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Energy analysis of waste heat-powered absorption cooling system for sustainable cooling

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Abstract

Energy wastage from power plants, which typically dissipates into the atmosphere, poses a significant challenge. The environmental consequences of such wasteful practices are manifold, contributing to climate change and resource depletion. The inefficient use of this waste heat contributes to economic and environmental concerns. Harnessing waste heat through integrating heat recovery systems with power plants effectively repurposing untapped energy. Addressing this issue optimizes energy utilization and aligns with the growing need for sustainable practices in the power generation sector. This study aims to harness the available waste heat by integrating an absorption cooling system (ACS) from the flue gas exhaust of a pressurized pulverized combined cycle power plant. Additionally, the thermodynamic performance of ACS with a cooling capacity of 30 tons has been examined. Using waste heat for cooling purposes offers a sustainable and efficient solution, reducing energy consumption and environmental impact. The working fluid used in the ACS is a binary mixture comprised of ammonia and water. Modelling and simulation were conducted using cycle tempo software, followed by energy analyses to assess the ACS's thermodynamic performance. The thermodynamic analysis discloses that the ACS achieves a coefficient of performance (COP) of 0.595. Additionally, variations in the temperatures of the generator, absorber, condenser, and evaporator significantly impact the COP of the ACS. This promising COP indicates the effectiveness of the ACS in harnessing waste heat for practical cooling applications, marking a substantial step towards sustainable energy utilization.

Keywords: ammonia-water, cooling system, COP, waste heat utilization

Abbreviations: COP, Coefficient of performance; h, enthalpy [kJ/kg]; $\dot{m}$, mass flow rate [kg/sec]; P, pressure [bar]; $\dot{Q}$, heat transfer rate [kW]; T, temperature [K]; v, specific volume [m^3/kg]; $\dot{W}$, power [kW]

Introduction

The global demand for cooling and air conditioning systems is increasing as a result of modernization and population growth. In the past, the requirements for cooling and air conditioning were met using traditional methods. On the contrary, traditional cooling methods that are highly dependent on electricity usage contribute to elevated energy requirements and the subsequent release of greenhouse gas emissions. Globally, these cooling systems consume approximately 15% of all electricity generated, as reported by the International Institute of Refrigeration.[1] It is anticipated that there will be an increase in conjunction with the projected global summer temperature rise of 2-4°C by the end of this century.[2] To address these challenges, there is a growing interest in sustainable and energy-efficient cooling systems. One such technology that holds promise is the absorption cooling system, which utilizes waste heat, solar energy etc., to provide cooling. India is a vast country with enormous and increasing electricity demand. In this scenario, the cooling system electricity demand creates an additional burden which can often be fulfilled by the waste heat utilization through the absorption cooling system (ACS). In ACS water serves as the absorbent and ammonia as the refrigerant. The main components of the ACS include the evaporator, absorber, condenser, and generator, with auxiliary elements such as the separator, throttle valves, HE, and pump. The system utilized the waste heat at the generator to heat the rich ammonia solution, causing ammonia to evaporate and leaving behind a hot weak solution. The ammonia vapor produced by the generator undergoes condensation within the condenser, forming high-pressure liquid ammonia. Subsequently, the condensed ammonia undergoes pressure reduction by passing through the throttle valve, leading to its evaporation within the evaporator, resulting in the generation of the cooling effect. Following this, it proceeds to the absorber, combining to form a concentrated solution with ammonia. This concentrated solution is then pumped back into the generator. Meanwhile, the generator's remaining weak hot ammonia solution passes through the solution heat exchanger (SHE) and throttle valve and returns to the absorber at low pressure. The system requires a separator to separate the pure ammonia from the solution before sending it into the condenser. For improved cycle performance, a SHE as shown in Figure 1, is typically incorporated into the system, which preheats the weak solution before entering the generator; this requires less external heat input to drive the absorption process. Notably, the pump is the only component that necessitates work input in the ACS. Nevertheless, the amount of work required is considerably insignificant in comparison to the compressor of the vapor compression system. The total installed energy generation capacity by each sector from different resources in India as of June 2023, according to the central electricity authority (CEA), was 421901.63 MW, shown in Figure 2.[3] The primary source of energy generation in India is coal, where coal-based power plants dominate 48.8% of the total installed capacity. In power plants, a massive amount of waste heat is present at very low temperatures, such as condenser, flue gas exhaust etc. This heat is difficult to convert efficiently into useful work from the conventional method, and because of that, it is mostly released into the atmosphere.[4] Many have proposed modifying the thermodynamic cycles in recent years to take advantage of waste heat.[5–8] The efficient utilization of waste heat from industrial processes has gained significant attention as a means to reduce energy consumption and minimize environmental impact, so the integration of the ammonia-water-based absorption cooling system with flue gas waste heat presents numerous advantages.

Firstly, it enables the utilization of waste heat, enhancing the overall energy efficiency of the power plant. By tapping into this waste heat stream, the cooling system significantly reduces the environmental impact associated with coal-based power generation. Moreover, as the system operates without relying on electricity, it reduces the demand for additional energy sources, leading to a decrease in greenhouse gas emissions. Additionally, the ACS does not harm the ozone layer, making it environmentally safe. Extensive literature is available on the performance characteristics and thermodynamic analysis of ACS. Chen and Schouten focused on optimizing the irreversible ACS performance, using an irreversibility factor to enhance the Coefficient of Performance (COP) by tuning various system parameters.[9] Chua et al. created a model for an irreversible ammonia-water absorption chiller that takes internal entropy production and heat exchanger thermal conductance into account. When this model was applied to a single-stage chiller, it was discovered that the rectifier had the greatest heat dissipation.[10] Sun compared the performance of different working fluid pair- based absorption refrigeration systems (ARS).[11] Keçeciler et al. conducted an experiment on the thermodynamic analysis of an ARS using geothermal energy as the power source and got a cooling effect of 225.57 kW.[12] Shankar et al. coupled the Kalina cycle and ARS for combined cooling and power a got a power output of 22.5kW with a cooling capacity of 200kW.[13] From the literature, it can be concluded that the ACS emerges as the most commonly used system, capable of harnessing various heat sources, including waste heat, geothermal energy, ocean thermal energy, and solar energy. However, there is a dearth of literature on utilizing power plant waste heat to drive the ACS. In addition, there is a limited discussion on the thermodynamic performance of the ACS.

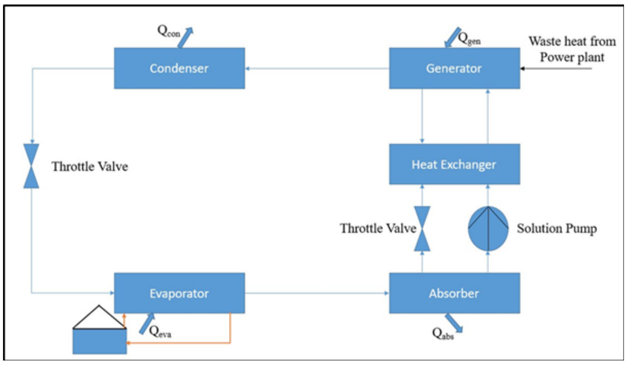

Figure 1 Absorption cooling system.

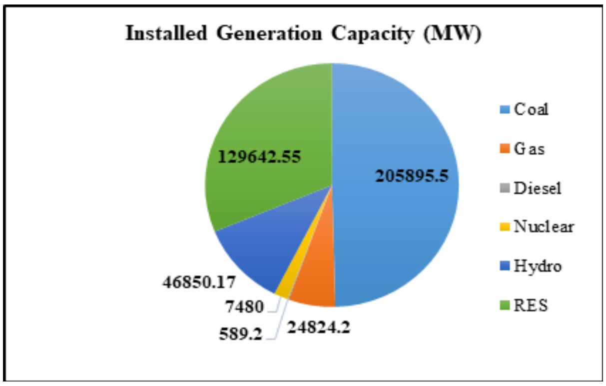

Figure 2 Total power production in India.

This study presents a thermodynamic analysis of ACS and an innovative approach to harnessing the waste heat generated by a coal-based power plant for powering an ACS in order to achieve sustainable and efficient cooling solutions. The proposed system utilizes the waste heat from the power plant, which would otherwise be dissipated into the environment, to drive an ACS. The system operates on the principle of utilizing a refrigerant-absorbent pair, typically ammonia-water, to produce cooling effects through the absorption and desorption of refrigerant vapor. By employing this technology, the system eliminates the need for the conventional electrically driven system, resulting in reduced electricity consumption and greenhouse gas emissions. The design of the ACS involves capturing the waste heat from the power plant's flue gases and transferring it to a generator that provides the necessary thermal energy for the absorption cycle.

Materials and methods

The proposed system is modelled and simulated using the Cycle Tempo software,[14] a robust application developed by the Delft University of Technology, used for analyzing and optimizing thermodynamic cycles. With its advanced features and user-friendly interface, Cycle Tempo provides a comprehensive toolset for modelling, simulating, and evaluating the performance of various energy conversion systems. This software is governed by thermodynamic equations such as mass, energy, exergy and chemical balance equations.

Thermodynamic modelling of ACS

The thermodynamic modelling of an ACS is conducted by applying the principles outlined in the first and second laws of thermodynamics to each component of the system. This comprehensive approach allows for a detailed examination of the energy transfers and transformations that take place within the system. The exergy analysis focuses on quantifying the quality of energy, taking into account both its availability and irreversibilities within a system. The mathematical equation, which is displayed below, has been written based on Figure 3.

In order to analyse the implementation of the first law of thermodynamics in this system, the quantities of mass and energy that enter and exit each component are calculated using the provided equations:

Mass balance:

$$\sum_i \dot{m}_i = \sum_e \dot{m}_e \tag{1}$$

Energy balance:

$$\sum_i \dot{m}_i h_i + \dot{Q} = \sum_e \dot{m}_e h_e + \dot{W} \tag{2}$$

$\dot{m}$, h and $\dot{Q}$ represent the mass flow rate, enthalpy and heat transfer rate, and the heat balance equation determines how much heat is transmitted to and from each part.

Below equation describes the energy balance of the generator, and evaporator:

$$\dot{Q}_{ge} = \dot{m}_{11} h_{11} - \dot{m}_7 h_7 \tag{3}$$

$$\dot{Q}_{ev} = \dot{m}_1 (h_4 - h_3) \tag{4}$$

Finally, the COP of the system is calculated, which is the ratio of heat transfer through the evaporator to the sum of heat transfer through the generator and the work done through the pump. The pump work required in the absorption system is very small that can be neglected.[15]

$$COP = \frac{\dot{Q}_{ev}}{\dot{Q}_{ge} + \dot{W}_p} \tag{5}$$

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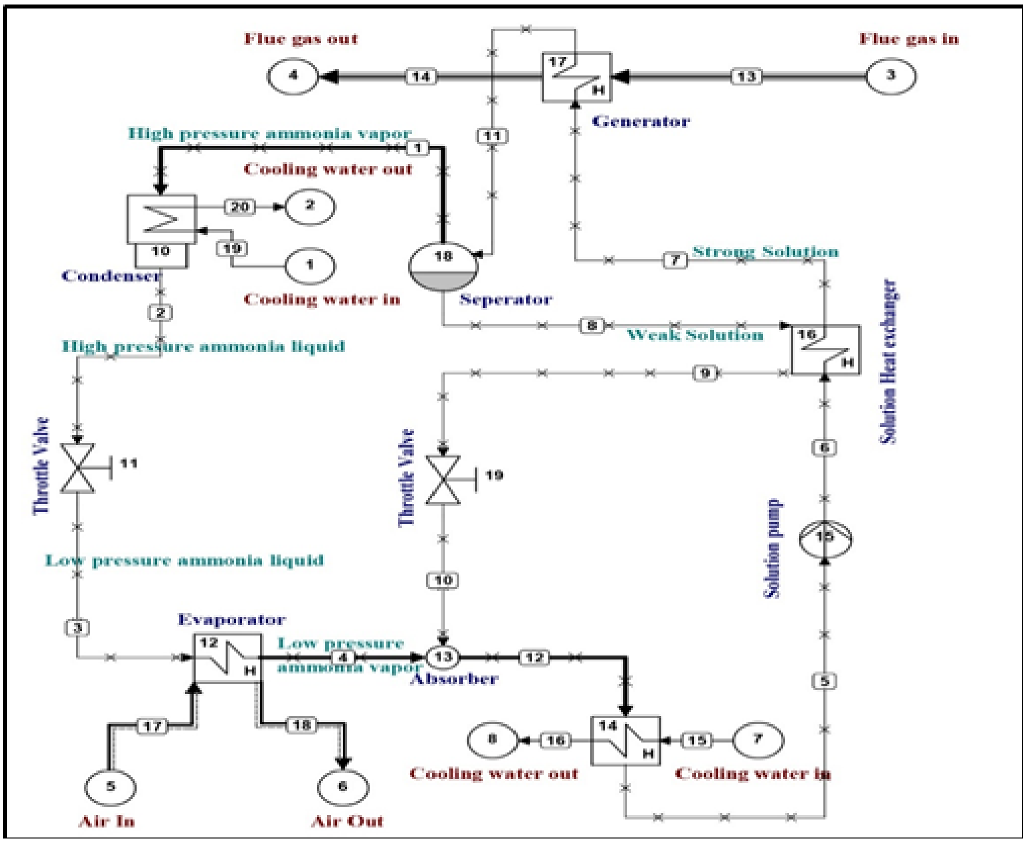

Figure 3 Absorption model.

Working fluid characteristics

In ACS, the working fluid typically consists of two main components: the refrigerant (in this case, ammonia) and the absorbent (water solution). The cooling process involves the refrigerant (ammonia) absorption into the absorbent (water) at low temperature and pressure and then releasing the refrigerant at high temperature and pressure to create a cooling effect. The characteristics of the ammonia-water solution depend on the concentration of ammonia in the water. As the ammonia concentration increases, the boiling point of the solution decreases, and its density, viscosity, and other thermodynamic properties change. The concentration is often expressed in the ammonia mass fraction or ammonia concentration in weight percentage.

Assumptions

1) The ambient conditions are set at 1.013 bar pressure and 25°C temperature.
2) Waste heat is harnessed from the flue gas exhaust of a 400 MWe PPCC plant.[16]
3) A 105kW of ACS system is considered for analysis.
4) The selected working fluid is a mixture of ammonia-water.
5) There are no pressure loss and heat leakage in the system except for the main components of ACS.

Parametric analysis

In the Parametric analysis, the ACS is investigated with respect to varying the temperature of the generator, evaporator, condenser and absorber. This analysis helps optimize the system's operation, identify critical parameters, and understand their impact on key performance metrics such as cooling capacity, COP.

Results and discussion

This section explains the findings and outcomes of the simulation analysis on ACS run by flue gas waste heat. It provides a comprehensive analysis of the system performance, including cooling capacity, coefficient of performance (COP), and the influence of temperature on system operation.

Thermodynamic results

From the thermodynamic analysis of ACS, the performance of each component has been calculated; based on the results, the COP has been determined. Table 1 provides a comprehensive insight into the thermodynamic performance of an absorption cooling system at different stages with a generator temperature of 80.45°C, condenser temperature of 30°C, absorber temperature of 30°C, evaporator temperature of 12.19°C and cooling capacity of 105kW (30 tons). It is evident that the system efficiently absorbs and releases heat at specific points, resulting in a cooling effect. The analysis of temperature, pressure, and enthalpy values of each component allows us to understand the energy transfer at different stages of the cooling cycle; also, the results are visually depicted in the graph as a temperature-dependent behaviour of each component within the ACS.

Table 2 shows the energy in and out through each component of the ACS. The table presents the thermodynamic results of an ACS. The system generator requires a heat input of 176.04 kW to drive the absorption process, while the condenser transfers 146.057 kW

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of heat to the environment during the cooling cycle. The evaporator provides a cooling capacity of 105 kW, absorbing heat from the space being cooled. The absorber facilitates heat transfer of 135.323 kW during the absorption process, and the solution heat exchanger (SHE) transfers 44.0765 kW of heat. The work input in the pump, responsible for circulating the absorbent, is relatively low at 0.36 kW. The pump requires a work input of 0.36 kW to circulate the working fluid. The Coefficient of Performance (COP) of the system is calculated to be 0.595, which represents the cooling output per unit of energy input.

Table 1 Thermodynamic properties at different state in ACS

Component	Temperature (°C)	Pressure (bar)	Mass flow (kg/sec)	Enthalpy (kJ/kg)
Generator Outlet (1)	80.45	13	0.111	1439.46
Condenser Outlet (2)	30	13	0.111	128.25
Throttle Valve outlet (3)	12.19	6.5	0.111	128.25
Evaporator outlet (4)	14.69	6.5	0.111	1070.92
Absorber solution Outlet (5)	30	6.5	0.351	-87.1
Solution HE inlet (6)	30	13	0.351	-86.17
Generator Solution inlet (7)	56.66	13	0.351	39.58
Generator Solution Outlet (8)	80.45	13	0.239	123.65
Solution HE outlet (9)	40	13	0.239	-60.67
Absorber solution inlet (10)	40	6.5	0.239	-60.67

Table 2 Thermodynamic results of ACS

Heat input in Generator	176.04 kW
Heat transfer through Condenser	146.057
Cooling capacity in Evaporator	105 kW
Heat Transfer through Absorber	135.323 kW
Heat transfer through Solution HE	44.0765 kW
Work input in Pump	0.36 kW
COP	0.595

Effect of evaporator temperature on COP

Figure 4 illustrates the impact of varying the evaporator temperature on the COP of the ACS. The results demonstrate that with an increase in evaporator temperature, the COP experience a decline. This is because higher evaporator temperatures lead to a decrease in the ACS's COP due to a reduced cooling capacity caused by a smaller temperature difference.

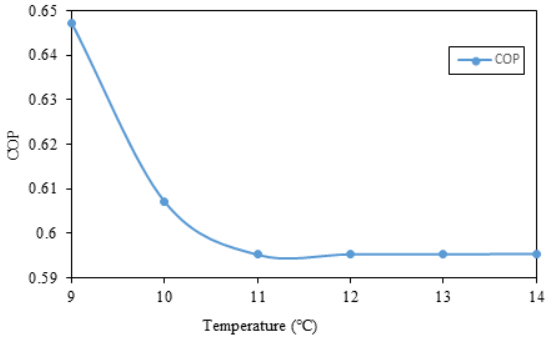

Figure 4 Effect of evaporator temperature on COP.

Effect of generator temperature on COP

Figure 5 depicts the impact of the generator temperature on COP of ACS. The COP reach their peak values between 74- 78 °C, beyond which the curve flattens and begins to exhibit a declining pattern. This behaviour is attributed to more ammonia vapor forming at higher generator temperatures; this, in turn, leads to a rise in the absorber solution temperature within both the absorber and generator units, resulting in a greater amount of exergy losses occurring in these components.

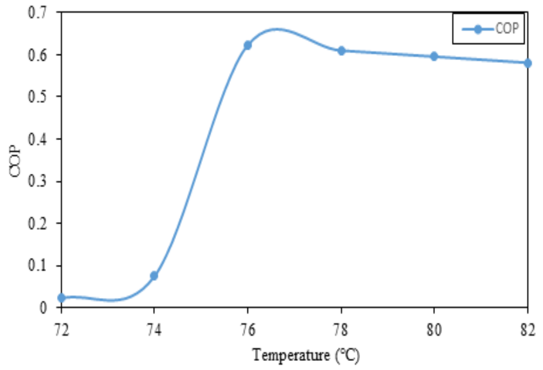

Figure 5 Effect of generator temperature on COP.

Effect of condenser temperature on COP

Figure 6 depicts the impact of condenser temperature on COP of ACS. And it shows that with increasing condenser temperature, the COP of the system decrease. For the constant cooling capacity of 105 kW, increasing condenser temperature leads to high thermal load in the generator, causing less ammonia vapour formation from the generator. Because of that, the COP of the system decrease. Hence, lowering the condenser temperature increases the temperature difference between the condenser and the ambient environment, allowing for more efficient heat rejection and enhancing the system's cooling capacity.

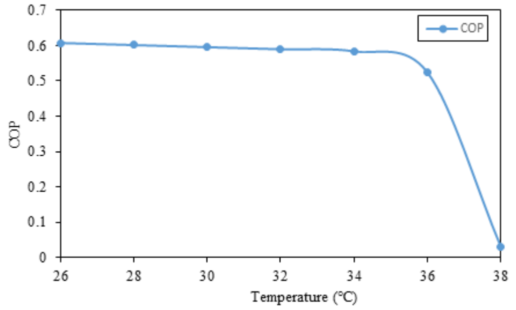

Figure 6 Effect of condenser temperature on COP.

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Effect of absorber temperature on COP

Figure 7 illustrates the impact of the absorber temperature on COP of ACS. Moreover, the effect of the absorber temperature exhibits a trend nearly identical to that of the condenser. The absorber temperature significantly influences ACS performance, exerting a critical role. A rise in absorber temperature leads to a reduction in the absorption efficiency of the solution, subsequently increasing the thermal load on both the generator and absorber. This, in turn, contributes to a decrease in the COP of the system. Concurrently, elevating the absorber temperature leads to a higher solution temperature within the absorber, resulting in increased mixing losses.

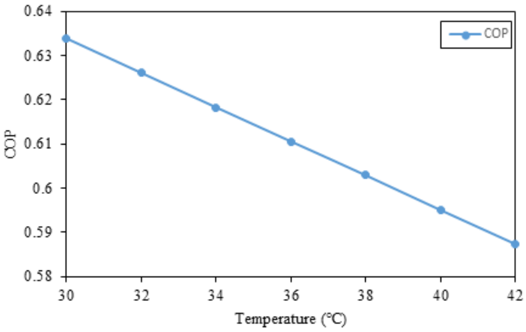

Figure 7 Effect of absorber temperature on COP.

Conclusion

The aim of this study is to harness the available waste heat from the flue gas exhaust of the plant. This research integrates an absorption cooling system with the pressurized pulverized combined cycle power plant to effectively utilize this waste heat and assess its thermodynamic performance. By incorporating the absorption cooling system, the power plant optimizes its energy utilization, leading to a reduction in its environmental impact. This strategy lessened the plant's dependence on supplementary electricity sources for cooling, resulting in improved energy efficiency and decreased carbon emissions. The thermodynamic analysis of the ACS indicates a coefficient of performance (COP) of 0.595. Moreover, variations in the generator, absorber, condenser, and evaporator temperatures affect the COP of the ACS. The analysis reveals that a slight increase in the COP of the system occurs with higher generator and lower evaporator temperatures, while raising the condenser and absorber temperature results in a COP decrease. In conclusion, integrating an ACS run by the power plant waste heat provides a promising solution for sustainable cooling requirements.

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Conflicts of interest

The authors declare no conflict of interest in writing the manuscript.

References

1. Kalkan N, Young EA, Celiktas A. Solar thermal air conditioning technology reducing the footprint of solar thermal air conditioning. *Renewable and Sustainable Energy Reviews*. 2012;16(8):6352–6383.
2. Kumar D, Layek A, Kumar A. Enhancement of thermal efficiency and development of Nusselt number correlation for the solar air heater collector roughened with artificial ribs for thermal applications. *Environmental Science and Pollution Research*. 2023:1–15.
3. Executive summary power sector. New Delhi: Government of India, Ministry of Power, Central Electricity Authority; 2023.
4. Loni R, Najafi G, Bellos E, et al. A review of industrial waste heat recovery system for power generation with Organic Rankine Cycle: Recent challenges and future outlook. *Journal of Cleaner Production*. 2021;287:125070.
5. Vidal A, Best R, Rivero R, et al. Analysis of a combined power and refrigeration cycle by the exergy method. *Energy*. 2006;31(15):3401–3414.
6. Kumar D, Layek A. Heat transfer augmentation of a solar air heater using a twisted V–shaped staggered rib over the absorber plate. *Journal of Solar Energy Engineering*. 2023;145(2):021013.
7. Micheli D, Pinamonti P, Reini M, et al. Performance analysis and working fluid optimization of a cogenerative organic Rankine cycle plant. *Journal of Energy Resources Technology*. 2013;135(2).
8. Kumar D, Faisal N, Layek A, et al. Performance improvement of a solar desalination system assisted with solar air heater: An experimental approach. *J Indian Chem Soc*. 2020;97(10b):1967–1972.
9. Chen J, Schouten JA. Optimum performance characteristics of an irreversible absorption refrigeration system. *Energy Conversion and Management*. 1998;39(10):999–1007.
10. Kumar D, Faisal N, Layek A, et al. May. Enhancement of mechanical properties of carbon and flax fibre hybrid composites for engineering applications. *AIP Conference Proceedings*. 2021;2341(1).
11. Sun DW. Comparison of the performances of NH3–H2O, NH3–LiNO3 and NH3–NaSCN absorption refrigeration systems. *Energy Conversion and Management*. 1998;39(5–6):357–368.
12. Keçeciler A, Acar Hİ, Doğan A. Thermodynamic analysis of the absorption refrigeration system with geothermal energy: an experimental study. *Energy Conversion and Management*. 2000;41(1):37–48.
13. Shankar R, Srinivas T. Coupled cycle with Kalina cycle system and vapor absorption refrigeration. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*. 2014;228(8):953–964.
14. Kumar D, Layek A. Experimental assessment of thermohydraulic performance of a rectangular solar air heater duct using twisted V–shaped staggered ribs. *Journal of Thermal Science and Engineering Applications*. 2023;15(4):041009.
15. Shahata AI, Aboelazm MM, Elsafty AF. Energy and exergy analysis for single and parallel flow double effect water–lithium bromide vapor absorption systems. *International Journal of Science and Technology*. 2012;2(2):85–94.
16. Kalimuthu S, Karmakar S, Kolar AK. 3–E analysis of a pressurized pulverized combined cycle (PPCC) power plant using high ash Indian coal. *Energy*. 2017;128:634–648.

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