressor is equal to:

$$\dot{E}x_{D,comp\ 1} = \dot{E}x_1 + \dot{W}_{c1} - \dot{E}x_2 \quad (13)$$

$$s_3 = s_{4s}$$

$$\eta_{c2} = \frac{h_3 - h_{4s}}{h_3 - h_4} \quad (14)$$

$$\dot{W}_{c2} = \dot{n}_4 \bar{h}_4 - \dot{n}_3 \bar{h}_3 \quad (15)$$

$$\dot{E}x_{D,comp\ 2} = \dot{E}x_3 + \dot{W}_{c2} - \dot{E}x_4 \quad (16)$$

Intercooler (intermediate cooler):

To analyze the intercooler, we need two coefficient effect equations and the energy survival equation for the intercooler, which are written as follows [21].

$$\epsilon_{IC} = \frac{q_{act}}{q_{max}} = \frac{C_{min}\ \Delta T}{C_{min}\ \Delta T_{max}} = \frac{T_2 - T_3}{T_2 - T_9} \quad (17)$$

The transferred heat from each current and $\mathbf{q_{max}}$ is the highest possible heat transmission in heat exchangers. Parameter **C** is the flow heat capacity. ε is one of the design parameters.

$$\dot{n}_w \left(\bar{h}_{10} - \bar{h}_9\right) = \dot{n}_a \left(\bar{h}_2 - \bar{h}_3\right) \quad (18)$$

By writing the energy balance for the intercooler, the energy destruction in the intercooler is obtained:

$$\dot{E}x_{D,IC} = \dot{E}x_2 + \dot{E}x_9 - \dot{E}x_3 - \dot{E}x_{10} \quad (19)$$

Recuperator:

Like the intercooler, the recuperator needs two equations, the impact factor and the energy survival equation, which are listed below:

$$\epsilon_{REC} = \frac{q_{act}}{q_{max}} = \frac{C_{min}\ \Delta T}{C_{min}\ \Delta T_{max}} = \frac{T_5 - T_4}{T_7 - T_4}$$

(20)

$$(\dot{n}_a + \dot{n}_f)\left(\bar{h}_7 - \bar{h}_8\right) = \dot{n}_a \left(\bar{h}_5 - \bar{h}_4\right) \quad (21)$$

Energy destruction is also described in the recuperator as follows:

$$\dot{E}x_{D,REC} = \dot{E}x_4 + \dot{E}x_7 - \dot{E}x_5 - \dot{E}x_8 \quad (22)$$

Combustion chamber:

To analyze the combustion chamber, it is first necessary to write the combustion equation in this chamber:

$$a\ CH_4 + (0.7748\ N_2 + 0.2059\ O_2 + 0.0003\ CO_2 + 0.019\ H_2O) \rightarrow (1+a)\left(x_{N_2}\ N_2 + x_{O_2}\ O_2 + x_{CO_2}\ CO_2 + x_{H_2O}\ H_2O\right) \quad (23)$$

The molar fractions of Nitrogen, Oxygen, Carbon dioxide [1, 22] and water vapor are obtained by the following equations:

$$x_{N_2} = \frac{0.7748}{1+a} \quad (24)$$

$$x_{O_2} = \frac{0.2059 - 2a}{1+a} \quad (25)$$

$$x_{CO_2} = \frac{0.0003 + a}{1+a} \quad (26)$$

$$x_{H_2O} = \frac{0.019 + 2a}{1+a} \quad (27)$$

In Equation (24) the molar ratio of fuel to air is as follows:

$$a = \frac{\dot{n}_f}{\dot{n}_a} \quad (28)$$

That:

$$\dot{n}_a = \frac{\dot{m}_a}{M_a} \quad (29)$$

$$\dot{n}_f = \frac{\dot{m}_f}{M_f} \quad (30)$$

You can also write:

$$1 + a = \frac{\dot{n}_p}{\dot{n}_a} \quad (31)$$

The energy survival equation for the combustion chamber is written as follows:

$$\bar{h}_a + a\bar{h}_f = (1 + a)\bar{h}_p + \dot{Q}_r \quad (32)$$

Where $\dot{\mathbf{Q}}_{\mathbf{r}}$ is the amount of heat dissipation from the combustion chamber, which is expressed by the following equation:

$$\dot{Q}_r = 0.02\, a\, .\, LHV_{CH_4} \quad (33)$$

$$(\dot{n}_a + \dot{n}_f)(h_6 - h_7) - \dot{n}_a (h_2 - h_1) - \dot{n}_a (h_4 - \bar{h}_3) = \dot{W}_{net} \quad (34)$$

There is also a relation between parameter ***a***, air and fuel mass flow rates:

$$\dot{m}_f = a \left(\frac{M_f}{M_a}\right) \dot{m}_a \quad (35)$$

Energy destruction in the combustion chamber is calculated by the following equation:

$$\dot{E}x_{D,comb} = \dot{E}x_5 + \dot{E}x_{11} - \dot{E}x_6 \quad (36)$$

Turbine:

By determining the temperature and pressure, and therefore the enthalpy related to the turbine input flow, as well as determining the turbine output pressure, using the following relations, the temperature and enthalpy at the turbine output and the ratio of turbine pressure are obtained [6, 23]:

$$s_6 = s_{7s} \quad (37)$$

$$\eta_T = \frac{h_6 - h_7}{h_6 - h_{7s}} \quad (38)$$

$$PR_T = \frac{P_6}{P_7} \quad (39)$$

Using the equations for energy and energy survival, the turbine output power and the energy destruction in the turbine are obtained:

$$\dot{W}_{GT} = (\dot{n}_a + \dot{n}_f)(\bar{h}_6 - \bar{h}_7) \quad (40)$$

$$\dot{E}x_{D,GT} = \dot{E}x_6 - \dot{E}x_7 - \dot{W}_{GT} \quad (41)$$

Using the following equation and the problems related to the combustion chamber, the amount of air flow rate and input fuel to the cycle is obtained:

Boiler:

In the boiler, the gas input and output temperature and the temperature difference between the boiler input gas and the output ammonia-water solution are specified. As a result, by writing the energy equation in the boiler, the amount of mass flow of ammonia water solution is calculated [24]:

$$(\dot{n}_a + \dot{n}_f)(\bar{h}_8 - \bar{h}_{18}) = \dot{m}_{NH_3H_2O}(h_{12} - h_{17}) \quad (42)$$

Energy destruction in the boiler is also calculated from the following equation:

$$\dot{E}x_{D,boiler} = \dot{E}x_8 + \dot{E}x_{17} - \dot{E}x_{12} - \dot{E}x_{18} \quad (43)$$

Pump:

Using the following relation, the output enthalpy of the pump is calculated:

$$\frac{v_{15}(P_{16} - P_{15})}{\eta_p} = h_{16} - h_{15} \quad (44)$$

To the right of the above equation shows the specific function required by the pump [25].

Energy destruction at the pump is also calculated as follows:

$$\dot{E}x_{D,pump} = \dot{E}x_{15} - \dot{E}x_{16} - \dot{m}_{NH_3H_2O}(h_{16} - h_{15}) \quad (45)$$

Heat exchanger:

The heat exchanger, like the recuperator needs to write the equations for the effect of energy efficiency and survival, which are written as follows [26]:

$$\epsilon_{HX} = \frac{q_{act}}{q_{max}} = \frac{C_{min}\ \Delta T}{C_{min}\ \Delta T_{max}} = \frac{T_{13}-T_{14}}{T_{13}-T_{16}} \quad (46)$$

$$h_{13} - h_{14} = h_{17} - h_{16} \quad (47)$$

And the energy destruction in the heat exchanger is as follows:

$$\dot{E}x_{D,HX} = \dot{E}x_{13} + \dot{E}x_{16} - \dot{E}x_{14} - \dot{E}x_{17} \quad (48)$$

Condenser:

A water cooler is used to cool the input ammonia solution condenser [27]. By determining the mass flow and condenser input water temperature and pressure, the output enthalpy and the energy destruction related to the condenser are respectively obtained by writing the energy survival equation and energy survival:

$$\dot{m}_{19}(h_{20} - h_{19}) = \dot{m}_{NH_3H_2O}(h_{14} - h_{15}) \quad (49)$$

$$\dot{E}x_{D,cond} = \dot{E}x_{19} + \dot{E}x_{14} - \dot{E}x_{15} - \dot{E}x_{20} \quad (50)$$

The output power in the ammonia water power generation cycle is calculated from the following equation:

$$\dot{W}_{NH_3H_2O} = \dot{m}_{NH_3H_2O}(h_{12} - h_{13}) - \dot{m}_{NH_3H_2O}(h_{16} - h_{15}) \quad (51)$$

The first term is on the right side of the turbine power generation equation and the second term is pump consumption power.

General cycle analysis:

The thermodynamic efficiency of the gas turbine cycle is calculated from the following equation:

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{m}_f.LHV} \quad (52)$$

Also, the total efficiency of the combined cycle is obtained from the following equation:

$$\eta_{th,overall} = \frac{\dot{W}_{net} + \dot{W}_{NH_3H_2O}}{\dot{m}_f.LHV} \quad (53)$$

The combined cycle power generation includes the total power generated in the gas turbine cycle and the ammonia water power generation cycle:

$$\dot{W}_{overall} = \dot{W}_{net} + \dot{W}_{NH_3H_2O} \quad (54)$$

The total energy losses in the gas turbine cycle and the ammonia water power generation cycle are equal to:

$$\dot{E}x_{D,tot,GT} = \dot{E}x_{D,tot,comp1} + \dot{E}x_{D,tot,comp2} + \dot{E}x_{D,tot,GT} + \dot{E}x_{D,tot,comb} + \dot{E}x_{D,tot,IC} + \dot{E}x_{D,tot,REC} \quad (55)$$

The Exercise performance ratio, which is the ratio of the power generated to the exercise losses, for the gas turbine cycle and the combined cycle, is obtained from the following relations [28]:

$$\dot{E}x_{D,tot,NH_3H_2O} = \dot{E}x_{D,tot,pump} + \dot{E}x_{D,tot,cond} + \dot{E}x_{D,tot,Tur} + \dot{E}x_{D,tot,boiler} \quad (56)$$

$$EPC = \frac{\dot{W}_{net}}{\dot{E}x_{D,tot,GT}} \quad (57)$$

$$EPC_{overall} = \frac{\dot{W}_{net} + \dot{W}_{NH_3H_2O}}{\dot{E}x_{D,tot,GT} + \dot{E}x_{D,tot,NH_3H_2O}} \quad (58)$$

The results of the turbine input temperature impact on performance of the combined cycle using EES software

By increasing the recuperator impact factor, the amount of net specific performance produced by the gas turbine cycle is reduced. On the other hand, by increasing the recuperator impact factor, the input air temperature to the combustion chamber increases.

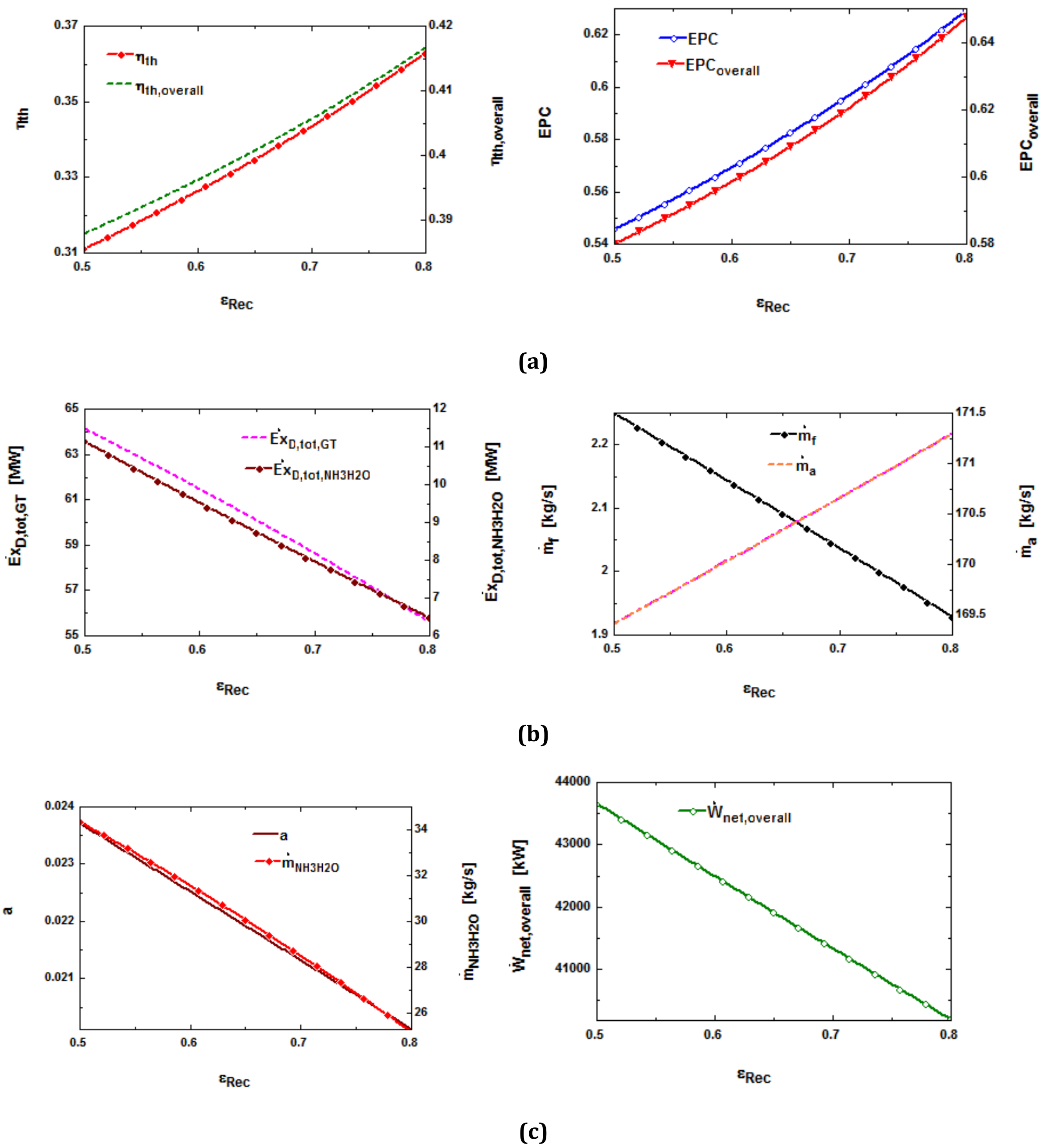

Fig. 5. The effect of turbine input temperature on combined thermodynamic cycle performance

Therefore, due to the constant net power generation of gas turbine cycle, according to the **Fig 5a**, the input air flow cycle rate increases and the input fuel flow cycle decreases, but in general the transient gas through the turbine increases. Considering the **Fig. 5b** and knowing that the net power generation of gas turbine is constant and input fuel mass flow cycle rate decreases, the thermodynamic efficiency of gas turbine cycle and combined cycle will increase.

Also, according to the **Fig. 5c**, by increasing the recuperator performance factor the mass flow rate of ammonia water solution will decrease and parameter ***a*** will decrease due to increase of air flow and decrease of fuel flow. However, as the performance factor increases the boiler input gas temperature of the ammonia water power generation cycle decreases. Therefore, due to the reduction of the ammonia water flow solution in the ammonia water power generation cycle, the net power generation of the ammonia water cycle has decreased and in general, due to the constant net power generation of the gas turbine cycle, the total power generation of the combined cycle will decrease by increasing the recuperator performance factor.

As the performance factor increases, the energy destruction of the combustion chamber decreases due to the increase in input air temperature and because this energy destruction predominates in the energy destruction gas turbine cycle, it reduces the energy destruction of the entire gas turbine cycle. It should be noted that by increasing the recuperator performance factor, the recuperator energy destruction decreases and the high and low pressure compressors energy destruction, intercooler and gas turbine increases. The same effect of combustion chamber is repeated in the ammonia water power generation cycle boiler and reduces the entire ammonia water cycle energy destruction. According to the Fig. 5b shows that the EPC behaves exactly the opposite of energy destruction and increases by increasing the recuperator performance factor, both in the gas turbine cycle and in the combined cycle and ammonia water cycle [29].

CONCLUSION

1. By increasing the recuperator impact factor, the net specific performance produced by the gas turbine cycle decreases, on the other hand, by increasing the recuperator impact factor, the input air temperature of combustion chamber increases.

2. By increasing the recuperator performance factor, the mass flow rate of ammonia water solution will decrease and parameter ***a*** will decrease due to increasing air flow and decreasing fuel flow.

3. However, as the performance factor increases, the boiler input gas temperature of the ammonia water power generation cycle decreases. Therefore, due to the flow reduction of ammonia water solution in the ammonia water power generation cycle, the net power generation of ammonia water cycle has decreased and in general, due to the constant net power generation of gas turbine cycle, the total power generation of combined cycle will decrease by increasing the recuperator performance factor.

4. As the performance factor increases, the energy destruction of combustion chamber decreases due to the increase in the input air temperature and because this energy destruction predominates in the gas turbine cycle energy destruction, it reduces the energy destruction of the entire gas turbine cycle. It should be noted that by increasing the recuperator performance factor, the recuperator energy destruction decreases and the high and low pressure compressors energy destruction, intercooler and gas turbine increases.

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