Energy, Exergy and Economic Analysis of Absorption Chiller Systems: A Case Study for a Wood Pencil Factory

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Abstract- This study examines the use of absorption chiller systems in a designated industrial facility having waste heat by conducting energy, exergy and economic analyses. The absorption chiller systems namely single-effect, double-effect series, double-effect parallel and double-effect reverse parallel were analysed to determine the best alternative for the wood pencil factory. The results indicated that the COP of the single-effect absorption chiller systems is changed from 0.758 to 0.763 when the temperature of the generator was increased from 89 ºC to 125 ºC. However, the exergetic performance of the single-effect absorption chiller system decreased by 40% in the same generator temperature range. On the other hand, COP of all double-effect absorption chiller systems increased about 8 % when the generator temperature was changed from 116 ºC to 155 ºC while the exergetic performance of all double absorption chiller systems decreased by around 14% for the same generator temperature range. The COP and exergetic efficiency values of the double-effect parallel system were found to be higher than other absorption systems at all generator temperature values. Overall, this study recommends that the double-effect parallel absorption chiller systems can be preferred for the factories having waste heat source wood chips. The average payback period of the system was also found to be 1.4 years. Furthermore, this study shows that double-effect parallel absorption chiller systems can be proposed for the facilities having wood chips waste sources instead of double-effect reverse parallel absorption chiller systems since they are easy to operate and have lower maintenance costs.

Keywords Absorption chiller, Waste heat recovery, Energy analysis, Exergy analysis, Economic analysis.

1. Introduction

Environmental issues such as greenhouse gas emissions and air pollution have reached critical levels and have become a growing worldwide health concern, [1-4]. Consequently, researchers have extensively started to study alternative energy systems having less environmental damage than traditional energy systems. Waste heat recovery (WHR) systems can be listed among alternative energy systems that are promising technology with their environmental and operational cost-economic features. The steam energy that is obtained from waste sources is called waste heat energy and the use of this energy significantly reduces the electricity consumption in the process besides environmental sustainability, [5,6]. Although different industries use various WHR devices, absorption chillers (ABC) are preferred by many industrial plants to maintain their HVAC operations as they can be integrated directly into the system. Despite the high initial investment costs of these systems, the electricity consumption is quite low compared to standard vapour compression systems (VCR) since the heat source can be cheaply obtained either from the waste heat of the process or solar energy, [7 - 9].

In the literature, there exist studies about different applications of ABC systems. Popli et al. [10] conducted sets of thermal and economic analyses for the use of single-effect H_2O-LiBr ABC systems to provide air cooling at the inlet of the compressor of the gas turbine. The waste heat source of the ABC system was provided from the exhaust emissions of the turbine. The results showed that three single-effect H_2O-

LiBr ABC systems provided 12.3 MW cooling rate in order to decrease the temperature of the air at the inlet by using 17 MW exhaust heat of the turbine. On the other hand, standard evaporator coolers only provided 2.3 MW cooling capacity under the same operational conditions. In addition, evaporative coolers required 2.7 MW of additional electrical energy to supply the same cooling rate that ABC supplied. In another study, Mohan et al. [11] numerically optimized the ABC system to provide the cooling requirement of large residential villas located in the UAE. The flue gases of the natural gas were utilized the waste heat source of the ABC system. They found that the ABC system can provide cooling for 124 large residential villas (~4.6 MW) at peak periods by reducing CO2 emission from 600 kg/MWh to 291 kg/MWh. On the other hand, the payback period of the proposed ABC system was determined as 1.38 years. Lu et al. [12] conducted a case study in the UK for the use of ABC systems to recover the industrial waste heat such as exhaust gases of the fuels. It was shown that the optimum COP of the ABC system is around 0.825 if the temperature of the generator was kept under 60 ˚C and evaporating temperature was set to 5 ˚C. On the other hand, the optimum COP value was determined as 0.86 if the temperature of the generator and evaporating temperature values are set to 55 ºC and 10 ˚C, respectively. They also reported that the payback time of the ABC system in the UK is about 2.5 years with an annual electricity cost saving of £105 per kW thermal heat supply. In another study, Shekarchian et al. [13] examined the annual energy demand and cost data in different climatic conditions of Iran for standard compression chiller and natural gas-driven ABC system. The waste heat source of the system was utilized as the exhaust gases of the natural gas. It was revealed that the required energy for cooling was higher in ABCs compared to standard compression chillers. However, the total energy cost of ABCs was quite less compared to standard compression chillers for all climates. The reason for this result was attributed to the lesser cost of natural gas compared to electricity. In a recent study, Panahizadeh et al. [14] conducted the first law, second law and economic analysis of single-effect ABC systems as a case study where the waste heat source was the flue gases of the fossil fuels in the facility. They reported that the effectiveness of heat exchangers and the temperature of the inlet cooling water have considerable effects on exergy, energy efficiencies and total annual cost. The authors also performed a multi-objective optimization study. It was found that if the economic and thermodynamic conditions are optimized the annual cost of the single-effect ABC system decreased by 3.24 %. The exergy destruction rates of the components of the single-effect ABC system was analysed by Lake et al. [15]. The generator of the system is designed to produce steam from wood chips since it was abundant in the region where the case study was conducted. Moreover, the wood chip waste produces stable steam energy and therefore provides steady and firm cold water flow rate production in the system. The authors found that the generator, condenser and absorber have the greatest exergy destruction contribution in the system. Also, it was found that the exergy destruction of the components is generally decreased with increasing the concentration of the working fluid. However, there found to be a threshold value for the maximum concentration. Le Lostec et al. [16] analysed the mobile wood chip drying process from thermal and economic perspectives. The researchers developed a model to predict the performance of the dryer having an absorption heat pump under various operating conditions. They utilized single-effect and double-effect absorption heat pump systems for comparison purposes. It was revealed that the use of a single-effect absorption heat pump system is logical if the temperature of the drying air is less than 60 ˚C. On the other hand, a double-effect absorption heat pump system should be selected when the temperature of the drying air is greater than 60 ˚C. Although ABC systems have considerable advantages, they have some drawbacks for different conditions. For instance, the crystallization of the working fluid is an important issue that influence the COP and operation of the ABC system negatively. Many working fluids such as NH3-NaSCN, NH3-LiNO3, H2O-LiCl, H2O-CaCl2, H2O-LiBr, H2O-NH3 can be used in ABC systems. However, the most commonly used solutions are H2O-LiBr are H2O-NH3 solutions in practice. Flores et al. [17] developed a mathematical model based on first law efficiency to determine the working fluid effect on the COP of the ABC system using six different working fluids as H2O-LiBr, H2O-NH3, NaSCN-NH3, LiNO3-NH3, H2O-LiCl and H2O-CaCl2. It was found that the H2O-LiBr and H2O-LiCl solutions provided higher COP in comparison with other solutions. Also, Kaymakli and Yamakaradeniz [18] concluded that the H2O-LiBr cycle would be a simpler process and yielded higher COP than the H2O-NH3 cycle when comparing two working fluids in a single-effect ABC system for the various condenser, evaporator, generator and absorber temperatures. Farshi et al. [19] developed an analytic model to investigate the crystallization issue for double-effect reverse parallel, double-effect parallel and double-effect series ABC systems using H2O-LiBr working fluid. The authors stated that the waste heat source of the system was the low-grade fossil fuel exhaust gases. They found that the double-effect reverse parallel and parallel ABC systems have a low risk of crystallization compared to the series configuration. ABC systems are divided into subcategories such as single-effect, double-effect, triple-effect and higher-effect systems. However, single-effect and double-effect systems are more appropriate in terms of commercially use. On the other hand, double-effect systems are divided into three connection types as serial flow, parallel flow and reverse parallel flow. Xiaojing et al. [20] investigated the connection configurations of double-effect absorption heat pump systems by carrying out sets of numerical simulations. In the ABC system, the waste heat source was low-grade fossil fuel exhaust gases. They concluded that the reverse-parallel flow configuration presented better performance in comparison with other configurations. The second-best configuration was found to be a parallel flow configuration and showed almost the same performance. In another study, Li and Liu [21] examined the effect of different types of connections for an ABC system on the heat capacity of a generator. It was found that the double-effect reverse-parallel ABC system exhibited better performance compared to other ABC systems from the COP point of view.

As can be inferred from the above literature review, ABC systems can be preferred for HVAC applications due to their environmental-friendly and operational cost-economic features. Furthermore, different configurations of the ABC systems can be utilized for various applications having different waste heat sources. Most of the ABC studies in the literature were based on the waste heat source of exhaust gases of fossil fuels where the heat source is generally low-grade. The quality and type of the waste heat source have a direct effect on the generator temperature and consequently, the type of waste heat source influences the COP, exergy efficiency of ABC systems and selection of the feasible configuration for the ABC system. The wood chip waste heat source can provide stable high-grade generator temperature, the corresponding cold water flow rate production is steady and firm compared to other waste heat sources. Besides, there is no detailed energy, exergy and economic comparison of various ABC systems for the facilities having wood chips as the waste heat source in the literature to the best of the authors' knowledge. In this study, energy, exergy and economic analyses of different ABC systems have been conducted for a wood pencil production factory (Adel Pencil Inc.) located in Kocaeli, Turkey. The factory was using a standard VCR system with an 885 kW cooling capacity to maintain the HVAC operations of the plant. Also, the factory was using the waste wood chips in boilers to obtain hot water and steam, and this energy generated in the boilers constituted more than the factory needs. It was found that the factory has enough waste heat energy capacity based on the measurements taken from the site to install an ABC system with an H2O-LiBr solution to the factory instead of their old VCR system. Accordingly, the energy, exergy and economic efficiency of four ABC systems were investigated to select the best alternative to an existing standard VCR system in the wood pencil factory.

2. Materials and Methods

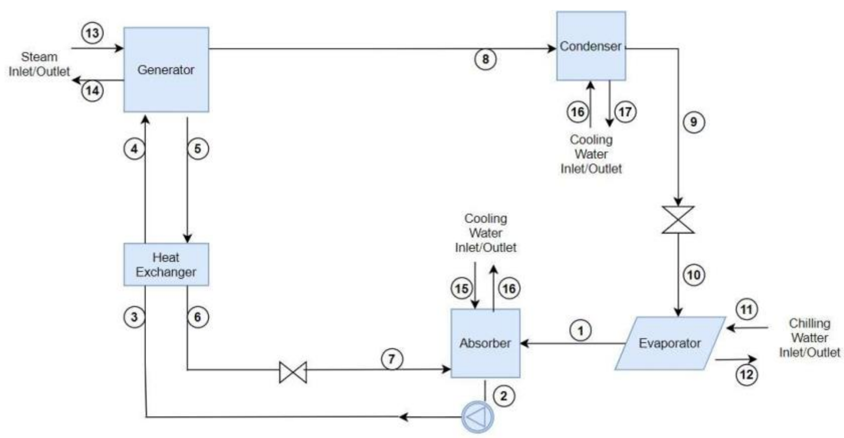
The wood pencil factory, where the case study was conducted, was using a conventional VCR system previously with R-134a as working fluid. The technical properties of the pre-existing standard VCR system are given in Table 1.

Table 1. Technical properties of the pre-existing standard VCR system

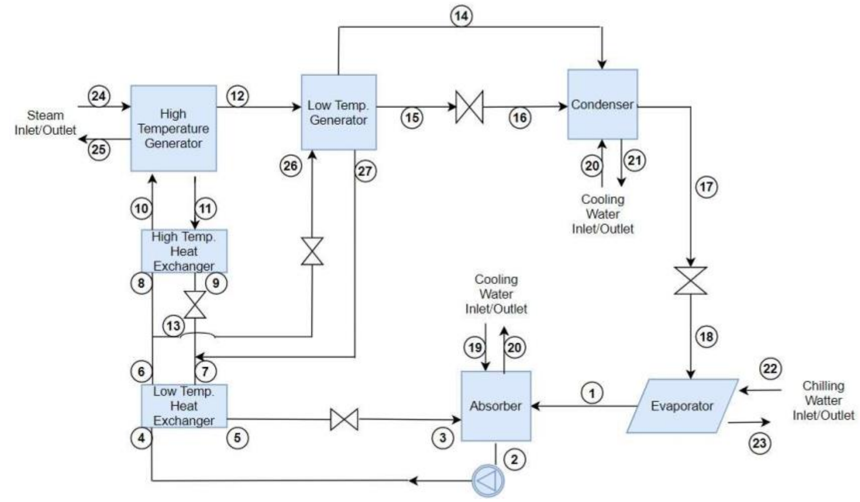
Cooling Capacity	885 kW
COP	3.14
Nonstandard Part Load Value	3.81
Full Load Electricity Consumption	282 kW
Partial Load Electricity Consumption	232 kW
Cooling Regime	7 – 12 ºC

Accordingly, the waste heat potential of the factory was calculated as 1.9 MW approximately. Therefore, the factory is an excellent candidate for a WHR system to maintain its HVAC operations instead of the standard VCR system. Subsequently, different ABC systems were investigated to choose the best alternative for the factory. The working schemes of these systems are given in Figs. 1 (a-d). Please note that the working fluid was utilized as H2O-LiBr in ABC systems due to the low risk of crystallization and widespread application as mentioned before.

Analysing Figs. 1(a-d), it can be clearly observed that the single effect ABC systems consist of basic elements such as a generator, condenser, evaporator, absorber, and heat exchanger. Apart from these, vacuum pump and measuring elements are used on the system since the system works under vacuum. On the other hand, the double-effect ABC systems have high-pressure steam and second stage generators which is different from the single effect ABC system. The information on the components and working principle of the systems can be found in detail in ref. [22].



(a)



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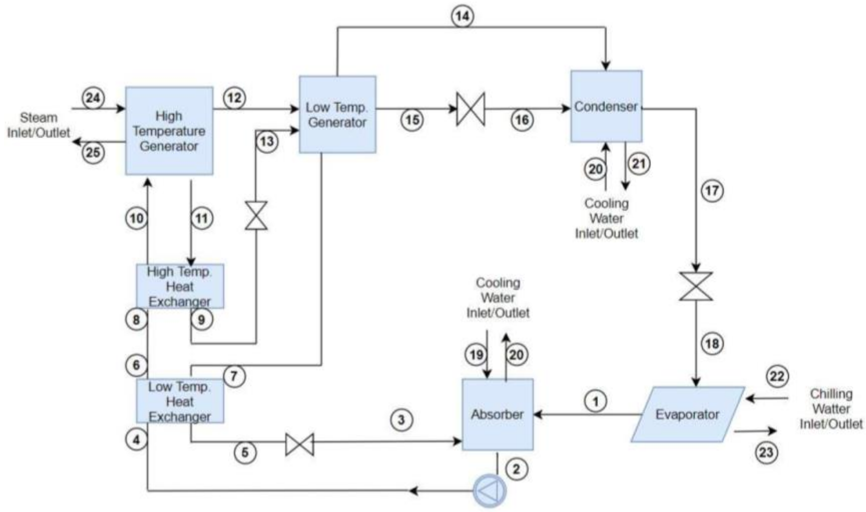

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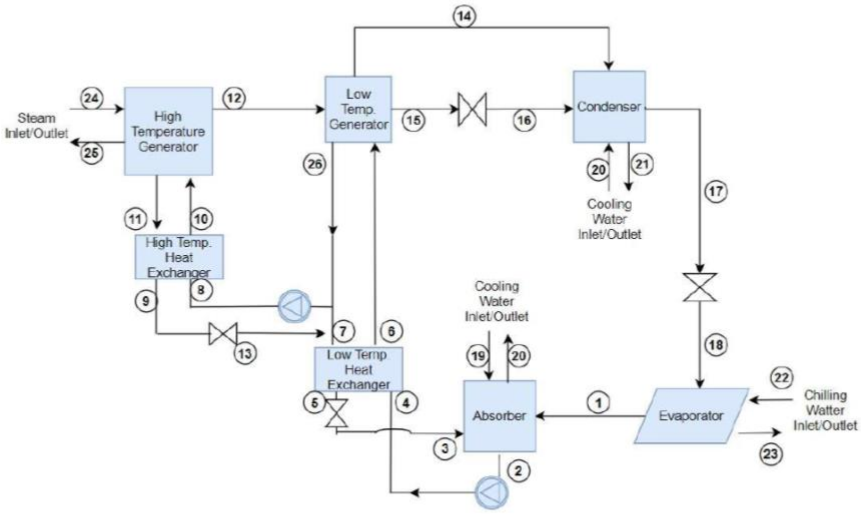

(d)

Fig. 1. Working schemes of WHR systems used in this study, a) Single effect system, b) Double effect parallel system, c) Double effect series system, d) Double effect reverse parallel system.

The general energy and mass balance equations of these five systems are given below.

$$\sum_{inlet} \dot{m} - \sum_{outlet} \dot{m} = 0 \tag{1}$$

$$\sum_{inlet} (\dot{m}h) - \sum_{outlet} (\dot{m}h) + \left[\sum_{inlet} \dot{Q} - \sum_{outlet} \dot{Q} \right] - \dot{W}_p = 0 \tag{2}$$

Consequently, the COP of the single-effect ABC systems and double effect ABC systems are defined in Eqs. (3) and (4) respectively.

$$COP_{se} = \frac{\dot{Q}_E}{\dot{Q}_G + \dot{W}_p} \cong \frac{\dot{Q}_E}{\dot{Q}_G} = \frac{\dot{m}_1 h_1 - \dot{m}_{10} h_{10}}{\left(\dot{m}_8 h_8 + \dot{m}_5 h_5 - \dot{m}_4 h_4 \right)} \tag{3}$$

$$COP_{de} = \frac{\dot{Q}_E}{\dot{Q}_{HTG} + \dot{Q}_{LTG}} = \frac{\dot{m}_1 h_1 - \dot{m}_{18} h_{18}}{\left(\dot{m}_{11} h_{11} + \dot{m}_{12} h_{12} - \dot{m}_{10} h_{10} \right)} \tag{4}$$

The exergy efficiency values of the investigated systems can be calculated through Eqs. (5) and (6).

$$\eta_{II,se} = \frac{\dot{m}_{11} \left[\left(h_{11} - h_{12} \right) - T_o \left(s_{11} - s_{12} \right) \right] + \dot{Q}_E \left(1 - \frac{T_o}{T_E} \right)}{\dot{m}_{13} \left[\left(h_{13} - h_{14} \right) - T_o \left(s_{13} - s_{14} \right) \right] + \dot{Q}_G \left(1 - \frac{T_o}{T_G} \right)} \tag{5}$$

$$\eta_{II,de} = \frac{\dot{m}_{22} \left[\left(h_{22} - h_{23} \right) - T_o \left(s_{22} - s_{23} \right) \right] + \dot{Q}_E \left(1 - \frac{T_o}{T_E} \right)}{\dot{m}_{24} \left[\left(h_{24} - h_{25} \right) - T_o \left(s_{24} - s_{25} \right) \right] + \dot{Q}_{HTG} \left(1 - \frac{T_o}{T_{HTG}} \right)} \tag{6}$$

In the above equations, the pump work can be neglected in ABC systems and assumed to be zero since the effects of the pump and the energy changes in the valves on the efficiency are not significant. In addition to above equations, the evaporation rate of the cooling tower needs to be considered to calculate the water loss, see Eq. (7).

$$e_L = L_{in} - L_{out} - d_L = G' \left(Y_{out} - Y_{in} \right) \tag{7}$$

The temperature of the cooling tower water coming to the absorber and condenser for all ABC systems is taken as 29 °C – 34 °C according to the wet-bulb temperature variation through the year of the region where the wood pencil factory is located. The efficiencies of the heat exchangers are accepted as 0.95 for all systems since the brazed type plate heat exchanger was used. The detailed design parameters for the proposed ABC systems are presented in Table 2.

Subsequently, the energy, exergy and economic performance parameters of all proposed systems were calculated through the EES® software. The results were compared to determine a suitable system for the wood pencil factory instead of pre-existing standard VCR system.

Table 2. Design parameters for proposed ABC systems

Absorber temperature	37 ºC	Dead state pressure	100 kPa
Chilled water inlet temperature	12 ºC	Double-effect system generator temperature range	110-170 ºC
Chilled water outlet temperature	7 ºC	Effectiveness of heat exchangers	0.95
Condenser temperature	37 ºC	Evaporator temperature	4 ºC
Cooling capacity	885 kW	Generator efficiency	0.95
Cooling water inlet temperature	29 ºC	Pump efficiency	0.95
Cooling water outlet temperature	34 ºC	Single-effect system generator temperature range	80-130 ºC
Dead state temperature	25 ºC		

3. Results and Discussions

The temperature of the waste heat source has a great influence on the efficiency of the ABC systems. The effect of the generator temperature on the COP of the single-effect and double-effect ABC systems are presented in Figs. 2 and 3. As can be seen from Fig. 2, the COP of the single-effect ABC system somewhat constant with the increase in the temperature of the generator. In other words, the variation of generator temperature does not affect the COP for single-effect ABC systems. Fig. 3 shows that the COP of the double-effect ABC systems enhances up to a certain value as the temperature of the generator increases. However, the COP values do not vary when the generator temperature becomes greater than ~155 ºC. Analysing Figs. 2 and 3, the COP of the single-effect ABC system is lower than all types of double-effect ABC systems. Because an additional generator is used in double-effect ABC systems and consequently the value of the generated energy becomes greater. The constant trend of the COP of the double-effect ABC systems for generator temperature higher than 155 ºC can be attributed to the issue of crystallization of working fluid H2O-LiBr. Moreover, the double-effect parallel ABC system have higher COP than the double-effect series and double-effect reverse parallel ABC systems due to the higher amount of working fluid that passes through HTG.

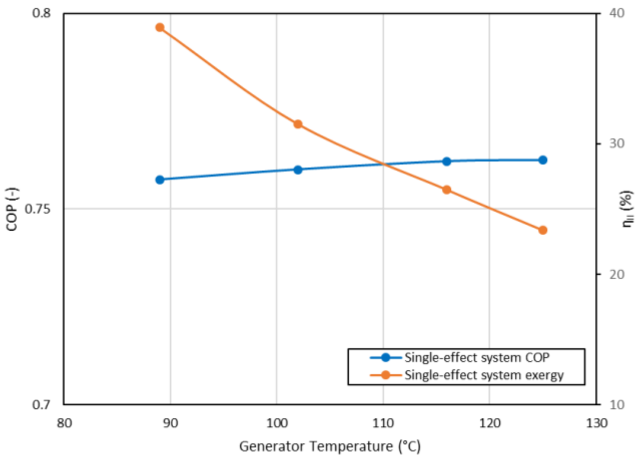

Fig. 2. Effect of generator temperature on the COP and exergetic efficiency of the single-effect ABC system.

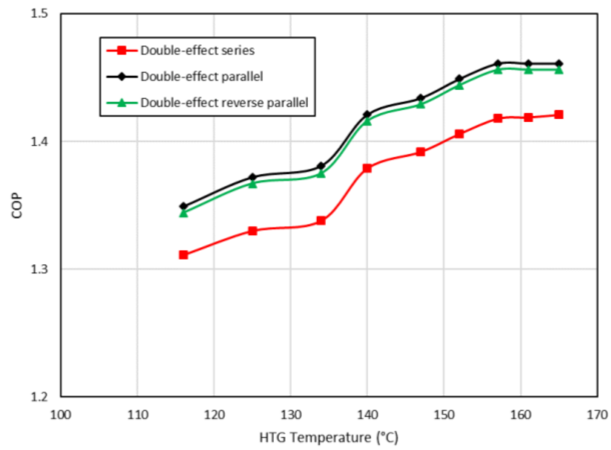

Fig. 3. Effect of generator temperature on the COP of the double-effect ABC systems.

The effect of the generator temperature on the exergetic efficiency of the single-effect and double-effect ABC systems are presented in Figs. 2 and 4 respectively. The exergetic efficiency decreases as the generator temperature increases for all ABC systems. The reason of this trend can be understood by analysing Eqs. 5 and 6. Although more energy is produced in the generator with the increase in generator temperature, the rate of exergy loss to the environment by the heat transfer mechanism increases. Besides, Fig. 4 shows that the double-effect parallel ABC system has higher exergetic efficiency for all generator temperature values than double-effect reverse parallel and double-effect series ABC systems.

These results indicate that double-effect parallel ABC systems have higher COP and exergetic efficiency than single-effect, double-effect series and double-effect reverse parallel ABC systems at the same generator temperature. Here, the higher first law and second law efficiency of the double-effect parallel ABC system compared to the others indicate that the same power can be generated with less hot source in other words less waste heat. Actually, using less waste heat provides an extra opportunity for the factories.

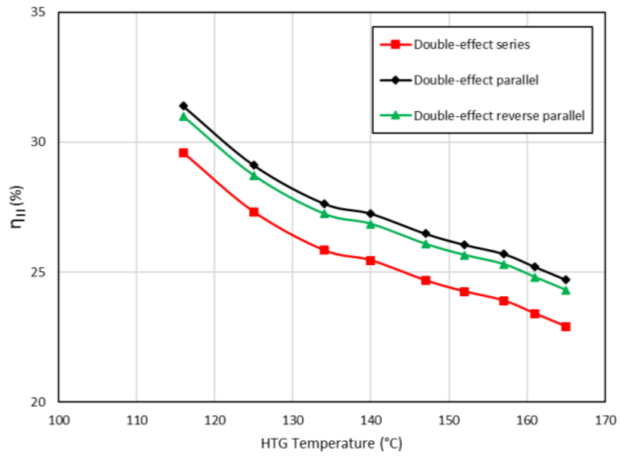

Fig. 4. Effect of generator temperature on the exergy efficiency of the double-effect ABC systems.

The above results agree with the findings in the literature in terms of the effect of the generator temperature on the energy and exergy performance variations of different ABC systems [23-25]. Furthermore, it was also found that the double-effect ABC systems have higher COP than the single-effect ABC systems in the literature, [23, 24]. However, the studies in the literature suggest the use of the double-effect reverse ABC systems in the comparison between double-effect ABC systems, [19-24]. Please note that the waste heat source was the exhaust gases of the fuels in these studies. The maintenance and operations of absorption chiller systems are complex compared to conventional chillers although they are environmental-friendly and sustainable systems. Furthermore, the double-effect parallel flow system is easier in operation and their maintenance are trouble-free compared to the double-effect reverse parallel system. The current study shows that the double-effect parallel flow system can be preferred in facilities having waste heat source as wood chips, which can provide steady and continuous generator temperature range between 116 °C and 165 °C, from energy and exergy perspectives.

The first law and second law performance values of a system are insufficient from the engineering point of view. The investment cost, operational cost and payback time should be also compared carefully for the feasibility of the ABC systems. Accordingly, the cost analyses have been conducted for all proposed ABC systems and the pre-existing standard VCR system in the wood pencil factory to present a general guideline for the factories having waste heat potential. The annual electricity and water consumption cost of proposed ABC systems and standard VCR system are compared in Tables 3 and 4. The annual electricity consumption was calculated according to AHRI Standard 550/590, see ref. [26]. The electricity consumption at the maximum cooling load is calculated by the ratio of cooling capacity to COP for a standard VCR system. On the other hand, the electricity and water consumption data of cooling towers need to be considered for ABC systems since the electricity consumption of pumps is negligibly small. During the analyses, the operating period of the devices is assumed 2808 hours per year. The unit electricity and water prices are taken from the refs. [27, 28]. It can be clearly observed from

Tables 3 and 4 that ABC systems are more favourable compared to a standard VCR system from economic points of view. The annual operational cost of the standard VCR system almost three times higher in comparison with the ABC systems. Moreover, the electricity cost increases every year in the worlds. Therefore, the use of ABC systems would yield huge economic gain for the factories.

Table 3. Technical and annual operational cost data of conventional type and single effect ABC system

Parameter	**Conventional Chiller**	**Single-effect ABC System**	**Cooling Tower**
Cooling capacity (kW)	885	885	2057
COP @ 100 %	3.14	0.76	-
Total Electricity Consumption (kW)	281	8.5	20
Annual Electricity Consumption ($)	43230	1384	4212
Annual Water Consumption ($)	-	-	9084
Total Annual Cost ($)	43230	14680	

Table 4. Technical and annual operational cost data of double-effect ABC systems

Parameter	**Series Flow**	**Cooling Tower**	**Parallel Flow**	**Cooling Tower**	**Reverse Parallel Flow**	**Cooling Tower**
Cooling capacity (kW)	885	1550	885	1526	885	1530
COP @ 100 %	1.34	-	1.38	-	1.38	-
Total Electricity Consumption (kW)	9.5	22	9.5	20	9.5	20
Annual Electricity Consumption ($)	1547	6178	1547	5616	1547	5616
Annual Water Consumption ($)	-	6845	-	6739	-	6750
Total Annual Cost ($)	14570		13902		13913	

Subsequently, the investment costs, annual operational cost and payback time data of all ABC systems and pre-existing VCR system are compared in Table 5. As can be inferred from Table 5, the payback periods of ABC systems are between 1.3 and 1.5 years. Please note that the investment cost data of the ABC systems and standard VCR system are taken from references [29, 30]. Besides, the investment cost of cooling towers can be calculated from the study of Sayyadi and Nejatolahi [31].

Table 5. Comparison of the overall cost consumption of the conventional chiller system with the all types of absorption system

Parameter	**Conventional VCR System**	**Single-effect System**	**Double-effect series System**	**Doubl-effect parallel System**	**Double-effect reverse parallel System**
Investment Cost ($)	60000	96140	101000	100520	100520
Annual Cost (Electricity+Water) ($)	43230	17488	14289	13902	13913
Payback Time (Year)	-	1.4	1.42	1.38	1.38

Taken together findings of energy, exergy and cost analyses, the double-effect parallel and reverse parallel ABC systems are the suitable ABC system instead of pre-existing standard VCR system for the wood pencil factory.

4. Conclusions

In this study, a detailed comparative analysis has been performed between single-effect, double-effect series, double-effect parallel and double-effect reverse parallel ABC systems in terms of energy, exergy and economic analyses for a wood pencil factory with waste heat. The factory uses a standard VCR system and this study has been conducted to determine the suitable ABC system instead of pre-existing standard VCR system. The main findings of this study can be listed as follows:

- The COP of the single-effect ABC system is almost constant with the increase in the temperature of the generator. The COP of the system changed from 0.758 to 0.763 when the temperature of the generator was increased from 89 ˚C to 125 ˚C.

- The COP of all double-effect ABC systems increased by 8 % as the generator temperature was increased from 116 ˚C to 155 ˚C. However, the COP was not affected for further generator temperature increase.

- The COP of double-effect ABC systems considerably higher than the COP of the single-effect systems. For instance, the COPs of the single-effect system and double-effect parallel flow system were found to be 0.74 and 1.37 respectively at the generator temperature of 125 ˚C. On the other hand, the double-effect parallel ABC system yielded better efficiency compared to other ABC systems. The COP of the double-effect parallel flow system was found to be 1.44 whereas the COPs of the double-effect reverse parallel flow system and double-effect series flow system were determined as 1.42 and 1.38 at the generator temperature of 145 ˚C.

- The exergetic efficiency decreases as the generator temperature increases for all ABC systems. The exergetic efficiency of the single-effect ABC system decreased by 40 % when the generator temperature was increased from 89 ºC to 125 ºC. On the other hand, the exergetic efficiency of all double absorption chiller systems decreased by around 14% for the generator temperature range of between 116 ºC and 155 ºC. In overall, the double-effect parallel ABC system exhibited better exergetic efficiency in comparison with other ABC systems.

- The ABC systems are found to be more favourable compared to a standard VCR system from annual operational cost point of view since the annual operational cost of ABC systems are almost three times less compared to standard VCR system. The total annual operational cost of the standard VCR system was calculated as 43230 $ whereas this value was around between 14000 $ and 18000 $ for different ABC systems.

- The payback periods of ABC systems are found to be between 1.3 and 1.5 year considering investment and annual operational costs.

- The double-effect parallel ABC system is found to be suitable instead of pre-existing standard VCR system for the wood pencil from findings of energy, exergy and cost analyses.

Finally, this study has been conducted to reduce carbon-based electricity consumption, which is one of the reasons for the increase in the global warming of the world in the last decades. Using ABC systems in facilities having waste heat is a very important factor in providing this contribution since the GWP of the ABS systems are zero whilst the GWP of the R-134a is around 1400.

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