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Thermo-Economic Analysis Of Ejector Cooling System

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ABSTRACT :

This study describes a thermo-economic analysis for an ejector cooling system. The energetic, exergy and economic analyses of an ejector cooling system were investigated by using four different operating conditions. The influences of generator, evaporator, condenser, expansion valve and pump on thermo-economic factors of the ejector cooling system were showed up. The results indicated that the thermo-economic factors of the ejector cooling system are dependent on the operating condition and the system components' irreversibility.

***Keywords**: Thermo-economic, exergy, economy, thermodynamic, ejector, cooling*

1. INTRODUCTION

The applications of refrigeration processes play an important role in industrial areas. These applications are used in providing the comfort of the building, food protection, storage, and industry. There are different types of refrigeration systems which are mechanical vapor compression, absorption, adsorption, acoustics, vortex tube, and steam ejector systems. Refrigeration applications with vapor compression cycles consume electrical energy. However, steam ejector cooling systems use renewable energy sources such as solar, geothermal, biomass, and industrial waste heat energy [1-9].

The ejector cooling systems using renewable energy sources consist of two subsystems which are renewable energy subsystem and ejector cooling subsystem. The major components in the cooling cycles are an ejector, a condenser, a generator, an evaporator, and an expansion valve. [10-18]. Ejector cooling systems have a low coefficient of performance (COP). However, this disadvantage can be eliminated by using renewable energy sources. In order to increase the performance and efficiency of the ejector cooling system and to present economical solutions, the thermo-economic analysis method is used for this system.

The thermodynamic considerations of thermo-economics are based on the exergy concept. The terms exergo-economics and thermo-economics can be used interchangeably [19-21]. Exergy is defined by Kotas [22] as the maximum amount of work potential of a given system in relation to its surrounding. Exergy analysis based on the concept of exergy can be used to decrease the system irreversibility and this results in an increase in the system performance [Kotas].

A complete thermo-economic analysis consists of an exergy analysis, an economic analysis, exergy costing, and a thermo-economic evaluation [19-21]. Pridasawas and Lundquist [7] studied the exergy analysis to analyze the performance of an ejector refrigeration cycle driven by solar energy. Their results showed that irreversibility occurs among the components and depends on the operating temperatures.

The first and second law analyses of thermodynamic as well as the economics of steam-jet refrigeration system were presented by sheriff et al [16]. Moreover, they investigated thermodynamic parameters including the coefficient of performance [COP], refrigerating effect, condenser heat rejection, motive steam requirements, second law efficiency, and system irreversibility. In recent years these systems have been preferred to investigate by some researchers [23]. There are some references that deal with the thermo-economic analysis [24-27].

In this study, the ejector cooling system is investigated in aspect to energetic, exergetic and economic. Thermo-economic variables are calculated for system units. The effects of the cooling system irreversibility on thermo-economic factors are analyzed. In these analyses, mass and energy conservation laws also exergy flow and irreversibility were applied to each component. The quantitative balance of the exergy and exergy costs, also the exergy destroy rates and (f) thermo-economic factors for each component and for the system were considered.The results showed that decreasing exergy destroy and operating – maintenance- cost depends on operating conditions of the system.

2. EJECTOR COOLING SYSTEM

An ejector cooling system consists of a generator, an evaporator, an ejector and a condenser as shown in Figure 1. During the operation, heat extracted from the renewable energy sources system cause the generator to produce saturated steam at sub-atmosphere pressure Pg and temperature Tg [1, 5].

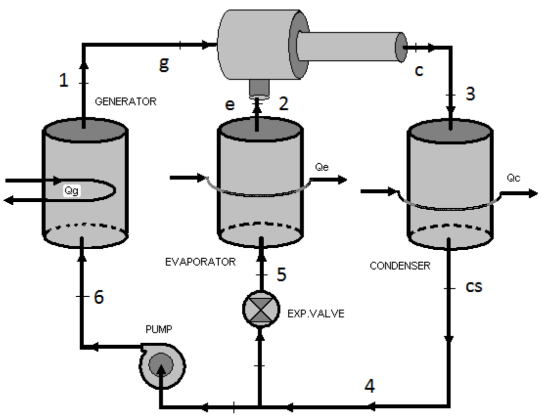

Figure 1. *Schematic view of an ejector cooling system*

Figure 2. shows the cross-section and shape of the ejector which is designed and manufactured. Motive vapor at high velocity exits from the converging-diverging nozzle in the ejector and sucks secondary vapor at low pressure and temperature from the evaporator. The mixed vapor from the ejector goes to the condenser. At this time, heat is transferred to the surroundings, and refrigerant is condensed. After the condenser, one part of the refrigerant goes to the generator and the other part goes to the evaporator by reaching the evaporating pressure through the expansion valve.

The design parameters of an ejector are dependent on the operating conditions (Tg, Te, Tcs, Tc). In this study, R141b was selected as the working fluid for the ejector cooling system. The design specifications of the ejector can be taken from references [3, 5, 13, 14]. In the present study, the generator temperature Tg was taken in the range of 70-90 º C and the evaporation temperature Te was taken in the range of 10-15 º C and condensing temperature Tcs was taken in the range 30- 40 º C (for different climatic conditions).

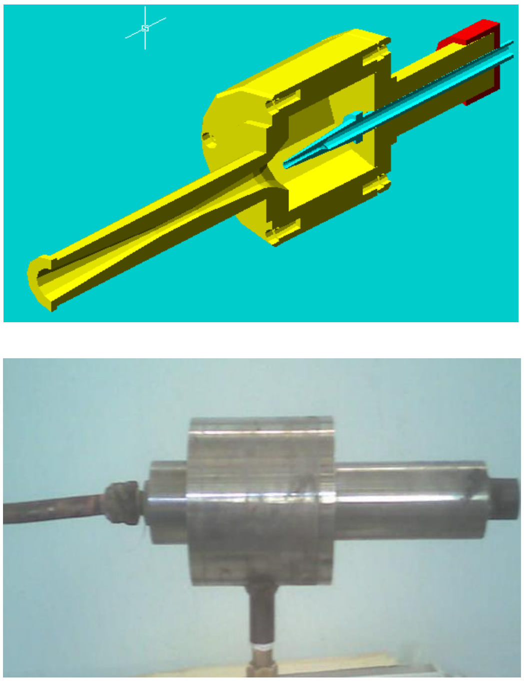

Figure 2. *The views of ejector. (a. The cross section of ejector which is designed. b.The shape of ejector which is manufactured.)*

3. METHOD

3.1. The mass and energy balance equations of the ejector cooling system

The heat balance equations of the system are given as follows. Generator heating requirement can be calculated from:

$$\dot{Q}_g = \dot{m}_g(h_1 - h_6) \quad (1)$$

$$\dot{m}_g = \dot{m}_1 = \dot{m}_6 \quad (2)$$

where, $\dot{m}_g$ is mass flow of driving fluid from the generator. Refrigerant effect on evaporation (cooling load) is:

$$\dot{Q}_e = \dot{m}_e(h_2 - h_5). \quad (3)$$

$$\dot{m}_e = \dot{m}_2 = \dot{m}_5 \quad (4)$$

For a given cooling load, the mass flow of the refrigerant ($\dot{m}_e$) from the evaporator can be calculated as:

$$\dot{m}_e = \frac{\dot{Q}_e}{h_2 - h_5}. \quad (5)$$

Condenser heat transfer rate is,

$$\dot{Q}_c = \dot{m}_c(h_3 - h_4) \quad (6)$$

where, $\dot{m}_c$ is mass flow at the condenser and is obtained from the mass balance as follows:

$$\dot{m}_g + \dot{m}_e = \dot{m}_c \;. \quad (7)$$

Heat balance is given as follows.

$$Q_g + Q_e = Q_c \;. \quad (8)$$

Energy and mass balances in expansion device are given as follows.

$$\dot{m}_e = \dot{m}_4 = \dot{m}_5 \quad (9)$$

$$h_4 = h_5 \quad (10)$$

Also, the same balances for pump are given as follows.

$$\dot{m}_g = \dot{m}_{4-5} = \dot{m}_6 \quad (11)$$

$$\dot{W}_p = \dot{m}_g(h_6 - h_{4-5}), \quad (12)$$

G is flow entrainment ratio defined as the entrained vapor (Secondary flow) to the motive steam (Primary flow) ratio given as,

$$G = \frac{\dot{m}_e}{\dot{m}_g} \quad (13)$$

and energy balance is.

$$h_1\dot{m}_g + h_2\dot{m}_e = h_3\dot{m}_c \quad (14)$$

G can be also obtained from the mass and energy balance Equations (7), (8) and (14).

$$h_1 + h_2G = h_3(1+G) \quad (15)$$

$$G = \frac{h_3 - h_1}{h_2 - h_3} \quad (16)$$

The mass and energy equations of system components are shown in Table 1.

Table 1. *The mass and energy equations of system components*

System Components	*Mass*	*Energy*
Generator	$m_{g6}=m_{g1}$	$Q_g+m_g.h_6=m_g.h_1+Q_k$
Ejector	$m_g+m_e=m_c$	$m_g.h_1+m_e.h_2=m_c.h_3$
Condenser	$m_{c3}=m_{c4}$	$m_c.h_3=Q_c+m_c.h_4$
Pump	$m_{g4}=m_{g6}$	$m_g.h_4+W_p=m_g.h_6$
Exp.Val.	$m_{e5}=m_{e4}$	$m_e.h_4=m_e.h_5$
Evaporator	$m_{e5}=m_{e2}$	$m_e.h_5+Q_e=m_e.h_2$

The energetic performance (COP) of the ejector cooling system is defined as the thermal ratio; which is given by the ratio of the cooling capacity ($\dot{Q}_c$) to the generator. Heat energy input ($\dot{Q}_g$):

$$COP = \frac{\dot{Q}_e}{\dot{Q}_g + \dot{W}_p} \quad (17)$$

Where, the pump work is not neglected. Consequently, from Eqs (1), (3) and (17) the energy performance (COP) of the ejector cooling system is obtained as follows:

$$COP = \frac{\dot{m}_e(h_2 - h_5)}{\dot{m}_g(h_1 - h_6) + \dot{m}_g(h_6 - h_{4-5})}, \quad (18)$$

or can be shown as,

$$COP = G\frac{(h_2 - h_5)}{(h_1 - h_6) + (h_6 - h_{4-5})}, \quad (19)$$

3.2. The exergy and irreversibility rate equations of the ejector cooling system

Exergy was defined as follow by Kotas [22]:

The exergy of a steady stream of matter is equal to the maximum amount of work obtainable when the stream is brought from its initial state to the dead state by processes during which the stream may interact only with the environment. There are physical and chemical components of exergy. Physical exergy was defined as follows:

Physical exergy is equal to the maximum amount of work obtainable when the stream of substance is brought from its initial state to the environmental state defined by P_o and T_o by physical processes involving only thermal interaction with the environment [22].

The expression for specific exergy can be written as:

$$\varepsilon = (h - T_0 S) - (h_0 - T_0 S_0) + \varepsilon_0 + \frac{C_0^2}{2} + g_E Z_0 \quad (20)$$

where the velocity Co, the altitude Z_o and standard chemical exergy ε_0 were neglected. Final form of specific exergy can be written as follow:

$$\varepsilon = (h - T_0 S) - (h_0 - T_0 S_0) \quad (21)$$

The exergy balance equations of the ejector cooling system can be calculated as:

$$\sum_{in} \dot{m}\varepsilon + \dot{E}_Q = \sum_{out} \dot{m}\varepsilon + \dot{W} + I \quad (22)$$

and total exergy of the working fluid in the system is,

$$E = \dot{m}.\varepsilon \quad (23)$$

According to Gauy-stodola Irreversibility is,

$I = To.S_{gen}$ (24)

Sum of the irreversibility for the system can be written as follow.

$$I = I_g + I_{ej} + I_c + I_p + I_{ex} + I_{ev} \quad (25)$$

Exergy and irreversibility rates of system components are shown in Table 2.

Table 2. *The exergy and irreversibility rate equations of system components*

System Components	*Exergy*	*Irreversibility*
Generator	$E_{qg}+m_g.e_6=m_g.e_1+I_g$	$I_g=To[m_g(s_1-s_6)+(Q_g/T_6)]$
Ejector	$m_g.e_1+m_e.e_2=m_c.e_3+I_{ej}$	$I_{ej}=To[m_c.s_3-m_g.s_1-m_e.s_2]$
Condenser	$m_c.e_3=E_{qc}+m_c.e_4+I_c$	$I_c=To[m_c(s_4-s_3)+(Q_c/To)]$
Pump	$m_g.e_4+W_p=m_g.e_6+I_p$	$I_p=W_p+m_g[(h_6-h_4)-To(s_6-s_4)]$
Exp.Val.	$m_e.e_4=m_e.e_5+I_{ex}$	$I_{ex}=To[m_e(s_5-s_4)]$
Evaporator	$m_e.e_5+E_{qe}=m_e.e_2+I_{ev}$	$I_{ev}=To[m_e(s_2-s_5)-(Q_e/T_r)]$

The exergetic performance (COPEX) of the solar ejector cooling system is defined as the exergy ratio, which is given by the ratio of the evaporator exergy rate (E_e) to the generator exergy rate(E_g) input as follows:

$$COPEX = \frac{E_e}{E_g} \quad (26)$$

The exergy rate of evaporator E_e and the exergy rate of generator E_g are obtained from

Eqs. (21) and (23) for generator and evaporator pressures and temperatures.

The comparisons of COP and COPEX values for R 141b and R 718 are shown in Fig.3 and Fig 4., respectively. It is quite clear from Figures 3. and 4. that the highest COP and COPEX values were seen in case 3 for R 141b and R 718. Also, it has resulted that R 718 had higher COP and COPEX values than R 141 b.

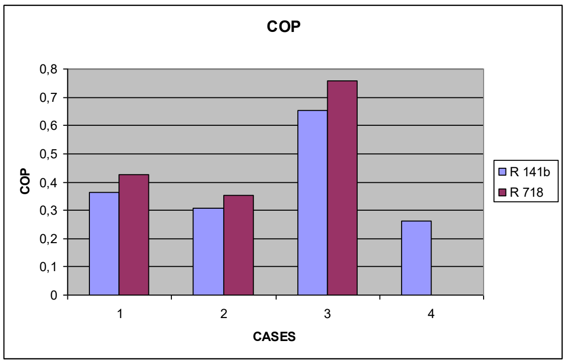

Figure 3. *The comparison of COP values for R 141b and R 718*

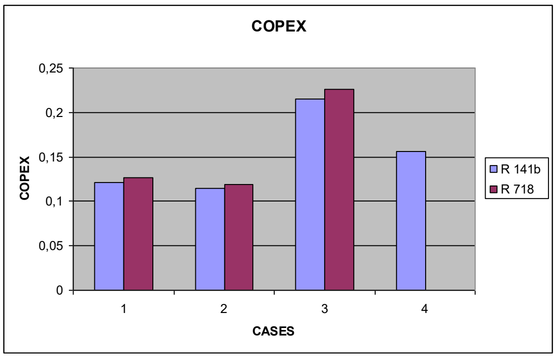

Figure 4. *The comparison of COPEX values for R 141b and R 718*

3.3. Economic analysis of the ejector cooling system

The exergo-economic analysis requires to be solved the mass balance, energy balance, exergy, and cost balance equations of the ejector cooling system.

The economic analysis based on Levelized cost method is applied for the ejector cooling system with considering an investment, operating and maintenance cost parameters.

According to Bejan [20] the levelization factor is,

$$K = k = \frac{1+r_n}{1+i_{eff}} \quad (27)$$

where r_n is the nominal escalation rate and i_{eff} is effective annual cost-of-money rate (or discount rate).

Capital recovery factor (CRF) is,

$$CRF = \frac{i_{eff}(1+i_{eff})^n}{(1+i_{eff})^n - 1} \quad (28)$$

The constant-escalation levelization factor (CELF) is,

$$CELF = \frac{k(1-k^n)}{1-k} CRF \quad (29)$$

The levelized value (A) is

$$A = \frac{CEF}{1-r_i} \quad (30)$$

where, r_i is constant average inflation rate.
Cost rates associated with capital investment Z_{cI}, operating and maintenance expences Z_{om}, and their sum Z is,

$$Z = Z_{cI} + Z_{om} \quad (31)$$

and

$$Z = \left[\frac{C_{cl}}{nxh} + \frac{C_{0m}}{h}\right] A \quad (32)$$

where C_{cl} is cost rate of capital investment, C_{om} is cost rate of operating and maintenance, n is economical life of system (year), h is operating time (hour/year).

Specific energy cost (ζ_i) for 1 kwh cooling effect is,

$$\zeta_i = \frac{Z}{E_h} \quad (33)$$

3.4. Thermo-economical evaluation of ejector cooling system

The economical data for Levelized cost method are shown in Table 3.

***Table 3**. The basis data for economical analysis*

Parameter	Value
n economical life of system (year)	**15**
ri interest rate	**2%**
rn nominal escalation rate	**3 %**
ieff effective return payback rate.	**4%**
h Annual operating hours (hour/year)	**2400**

The operating conditions for ejector cooling system are shown in Table 4.

***Table 4.** The cases including operating conditions for ejector cooling system*

Cases	Generating Temperature Tg [°C]	Condensing Temperature Tc [°C]	Evaporating Temperature Te [°C]
Case 1	90	35	5
Case 2	80	35	5
Case 3	90	25	5
Case 4	90	35	-5

The equipment costs of the ejector cooling system are taken from unit cost index of venders or the ministry of public works and settlement [25-28].

The exergy cost balance equations of system components are shown in Table 5.

***Table 5.** The exergy cost balance equations of system components*

System component	Exergy Cost Balance-1	Exergy Cost Balance-2
Generator	$C_{qg}E_{qg}+C_6E_6=C_1E_1+Z_g$	$c_{qg}E_{qg}+c_6m_g.e_6=c_1m_g.e_1+Z_g$
Ejector	$C_1E_1+C_2E_2=C_3E_3+Z_{ej}$	$c_1m_g.e_1+c_2m_e.e_2=c_3m_c.e_3+Z_{ej}$
Condenser	$C_3E_3=C_{qc}E_{qc}+C_4E_4+Z_c$	$c_3m_c.e_3=c_{qc}Eqc+c_4mc.e_4+Zc$
Pump	$C_4E_4+CwWp=C_6E_6+Zp$	$c_4mg.e_4+cwWp=c_6mg.e_6+Zp$
Exp.Val.	$C_4E_4=C_5E_5+Zex$	$c_4me.e_4=c_5me.e_5+Zex$
Evaporator	$C_5E_5+C_{qe}Eqe=C_2E_2+Zev$	$c_5me.e_5+c_{qe}Eqe=c_2me.e_2+Zev$

The thermodynamic evaluation of a system component is based on the exergy destruction ratio y_k, which compares the irreversibility in the k_{th} component with the irreversibility of the overall system [21].

$$y_k = \frac{I_{k_{th}}}{I_{tot}} \tag{34}$$

Exergo-economical factor: it expresses the contribution ratio of the non-exergy-related cost to the total cost increase [29].

$$f = \frac{\dot{Z}}{\dot{Z} + C_b I_{k_{th}}} \tag{35}$$

The system component equations of the exergy destruction ratio y_k, and the exergo-economic factor f are shown in Table 6.

***Table 6.** The system component equations of y_k, and f parameters*

System component	y	f
Generator	$y_{kg}=I_g/I_{tot}$	$f_g=Z_g/(Z_g+css.I_g)$
Ejector	$y_{kej}=Iej/Itot$	$f_{ej}=Zej/(Zej+cb.Iej)$
Condenser	$y_{kc}=Ic/Itot$	$f_c=Zc/(Zc+cb.Ic)$
Pump	$y_{kp}=Ip/Itot$	$fp=Zp/(Zp+cb.Ip)$
Exp.Val.	$y_{kex}=Iex/Itot$	$f_{ex}=Zex/(Zex+cb.Iex)$
Evaporator	$y_{kev}=Iev/Itot$	$f_{ev}=Zev/(Zev+cb.Iev)$

The calculated values of thermo-economic parameters (y_k and f) of the system components are based on the operating conditions (Case 1,2,3 and 4), which indicates the contribution of the capital cost of the sum of capital cost and cost of exergy destruction.

The calculated values of thermo-economic parameters (y_k and f) are shown in Tables 7,8,9 and 10 for cases 1,2,3 and 4., respectively.

***Table 7**. The calculated values of thermo-economic parameters (y_k and f) for case 1*

Case 1				
System component	**Thermoeconomic Parameters**			
	y		**f**	
Refrigerant	R141b	R718	R141b	R718
Generator	0.6233	0.7881	2.5834	2.1493
Ejector	0.0068	0.0054	0.0164	0.0086
Condenser	0.0703	0.1031	0.1702	0.1642
Pump	0.1974	0.0555	0.4779	0.0884
Exp.Val.	0.0493	0.0233	0.1194	0.0372
Evaporator	0.0529	0.0246	0.1282	0.0391

Table 8. *The calculated values of thermoeconomic parameters (y_k and f) for case 2*

Case 2				
System component	**Thermoeconomic Parameters**			
	y		**f**	
Refrigerant	R141b	R718	R141b	R718
Generator	0.6947	0.8249	3.092	2.6114
Ejector	0.0056	0.0059	0.0146	0.0109
Condenser	0.072	0.0975	0.1871	0.1804
Pump	0.1325	0.0304	0.3444	0.0563
Exp.Val.	0.0459	0.0201	0.1194	0.0372
Evaporator	0.0493	0.0212	0.1282	0.0391

Table 9. *The calculated values of thermoeconomic parameters (y_k and f) for case 3*

Case 3				
System component	**Thermoeconomic Parameters**			
	y		**f**	
Refrigerant	R141b	R718	R141b	R718
Generator	0.5136	0.7426	1.4059	1.1984
Ejector	0.0065	0.004	0.0104	0.0037
Condenser	0.0606	0.1014	0.0968	0.0956
Pump	0.3212	0.0986	0.5135	0.0929
Exp.Val.	0.0477	0.0263	0.0762	0.0257
Evaporator	0.0504	0.0272	0.0806	0.0248

Table10. *The calculated values of thermoeconomic parameters (y_k and f) for case4*

Case 4				
System component	**Thermoeconomic Parameters**			
	y		**f**	
Refrigerant	R141b	R718	R141b	R718
Generator	0.6641	unsuitable for Case 4	3.5585	unsuitable for Case 4
Ejector	0.0085		0.0265	
Condenser	0.0649		0.203	
Pump	0.1519		0.4754	
Exp.Val.	0.053		0.1658	
Evaporator	0.0577		0.1807	

4. RESULTS AND DISCUSSION

The result of the Thermo-economic analysis is obtained as a Levelized cost factor which is A=1.2714 calculated from Eqs.29. The cost equations (Z) given in Eqs.31 are used for economical evaluation.

As a result of the economical evaluation in solar ejector cooling system, complete plant cost per unit cooling load is calculated as 1100 Euro/ kWh $_{\text{(cooling load)}}$. Also, Annual Operating and Maintenance costs are obtained as 9033.6 Euro/Year and 424032 Euro/Year for the solar ejector cooling system and conventional cooling system, respectively. Because the conventional cooling system has already been established, the total capital investment cost was not considered. However, the same cost was considered for the solar ejector cooling system. The other costs were taken as equal for both systems.

The capital and other costs per hour are calculated basing on the Levelized cost method as Z_{es}=37.6242 Euro/hour and Z_{ccs}=209,563 Euro/hour for the ejector cooling system and the conventional cooling system, respectively.

y_k, the exergy destruction ratio and f, Exergo-economic factor are thermo-economic parameters. The high value of f indicates that the contribution rate of investment and operating cost are effective on the total costs. The four different operating conditions were given in Table 4. and the two different refrigerants as R141b and R718 were considered in the thermo-economic evaluation of the solar ejector cooling system.

It is quite clear from Table 7-10 that the best operating condition is Case 3 with regard to the least exergy destruction rate (y_k) and the optimum value of exergo-economic factor (f).

As a result of the economical evaluation, specific energy unit cost (ζ_i) for 1kWh cooling effect (CE) is found as ζecs=0.04 Euro/kWh$_{CE}$ and ζccs$_{=}$ 0.18 Euro/kWh$_{CE}$ for the ejector cooling system(ecs) and the conventional cooling system(ccs), respectively.

5. CONCLUSION

Secondary energy as electrical energy is produced at the rate of 75% from fossil origin primary energy resources such as coal, oil, natural gas, etc. in Turkey.

The cooling and air-conditioning plants consume electrical energy intensively. However, electrical energy is deemed to be harmless for the environment, in fact, its environmental effect cannot be ignored in aspect to the origin of the electrical production.

The ejector cooling systems use renewable energy resources such as solar, geothermal, waste heat, etc. which have heat energy potential. The environmental effects of these resources are at a minimum level so that they can be ignored. Thus, the ejector cooling systems is the most suitable option for the future.

In the present study, although the total investment cost of the ejector cooling system is high, it is concluded that the payback period of the investment cost of these systems are quite short.
Besides, it results that the operating costs of the ejector cooling systems (Zes=37.6242 Euro/hour) are more economical than the conventional cooling system (Z_{ccs}=209,563 Euro/hour) and these systems are friendly environment.

Consequently, the ejector cooling systems are hoped to be the best option over the next decades for the large-scaled cooling and air-conditioning plants.

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