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Exergy-Driven Optimization of Ammonia as a Sustainable Cooling Agent for Water-Constrained Power Systems

Zahra Khodabandeh[1], Seyed Mahmood Kia[1], Fatemeh Aminipour[1], Asma Mozaffari[1], Hasan Hosseini[1], Ali Jahangiri[1,*]

[1] Faculty of Mechanical and Energy Engineering, Shahid Beheshti University, Tehran, Iran; zahra.khdbndh@gmail.com; mahmoud.kia.73@gmail.com; aminipourfateme27@gmail.com; a.mozefferi@mail.sbu.ac.ir; Hs.hoseini24@gmail.com; a_jahangiri@sbu.ac.ir.

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Abstract

The present study investigates the exergy analysis of an ammonia-based cooling system for combined cycle power plants as an alternative to conventional methods using water. The study, in particular, looks at the influences of ammonia on exergy change and environmental advantages by using ammonia as a substitute for water in the cooling system. Its lower boiling point and higher latent capacity make it an attractive alternative, especially in water-scarce regions. The performances of ammonia-based systems are compared with those of water-cooled counterparts through thermodynamic simulations and case studies. It is shown that from the ammonia-based cooling cycle, exergy losses are 27.34% less than water-cooled systems during the colder seasons, mainly due to smaller losses in other components than the condenser. On the other hand, exergy losses rise by 5.57% in warmer seasons because ammonia's efficiency drops at high temperatures due to enthalpy and entropy effects. This clearly shows that ammonia-based systems experience higher inefficiencies in warmer environments than water-cooled systems, which stamps the temperature sensitivity of ammonia in cooling applications. These findings suggest that ammonia-based cooling systems improve efficiency and significantly reduce water.

Keywords: Exergy analysis, Ammonia, Cooling systems, Power plants, Energy efficiency.

1 | Introduction

The efficiency of cooling systems is very critical to power plants to keep at bay the excess heat produced during the generation of electricity. Water has been the traditional and widely used cooling medium due to its abundance and effective heat-removal ability. However, with increased environmental concerns and increasing water scarcity, especially in arid regions, searching for alternative cooling methods has become

Corresponding Author: a_jahangiri@sbu.ac.ir

important. Among the candidates, ammonia should be one of the most promising substitutes, since it has better thermodynamic properties, such as a lower boiling point and a higher latent heat, making it more efficient at heat absorption and rejection compared with water. Replacement aims at the reduction of the flow rate of the cooling fluid, improvement of heat transfer conditions, and recovery of part of the losses in the cooling system [1]. If it is the case that, during heat transfer inside the condenser, the cooling fluid undergoes a phase change, then a lower flow rate and a smaller heat transfer surface can achieve the required thermal power. Since the water thermodynamically behaves at temperatures corresponding to steam and ambient conditions without undergoing phase change within the cooling pipes, Therefore, to use the phase change of the cooling fluid, it has to be replaced by some other fluid different from water. By researching the thermodynamic conditions of several fluids and considering their cost as well, ammonia might seem to be a good replacement for water in the cooling system.

The thermodynamic benefits of ammonia make it not only an effective cooling medium but also a substance open to further improvements in heat transfer efficiency. Such improvement, brought about by the use of advanced techniques like the addition of nanofluids, optimization of flow patterns, and modification of the flow regime, is quite substantial. Nanofluids with better thermal conductivity vastly improve heat transfer when used with design optimizations like turbulators and optimized pipe geometries [2–4]. These changes increase fluid mixing and flow patterns, thereby enhancing the system performance along with the reduction in fossil fuel consumption and lowering CO2 emissions. These thermal management improvement integrations when incorporated with the ammonia-based systems result in maximum cooling and enhance the environmental sustainability due to the power plant operations [5–8].

Furthermore, exergy analysis is a powerful second-law-based tool for putting a finger on inefficiencies in cooling systems. Energy quality, as measured by exergy analysis, shows massive energy losses occurring in condensers during the ammonia evaporation process. This lost energy, possessing more work potential than liquid water, can be recovered using turbo expanders, converting wasted energy into useful work and thus further improving the overall efficiency of the power plant. The recovery of this otherwise wasted energy is the key to increasing ammonia's role as an alternative cooling medium. Most of the previous research has been centered on the optimization of cooling systems using different refrigerants such as water, ammonia, and organic fluids [8–14]. Studies showed that ammonia, due to its lower boiling point and higher latent heat, was a better alternative in power plants, especially in regions where water scarcity was a big issue. Few studies examined the integration of ammonia-water mixtures into complex systems to demonstrate great promise in water savings and enhancements in cooling and power generation efficiencies, mainly for arid regions. Energy and exergy analyses for a 200 MW steam power plant by Ahmadi and Toghraie [15].

They applied the mass, energy, and exergy balance equations for each component of the power cycle to the entire system for the calculation of energy efficiency, exergy efficiency, and irreversibility for every component. Their analysis showed that the condenser has the most significant energy loss while the boiler leads to the largest exergy loss. Similarly, Yuan and Mi [16] analyzed the energy and exergy of the Rankine cycle for underwater power plants and compared working fluids like water and CO2. They found that an increase in water depth enhances the thermal efficiency. The water cycle was found to have the highest values for thermal and exergy efficiencies but demanded the most energy input, while CO2 works effectively with lower input and has a smaller turbine output. The highest exergy losses of about 90% occurred in the condenser and boiler. Mehrpooya et al. [17] optimized a combined system comprising a Rankine cycle, an ammonia-water absorption refrigeration cycle, and a solid oxide fuel cell. In this system, the recovered heat in the Rankine cycle is used in the absorption refrigeration cycle, and the exceeded energy will be stored in the fuel cell. The ammonia-water solution is used as the working fluid in the refrigeration cycle. The parameters under study were turbine steam pressure and gas outlet temperature, and the results achieved were an electrical efficiency of 62.4% and a cooling capacity of 110 kW.

The effectiveness of an ammonia-water power and cooling system was also realized by Pacheco-Reyes et al. [18], reaching an exergy efficiency of 26%, demonstrating its effectiveness for areas where water is scarce.

Jiménez-García et al. [19] analyzed the ammonia-water absorption cooling system; the highest ECOP obtained was 14.4%, depending on heating and cooling water temperatures. All studies point out that ammonia-based systems are quite promising for overcoming exergy losses and hence enhance performance in water-scarce environments. Ammonia-based systems hold great promise not only in the aspect of increasing energy efficiency but also in sustainability, as it drastically reduces water usage in power generation. Traditional thermal power plants use huge amounts of water for cooling; this is particularly problematic where water resources are already scarce. The studies conducted emphasize the use of ammonia-based cooling systems that can save water consumption up to 90%, thus making them attractive for power plants in arid areas [20]. Srivastava et al. [21] also worked on the concept of substituting alternative working fluids in place of water/steam in power plants, and their study showed a large destruction of energy at the source of heat; the losses were found to be as high as 1970 kJ/s at 500°C.

This paper explores ammonia as an alternative to water in the cooling systems of power plants, mostly in areas where water is scarce. Through detailed thermodynamic simulations and exergy loss analysis, this study attempts to answer the question of whether systems based on ammonia can bring improvements in cooling efficiency while reducing the overall environmental impact of power plant operations. Ammonia also has a higher latent heat, which allows for better heat transfer properties; this might result in a lower flow rate and smaller heat transfer surface area, potentially reducing the condenser size and cost. Further, the use of a turbo-expander in recovering energy from the ammonia vapor offers an opportunity to elevate overall plant efficiency by converting otherwise wasted energy into useful work.

2 | System Simulation

2.1 | Case Study

This research evaluates the integrated-cycle power plant, two of which are GE F9-type gas turbine units, each with a capacity of 123.4 MW, totaling 246.8 MW. These turbines act as primary energy conversion units and have a characteristic of high efficiency and operational flexibility, hence highly fitting in the satisfaction of both base-load and peak electricity demands. Apart from these gas turbines, the plant has a steam turbine that contributes an additional 102.5 MW to the total installed capacity of about 350 MW. This steam turbine is used in a combined cycle arrangement using waste heat from the gas turbines, greatly improving the overall thermal efficiency and thereby leading to more energy production with less fuel consumption [22], [23].

2.2 | Methodology

To calculate the exergy of water and ammonia cycle and compare them with each other, Thermoflow software has been used. The initial assumptions in using the ammonia cycle instead of the water cycle are the following: 1) It is assumed that the thermodynamic properties as well as the mass flow rate of the vapor leaving the turbine and entering the condenser, and of the water leaving the condenser and returning to the boiler, remain the same. 2) The physical parameters of the dry cooling tower are considered to be fixed, including its dimensions and the size and number of heat exchangers. 3) The airflow rate through the tower is considered constant. 4) Assuming ammonia evaporation in the steam condenser, the condenser outlet flow will be a vapor stream at substantial pressure. The resulting vapor stream can be used to generate electricity by incorporating an ammonia turbo-expander. This turbo-expander is mechanically compatible with the thermophysical properties of the ammonia vapor. It is of lesser size and power output compared to the main turbine.

The cycle considered here, shown in *Fig. 1* and *2*, starts with ammonia in the evaporator, which plays the role of the steam condenser in the main power plant cycle. This ammonia furnishes the cooling required by the steam leaving the turbine to condense and, in the process of absorbing heat from the steam, evaporates into vapor. This ammonia vapor flows into the turbo-expander, where it produces electrical power. Afterward, the vapor is directed to the cooling tower, where it condenses back into a liquid by transferring heat to the airflow passing through the tower's heat exchangers. In this setup, the cooling tower functions as the ammonia condenser. Finally, a pump compensates for the pressure drop caused by power generation in the expander, as well as frictional losses in other cycle components, enabling the liquid ammonia to return to the evaporator and complete the cycle. Another key characteristic of this facility is that it uses a dry cooling system, which dramatically reduces water consumption by as much as 95% compared with conventional evaporative methods. This system depends on air for the condensation of steam and is thus adapted to water-short areas. However, this is less efficient in elevated temperatures; on the other hand, dry cooling could offer a sustainable application by minimizing water withdrawals and supporting environmental water conservation policies [24], [25].

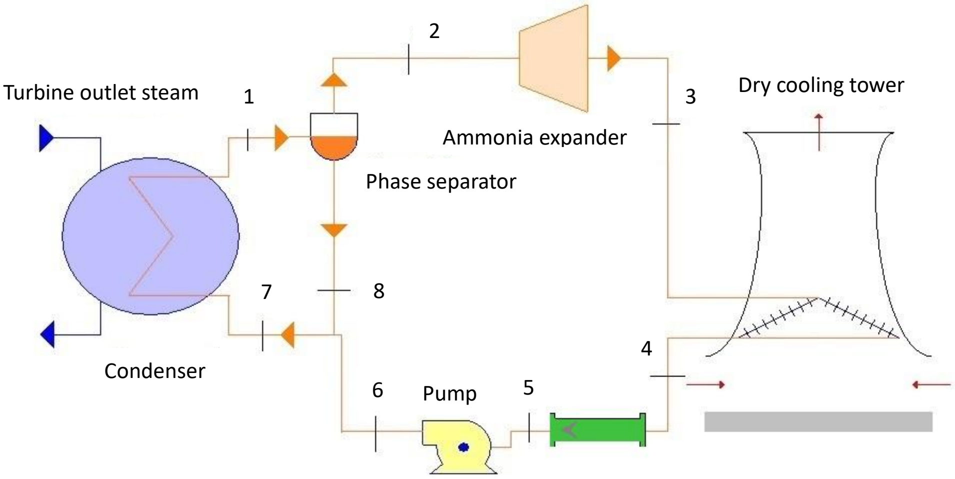

Fig. 1. Cooling cycle with ammonia replacement.

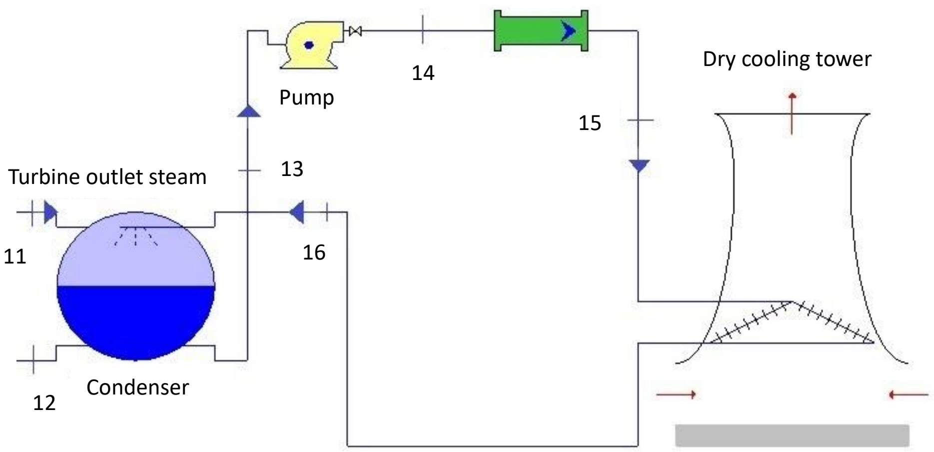

Fig. 2. Primary cooling cycle.

3 | Mathematical Formulation

Energy balance and exergy balance equations are the key ones for energy quality and degradation. Energy degradation refers to the irreversible losses accompanying all real processes. From the second law of thermodynamics [25], the exergy balance is written by the following *Eq. (1)*.

$$\sum \psi_Q + \sum \dot{m}_i \psi_i \, \psi_i = \sum W + \sum \dot{m}_o \psi_o + \dot{I}_{destroyed}. \tag{1}$$

In *Eq. (1)*, ψ_i and ψ_o represent the exergy input to and output from, the control volume, respectively. The term $\dot{I}_{destroyed}$ is the irreversibility, and ψ_Q represents the exergy due to heat transfer at temperature T, given by the relation in *Eq. (2)* [26].

$$\psi_Q = Q(1 - \frac{T_0}{T}). \tag{2}$$

Since the changes in potential and kinetic energy are insignificant, the specific exergy of the flow could be determined from *Eq. (3)* [27].

$$\psi = (h - h_0) - T_0(s - s_0). \tag{3}$$

where T_0, h_0, and s_0 are the ambient reference state. The flow exergy, Ex, is obtained as a product of the mass flow rate by the specific exergy given by *Eq. (4)* [28].

$$Ex = \dot{m}\,\psi. \tag{4}$$

The second-law efficiency $\eta_{2,l}$ defines the effective utilization of the exergy input, and it is defined in *Eq. (5)* [29].

$$\eta_{2,l} = \frac{\text{Work or heat taken from the control volume}}{\text{The total exergy provided for the desired work or heat}}. \tag{5}$$

By simplifying *Eq. (3)* for the individual cycle components and by applying the second law efficiency definition, the exergy destruction $\dot{I}_{destroyed}$ and second law of efficiency $\eta_{2,l}$ for each cycle component is determined in *Table 1* [30].

Table 1. Simplified relationships for calculating exergy loss and the efficiency of the second law of thermodynamics for cycle components.

Component	Wasted Exergy	Efficiency of the Second Thermodynamics Law of
Condenser	$\dot{I}_{des.} = (Ex_7 + Ex_{11}) - (Ex_1 + Ex_{12})$	$\eta = \frac{Ex_1 + Ex_{12}}{Ex_7 + Ex_{11}}$
Expander	$\dot{I}_{des.} = Ex_2 - Ex_3 - W_{Expander}$	$\eta = \frac{W_{Expander}}{Ex_2 - Ex_3}$
Cooling tower	$\dot{I}_{des.} = Ex_3 - Ex_4$	$\eta = \frac{Ex_4}{Ex_3}$
Pipe pressure drop	$\dot{I}_{des.} = Ex_5 - Ex_4$	$\eta = \frac{Ex_4}{Ex_5}$
pump	$\dot{I}_{des.} = Ex_6 - Ex_5 + W_{Pump}$	$\eta = \frac{Ex_6 - Ex_5}{W_{Pump}}$
Mixing process	$\dot{I}_{des.} = (Ex_6 + Ex_8) - Ex_7$	$\eta = \frac{Ex_7}{Ex_6 + Ex_8}$

4 | System Analyzes

To achieve the conditions of exergy in the cooling system, the exergy analysis is performed on both the initial water-cooled system and the ammonia-based system for both cold and warm seasons. The input and output flows are drawn out for each component through the cycle in both systems illustrated in *Figs. (1)* and *(2)*. Also, the thermodynamic properties of each cycle point during cold and warm seasons are listed in *Tables 2-5*. From the given data, an ambient temperature of 36°C is considered for the warm season in the current power plant configuration [31], [32].

Table 2. Thermodynamic and exergy conditions of the flow at various points in the cooling cycle during the initial state in the cold season.

point	T (°C)	P (bar)	h (kj/kg)	s (kj/kg K)	$\dot{M}$ (kg/s)	ψ (kj/kg)	E_x (kW)
11	48.08	0.1121	2354.028	7.3804	112.5	228.9896	25761.33
12	48.08	0.1121	201.31	0.6789	112.5	7.3066	821.99
13	48.08	0.1121	201.31	0.6789	5294.6	7.3066	38685.4
14	48.14	0.9927	201.64	0.6796	5294.6	7.4202	39286.8
15	48.14	0.8818	201.63	0.6796	5294.6	7.4091	39228.36
16	37.12	0.8818	155.58	0.5338	5294.6	3.3842	17917.89

Table 3. Thermodynamic conditions and exergy of the flow at different points in the cooling cycle with ammonia substitution in the cold season.

point	T (°C)	P (bar)	h (kj/kg)	s (kj/kg K)	$\dot{M}$ (kg/s)	ψ (kj/kg)	E_x (kW)
1	36.9	14.288	1221.6	4.3264	287.82	332.69	95754
2	36.9	14.288	1488.8	5.1885	212.98	351.5	74864
3	30.98	12.032	1468.2	5.2524	212.98	312.47	66551
4	30.72	11.938	345.3	1.4993	212.98	271.05	57730
5	30.45	11.838	344	1.4951	212.98	270.97	57713
6	30.51	14.388	344.34	1.4952	212.98	271.33	57788
7	32.06	14.326	351.86	1.5198	287.82	271.73	75762
8	36.9	14.288	375.41	1.5966	74.832	273.14	20440
11	48.08	0.1121	2354	7.3804	112.5	228.99	25761
12	48.08	0.1121	201.31	0.6789	112.5	7.3066	821.99

Table 4. Thermodynamic conditions and exergy of the flow at different points in the cooling cycle with ammonia substitution in the warm season.

point	T (°C)	P (bar)	h (kj/kg)	s (kj/kg K)	$\dot{M}$ (kg/s)	ψ (kj/kg)	E_x (kW)
1	56.16	23.818	1246.1	4.2437	320.16	430.68	137885
2	56.16	23.818	1490.5	4.9859	242.79	445.66	113203.98
3	52.53	21.742	1475.4	4.9759	242.79	433.66	105287
4	52.43	21.685	452.98	1.8364	242.79	381.79	92693
5	52.25	21.585	452.06	1.8336	242.79	381.73	92678
6	52.31	23.857	452.37	1.8332	242.79	382.16	92784
7	53.24	23.848	457.11	1.8478	320.16	382.4	122430
8	56.16	23.818	472.11	1.8936	77.373	383.22	32333.27
11	67.37	0.2778	2448.5	7.285	116.5	205.76	23972
12	67.37	0.2778	282	0.9228	116.5	6.1776	719.69

Table 5. Thermodynamic and exergy conditions of the flow at various points in the cooling cycle during the initial state in the warm season.

point	T (°C)	P (bar)	h (kj/kg)	s (kj/kg K)	$\dot{M}$ (kg/s)	ψ (kj/kg)	E_x (kW)
11	67.37	0.2778	2448.5	7.285	116.5	205.76	23972
12	67.37	0.2778	282	0.9228	116.5	6.1776	719.69
13	67.37	0.2778	282	0.9228	5294.6	6.1776	32708
14	67.43	0.9275	282.31	0.9235	5294.6	6.2659	33191
15	67.44	0.8818	282.35	0.9236	5294.6	6.2652	33172
16	55.97	0.8818	234.36	0.7803	5294.6	2.5857	13690

The electric power consumed by the pump is the work done by the pump divided by the efficiency of the electric motor. It is assumed that for the pump in the ammonia cycle, 0.8. Also in the technical data of the cooling water cycle, the electric power of the pump is given. These values, along with the power output of the expander in cold and warm seasons are presented in *Table 6*.

Table 6. Production power of the expander and consumption power of the pump under different conditions.

Power (KW)	Ammonia Cycle Pump	Water Cycle Pump	Ammonia Cycle Expander
Cold season	113.63	1885.7	4388.51
Warm season	123.53	1903.8	3665.83

5 | Result and Discussion

Using the given relations, the exergy loss in each of the components of the cooling cycle is calculated for both states of ammonia and water. For each state, the sum of the exergy wasted and work produced is obtained. *Fig. 3*, for the condenser, it is obvious that exergy loss in this component increases by 18.58% with the ammonia replacement, due to the great entropy generation during the process of ammonia evaporation in the condenser. From *Table 3*, it can be seen that the specific entropy produced between the input and output points of the ammonia in the condenser, points 7 and 1, is approximately 2.8066 kj/kg K, while this value for the water-cooled case between points 13 and 16 in *Table 2* is roughly 0.1451 kj/kg K. In other cycle components, with ammonia replacement, there is a dramatic drop in exergy loss, while the exergy loss of the pump drops by 90% compared with the water-cooled case. The reason for this can be mainly attributed to the fact that the mass flow rate drops with ammonia replacement. It can be seen from Equation 4 that the flow exergy is directly affected by the mass flow rate.

This amount is 5294.6 kg/s in the case of an initial state with water flow and for ammonia will be 212.983 kg/s (in components other than condenser). From the relation given for the determination of exergy loss in the pump in *Table 1*, it can be inferred that this amount directly influences the power input for the pump. With the mass flow rate reduction, the required power of the pump considerably decreases (*Table 6*), which reduces pump losses. Meanwhile, for the cooling tower, the larger entropy reduction in ammonia condensation contributes more to reducing the exergy loss. The more significant loss in the condenser is compensated by the reduction in loss in other components, except the condenser, leading to a 27.34% decrease in total exergy loss compared with the water-cooled state.

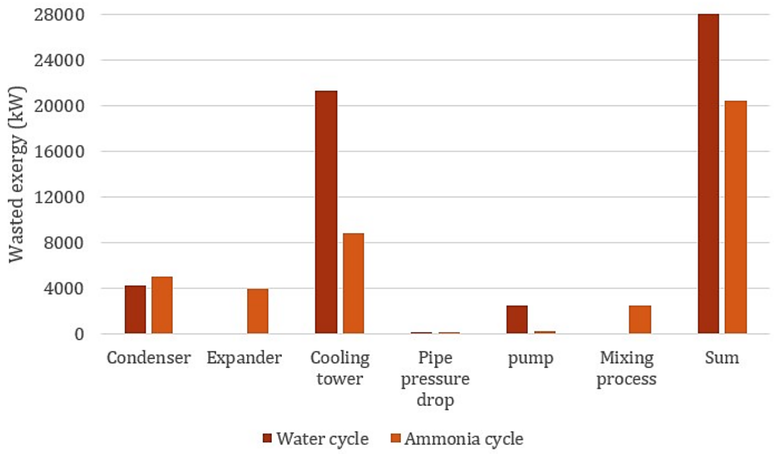

Fig. 3. Exergy destruction in the components of the refrigeration cycle in two initial states and with the replacement of ammonia in the cold season.

Increasing the exergy loss in the condenser with ammonia replacement is also noticed during the warm season (*Fig. 4*). But the increase is much more significant when compared to the cold season. This is because of the decrease in the entropy and enthalpy difference of ammonia between the inlet and outlet of the condenser during the warm season when compared to the cold season. This is a consequence of the thermodynamic behavior of ammonia at higher temperatures; that is, with increasing temperature, changes in enthalpy and entropy become less sensitive to changes in temperature.

The reduction of Enthalpy, according to *Table 3* (Points 1 and 7), for the cold season is 869.698 kJ/kg and for the warm season, according to *Table 4*, it is 789.002 kj/kg. This difference for entropy in the cold season is 2.8066 kj/kg K and for the warm season, it is 2.3959 kj/kg K. This will increase the overall exergy loss of the condenser. This loss increase is so high that the loss reduction of the other cycle components – compared to the water-cooled state – cannot compensate for this increase. Also, comparing the exergy loss of other cycle components for the water-cooled state in both warm and cold seasons, we see a reduction in loss during the warm season compared to the cold season. Specifically, the total exergy loss for the water-cooled cycle in the cold season is 28027.84 kW, while in the warm season, it is 26120.91 kW. The overall outcome of these changes leads to an increase in the total exergy loss of the cycle by 5.57% during the warm season using ammonia. It can be said that the efficiency of ammonia at higher temperatures, both in terms of enthalpy and entropy, faces a significant decline, which results in larger losses in the new cycle with ammonia replacement during the warm season when compared to the baseline water-cooled state.

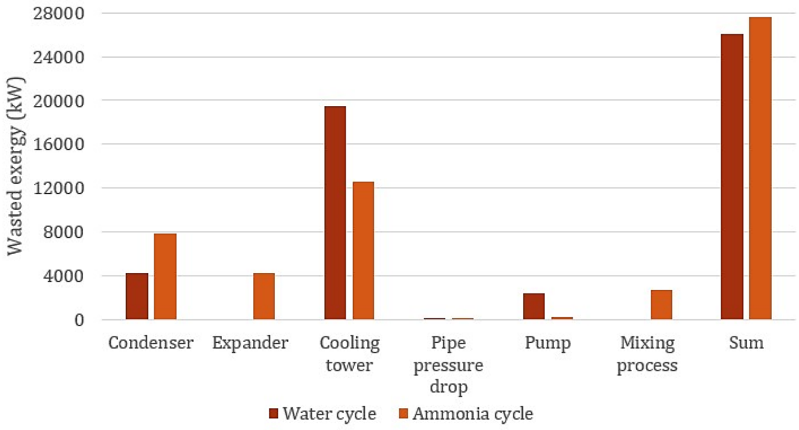

Fig. 4. Exergy destruction in the components of the refrigeration cycle in two initial states and with the replacement of ammonia in the warm season.

In the cold season (*Fig. 5*), the water cycle generally has higher efficiencies compared to the ammonia cycle, especially in the cooling tower and expander. The condenser and mixing process have almost 100% efficiency for both cycles, with the water cycle slightly better for ammonia in the condenser. The ammonia cycle has relatively low efficiencies for components such as the pipe pressure drop and pump.

In the warm season (*Fig. 6*), the efficiency of ammonia improves, especially in the expander and cooling tower, which narrows the gap with the water cycle.

The water cycle still holds its high efficiency across components, especially in the cooling tower. Both cycles are almost performing equally in the condenser and mixing process, showing a consistently high efficiency for both seasons. Overall, this analysis indicates that even though the water cycle is generally better across both seasons, the ammonia cycle shows improved efficiency during warmer conditions, mainly due to the heat transfer components.

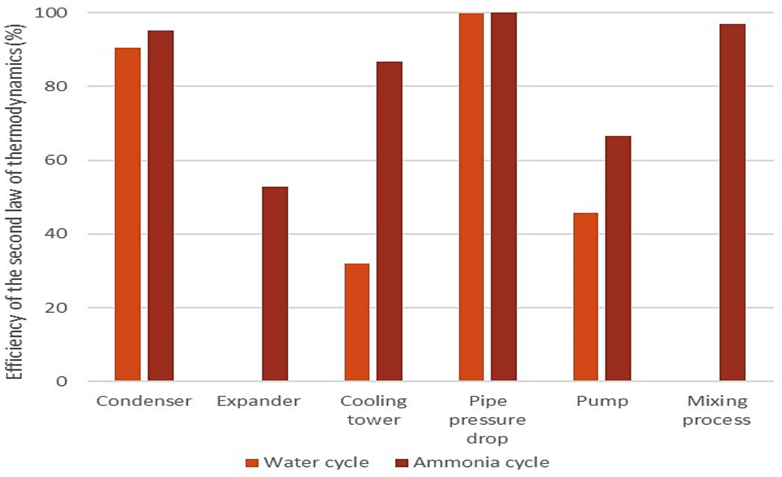

Fig. 5. Efficiency of the second law of thermodynamics in the components of the refrigeration cycle in two initial states and with the replacement of ammonia in the cold season.

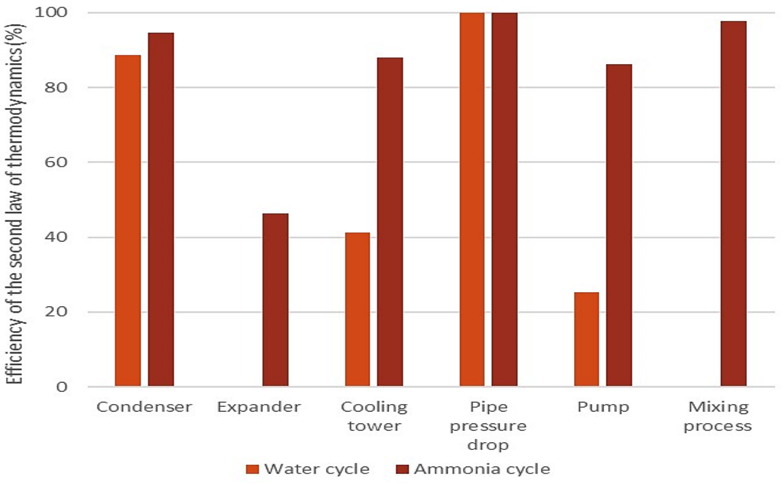

Fig. 6. Efficiency of the second law of thermodynamics in the components of the refrigeration cycle in two initial states and with the replacement of ammonia in the warm season.

6 | Conclusion

The study establishes that ammonia could be a powerful alternative to water as a coolant in combined-cycle power generation, more so in regions where water resources are scarce. The superior thermodynamic properties of ammonia, including its lower boiling point and larger latent heat, allow more excellent cooling efficiency and considerable water consumption savings.

Exergy analysis reveals that ammonia-based systems save 27.34% of total exergy losses in colder seasons because most of the losses are in components other than the condenser. On the other hand, with increasing temperatures, the efficiency of ammonia drops, and at a certain temperature, it suffers from a 5.57% increase in exergy losses compared to water-cooled systems. This marks the sensitivity of ammonia concerning temperature changes: having great efficiency in cooler climates but showing some limitations in warmer ones.

In all, ammonia-based cooling systems mean the way ahead for sustainable power plant operations with water conservation and reduced environmental impacts. While achieving lesser total exergy losses, these systems would benefit from further optimization to enhance performance over a wider range of temperatures and ensure year-round efficiency.

Author Contributions

Zahra Khodabandeh, Seyed Mahmood Kia, Fatemeh Aminipour, Asma Mozaffari, Hasan Hosseini, and Ali Jahangiri contributed equally to the development of this research. Zahra Khodabandeh conceptualized the study, conducted the exergy analysis, and led the manuscript writing. Seyed Mahmood Kia contributed to the thermodynamic simulations and performance analysis of the ammonia-based cooling system. Fatemeh Aminipour and Asma Mozaffari assisted in data collection and analysis, focusing on the environmental and thermodynamic aspects. Hasan Hosseini provided insights into the implementation of the cooling system in power plants. Ali Jahangiri supervised the research and contributed to the final manuscript revision. All authors approved the final version of the manuscript.

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Data Availability

Data supporting the findings of this study are available within the article and can be obtained upon reasonable request from the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this research.

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