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Research Article

Performance analysis of a new combined absorption-adsorption refrigeration system to improve energy performance

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ABSTRACT

In this study, a new cascaded absorption-adsorption refrigeration cycle (ABS-ADS) is investigated under a variety of various operating conditions. Combined both absorption and adsorption refrigeration cycles can increase the overall energy performance. The condenser of the ABS cycle is cooled down by the evaporator of the ADS cycle. In this way, low-temperature cooling at low-grade heat source temperatures may be provided, and the benefit of each cycle can be utilized. Additionally, a comparison is also made between the performance of the proposed ABS-ADS and that of the standalone ABS and ADS cycles, as well as with other studies taken from the literature. Results demonstrated that, at heat source temperatures of 75°C, the cooling capacity of the proposed cascade ABS-ADS (25.5 kW) is greater than that of ABS and ADS by 16.8 and 177% with 0.644, 0.69, and 0.36 systems COP, respectively. In addition, it is superior to that of the ABS and ADS by 8.39% and 44%, respectively. The influence of mass flowrate of the heat source is high in the range lower than 1.0 kg/s; however, when the mass flowrate is more than 1.0 kg/s, the impact on the cooling effect and the COP is only marginal. When the flow rate of the solution pump is increased from 0.06 to 0.16 kg/s, the cooling capacity grows linearly from 16 to 44 kW, and the COP increases from 0.61 to 0.63. Increasing the temperature of the chilled water from 8 to 16°C raises the cooling capacity linearly from 20.6-36 kW and the COP from 0.58 to 0.622. In conclusion, the performance of the suggested cascade ABS-ADS cycle can operate effectively at low-grade heat sources and produce good thermal performance in comparison to other former studies.

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INTRODUCTION

One of the most essential topics of research in energy-related applications is how to improve energy efficiency while simultaneously mitigating the impact of associated environmental issues. The amount of energy that is used all over the globe is steadily growing and is anticipated to increase by 28% from 2015 to 2040 [1-2]. Due to the long and hot summer months in the gulf countries, one of the key contributors to the region's ever-increasing energy consumption is the ever-increasing burden placed on refrigeration

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and air-conditioning systems. The overall trend in cooling applications is rising, which may be attributed to the rising rates of energy consumption, population growth, and economic activity. Traditional vapor compression refrigeration cycles (VCRC) are the basis for the most popular types of cooling cycles and the commonly utilized today due to the great performance they provide. Harby and Fahad [3] concluded that traditional VCRC have a high rate of electrical energy consumption, which is generated by fossil fuels, and they use refrigerants that are harmful to the environment. Therefore, alternative cooling solutions need to be introduced to strike a balance between the development of new technologies, the consumption of energy, and the conservation of the environment.

In today's world, thermally driven sorption technology (absorption/adsorption) has become of great importance nowadays compared with traditional systems (VCRC). Recently, there is a lot of interest in thermally driven sorption systems because of the benefits they provide. This technology can be run on clean and sustainable energy, it is inexpensive, it does not have any moving parts, and it uses working fluids that are beneficial to the environment [4-5]. Ali et al. [6] declared that absorption systems (ABS) are widely used compared with ADS for large cooling capacity and high COP. Harby et al. [7] concluded that ADS can work effectively at low heat-source temperatures compared to ABS. Stephan [8] showed that the COP of L_iB_r/H_2O ABS varied from 0.6 to 0.8 when tested with heat sources between 80 and 100°C and cooling water at 20°C. Adsorption systems can be operated at lower heat source temperatures. Because it can withstand temperatures in this range, sorption cycles are an excellent choice for low-grade heat source temperatures. However, because of their low COP and large sizes, sorption cycles (ABS and ADS) have limitations in the more widespread implementation and commercialization that have been carried out worldwide [9-11]. Various research projects on the assessment of ABS's performance have been carried out recently. Sun et al. [12] provide a comprehensive overview of the working fluids that are utilized for ABS. Different studies have focused on improving the heat and mass transfer coefficients of the heat exchanger elements [13-14]. Sun et al. [15] suggested new working fluids. Ibarra-Bahena and Wang [16-17] proposed new designs and configurations of the cycle components. Other studies utilized a variety of low-grade heat sources [18-21]. Seyfouri et al. and Bruno et al. [22-23] utilized a combined with cogeneration power plants. Many other studies focused on the investigation of increase the rate of heat transfer rate [24-26]. In addition, investigations on multi-effect ABS are being examined [27-30]. Cascade absorption systems are also investigated with the goal of improving energy usage [31]. Integration of the single effect ABS with other cooling technologies, such as VCRs, has also been researched [32-36] with the goal of increasing the system's coefficient of performance (COP).

In addition, a great deal of work is put in to improving the performance of ADS, which includes the creation of more advanced strategies [37-39]. There have been several research also that have concentrated on enhancing the heat and mass transfer coefficients of the adsorbent beds [40-41]. Additional adsorbent pairs were also investigated by several research [42-44]. Alam et al. [45] provided a new design and construction of adsorbent bed heat exchangers to achieve greater heat transmission. Tamainot et al. [46] provided several investigations on the relationship between energy efficiency and the use of a variety of heat sources. A great number of additional research recommends the use of multi-stage and multi-bed multi-stage ADS to improve overall efficiency [47-50]. Additional studies are being done to investigate the possibility of integrating the ADS with several alternative cooling methods [51-55]. It has been observed in the past. Meunier and Akahira et al. [56-57] concluded that, combined cascade of two-bed two-stage ADS may increase the total system COP by up to 50-60% as reported.

As was just said, the cooling cycles cause consumers to utilize higher-grade energy, which in turn increases the consumption of fossil fuels and the amount of CO_2 emissions. A considerable number of studies have been performed on sorption cooling systems that are either single or combined or integrated with other cooling technologies such as VCRC. Deshdeep et al. and Touaibi et al. [58-59] showed that the COP of the integrated systems which may include a cascade cycle can be improved leading to greater energy efficiency. As a result of the low COP, there are still obstacles in the way of the broad deployment and commercialization of sorption cooling systems around the globe. A decrease in the use of primary energy as well as a reduction in CO_2 and other emissions may result from improved energy efficiency. Additional research is still required to improve the technologies' coefficients of performance (COP) and energy consumption efficiency.

The purpose of this work was to explore the performance of combined absorption-adsorption cascade refrigeration systems (ABS-ADS) to increase energy efficiency and provide low-temperature cooling. In this work, the upper cycle makes use of the single-stage ADS, while the bottom cycle operates with the single-effect ABS. A shell and tube heat exchanger connects the evaporator of the ADS to the condenser of the ABS. Additionally, in a series arrangement, the hot water that is discharged from the generator of the ABS chiller is used to power the desorber of the ADS chiller. This configuration has the potential to enhance energy usage, raise the total COP, save the environment, and create chilled water at low temperatures using sources of heat with low temperatures. In addition, combining the two methods may provide the benefits that each cycle offers while simultaneously minimizing the drawbacks. The outcomes of the suggested combined ABS-ADS chiller are evaluated and compared with the findings of previous research using standalone ABS, ADS, and other methodologies. The impact that the various operating circumstances have on the output of the proposed system is another aspect that is being investigated.

DESCRIPTION AND WORKING PRINCIPLE OF THE PROPOSED CASCADE ABS-ADS

The suggested combined cascading absorption-adsorption refrigeration systems (ABS-ADS) that are driven by low-grade heat sources are shown in Figure 1 with a conceptual structure of the system. In the bottom cycle of this system is an ABS chiller with a single effect, and in the top cycle is ADS chiller with a single stage. The evaporator of the ADS and the condenser of the ABS are included in the same shell and tube heat exchanger, which couples the two components together. In a series configuration, the hot water that is discharged from the generator of the ABS chiller is routed to the desorber of the ADS chiller, where it is utilized to drive the system at the same mass flow rate.

Figure 2 is a schematic representation of the different components of the ABS-ADS system. The single-effect L_iB_r-H_2O ABS contains an evaporator element, a condenser element, a generator element, an absorber element, a throttling valve, a pump, and a heat exchanger. The single-stage Silica-gel-water ADS contains two adsorbent beds (A and B), a condenser, an expansion valve, and an evaporator element. The evaporator of the ADS is thermally coupled with the condenser of the ABS in the same shell and tube heat exchanger. The system cooling capacity $\dot{Q}_{evap}$ is obtained from the evaporator of the ABS. The hot water from the heat source is firstly used to drive the generator of ABS and is then used to generate the desorber of the ADS.

At the beginning of operation, hot water from heat source ($\dot{Q}_{gen}$) is flows to power the generator of ABS causing water evaporates from L_iB_r/H_2O solution. The water evaporates quickly and flows to the shell side of integrated condenser-evaporator heat exchanger. The water vapor condensed at high pressure ($\dot{Q}_{cond}$), and the strong solution returns to the absorber through the internal heat exchanger. The condensation water vapor is throttled through the throttling valve and flows to evaporator of ABS providing the overall cooling capacity ($\dot{Q}_{evap}$) of the cascade cycle.

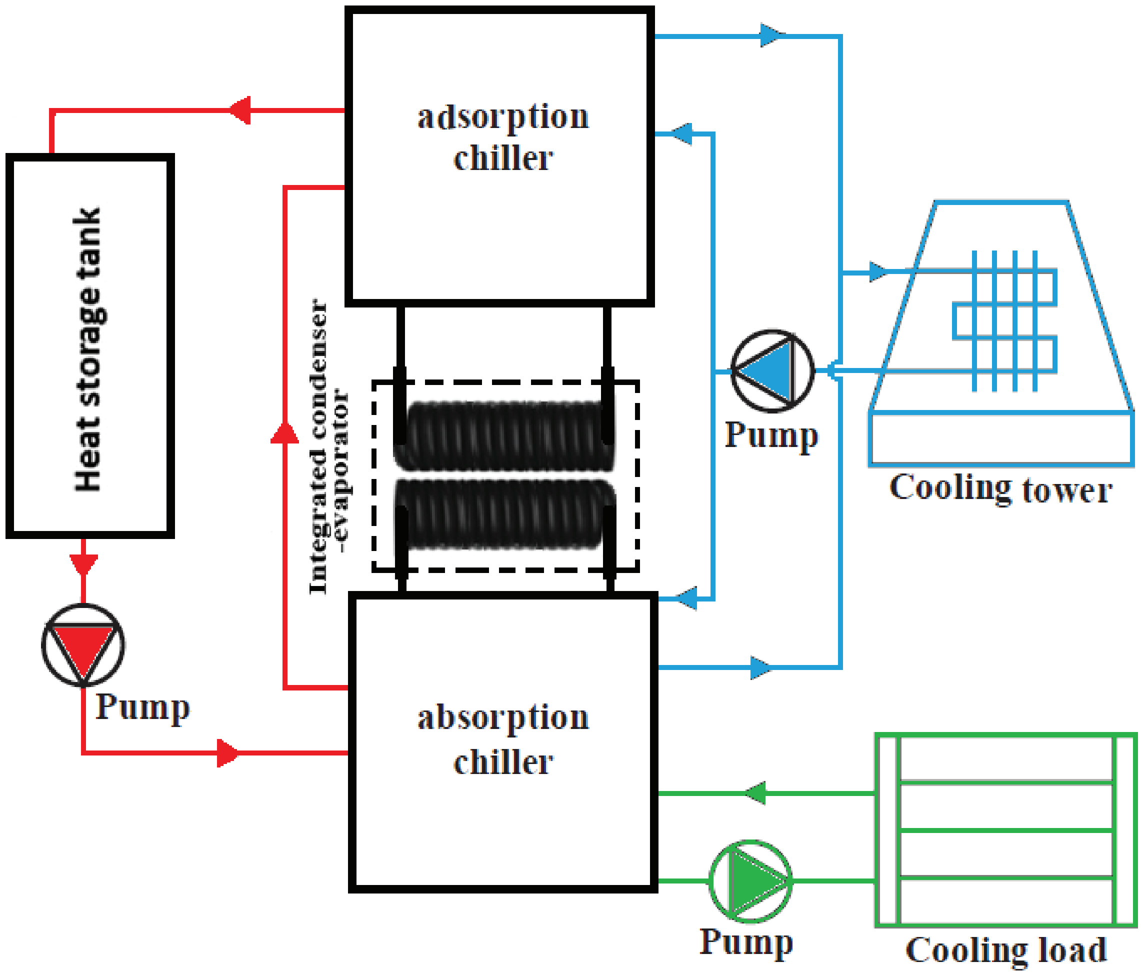

Figure 1. General layout of the cascade combined ABS and ADS.

The water vapor leaving the evaporator is then absorbed by the strong L_iB_r solution in the absorber. The weak solution L_iB_r/H_2O from the absorber element is then pumped again to generator through the solution heat exchanger and the cycle repeated. A detailed operating work of ABS can be found in the literature [17].

The outlet hot water from the ABS chiller flows to drive the desorber bed (A) of ADS to heat the Silica-gel. At the same time, cold water ($\dot{Q}_{ads}$) from the cooling tower is flows to cool the second adsorber bed (B). During these processes (pre-cooling/pre-heating), all valves (V_1, V_2, V_3, V_4) are closed and no adsorption/desorption process occurs. After this short intermediate period, valves V_3 and V_2 are opened to allow refrigerant (water vapor) to flow from the bed (A) to condenser and refrigerant transfer from integrated condenser-evaporator heat exchanger to bed (B). The vapor is condensed as it travels through the condenser element to the throttling mechanism, which then allows it to go to the evaporator. Because of the condensation load that ABS places on the integrated condenser-evaporator heat exchanger, water is turned into vapor there. When the concentration of the working fluid reaches the level

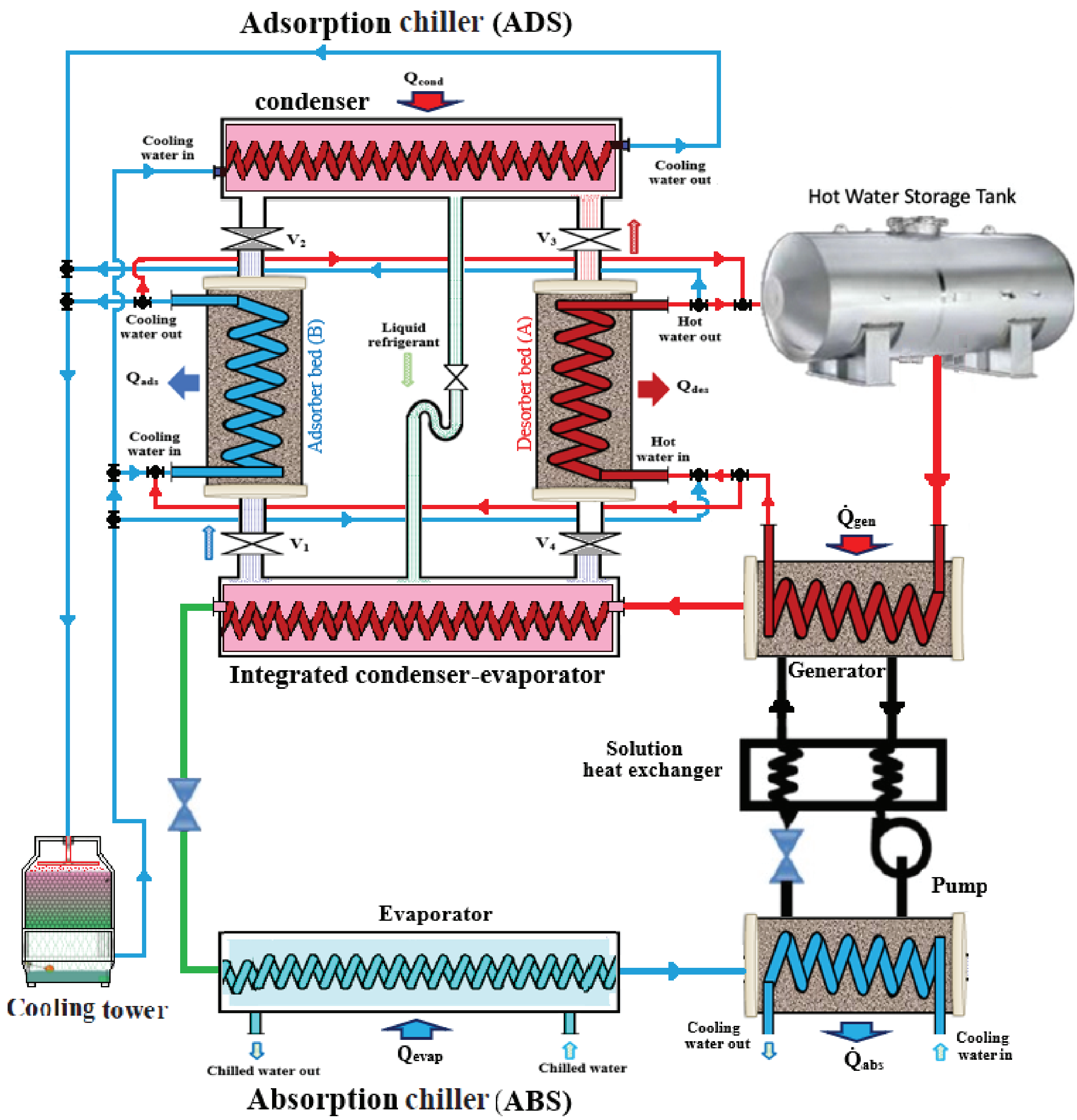

Figure 2. Schematic of the proposed combined cascade ABS-ADS in series arrangement with the heat source.

of equilibrium, the flows of heated and cooling fluid are diverted by switching the three-way valves. This allows for the concentration of the working fluid to remain constant. Several research have already described how the ADS operates according to its fundamental concept [60-61].

Simulation Modeling of the Cascade ABS-ADS Cycle

Adsorption isotherm and kinetics

The equilibrium of the RD silica gel/water pair calculated by Ahmed et al. [43]:

$$X = X_0 exp\left\{-(RT\frac{RT}{E} ln\left[\frac{P_s}{P}\right]^n)\right\} \quad (1)$$

The rate of adsorption and desorption the RD silica gel/water pair calculated by:

$$\frac{dx}{dt} = k_s a_v (X - x) \quad (2)$$

where

$$k_s a_v = F_s \frac{D_s}{R_P^2} \quad (3)$$

The surface diffusivity (D_s) model as:

$$D_s = D_{s0} \exp\left(-\frac{E_a}{RT}\right) \quad (4)$$

The parameters used in the previous equations are given by [43].

Energy equilibrium

The energy balance equation for the two-bed adsorption cooling system was given previously by Khairul et. al [49] and El-Sharkawy et. al [50]. The same model is used here for RD silica gel/water pair while considering the proposed cascading part of the ABC section.

The correlation of energy balance in the adsorber/desorber beds of ADS given by:

$$\left[M_{sg}(C_{p,sg} + C_{p,ref}X_i) + (MC_p)\right]\frac{dT_i^{bed}}{dt} = \Phi\Delta h_{st} M_{sg}\frac{dX_i^{bed}}{dt} + (\dot{m}_w C_{p,w})_j (T_{in} - T_{out})_j + M_{sg}(C_{p,ref}(T_s - T_i)\frac{dX_i^{bed}}{dt} \quad (5)$$

The outlet temperature of adsorber/desorber beds of ADS given by:

$$T_{j,out} = T_{bed} + (T_{j,in} - T_{bed}) exp\left(-\frac{UA_{bed}}{(\dot{m}_{cw}C_{p,cw})_j}\right) \quad (6)$$

Energy balance of the condenser of ADS given by:

$$\left[(C_pM)_{ref,cond} + MC_{p)con,Cu}\right]\frac{dT_{cond}}{dt} = -M_{sg}C_{p,ref}(T_{des} - T_{cond})\frac{dX_{des}}{dt} - \varphi M_{sg}h_{fg}\frac{dX_{des}}{dt} \quad (7)$$

The outlet temperature from the condenser of ADS:

$$T_{cwc,out} = T_{cond} + (T_{cwc,in} - T_{cond}) exp\left(-\frac{UA_{cond}}{(\dot{m}_{cw}C_{p,cw})}\right) \quad (8)$$

Energy balance of evaporator for of ADS:

$$\left[(C_pM)_{ref,eva} + (C_pM)_{evap,Cu}\right]\frac{dT_{eva}}{dt} - \phi h_{fg} M_{sg}\frac{dX_{ads}}{dt} - M_{sg}C_{p,ref}(T_{evap} - T_{cond})\frac{dX_{des}}{dt} + (mC_p)_{ch,w}(T_{chw,in} - T_{chw,out}) \quad (9)$$

The outlet temperature of evaporator for of ADS:

$$T_{chw,out} = T_{eva} + ((T_{cw,out})_{cond,Abs} - T_{eva}) exp\left(-\frac{UA_{eva}}{(\dot{m}_{chw}C_{p,chw})}\right) \quad (10)$$

Energy balance absorber for the ABS:

$$\left[(C_pM)_{sol,abs} + (C_pM)_{abs,cup}\right]\frac{dT_{abs}}{dt} = h_{fg}(\dot{m}_{ws} - \dot{m}_{ss}) + \dot{m}_{ss}h_{sol}(T_{ss,abs}, X_{ss}) - \dot{m}_{ws}h_{sol}(T_{abs}, X_{ws}) + (\dot{m}C_p)_{cw,abs}(T_{in} - T_{out})_{cwa} \quad (11)$$

The outlet temperature from absorber of the ABS:

$$T_{cw,out} = T_{abs} + (T_{cw,in} - T_{abs}) exp\left(-\frac{UA_{abs}}{(\dot{m}_{cw}C_{p,cw})}\right) \quad (12)$$

Energy balance of generator for ABS:

$$\left[(C_pM)_{sol,gen} + (C_pM)_{gen,cup}\right]\frac{dT_{gen}}{dt} = h_{fg}(\dot{m}_{ws} - \dot{m}_{ss}) + \dot{m}_{ws}h_{sol}(T_{gen}, X_{ws}) + \dot{m}_{ws}h_{sol}(T_{ws,gen}, X_{ws}) + (\dot{m}C)_{hw,gen}(T_{in} - X_{out})_{hw} \quad (13)$$

The outlet temperature of generator for ABS:

$$T_{hw,out} = T_{gen} + (T_{hw,in} - T_{gen}) exp\left(-\frac{UA_{gen}}{(\dot{m}_{hw}C_{p,hw})}\right) \quad (14)$$

Energy balance of condenser for ABS:

$$\left[(C_pM)_{ref,cond} + (C_pM)_{cond,Cu}\right]\frac{dT_{cond}}{dt} = h_{fg}(m_{ws} - m_{ss}) + C_{p,ref}(m_{ws} - m_{ss})(T_{cond} - T_{gen}) + (mC_p)_{cw}(T_{cw,in} - T_{cw,out}) \quad (15)$$

The outlet temperature of condenser for ABS:

$$(T_{cw,out})_{cond,Abs} = T_{cond} + ((T_{chw,out})_{evap,Ads} - T_{cond}) exp\left(-\frac{UA_{cond}}{(m_{cw}C_{w,cond})}\right) \quad (16)$$

Energy balance of evaporator of ABS:

$$\left[C(_pM)_{ref,eva} + (C_pM)_{evap,Cu}\right]\frac{dT_{eva}}{dt} = -M_{sg}h_{fg}\frac{dw_{ads}}{dt} - h_{fg}(m_{ws} - m_{ss}) + (mC_p)_{chw}(T_{in} - T_{out})_{chw} - ((m_{ws} - m_{ss}))C_{p,ref}(T_{eva} - T_{cond}) \quad (17)$$

The outlet chilled temperature evaporator of ABS:

$$T_{chw,out} = T_{eva} + \left(T_{chw,out} - T_{eva}\right) exp\left(-\frac{UA_{eva}}{(m_{chw}c_{p,chw})}\right) \quad (18)$$

Performance indicators

The system performance includes cooling capacity (Cap) and COP is typically given by:

$$Cap = \frac{m_{chw}Cp_{chw}\int_0^{t_{cycle}}(T_{chw,in}-T_{chw,out})dt}{t_{cycle}} \quad (19)$$

$$COP = \frac{m_{chw}Cp_{chw}\int_0^{t_{cycle}}(T_{chw,in}-T_{chw,out})dt}{m_{hw}C_{phw}\int_0^{t_{cycle}}(T_{hw,in}-T_{hw,out})dt} \quad (20)$$

The above developed model is implemented and solved simultaneously by MATLAB code that was just generated. The design conditions that were intended to be used for the ABS-ADS system are shown in Table 1 [62]. During the computation, a period of 0.01 seconds was used. When the absolute difference between subsequent cycles becomes less than 10^{-4}. the iteration has reached its conclusion. As soon as we have the collection of equations, the next step is to think about the relevant assumptions, define the collection of model inputs, and choose the appropriate property correlations.

Model Validations

The mathematical model that was built for ABS-ADS chiller is validated by comparing the findings obtained results with the results obtained from the standalone ABS chiller model, ADS chiller model, and with experimental data that can be found in the literature. Table 2 shows the comparison of the findings of current model and experimental data from Balghouthi et al. [63] at the same design and operating characteristics. The findings from the current model and the experimental data [63] were found to be in excellent agreement with each other, with the greatest error being less than ±2%.

Figure 3 depicts the comparison between the temperature profiles of the adsorber (T_{ads}) and desorber (T_{des}) heat exchangers results from the present simulation model and the those from the experimental data collected by Almohammadi and Harby [64] under the same design and operating circumstances. The heat source temperature was 85°C. As indicated, the inaccuracy is not more than ± 4% of the experimental data. Hence, it demonstrates that the present model can predict experimental data well.

Table 1. Design conditions for the ABS-ADS cycle [62]

Parameters	Symbols	Value	Unit
Overall heat transfer coefficient of the utilized evaporator	$(UA)_{eva}$	2.558 × 3.82	kWK^{-1}
Overall heat transfer coefficient of the utilized generator	$(UA)_{gen}$	1.724 × 2.66	kWK^{-1}
Overall heat transfer coefficient of the utilized absorber	$(UA)_{abs}$	1.724 × 2.66	kWK^{-1}
Effectiveness of solution heat exchanger	ε_{SHX}	0.75	-
Overall heat transfer coefficient of the utilized bed	$(UA)_{bed}$	1.724 ×2.66	kWK^{-1}
Overall heat transfer coefficient of the utilized evaporator	$(UA)_{eva}$	2.550 × 3.82	kWK^{-1}
Overall heat transfer coefficient of the utilized condenser	$(UA)_{cond}$	4.115 × 7.46	kWK^{-1}
Weight of copper in adsorbent bed	$M_{Cu,bed}$	64	kg
Overall heat transfer coefficient of the utilized bed	$(UA)_{bed}$	1.724 ×2.66	kWK^{-1}
Weight of copper in the utilized condenser	$M_{cond,cup}$	48	kg
Weight of copper in the utilized evaporator	$M_{evap,cup}$	24	kg
Weight of silica gel in utilized adsorbent beds	M_{sg}	50	kg

Table 2. Simulation model validation with experimental data

	Present study	Balghouthi et al. [63]	Error (%)
$\dot{Q}_{abs}$ [kW]	14.72	14.67	0.33
$\dot{Q}_{cond}$ [kW]	11.91	11.89	0.17
$\dot{Q}_{gen}$ [kW]	15.31	15.26	0.33
$\dot{Q}_{evap}$ [kW]	11.35	11.31	0.35
COP [-]	0.75	0.74	1.33

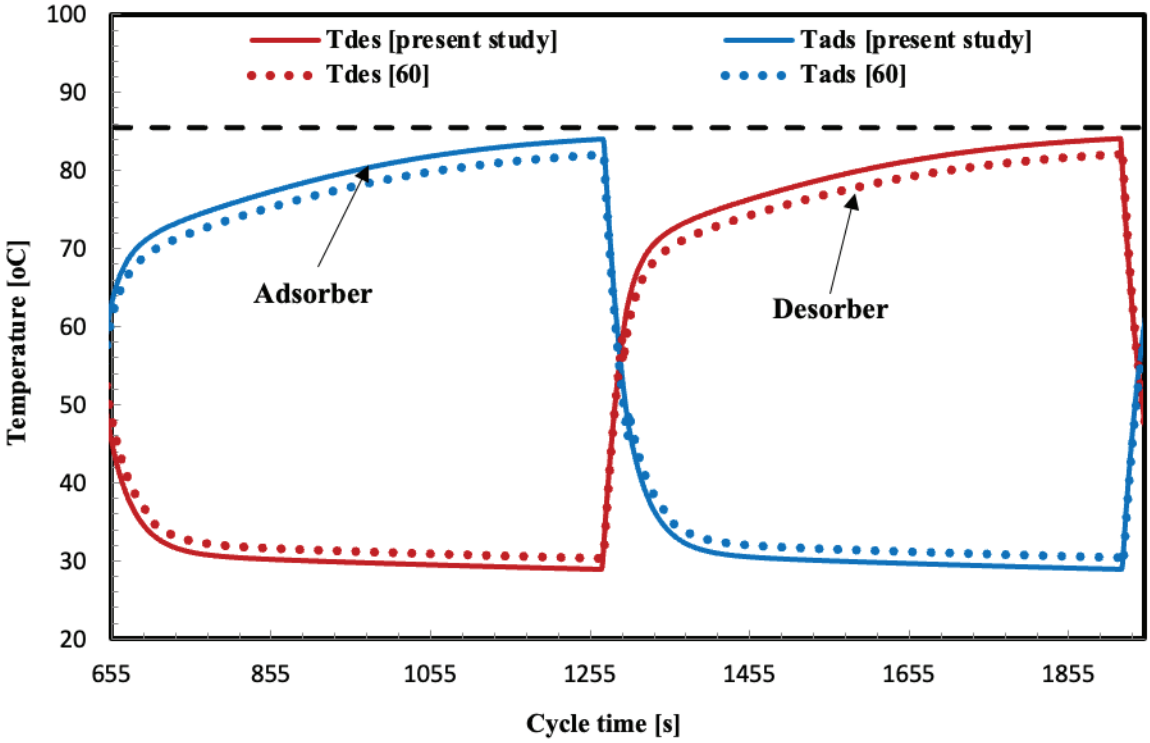

Figure 3. Validation of the simulated model of adsorption chiller with experimental data.

RESULTS AND DISCUSSION

The purpose of this study is to evaluate the performance of a cascade ABS-ADS under a variety of various operating situations, with the goal of using low-grade heat source temperatures between 65-90°C and making effective use of the heat source. The findings of the ABS-ADS are analyzed and compared to those obtained from the single-effect ABS, the two-bed ADS, and other research of a similar kind.

Figure 4 examines the temperature profiles of several components of the ABS-ADS chiller along the half cycle period. These temperatures include those of the adsorbent beds, the condenser, the evaporator, the generator, the absorber, and the hot and cold water. The hot water temperature for desorber and absorber beds is 85°C, while the cooling water temperature is 25°C. At the operating parameters detailed in Table 1, the adsorption/desorption cycle lasts for a duration of 400 seconds, whereas the switching time lasts for 25 seconds.

As shown, during two-half cycles, the cycle transitions from a fluctuating condition to an almost steady state condition. After circumstances have reached steady state, the temperature of the desorber bed is about 2.7°C lower than the temperature of the hot water input, and the temperature of the adsorber bed is approximately 3°C higher than the temperature of the cooling water exit. The refrigeration capacity is 25.4 kW, and the average temperature of the cooled water is 12°C.

Figure 5 shows a comparison between cooling capacity of cascade ABS-ADS, single-effect ABS, and single-stage ADS versus regeneration temperature. Increasing regeneration temperature increases linearly the cooling capacity for all cycles. Increasing regeneration temperature from 65 to 90°C increases the cooling capacity from 3.5-16.8 and 10-36 and 13.2-40.8 for single stage two beds ADS, single effect ABS, and cascade ABS-ADS systems respectively. The cooling capacity by ABS-ADS is higher than that of ABS and ADS. The high temperatures of the heat source cause a partial desorption with a larger cycle time which increases the cooling effect.

Figure 6 shows a comparison between cooling capacity of cascade ABS-ADS, ABS, and ADS versus regeneration temperature. It is also shown that in all systems, the COP first increases with the temperature of the heat source up to 75°C and then begins to decline as the temperature continues to rise. This might be because heat is insufficient for complete desorption process at temperatures lower than 75°C. Subsequently, the working fluid that has not been undesorbed has an impact on the subsequent adsorption process, which in turn reverses the cooling effect. The system needed more time and an additional water cycle in order to achieve the same level of cooling which resulted in a low COP. Because of the high temperatures of the regeneration process, more input energy is required for the operation, which results in larger losses from the system.

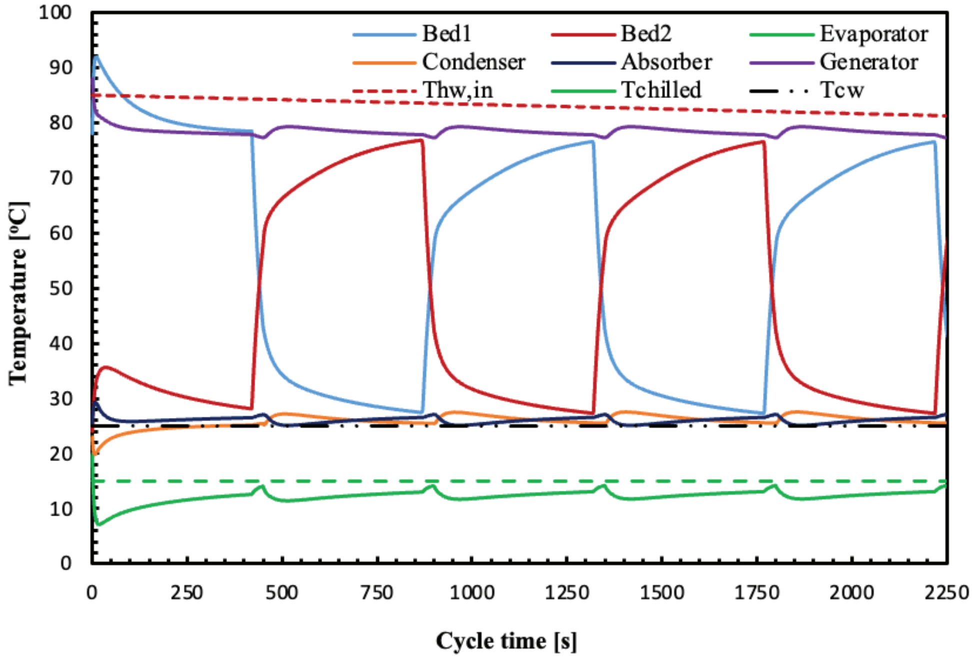

Figure 4. Temperature profiles of components for the cascade ABS-ADS cycle.

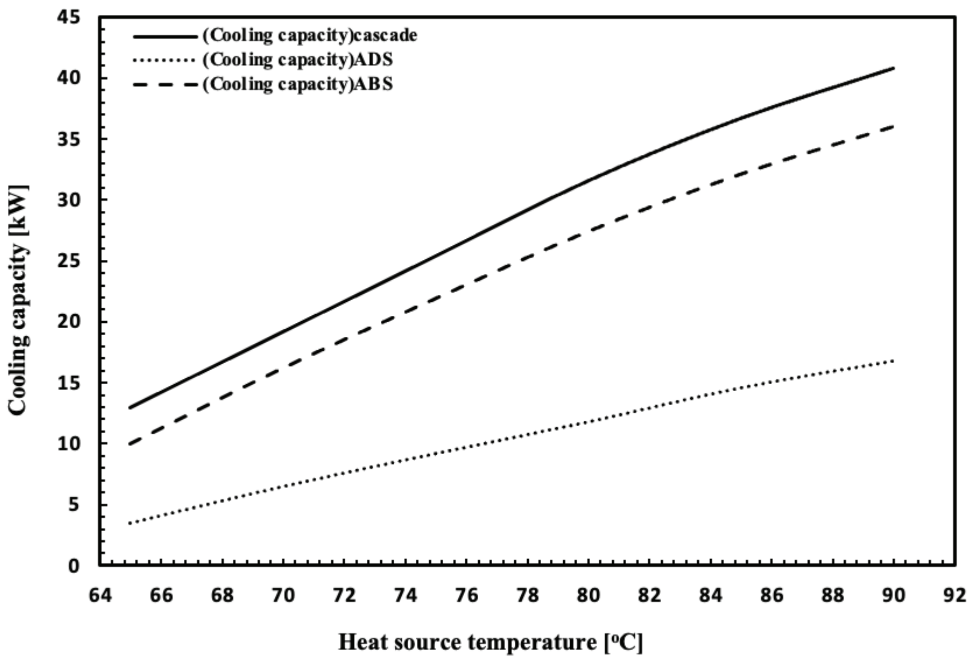

Figure 5. Comparison of cooling capacity for single-effect ABS, single-stage ADS, and cascade ABS-ADS vs temperatures of heat source.

The greatest system COPs that were achieved were at a temperature of 75°C, and they were 0.36 for single-stage two-beds ADS, 0.59 for single-effect ABS, and 0.644 for cascade ABS-ADS systems. The COP of the proposed cascade ABS-ADS cycle is superior to that of the ABS cycle by 8.39% and the ADS cycle by 44%. In addition to the COP, cooling capacity is also an important indicator that should be used to determine the performance of heat driven cooling systems.

Figure 7 presents the variation of hot water flow rate ($\dot{m}_{hw}$) on both cooling effect and system COP of the cascade ABS-ADS cycle. As shown, the cooling capacity and

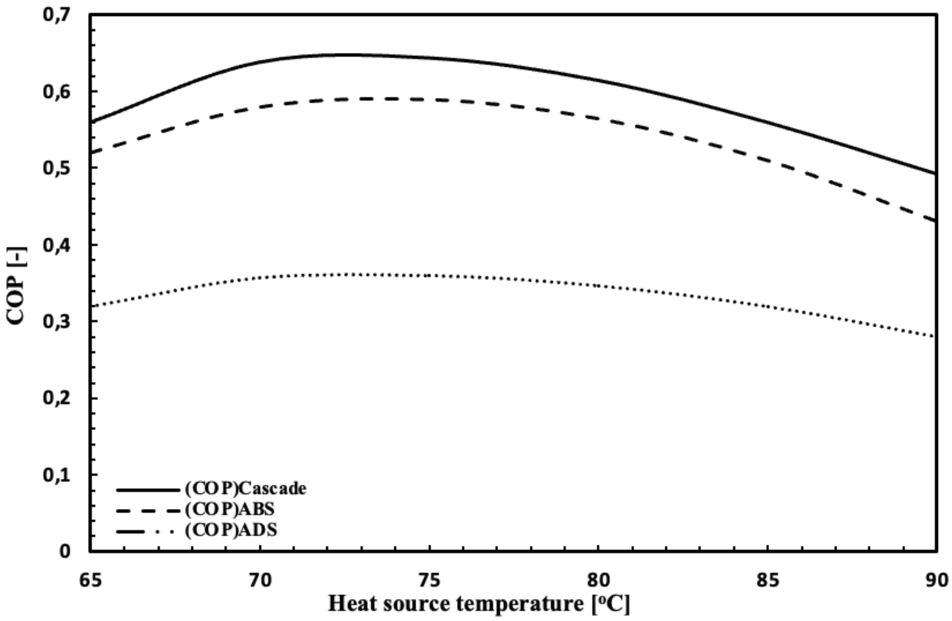

Figure 6. Comparison of COP for ABS, ADS, and cascade ABS-ADS vs temperatures of heat source.

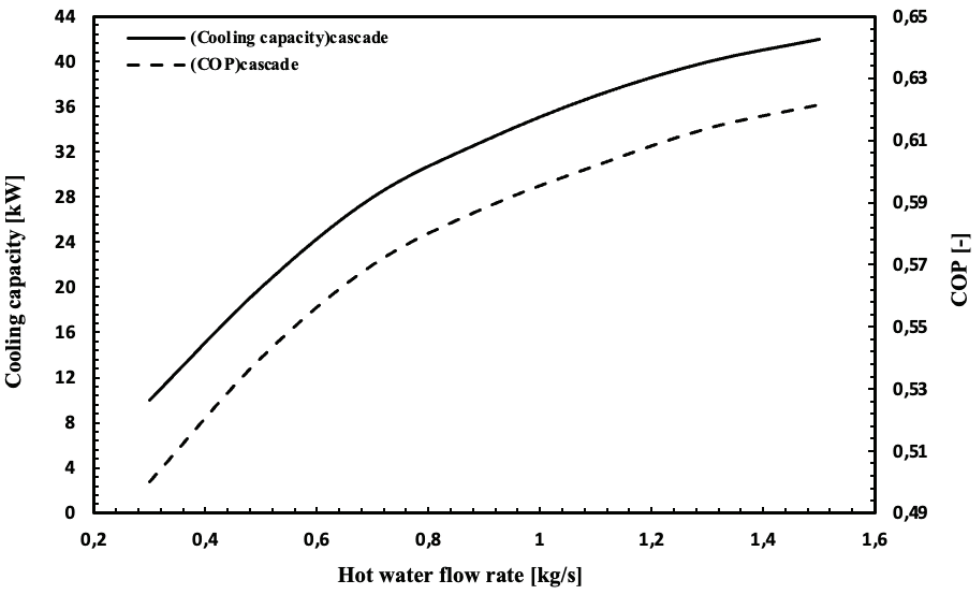

Figure 7. Effect of hot water flow rate of cascade ABS-ADS on cooling capacity and COP.

COP raise with increasing hot water flow rates. However, the effect of hot water flow rate is high in lower than 1.0 kg/s, over that the raise in cooling effect and system COP is only minor.

Figure 8 shows the variation of solution pump mass flow rate on cooling effect and system COP of cascade ABS-ADS. As observed, increasing solution pump flow rate from 0.06-0.16 kg/s increases cooling capacity linearly from 16-44 kW and COP from 0.61-0.63. The maximum value of achieved COP is 0.63 obtained at 0.12 kg/s. The COP remains constant after 0.12 kg/s solution flow rate. A higher solution flow rate required more pumping work, which reduces COP by additional energy input to the system.

Figure 9 presents the variation of chilled water inlet temperature with capacity and COP of the cascade ABS-ADS system. Increasing chilled water inlet temperature of ABS system from 8-16°C increases cooling capacity linearly from 20.6-36 kW and COP from 0.58-0.622. It is observed

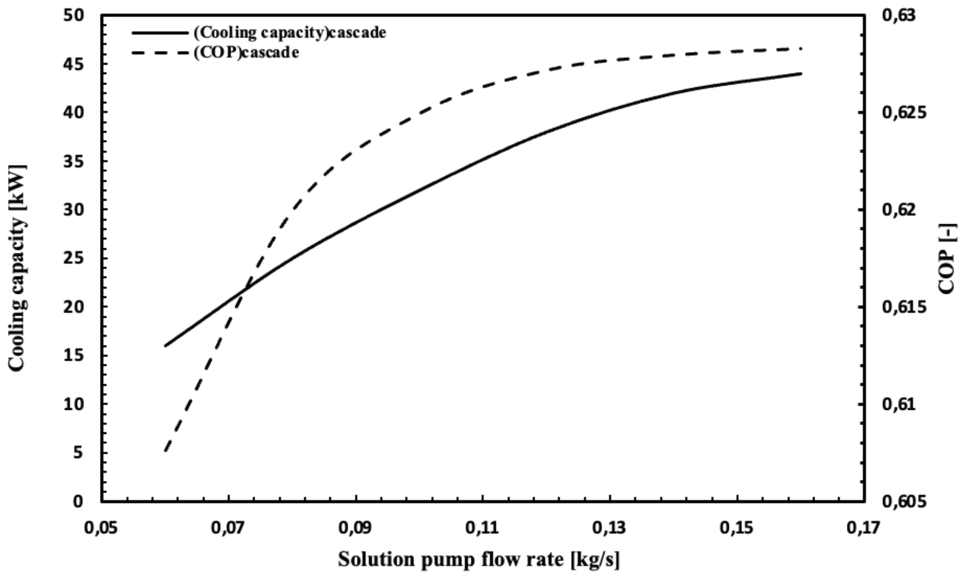

Figure 8. Effect of solution pump flow rate of cascade ABS-ADS on cooling capacity and COP.

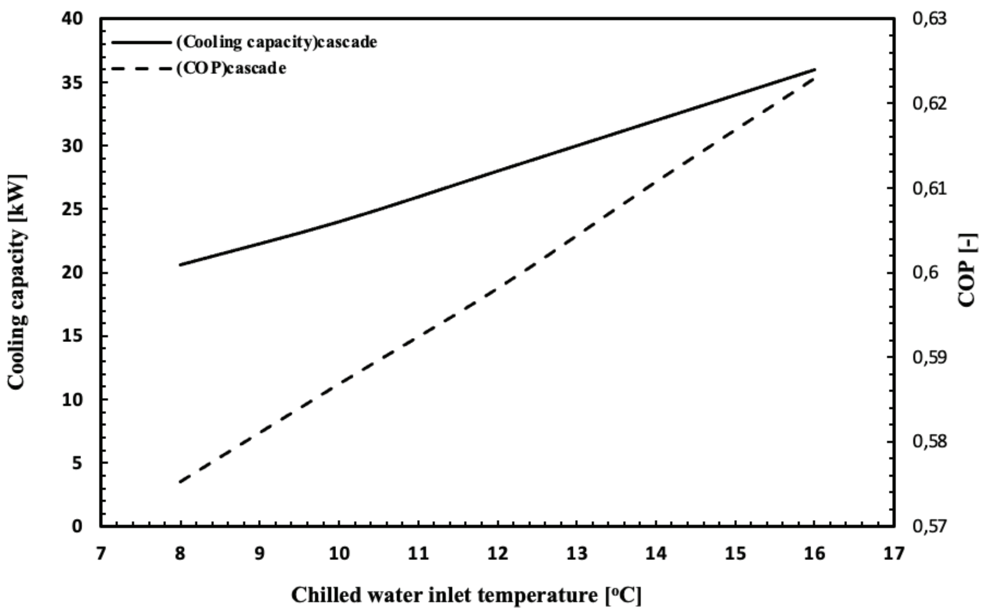

Figure 9. Chilled water inlet temperature variation vs cooling capacity and COP of cascade ABS-ADS.

that a rise of 6°C in the chilled water temperature can cause around 7.2% enhancement of COP and around 71% that of cooling capacity at the same operating conditions. Rising chilled water temperatures have only small effects on the system COP.

Comparison with Other Related Studies

As mentioned earlier, the primary purpose of this work is to enhance the energy utilization and total COP of sorption systems at low grade heat source temperatures. The performance of the combined cascade absorption-adsorption cooling systems is investigated under different temperature heat sources between 65 and 90 °C. Figure 10 shows a performance comparison between the present cascade ABS-ADS cycle and different standalone absorption systems and combined cascade absorption/absorption systems [72] found in the literature. The performance of the present cascade ABS-ADS cycle is driven by a low temperature heat source at 65 °C compared with other studies. The standalone conventional ABS cycles cannot operate effectively below 70 °C [71]. As can be seen, the performance of the

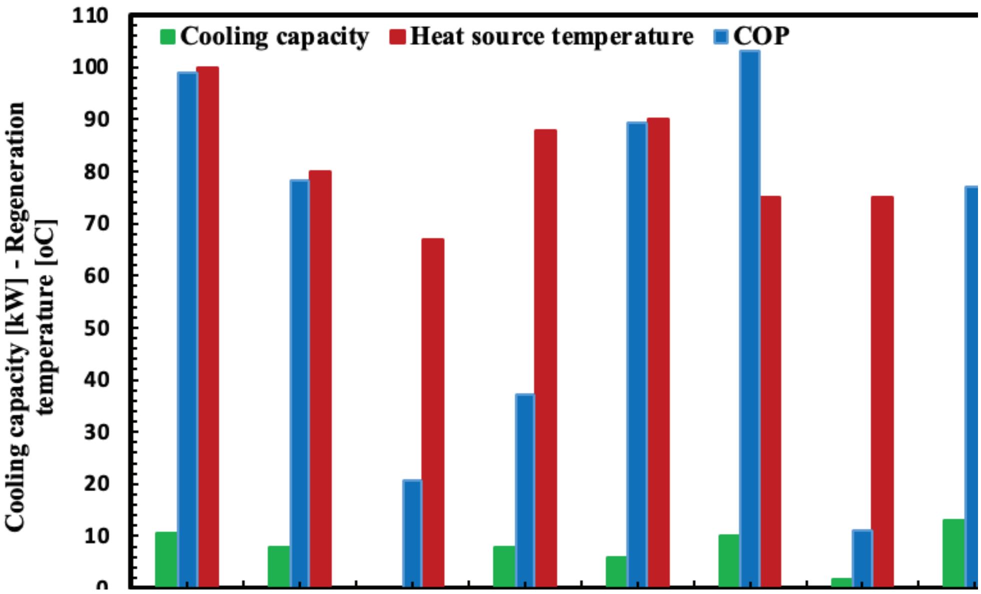

Figure 10. Comparison between present cascade ABS-ADS cycle and other previous single effect ABS cycle.

proposed cascade ABS-ADS cycle works at low heat source temperatures (65°C) and produces around 13 kW cooling capacity with 0.56 COP. The proposed cascade ABS-ADS cycle provides a good value of COP and cooling capacity. In addition, at 60°C heat source temperature, the proposed cascade ABS-ADS cycle provides higher performance than other cycles working at higher heat source temperatures including the combined cascade absorption/absorption systems [72].

CONCLUSION

The current study investigates the performance assessment of a proposed combined cascade absorption-adsorption refrigeration system (ABS-ADS). The primary purpose is to increase energy efficiency and provide low-temperature cooling. The system under consideration is propelled by the low-grade heat source at low temperatures. The results from the ABS-ADS study are compared to those from the solo ABS and ADS investigations, as well as other research in the literature that is relevant to this topic. The following observations may be made as a result:

1. The cooling capacity of the ABS-ADS is 25.5 kW more than the single-stage ABS and ADS, which is a difference of 16.8% and 177% at hot water outlet temperatures of 75°C generated from a low-grade heat source.
2. The temperature at which the COP is at its highest for all systems is 75°C; beyond that, it begins to fall as the temperature of the heat source increases.
3. The COP of the proposed cascade ABS-ADS system is superior to that of the ABS and ADS by 8.39% and 44%, respectively.
4. The effect of hot water flow rate is significantly lower than 1.0 kg/s, after that the rise in cooling effect and system COP is only marginally significant.
5. The cooling capacity of the ABS-ADS system grows linearly from 16 to 44 kW when the solution pump flow rate is increased from 0.06-0.16 kg/s. The coefficient of performance also increases from 0.61-0.63.
6. The highest value of COP that may be attained is 0.63, which can be acquired by operating the ABS-ADS system at 0.12 kg/s.
7. Raising the temperature of the chilled water from 8-16°C raises the cooling capacity of the ABS-ADS system linearly from 20.6-36 kW and raises the COP from 0.58 to 0.622.
8. It has been discovered that a rise of 6°C in the temperature of the chilled water may produce an increase of about 7.2% in COP and approximately 71% in that of cooling capacity when the ABS-ADS system is operated under the same circumstances
9. The performance of the suggested ABS-ADS system can function at a temperature of 75°C and generate a high cooling effect in comparison to the other published research from the literature on various system designs and sizes.

NOMENCLATURE

A	area, m^2
C_p	specific heat capacity, $Jkg^{-1}k$
E_a	activation energy of surface diffusion, $jmol^{-1}$
F_0	constant
h	enthalpy jkg^{-1}
$\dot{m}$	mass flow rate, kgs^{-1}

M	mass, kg
P	pressure, Pa
p_s	saturated pressure, Pa
Q	heat transfer, kW
R	universal gas constant, $jmol^{-1}K^{-1}$
R_p	radius of the adsorbent particle, m
T	temperature, °C
U	overall heat transfer coefficient, $Wm^{-1}K$
ΔH_{st}	isosteric heat of adsorption, Jkg^{-1}
ω	uptake, $kgkg^{-1}$
X	concentration, %
ρ	density, kgm^{-3}

Subscripts

Al	aluminum
abs	absorption
ads	adsorption
des	desorber
ads	adsorbent
bed	sorption bed
h	Enthalpy, $kJkg^{-1}$
hw	hot water
Cu	copper heat transfer tube
chw	chilled water
cond	condenser
cwa	cooling water in adsorber/desorber
cwc	cooling water in condenser
des	desorption
gen	generator
hex	heat exchanger
sg	Silica gel
sol	solution
ss	strong solution
ws	weak solution
eva	evaporator
in	inlet
out	outlet
ref	refrigerant
w	water

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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