Performance analysis of a geothermal heat-powered resorption cooling system: a case study for cold storage of apple fruit

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Abstract

Renewable energy use in agricultural applications is essential for sustainable production. Resorption cooling systems can be operated for agricultural cooling applications by using thermal energy derived from geothermal springs with sufficient temperature. Since the resorption cycle uses ammonia-water solution, cold storage and industrial cooling processes below 0°C can be actualized efficiently. In this article, a geothermal powered resorption system for cold storage of apple fruit is investigated. Technical features and cooling performance of the resorption system are analysed and compared to the other conventional cooling systems. Results showed that, geothermal powered resorption cooling systems can annually cover the cooling load of the cold storage application with adequate cooling temperature and capacity. Moreover, the use of the geothermal powered resorption system enables to set up safer and more economic cooling applications with the similar cooling performance compared with the alternative sorption cooling systems, and provides substantial economic benefits by reducing the cooling costs in agricultural production with lower operational costs.

Keywords: Cold storage; Agriculture; Cooling; Geothermal energy; Resorption

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1 INTRODUCTION

In order to improve the sustainable energy technologies, researchers and scientists perform significant studies all over the world [1–6]. Many problems that threaten our future are related to the energy, thus, use of clean, renewable and sustainable energy to derive industrial and domestic energy requirements plays a key role to solve these issues. Since the energy requirement for cooling applications accounts for a large share of global energy consumption, renewable energy powered cooling systems appear to be an appropriate solution for addressing the existing problems. Thermally driven sorption cooling systems, can be used efficiently to satisfy cooling demand by using renewable energy sources such as geothermal and solar with relevant temperature. Many numerical [7–13] and experimental [5, 14, 15] analyses were performed for these systems and the results showed that it is feasible to use thermally driven sorption cooling systems for industrial and domestic cooling applications. Even though the renewable energy powered sorption cooling systems have low operating and maintenance costs and promise great economic and ecologic benefits, they are still not competitive with the conventional vapour compression refrigeration systems because of their technical features, cooling performances and investment costs. Resorption cooling cycle has significant superiority in technical and economic aspects compared to conventional thermally driven sorption systems such as absorption and adsorption cycles. Resorption cooling systems use ammonia-water solution as the refrigerant and the operation pressure in the cycle is adjustable and lower than the ammonia based absorption cooling cycles, while it is not possible in conventional ammonia based sorption systems. Thus, the temperature of the heat source that drives the resorption cycle is lower and it is possible to actualize safer and economic cooling applications below 0°C with the similar cooling performance, compared to conventional absorption cooling systems with ammonia-water solution. As a result of the technical superiorities of the resorption cooling systems, the use of these systems in different industrial cooling applications with a wide temperature range provides great technical, economic and ecological benefits.

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Many researchers present their studies on resorption systems. Costiuc and Costiuc [16] studied on solar powered resorption systems. They designed, built and analysed a resorption refrigeration system that uses parabolic solar collectors to derive thermal energy. They reported that the system can be driven at relatively low heat source temperatures achieved by solar collectors. Bao *et al.* [17] and Pastakkaya *et al.* [18] investigated the resorption cooling system for cold storage applications and both reported that it is possible and feasible to actualize cooling applications below and above 0°C by using resorption cooling systems. Helle [19] performed an experimental analysis on resorption cooling system with the maximum cooling capacity of 1.8 kW. She reported that it is possible to perform cooling applications while the cooling temperature is 8°C and the heat source temperature is 65°C. Grund *et al.* [20] carried out a study to present the performance of a resorption chiller. The results of the study showed that the resorption refrigeration system provided cooling temperatures below 0°C by using waste heat at temperatures in the range of 65°C to 90°C, and attached ice storage system enabled the temporarily decoupling of the cooling demand from the generated thermal capacity. Ziegler and Hesse [21] experimentally and theoretically investigated an absorption–resorption system and they reported that the resorption system is more advantageous than the conventional absorption systems because of the difference in system design and required components. Jaehner and Grund [22] carried out an experimental study to determine the performance of a trigeneration system with resorption chiller. The study indicated that it is possible to reach the low cooling temperatures, such as 0°C, thus it enables the trigeneration system to store the energy in ice form efficiently, that can cover cooling demand for 8 hours. Pastakkaya *et al.* [23] presented the renewable energy powered resorption cooling systems. They concluded that renewable energy powered resorption systems will have wide spread use in industrial and residential applications because of their advantages among alternative systems.

Eco-friendly cold storage applications of the agricultural products offer new alternative solutions not only for the world's starvation problem [24] but also for the economic and ecological problems related to energy use in agricultural cooling applications. Resorption cooling systems provide great benefits also in agricultural cooling. Pastakkaya *et al.* [25] reported that resorption cooling systems provide approximately 60% of energy saving in cold storage application compared to the conventional cooling systems. They also indicated that, a geothermal resorption cooling plant with 100 kW cooling capacity, annually provides 295 650 kWh electric energy savings and the payback period of the system is 3.5 years. Anese *et al.* [26] reported that apple fruit storage is crucial to provide fruit to consumers during the off-season and new strategies to reduce apple fruit decay and maintain fruit quality during postharvest with low environmental impact are essential. In the 2020–21 season, Turkey ranked third in apple fruit production, 10th in exports after EU countries in the world ranking and it is estimated that apple fruit production will increase by 4.5% compared to the previous year and will reach 4.7 million tons [27]. Since it is too difficult for the producers to cover the operational costs of the cold storage of apple fruit with conventional vapour compression refrigerator, cooling applications with resorption systems enable to enhance agricultural production's efficiency and provide added value for national economy with reducing energy cost of the agricultural cold storage and CO_2 emissions by using clean and renewable energy. Consequently, the use of resorption system in many different kinds of cooling applications engaged many scientists and researchers to investigate the features and the benefits of these systems [5, 28–33]. In this study, the use of a novel geothermal powered resorption cooling plant is investigated to propose an alternative solution for the issues related to energy use and the global starvation problem, by using an eco-friendly and efficient cooling system. Operational features, technical superiorities and the cooling performance of the system are analysed and compared to the other conventional cooling systems.

2 METHODS

Resorption cooling cycle has a different working principle compared to the conventional ammonia based absorption cooling cycle. The resorption system uses ammonia-water solution as refrigerant and water as absorbent. There is a second solvent circuit in the resorption cycle named as mix flow. The condenser in the conventional absorption cycle is replaced by a high pressure absorber and evaporator is renamed as a cold desorber. The illustration of a sample resorption cooling cycle is presented in Figure 1. The numbers on the figure (1–9) represent the components and the flow lines. (Figure 1).

Ammonia-water solution in the hot desorber (1) is vaporized by the thermal energy of a geothermal source with the relevant temperature. Gaseous ammonia is transferred between the hot desorber and the high pressure absorber passing through a phase separator. Gaseous ammonia from hot cycle is absorbed by the ammonia-water solution and flows from the cold desorber (2) in the cold cycle, and the waste heat of the absorption process is rejected by an external heat rejection system. The ammonia-water solution from the high pressure absorber (3) passes through a solution heat exchanger for heat recovery in order to improve the thermal efficiency of the system, and then an expansion valve to reduce its pressure to the cold desorber pressure, respectively. The solution in low pressure enters the cold desorber and evaporates (4). Thus, the cooling energy for covering the cooling demand of the cooling applications is provided and distributed by an external cold distribution loop. The ammonia water solution from the cold desorber (5) is pressurized by a solution pump and transferred to the high pressure absorber (2) to absorb the ammonia vapour from the hot desorber by passing through a heat exchanger.

The ammonia vapour from the cold desorber passes through a phase separator and enters the low pressure absorber. The ammonia vapour from cold desorber is absorbed by ammonia water solution from the hot desorber in the low pressure absorber. The waste heat from absorption process in the low pressure absorber is rejected as occurred in the high pressure absorber. Ammonia water solution is pumped from the low pressure absorber (6) to

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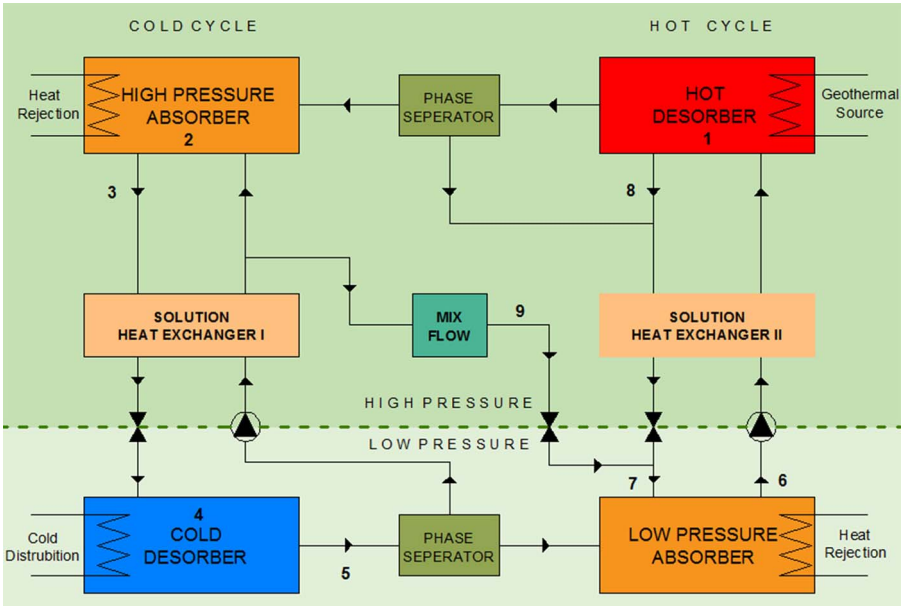


Figure 1. *Resorption cooling system working principle.*

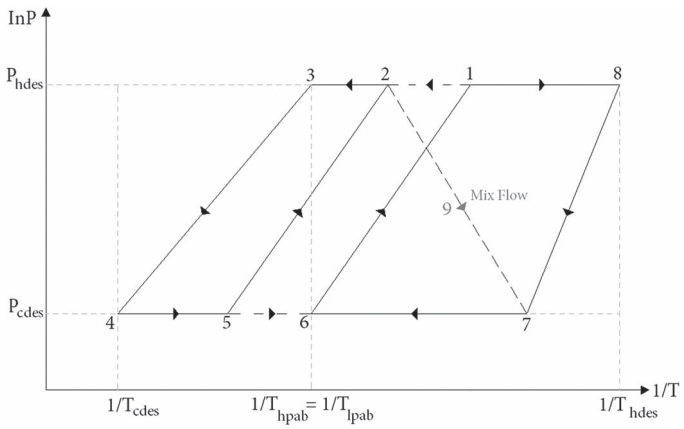


Figure 2. *InP-1/T diagram of the resorption cycle.*

the hot desorber. Meanwhile, the ammonia vapour from the cold desorber absorbed by the solution returns from the hot desorber and enters the low pressure absorber (7). Before the absorption process, ammonia water solution from hot desorber (8) passes through a second solution heat exchanger for heat recovery, and then an expansion valve to reduce its pressure to the low pressure level of the cycle. As a consequence, the resorption cycle is completed. There is a mix flow between the cold and hot cycles (9) for an equalization of the concentrations to avoid an enrichment of the refrigerant in the cold cycle. Figure 2. represents the InP-1/T diagram of the resorption cycle.

The pressure levels in the resorption cycle are substantially lower than the conventional ammonia based absorption cycle and can be adjusted by the alteration of the ammonia-water concentrations. Therefore, the ammonia leakage risk and the wall thickness of the stainless steel components in the resorption cooling system are reduced. This feature enables to design safer, more compact and cost effective cooling facilities. Furthermore, since the pressure levels are lower in the system, the temperature levels of the thermal energy that drives the hot desorber are lower and can be reduced to temperature range of 65–90 °C, while the coefficient of performance (COP) of the resorption system is similar to the conventional ammonia based absorption system [19, 23]. The resorption cooling system uses the ammonia-water solution as refrigerant, so it is possible to actualize cooling applications below 0 °C and the resorption system can be used in cold storage applications. In addition to that, the system can be used to store cooling energy in ice form [34], which enables the cooling energy to be stored, used or transported efficiently. It also enables to set up hybrid systems and use the resorption cooling system as an auxiliary chiller with the conventional vapour compressed refrigerating systems. Figure 3 shows the actual image of two different resorption cooling systems used in real projects.

In this study, the performance of a geothermal powered resorption cooling system that is used for the cold storage of the apple fruit in Bursa region of Turkey is analysed. Bursa region is an important producer of apple fruit and it has a great geothermal energy potential and many geothermal sources that vary between the temperature of 35–88 °C [35]. Kaynarca geothermal spring in Bursa region, Turkey is used as the thermal energy source for the resorption cooling plant. The temperature of the Kaynarca spring is 88 °C and the flow rate is 2 l/s, at the constant value in annual period. Since the apple fruit requires low temperatures for the storage periods [36], cold storage temperature is determined between the range of 0–4 °C [37, 38] and the required average cooling power for cold storage of apple fruit in Bursa is 0.7 kW/ton [38]. However, many agricultural products require

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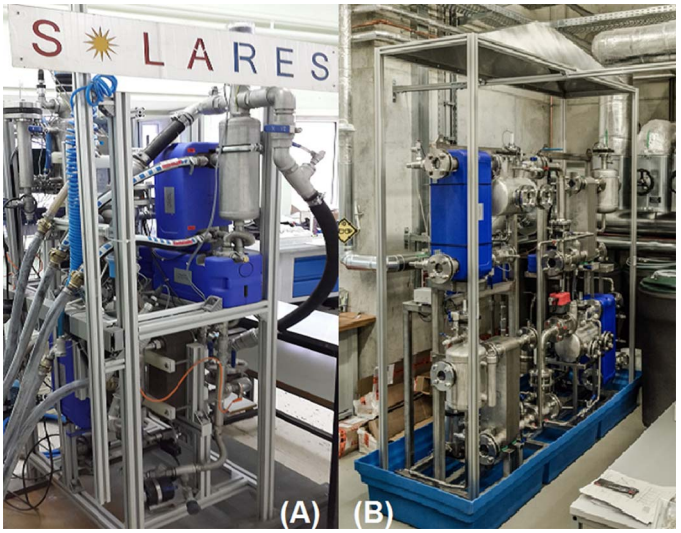


Figure 3. *Resorption chillers in real projects with the cooling capacity of 5 kW (A) and 25 kW (B) [22].*

different climatic conditions in a wide range of cooling temperatures, the cooling performance and the capacity of the resorption system are affected by the environmental conditions. Therefore, it is essential to estimate optimum working conditions of the resorption system for an efficient cooling. In order to evaluate the system performance in different scenarios, a program based on the mathematical model of the resorption cycle [39] built up with Refprop [40] is used for the numerical analyses. The program enables to calculate cooling capacities of the resorption unit, coefficient of performance (COP) value which is the ratio of the cold desorber and the hot desorber capacity, temperatures, pressures and the properties of the ammonia-water solution in the cycle [41]. The environmental conditions are calculated by Transient System Simulation Tool TRNSYS simulation program [42] to evaluate the effect of the heat rejection system on the cooling plant's efficiency.

3 RESULTS AND DISCUSSION

Cooling performance of the sorption cooling cycles, fluctuates with the heat source temperatures, heat rejection temperatures and the pressure levels. In order to evaluate the geothermal heat powered resorption cooling system's performance in cold storage application, analyses were performed to see the correlation between these and the cooling performance parameters, such as cooling temperature, cold desorber's cooling capacity and the COP of the resorption chiller. Table 1. represents the resorption cooling system's cold desorber temperature and COP variation according to the different hot desorber and absorber temperatures.

In all analyses, Kaynarca geothermal spring with the 88°C temperature, 2 l/s volumetric flow rate and 41.8 kW heat power is used as the heat source to power the hot desorber of the

Table 1. *Resorption cooling system's specifications in different operational conditions*

P_{hdes} = 6 bar	T_{hdes} = 90°C	T_{hdes} = 80°C	T_{hdes} = 70°C
	T_{abs} = 15°C		
T_{cdes} [°C]	−18.90	−13.18	−7.14
COP [−]	0.38	0.48	0.56
T_{abs} = 20°C			
T_{cdes} [°C]	−10.55	−4.47	1.89
COP [−]	0.44	0.53	0.60
	T_{abs} = 25°C		
T_{cdes} [°C]	−1.83	4.59	11.8
COP [−]	0.48	0.57	0.65
	T_{abs} = 30°C		
T_{cdes} [°C]	7.52	15.37	23.25
COP [−]	0.52	0.61	0.69

resorption cycle. Since the heat losses are negligible in the heat distribution system, it was assumed that all thermal energy in the geothermal source is transferred to the hot desorber to evaporate the ammonia-water solution. The ambient temperature, relative humidity and the wet bulb temperature directly affect the heat rejection system's performance which changes the design temperature of the low and high pressure absorber of the resorption cycle. In order to determine the heat rejection system's parameters, meteorological design values for Bursa region that are represented in American Society of Heating, Refrigerating and Air-Conditioning Engineers ASHRAE standards are used in the calculations [43]. Figure 4 represents the correlation between the cold desorber temperature that is used for providing cooling energy to the cold storage area and the pressure level of the hot desorber of the resorption cycle that means the high pressure of the cycle, in three different absorber temperatures.

Since the maximum monthly design wet bulb temperature for summer is 25°C, the mean annual design wet bulb temperature is 20°C and the average temperature for winter is approximately 15°C for Bursa-Turkey [41], calculations were performed for the absorber temperatures of 25°C, 20°C, 15°C, respectively. Figure 4 shows that, resorption cooling system can operate in lower cooling temperature with the lower absorber temperature and higher hot desorber pressure. Even in hot summer conditions while the absorber temperature is 25°C, and hot desorber pressure is 6 bar or higher, resorption chiller can provide cooling energy below 0°C. Since the design temperature of the cold storage of apple fruit is reported as 0°C to 4°C [38], it is possible to provide cooling energy at 0°C with the geothermal powered resorption cooling system even on the hottest days of summer if the hot desorber pressure is settled to 6 bar.

Cold desorber's cooling capacity determines the amount of the product to be stored in the cold storage. Consequently, it is important to calculate the cooling capacity of the cold desorber in the resorption system. Figure 5 represents the variation of cooling capacity between the cold desorber's cooling capacity and hot desorber pressure for three different absorber temperatures.

It is seen on the Figure 5 that, cold desorber's cooling capacity increases with the increase of the hot desorber pressure and gets

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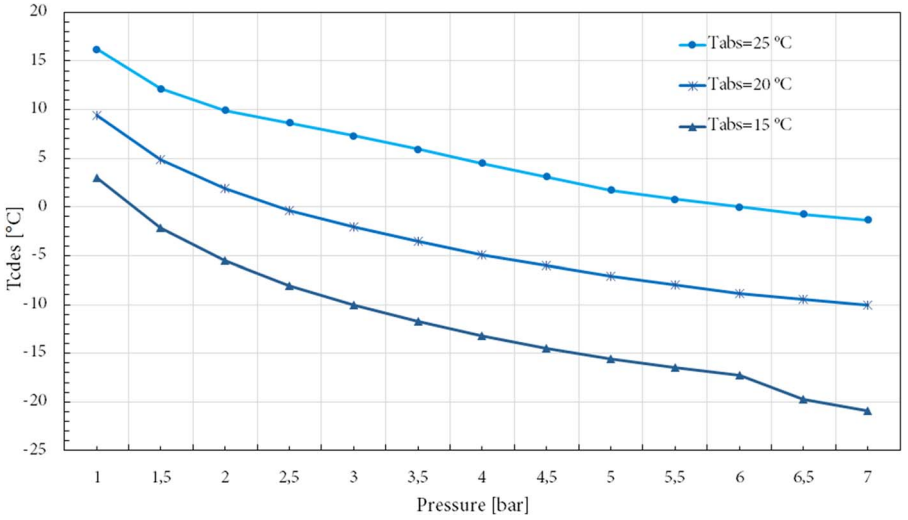


Figure 4. *Change of cold desorber temperatures with hot desorber pressure in three different absorber temperatures.*

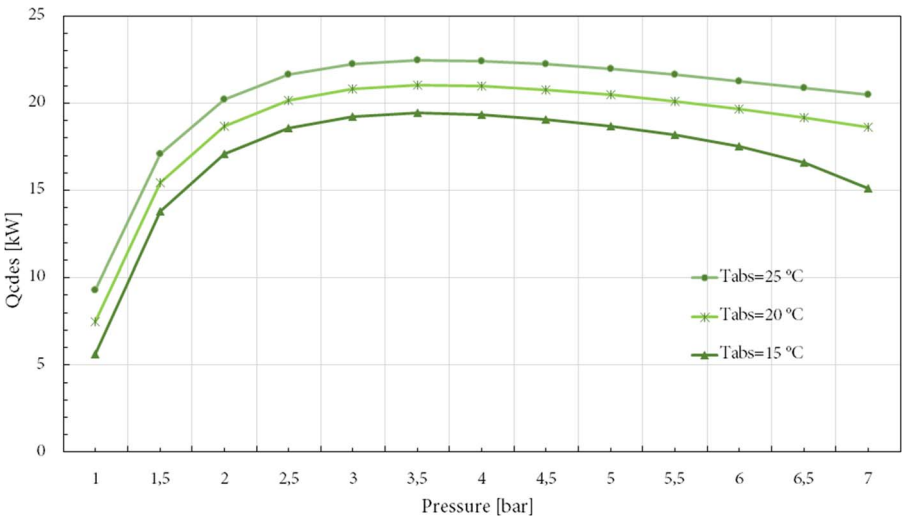


Figure 5. *Change of cold desorber cooling capacity with hot desorber pressure in three different absorber temperatures.*

the highest value at the pressure level of 3.5 to 4 bar. After that, it slightly decreases with the increase of the pressure. Since the cold desorber temperature decreases with the low absorber temperatures, enthalpy of ammonia solution and the cooling capacity of the system decrease as well.

It is also seen in the change COP of the system (Figure 6). The hot desorber capacity remains the same during the cooling application because of the fact that the hot desorber is powered with the geothermal source. Therefore, there is no change in temperature and flow rate in the hot desorber. Yet, the decrease in the cooling capacity also causes a reduction in COP of the resorption cooling system, and gets lower values at the lower absorber temperatures for the same reasons.

COP of the resorption system varies between the range of 0.51 to 0.36 in different temperatures and pressures (Figure 6). Since the conventional ammonia based absorption cooling systems have the similar COP values at the similar working conditions [19, 34], resorption cooling systems offer better techno-economic solutions without compromising cooling efficiency compared to their conventional alternatives. Resorption cooling systems' advantages are mainly based on the alteration of the ammonia-water (NH_3-H_2O) solution's concentration in the hot and the cold cycle, which enables to reduce pressure levels in the system; so, monitoring the ammonia concentration in the ammonia-water solution is important in the performance analyses in different working conditions. Figure 7. shows the change of the ammonia water concentrations in the resorption system's components in the different hot desorber pressure levels between 1 to 7 bar. The design conditions determined as the low and the high pressure absorbers' temperatures are 25°C, and the hot desorber temperature is 88°C, considering the working conditions.

Results show that ammonia concentrations vary between 0.03–0.29 and 0.25–0.59 in the hot desorber and cold desorber, and 0.10–0.40 and 0.31–0.57 in the low pressure and high pressure

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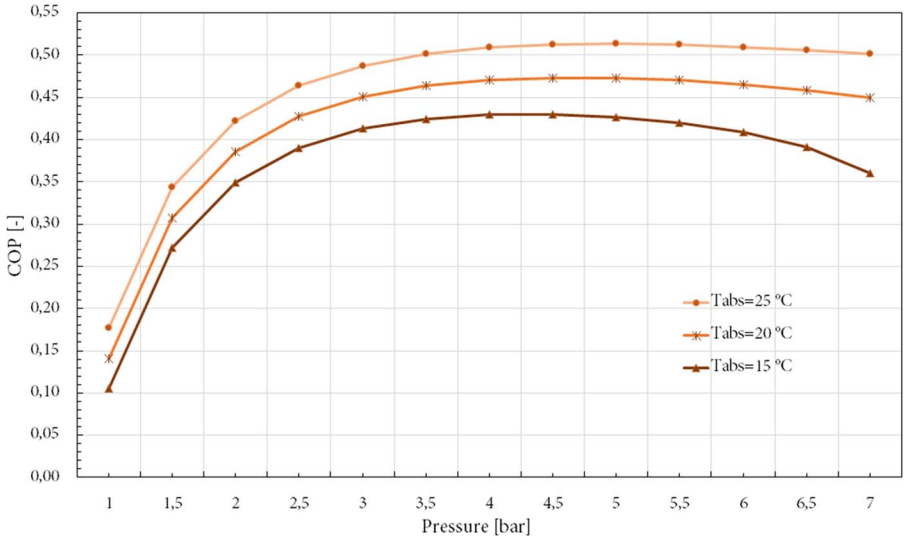


Figure 6. *COP value of the resorption system in different desorber pressure and absorber temperatures.*

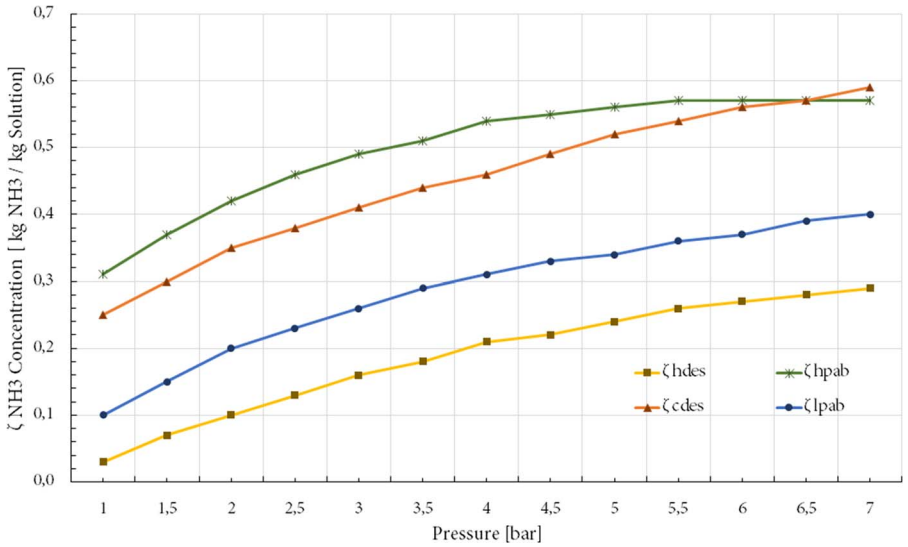


Figure 7. *Ammonia concentrations in solution in the resorption cooling system's components.*

absorbers, respectively. As the hot desorber pressure increases, ammonia concentrations increase in all absorbers and desorbers as well until the pressure reaches 6 bar. As seen on the Figure 7 and Figure 4, by alteration of the ammonia concentration and pressure levels in the resorption cycle, it is possible to actualize cooling applications in different cooling temperatures and cooling capacities by using thermal energy such as geothermal, solar or the waste heat with the sufficient temperature.

In order to evaluate the transient cooling performance of the system, a daily performance analysis is performed for the geothermal powered resorption system for 24 hours' period on a hot summer day. Ambient temperature and the relative humidity are calculated [35, 36] for the day of 15 August and the location of Bursa-Turkey. Kaynarca geothermal spring in Bursa is used as the heat source to power the hot desorber. Since the maximum wet bulb temperature and absorber temperature reach up to 25°C in daily calculation, pressure of the hot desorber level in resorption system is determined as 6 bar. As seen on Figure 4, cold desorber temperature can decrease to 0°C only after the hot desorber pressure increases to 6 bar while the absorber temperature is 25°C.

Figure 8 represents the daily variations of the ambient temperature, the cold desorber and the absorber temperatures of the resorption system, in August, in Bursa-Turkey. Because of the ambient climatic conditions, all temperatures reach the highest value at 15:00, but cold desorber temperature still remains below 0°C and continues the cooling process with the sufficient temperature for cold storage of apple fruit. Moreover, while the design

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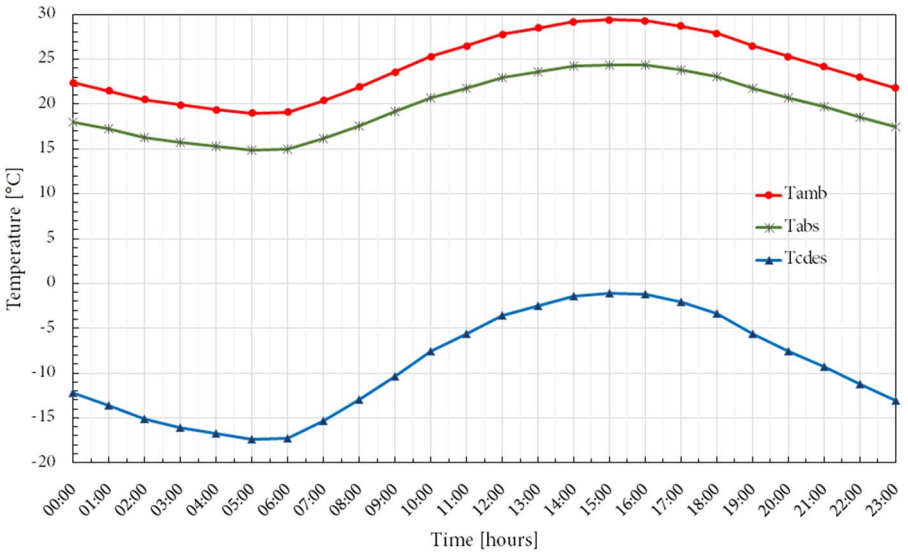


Figure 8. *Variations of the daily cooling temperature of the resorption system on a hot summer day.*

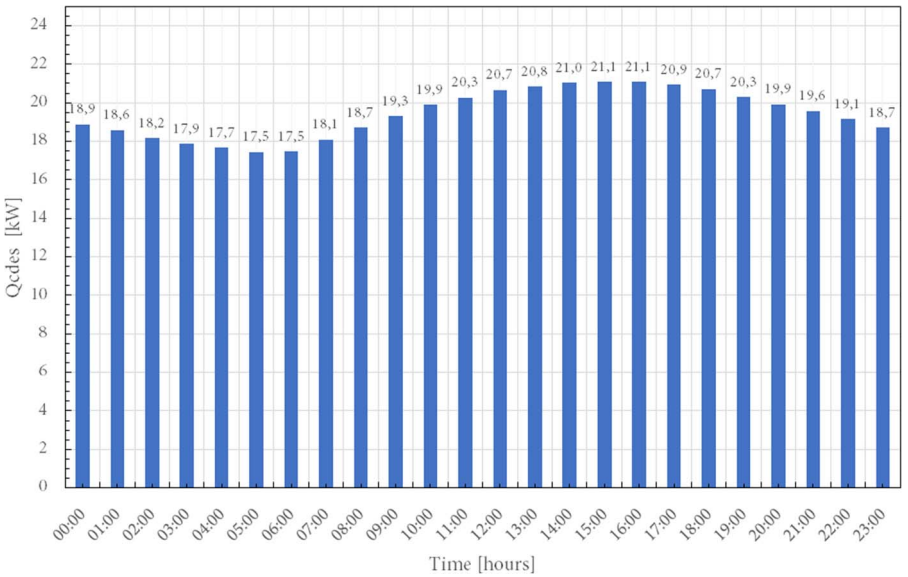


Figure 9. *Change of the daily cooling capacity of the cold desorber in daily cooling period.*

temperature of cooling is 0°C to 4°C for the cold storage, cold desorber temperature decreases down to −17°C at night, and does not increase over −15°C for 12 hours between 21:00 to 9:00 am. So, integrated with ice storage units, it is possible to store cooling energy in ice form [22, 39] and use it as a backup cooling system or for other purposes.

Figure 9 illustrates the change of the cold desorber cooling capacity for 24 hours. Based on the variation of the cold desorber and absorber temperature, the cold desorber cooling capacity fluctuates between 17.5 to 21.0 kW. Since the required average cooling power for cold storage of apple fruit is calculated as 0.7 kW/ton, it is possible to actualize cold storage of apple fruit with the minimum amount of 25 tons by using geothermal resorption cooling system on a hot day on 15 August in Bursa region. Also the efficiency of resorption cooling system in daily period is similar to the conventional ammonia based absorption cooling system. COP of the resorption system gets the highest value of 0.51 and the minimum value is 0.41. The mean COP value for the daily cooling period is 0.46.

Results showed that, resorption cooling system covers the cooling load of the cold storage application efficiently, even on the hot summer days without compromising thermal design conditions. In addition, resorption cooling system has lower operational costs than its alternatives, thus using a resorption system enables to actualize cooling applications with lower CO_2 emissions and similar cooling efficiencies.

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4 CONCLUSION

Thanks to its technical superiorities, resorption cooling systems enable to use renewable thermal energy sources in cooling applications and actualize more advantageous projects compared to its alternatives. Within the scope of this study, working principles and features of a resorption cooling system are presented and a geothermal powered resorption system's performance is analysed with the actual operational conditions.

Results showed that, by using a geothermal energy source with the 88°C temperature and 41.8 kW heat power to drive a resorption chiller, it is possible to carry out a cooling application for cold storage of apple fruit with the amount of 25 tons and cooling temperature range of 0°C to 4°C efficiently, even on the hottest summer days, in Bursa region, Turkey. Since the system can provide cooling energy below 0°C, it is also possible to store cooling energy in ice form to use it as a backup or auxiliary cooling system for other domestic or industrial cooling applications.

Moreover, it is concluded that, by using totally clean, renewable and independent geothermal energy in resorption cooling applications in agricultural processes, it is possible to make a major contribution to provide alternative solutions for economic and ecological issues related to energy use and for starvation and malnutrition in national and international scale.

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DATA AVAILABILITY STATEMENT

Detailed information and the link for the project is given below: Reducing Operational Cost of Agricultural Cooling Applications Using Resorption System in Orhangazi Region, Bursa Uludağ University Rectorate Scientific Research Projects, BAP 2013/42 - Orhangazi Bölgesinde Tarımsal Soğutma Maliyetlerinin Düşürülmesi Amacıyla Resorbsiyonlu SoğutmaTeknolojisinin Kullanımının Araştırılması, BAP 2013/42 https://bursauludagtto.com/Uploads/FileManager/2022/9/MESLEK_YÜKSEK_OKULLARI_AKADEMİSYEN_KATALOĞU_onaylı.pdf, please check page 46.

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