



Research Article

Selection of prime mover to meet heating demand of a single effect absorption chiller based on laws of thermodynamics

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Abstract

In this study the first and the second laws of thermodynamics are evaluated for a single effect absorption chiller. Entropy generation and COP are selected as the objective functions and their variations are studied by varying the generator temperature for various condensing temperatures. For this purpose, the enthalpy and the entropy data of the superheated steam, saturated steam and the saturated water are formulated in the mathematical equations. Also to provide the required steam of generator, prime mover in the form of internal combustion engine is applied and its partial load conditions are analyzed. A residential tower is considered as the case study for selecting the proper prime mover capacity. The number of prime movers is estimated based on the required heating power of the generator steam for each partial load. It is seen, the entropy generation would be decreased rapidly by increasing the generator temperature and after a while, the entropy generation would be approximately constant. The optimum entropy generation for each condensing temperature and the generator temperature may be decreased by increasing the evaporator temperature. It is deduced that COP is increased rapidly by increasing the generator temperature but in the following, the COP will be constant. The maximum amount of COP is decreased by increasing the condensing temperature. Also the COP is increased by increasing evaporator temperature for a certain generator and condensing temperatures.

Keywords Single effect absorption chiller · Prime mover · Entropy generation · Generator temperature · COP

List of symbols

CCHP	Combined cooling, heating and power
CFC	Chlorofluorocarbon
COP	Coefficient of performance
\dot{E}	Electrical power (kW)
h	Enthalpy (kJ/kg)
hr	Hour
LHV	Low heat value (kJ/kg)
\dot{m}	Mass flow rate (kg/s)
p	Pressure (kpa)
\dot{Q}	Heat power (kW)
s	Specific entropy (kJ/kg K)
S	Entropy generation (kW/K)
T	Temperature (C)

\dot{W}	Working power (kW)
X	Solution concentration

Greek letters

ϵ	Effectiveness
η	Efficiency

Subscripts

a	Absorber
c	Condenser
CHW	Chilled water
CTW	Cooling tower water
e	Evaporator
ev.	Evaporation
Ex.	Exhaust
f	Saturated and subcooled

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g	Generator
gen	Generation
HS	Superheated
nom	Nominal
p	Pump
PL	Partial load
PM	Prime mover
r	Refrigerant
s	Solution
SS	Strong solution
WJ	Water jacket
WS	Weak solution

1 Introduction

CCHP systems are known as the facilities in which produces cooling, heating and power simultaneously through recovering waste heat of prime movers such as internal combustion engines, gas turbines etc. CCHP systems also attract attentions due to environmentally friendly compared to the other conventional systems [1, 2]. Also absorption chillers may be applied as cooling system since they are CFC free [3]. These chillers need low energy that may be provided by the solar energy or waste heat which is extracted from the prime movers. Avanesian et al. [4] evaluated a single effect absorption chiller from the energy, exergy and the economical point of view. Roman et al. [5] investigated on the selection of type of the prime mover and absorption chiller in CCHP systems. They studied the energy consumption, economical and emission parameters. They concluded that emission saving for carbon would be about 9% and the primary energy consumption saving can be reached till 8%. Fong and Lee [6] studied a high rise office building in Hong Kong and used internal combustion engine beside absorption chiller to provide cooling and heating demand of the building. They compared energy consumption of their proposed system with the conventional system in which uses electrical power. Their study showed that the energy consumption reduction would be about 10.9%. Karimi and Sayyadi [7] studied a Stirling engine beside an absorption chiller. They evaluated primary energy saving, Co₂ emission reduction and the annual total cost. They found that in extremely hot and humid weather, Stirling-CCHP system is not recommended. Ünal et al. [8] proposed a linear optimization model to minimize maintenance cost. The optimization procedure was held by comparing four different kinds of prime movers for three different load conditions of an industrial facility. They showed that, tri-generation is more cost effective than the separate production. Chahartaghi and Alizadeh [9] studied a CCHP system in which its prime mover was PEM fuel cell. The objective functions were

energy, exergy and fuel energy saving. Their proposed model was compared to the conventional energy supply systems and the fuel energy saving ratio was calculated to about 45%. Eisavi et al. [10] used solar energy beside Rankine cycle and absorption chiller as CCHP system. They evaluated the energy and the exergy of the system. Ebrahimi and Keshavarz [11] studied CCHP system for various climate conditions of Iran. They selected absorption chiller as cooling system and evaluated the size of prime mover for each climate condition. Mohammadi and Ameri [12] studied a prime mover beside absorption chiller. They evaluated ambient conditions effects on the proposed system performance. Al-Sulaiman et al. [13] used parabolic solar collector, Rankine cycle and the absorption chiller as a CCHP system. They studied the effect of pump inlet temperature and the inlet pressure of the turbine on the performance of the proposed system. Maindment and Tozer [14] used CCHP system for a supermarket that the prime mover was gas turbine and cooling system was absorption chiller. They compared gas turbine and internal combustion engine. They showed that CCHP energy consumption is lower than the energy usage of the conventional systems. Samanta and Basu [15] analyzed a single effect absorption chiller with heat exchanger in refrigerant side. They found that absorber has dominant role in any increase in entropy generation. Myat et al. [16] analyzed performance of an absorption chiller using an entropy generation analysis. They found that overall entropy generation is 41% for the generator, 10% for the condenser, 30% for the evaporator and about 19% for the absorber. Ren et al. [17] analyzed an absorption chiller using the Matlab software for thermodynamic analysis. They found COP could be improved by increasing the temperature of hot water or chilled water properly.

In the current study a single effect absorption chiller is applied and the assumptions are considered in which chiller operates properly. The first and the second laws of thermodynamic are evaluated for each part of chiller. COP and the entropy generation are selected as objective functions and they are studied to find their optimum situation by considering permissible concentration range of weak and strong solutions. To evaluate enthalpy and entropy of water, in the saturated and superheated states, its thermodynamic data is formulated by applying genetic algorithm and by minimizing the error between calculated and thermodynamic data. The COP variations and the entropy generation variations is studied by varying generator temperature in various evaporator temperatures. To meet heating demand of generator, prime mover in the form of internal combustion engine is applied. Since this prime mover does not operate in the full load situation, then its partial load operation is modeled to evaluate the waste heating and the extracted power for each partial load and

the proper number of prime movers will be calculated in the various partial loads.

2 Mathematical model

In this study, a single effect absorption chiller is considered which is shown in the Fig. 1. In the chiller, energy demand of the generator (Q_g) may be supplied by the water steam and the heating energy is absorbed through the evaporator (Q_e) from the low temperature heat source and may be transferred to a high temperature heat source by the condenser (Q_c).

In the absorption chiller, the LiBr and the water are used as the absorber and the refrigerant respectively. Outlet solution of the generator is known as the strong solution due to high LiBr content and outlet solution of the absorber is called weak solution due to low LiBr.

Following assumptions are considered to evaluate the absorption chiller:

1. Chiller operates in the steady state.
2. The temperature of the outlet solution from the absorber (state 1) is equal to the outlet water temperature of the condenser (state 8).

3. Solution pump does not effect on the solution temperature ($T_1 = T_2$).
4. Fluid flows through the expansion valves are isenthalpic.
5. Concentration of LiBr free solution equals to zero ($X_7 = X_8 = X_9 = X_{10} = 0$).
6. Friction losses are ignorable.
7. Pressure drop and heat loss in the components of the system were not considered [17].

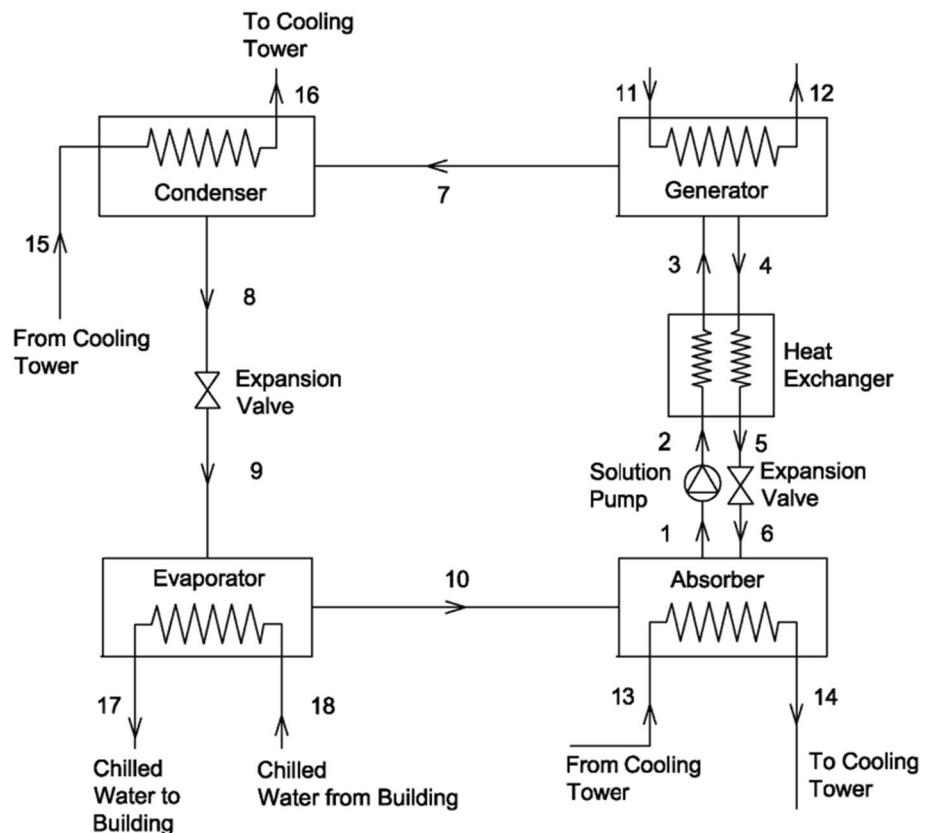
Solution concentration should be in the range of 0.5 to 0.65 [18]. For the strong and weak solutions, this quantity may be calculated from the Eqs. (1) and (2) respectively [18].

$$X_i = \frac{49.04 + 1.125T_a - T_e}{134.65 + 0.47T_a} \quad \text{strong solution} \quad (1)$$

$$X_j = \frac{49.04 + 1.125T_g - T_c}{134.65 + 0.47T_g} \quad \text{weak solution} \quad (2)$$

Concentration of the weak and the strong solutions are defined as Eqs. (3) and (4).

Fig. 1 Absorption chiller cycle



$$X_{ws} = \frac{\dot{m}_{LiBr}}{\dot{m}_{ws}} \tag{3}$$

$$X_{ss} = \frac{\dot{m}_{LiBr}}{\dot{m}_{ss}} \tag{4}$$

Equations (5) and (6) may be resulted from the mass conservation law [15].

$$\dot{m}_{ss} = \dot{m}_r + \dot{m}_{ws} \tag{5}$$

$$\dot{m}_{ss} X_{ss} = \dot{m}_{ws} X_{ws} \tag{6}$$

By taking into account Eqs. (5) and (6), the mass flow rate of weak and strong solution is given by:

$$\dot{m}_{ss} = \frac{X_{ws}}{X_{ws} - X_{ss}} \dot{m}_r \tag{7}$$

$$\dot{m}_{ws} = \frac{X_{ss}}{X_{ws} - X_{ss}} \dot{m}_r \tag{8}$$

Energy equation for major parts of single effect absorption chiller (such as generator, condenser, absorber and evaporator) may be written as follows:

Generator:

$$\dot{m}_{11} h_{11} + \dot{m}_3 h_3 - \dot{m}_7 h_7 - \dot{m}_4 h_4 - \dot{m}_{12} h_{12} = 0 \tag{9}$$

Condenser:

$$\dot{m}_{15} h_{15} + \dot{m}_7 h_7 - \dot{m}_8 h_8 - \dot{m}_{16} h_{16} = 0 \tag{10}$$

Absorber:

$$\dot{m}_{10} h_{10} + \dot{m}_{13} h_{13} + \dot{m}_6 h_6 - \dot{m}_1 h_1 - \dot{m}_{14} h_{14} = 0 \tag{11}$$

Evaporator:

$$\dot{m}_9 h_9 + \dot{m}_{18} h_{18} - \dot{m}_{17} h_{17} - \dot{m}_{10} h_{10} = 0 \tag{12}$$

The fluid of flow through expansion valves is an isenthalpic process. So enthalpy will be constant.

$$h_8 = h_9 \tag{13}$$

$$h_5 = h_6 \tag{14}$$

Often effectiveness may be used to evaluate heat exchangers as follows:

$$\epsilon = \frac{T_2 - T_3}{T_2 - T_4} = \frac{T_4 - T_5}{T_4 - T_2} \tag{15}$$

COP of a single effect absorption chiller may be defined as follows:

$$COP = \frac{\dot{m}_{CHW}(h_{18} - h_{17})}{\dot{m}_{HS}(h_{11} - h_{12}) + \dot{W}_p} \tag{16}$$

It is essential to evaluate the enthalpy of LiBr solution. This may be done by the following equation [19]:

$$h_{LiBr} = \sum_{n=0}^{n=4} L_n X^n + T_s \sum_{n=0}^{n=4} M_n X^n + T_s^2 \sum_{n=0}^{n=4} N_n X^n \tag{17}$$

i	L_i	M_i	N_i
0	-2024.33	18.2829	-3.7008214E-2
1	163.309	-1.1691757	2.8877666E-3
2	-4.88161	3.248041E-2	-8.1313015E-5
3	6.302948E-2	-4.034184E-4	9.9116628E-7
4	-2.913705E-4	1.8520569E-6	-4.4441207E-9

To analyse the thermodynamic model, a Matlab code is developed. So it is required to have the enthalpy and the entropy equations of the water. To evaluate the enthalpy of super-heated steam, thermodynamics tables are applied. These data may be shown as Eq. (18) by using genetic algorithm and by minimizing error between the calculated and the measured data:

$$h_{HS} = (a_1 T^{a_2} + a_3) (a_4 T^{a_5} + a_6) \tag{18}$$

$a_1 = 1.34437672$ 500784	$a_2 = 1.0636647$ 9289381	$a_3 = -2058.09$ 317323101
$a_4 = 6316.190026$ 72389	$a_5 = -0.0006973622$ 32285187	$a_6 = -1741.$ 36346240702

The above equation is valid for $46\text{ C} < T < 200\text{ C}$ and $10\text{ kpa} < p < 200\text{ kpa}$. The comparison between the

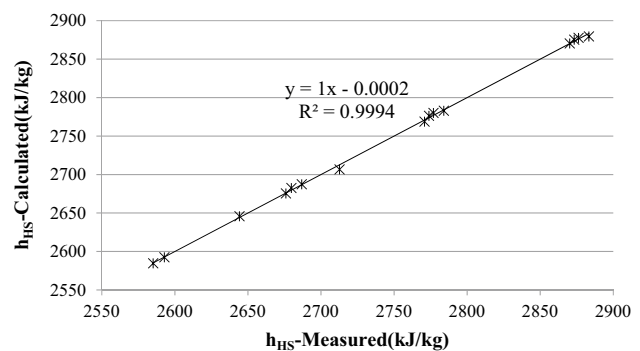


Fig. 2 Calculated enthalpy VS. measured enthalpy for super-heated steam

calculated and the measured enthalpy of super-heated steam is shown in Fig. 2.

Enthalpy of saturated water may be written as follows by using genetic algorithm and by minimizing error between the calculated and the measured data:

$$h_{\text{sat.,water}} = (a_7 T^{a_8} + a_9)(a_{10} T^{a_{11}} + a_{12}) \tag{19}$$

$a_7 = 4.2507554$ 1441917	$a_8 = 0.995768$ 160932023	$a_9 = 0.6663$ 56232217841
$a_{10} = 0.047134871$ 3699375	$a_{11} = 0.8374314$ 02908669	$a_{12} = -0.7844$ 85525587839

The above equation is valid for $0\text{C} < T < 120\text{C}$ and $0.6\text{ kpa} < p < 195\text{ kpa}$. The comparison between the calculated and the measured enthalpy of saturated water is shown in Fig. 3.

Enthalpy of saturated steam may be given by:

$$h_{\text{sat.,steam}} = (a_{13} T^{a_{14}} + a_{15})(a_{16} T^{a_{17}} + a_{18}) \tag{20}$$

$a_{13} = 15.69123$ 76003977	$a_{14} = -0.004865766$ 7363225	$a_{15} = 1790.96$ 521687448
$a_{16} = 257.87843$ 5466569	$a_{17} = 0.10560011$ 4164934	$a_{18} = 449.5705$ 79620051

The above equation is valid for $0\text{C} < T < 120\text{C}$ and $0.6\text{ kpa} < p < 195\text{ kpa}$. The comparison between calculated and measured enthalpy of saturated steam is shown in Fig. 4.

Also the enthalpy of sub cooled water may be calculated from the enthalpy equation of saturated water. The temperature of sub-cooled water can be calculated by applying its related enthalpy and the pressure as follows:

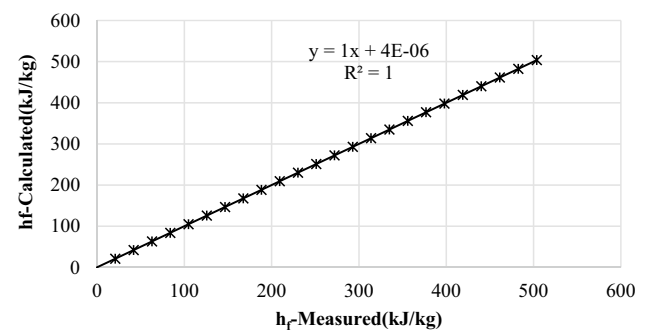


Fig. 3 Calculated enthalpy VS. measured enthalpy for saturated water

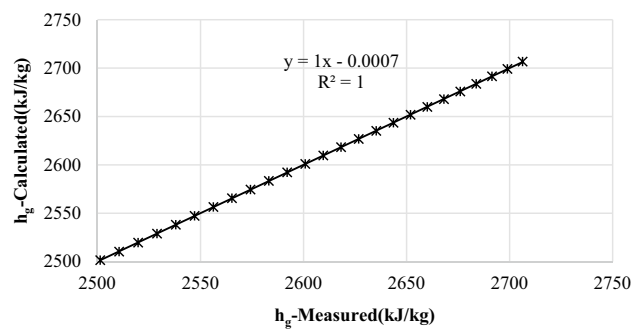


Fig. 4 Calculated enthalpy VS. measured enthalpy for saturated steam

$$T = \left(\frac{h/a_7}{a_{10} p^{a_{11}} + a_{12}} - \frac{a_9}{a_7} \right)^{\frac{1}{a_8}} \tag{21}$$

The second law of thermodynamics may be applied to evaluate the entropy generation. The law, states that the entropy variation is not negative in the insulated system. In fact entropy is a criterion to evaluate irreversibility. The system may be optimized from the engineering point of view and the thermodynamic operation can be improved by minimizing the entropy generation. The general equation to evaluate entropy generation can be written by [20]:

$$S_{\text{gen.}} = \sum_{\text{out}} \dot{m}s - \sum_{\text{in}} \dot{m}s \tag{22}$$

Entropy generation may be evaluated for major parts of absorption chiller by applying the Eq. (22):

Generator:

$$S_g = \dot{m}_7 s_7 + \dot{m}_4 s_4 - \dot{m}_3 s_3 + \dot{m}_{11}(s_{12} - s_{11}) \tag{23}$$

Condenser:

$$S_c = \dot{m}_7(s_8 - s_7) + \dot{m}_{15}(s_{16} - s_{15}) \tag{24}$$

Absorber:

$$S_a = \dot{m}_1 s_1 - \dot{m}_{10} s_{10} - \dot{m}_6 s_6 + \dot{m}_{13}(s_{14} - s_{13}) \tag{25}$$

Evaporator:

$$S_e = \dot{m}_9(s_{10} - s_9) + \dot{m}_{17}(s_{17} - s_{18}) \tag{26}$$

So the entropy generation of single effect absorption chiller may be calculated by the following expression:

$$S_{\text{abs.,chiller}} = S_g + S_c + S_a + S_e \tag{27}$$

To evaluate the entropy of super-heated steam, thermodynamic data would be applied. These data may be written as the following formula by using genetic algorithm and by minimizing error between the calculated and the measured data:

$$s_{HS} = (b_1 T^{b_2} + b_3)(b_4 T^{b_5} + b_6) \tag{28}$$

$b_1=0.0183083$	$b_2=0.776431$	$b_3=-54.680$
42545615	743136796	1821097401
$b_4=222.7083$	$b_5=-0.0021266$	$b_6=-159.1$
21981383	2182407585	4714450636

The comparison between the calculated and the measured entropy of super-heated steam is shown in Fig. 5.

The entropy of saturated water may be written as follows:

$$s_{sat,water} = (b_7 T^{b_8} + b_9)(b_{10} T^{b_{11}} + b_{12}) \tag{29}$$

$b_7=0.00647809$	$b_8=0.9873167$	$b_9=-4.8407$
527094119	29289612	1962904189
$b_{10}=4.0569$	$b_{11}=0.0314$	$b_{12}=0.84580$
2825941513	263248450064	8766192197

The comparison between the calculated and the measured entropy of saturated water is shown in Fig. 6.

The entropy of saturated steam may be given by:

$$s_{sat,steam} = (b_{13} T^{b_{14}} + b_{15})(b_{16} T^{b_{17}} + b_{18}) \tag{30}$$

$b_{13}=0.00011583$	$b_{14}=0.947356$	$b_{15}=1.0567141$
0766898754	058095848	0322986
$b_{16}=20.90393$	$b_{17}=-0.0175695$	$b_{18}=-12.985$
67183081	377669539	8906826755

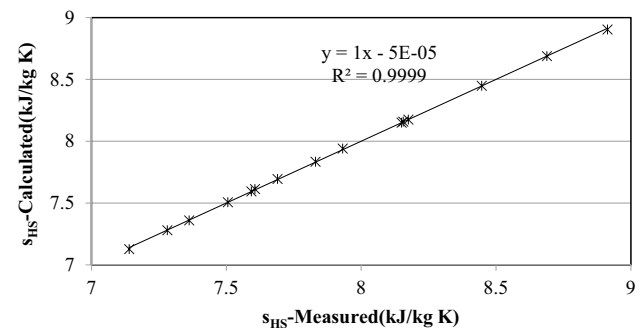


Fig. 5 Calculated entropy VS. measured entropy for super-heated steam

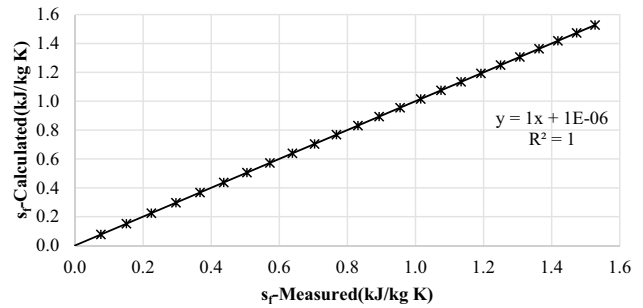


Fig. 6 Calculated entropy VS. measured entropy for saturated water

The comparison between the calculated and the measured entropy of saturated steam is shown in Fig. 7.

The temperature and the pressure range of Eqs. (28) to (30) are equal to the temperature and pressure ranges of Eq. (18) to (20). Also entropy of sub-cooled water may be calculated as follows:

$$s_{sub-cooled\ water} = 0.2966 + 4.184 \ln\left(\frac{T + 273.15}{293.15}\right) \tag{31}$$

Entropy of the lithium Bromide-water solution may be calculated through the following equation [21]:

$$s_{LiBr} = -(A_0 + A_1 X + A_2 X^2 + A_3 X^3 + A_4 X^{1.1}) - 2(T_s + 273.15)(B_0 + B_1 X + B_2 X^2 + B_3 X^3 + B_4 X^{1.1}) - 3(T_s + 273.15)^2(C_0 + C_1 X + C_2 X^2 + C_3 X^3 + C_4 X^{1.1}) - 4(T_s + 273.15)^3(D_0 + D_1 X) + \frac{E_0 + E_1 X}{(T_s - T_0)^2} - p(F_0 + F_1 X + F_2 X^2 + 2F_3(T_s + 273.15) + 2F_4 X(T_s + 273.15)) - \frac{1}{(T_s + 273.15)}(G_0 + G_1 X + G_2 X^2 + G_3 X^3 + G_4 X^{1.1}) - (1 + \ln(T_s + 273.15))(H_0 + H_1 X + H_2 X^2 + H_3 X^3 + H_4 X^{1.1}) \tag{32}$$

i	A _i	B _i	C _i	D _i
0	1.452749 674E2	2.64836 4473E-2	-8.5265 16950E-6	-3.8404 47174E-11

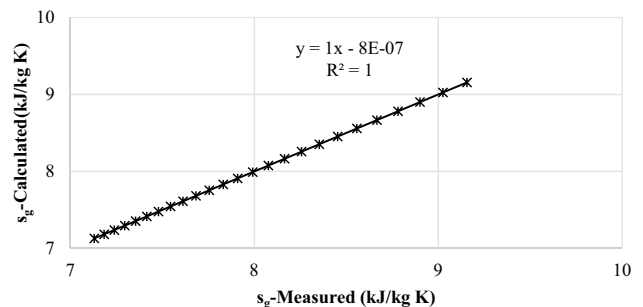


Fig. 7 Calculated entropy VS. measured entropy for saturated steam

i	A _i	B _i	C _i	D _i
1	-4.9848 40771E-1	-2.3110 41091E-3	1.32015 4794E-6	2.62546 9387E-11
2	8.83691 9180E-2	7.559736 620E-6	2.79199 5438E-11	0
3	-4.870 995781E-4	-3.7639 34193E-8	0	0
4	-2.905 161205	1.176 2406 49E-3	-8.511 514931E-7	0

i	E _i	F _i	G _i	H _i
0	-5.159 906276E1	-1.497 1869 05E-6	-2.18 342 9482E3	-2.2670 95847E1
1	1.114 573398	2.5381 76345E-8	-1.2669 85094E2	2.9837 64494E-1
2	0	5.81581 1591E-11	-2.36 4551372	-1.2593 93234E-2
3	0	3.05799 7846E-9	1.38 9414858E-2	6.8496 32068E-5
4	0	-5.12958 9007E-11	1.5834 05426E2	2.7679 86853E-1

Table 1 Process data of chiller [22]

Point	T (C)	h (kJ/kg)	s (kJ/kg K)	X (%)	ṁ (kg/s)
1	40	107.1	0.2379	55.2	5.81
2	40	107.1	0.2379	55.2	5.81
3	67	160.5	0.3986	55.2	5.81
4	81	202.7	0.45	60.64	5.31
5	55	153.8	0.3087	60.64	5.31
6	41	153.8	0.3087	60.64	5.31
7	73.36	2632	8.6	0	0.5
8	34	142.4	0.5579	0	0.5
9	5	142.4	0.07	0	0.5
10	5	2510.21	9.026	0	0.5
11	115	2699.18	7.18	0	0.65
12	95	398	1.35	0	0.65
13	28	117.3	0.41	0	70.92
14	33	138.2	0.48	0	70.92
15	28	117.3	0.41	0	59.97
16	32	134	0.48	0	59.97
17	9	37.8	0.14	0	56.42
18	14	58.73	0.21	0	56.42

Table 2 Comparison between the current calculated data and the measured results by Panahizadeh and Bozorgan [22]

Parameter	Q _{calculated} (kW)	Q _{measured} (kW) [22]
Generator	1980.3	1910
Evaporator	1330.2	1360
Absorber	1863.1	1878
Condenser	918.3	920.4

T₀ = 220 K

T₀ = 220 K was arrived by iteration outside the linear coefficient calculations [21].

3 Evaluation of an absorption chiller

To analyze the chiller, the heat exchanger effectiveness is assumed to be 0.7 and the mass flow rate of refrigerant is 0.5 kg/s. The water steam enters to the generator at 115 C and leaves it at 95 C. Also the solution pump has ignorable effect on the solution temperature and the absorber and the condenser temperatures are the same. Process data of the chiller is shown in Table 1 [22].

The current results were compared with the data which is presented by Panahizadeh and Bozorgan [22]. The corresponding calculated values are presented in Table 2. A good agreement can be observed with the maximum discrepancy in heat transfer rate lying 3.6% of the data of Panahizadeh and Bozorgan [22].

3.1 Effect of the generator temperature on entropy generation and COP

Generator temperature effect on the entropy generation and COP is shown in the Fig. 8 for various T_c and T_e. At the beginning, entropy generation would be decreased rapidly by increasing generator temperature and in the following, the entropy generation is approximately constant. Also the minimum entropy generation may be decreased by decreasing T_c and the entropy generation for each T_c and T_g may be decreased by increasing T_e. Also at the beginning, the COP is increased rapidly but after a while the COP will be constant. The maximum amount of COP is decreased by increasing T_c and COP is increased by increasing T_e for each T_g and T_c.

In this study the optimum generator temperature is defined as the temperature that S_{gen} is the minimum and COP is the maximum. In the lower T_c the maximum COP

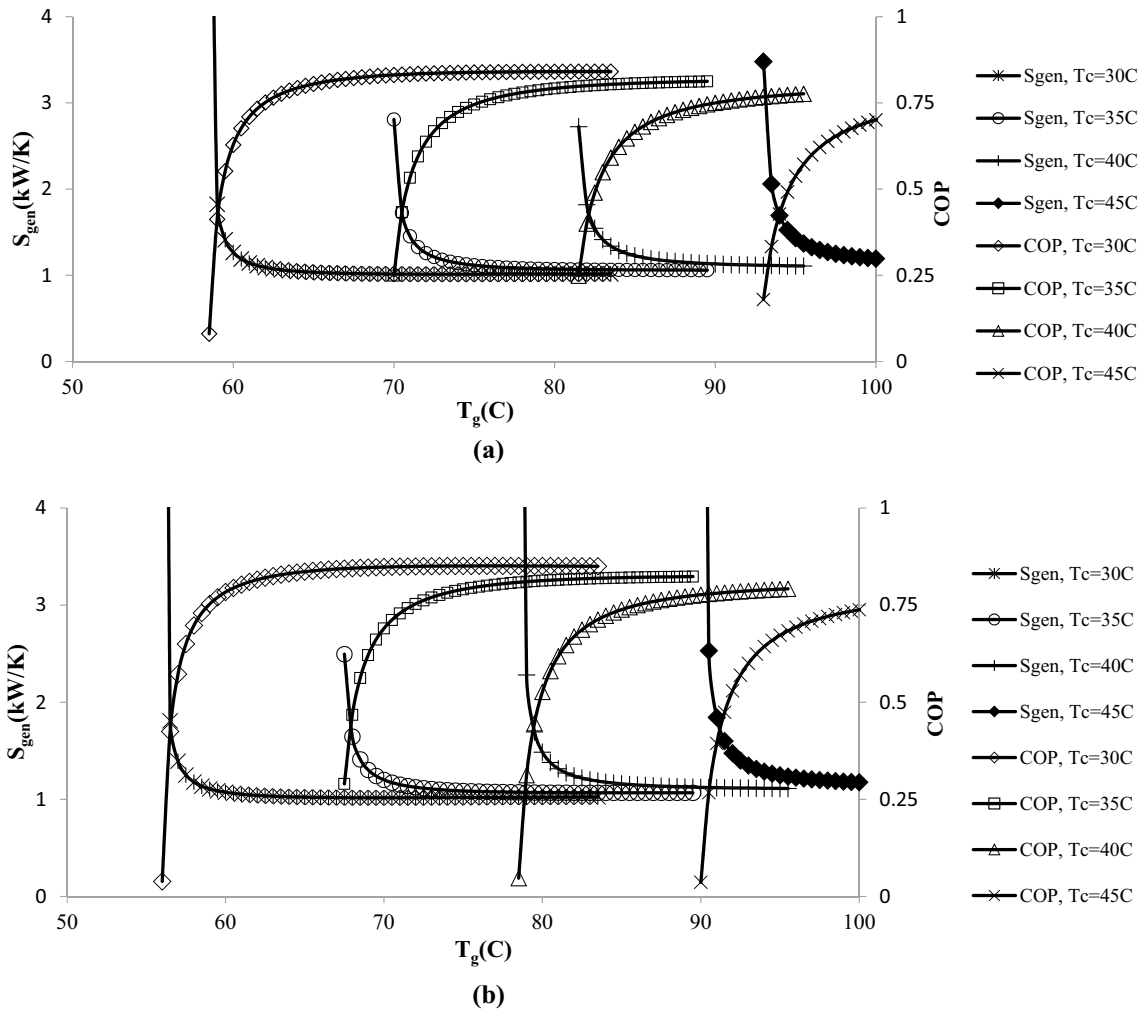
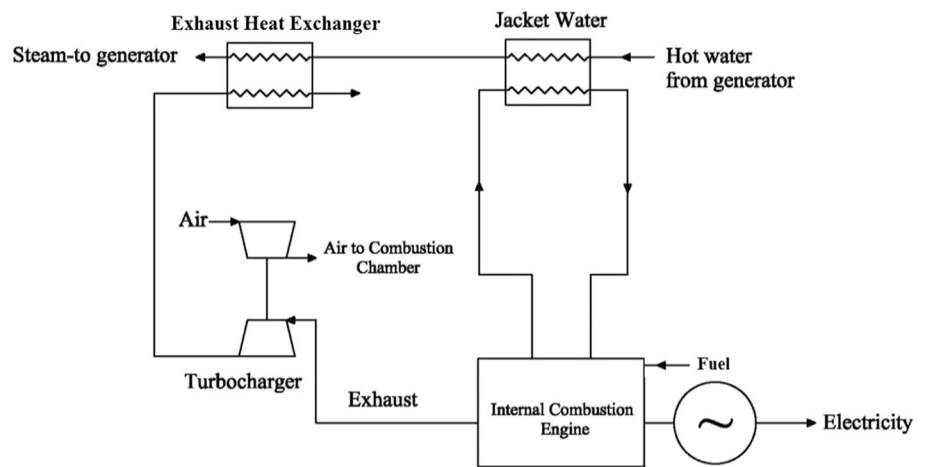


Fig. 8 Generator temperature VS. S_g and COP (a) $T_e = 3$ C and (b) $T_e = 7$ C

Fig. 9 Schematic of internal combustion engine with turbocharger



and the minimum S_{gen} are in a specific T_g and there is insignificant change by increasing generator temperature.

It means there is no need to increase T_g , so energy consumption would be optimized.

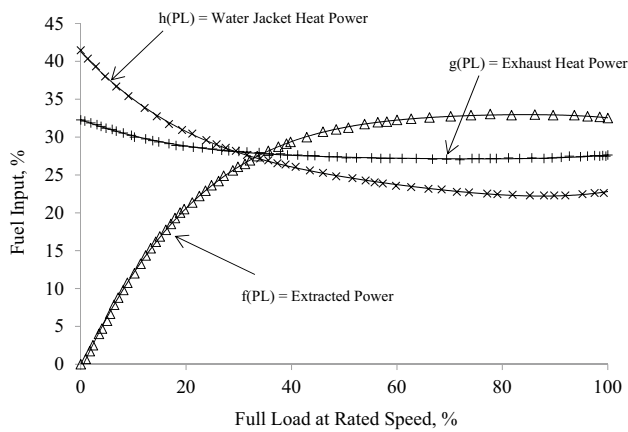


Fig. 10 Equations of internal combustion engine VS. partial load [23]

Table 3 Building specifications [25]

Item	Description
Average occupancy (Person)	5
Number of floors	10
Walls' overall U-value (W/m ² /K)	2.14
Roofs' overall U-value (W/m ² /K)	0.33
Windows' overall U-value (W/m ² /K)	6.4
Doors' overall U-value (W/m ² /K)	1.7
Floor' overall U-value for first floors (W/m ² /K)	0.568
Lightings (kW)	0.75

4 Prime mover

In the current manuscript, internal combustion engine is applied to provide heating demand of the chiller. The schematic of an internal combustion engine may be shown as Fig. 9.

Since prime movers may not work in the full load for a long time, so the partial load operation is studied here. To analyse the extracted heating power of the engine, the existing graph [23] is applied. The related output heating and the power may be calculated through this graph (Fig. 10) and Eqs. (33)–(37).

$$f(PL) = \frac{\dot{E}_{PM,PL}}{\dot{m}_f LHV_f} = (-7.28E - 07)(PL)^4 + 0.000225(PL)^3 - 0.02724(PL)^2 + 1.530561(PL) - 0.80065 \tag{33}$$

$$g(PL) = \frac{\dot{Q}_{Ex,PL}}{\dot{m}_f LHV_f} = (2.182E - 07)(PL)^4 - (5.527E - 05)(PL)^3 + 0.005517(PL)^2 - 0.26403345(PL) + 32.3062 \tag{34}$$

Table 4 Monthly cooling load of the tower in Tehran (kW) [25]

Month	Cooling load
January	0
February	0
March	0
April	136.1
May	350.9
June	554.8
July	915.2
August	604.6
September	461.2
October	161.9
November	0
December	0

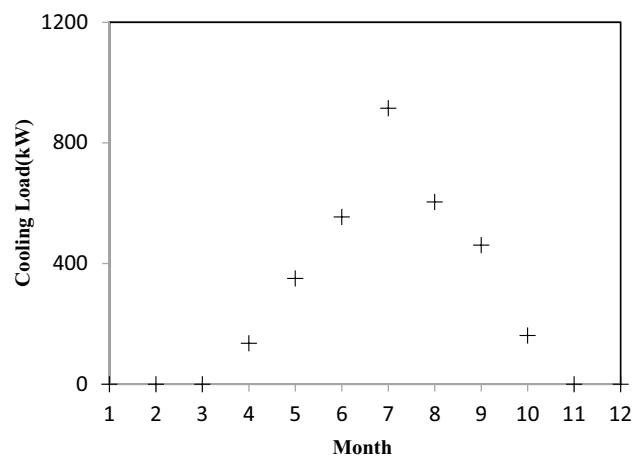


Fig. 11 Cooling load variation for Tehran [25]

$$h(PL) = \frac{\dot{Q}_{WJ,PL}}{\dot{m}_f LHV_f} = (5.657E - 07)(PL)^4 - 0.000141494(PL)^3 + 0.014249421(PL)^2 - 0.760595(PL) + 41.294 \tag{35}$$

$$J(PL) = \frac{\dot{m}_{f,PL}}{\dot{m}_{f,nom.}} = -0.02836 \exp(0.03254(PL)) + 0.2556 \exp(0.01912(PL)) \tag{36}$$

$$\dot{m}_{f,nom.} = \frac{\dot{E}_{PM}}{\eta_{PM,nom.} LHV_f} \tag{37}$$

In the Fig. 10, "Fuel Input, %" means the approximate percentage of input fuel energy ($\dot{m}_f LHV_f$) would be changed to the engine power.

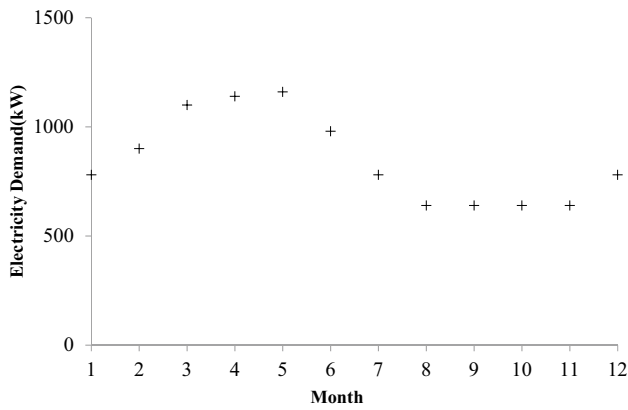


Fig. 12 Electrical demand variation of the considered tower [25]

Table 5 Power and heating load of a prime mover in partial load ($\dot{E}_{pM,nom.} = 400 \text{ kW}$)

PL (%)	\dot{E}_p (kW)	$\dot{Q}_{Exhaust}$ (kW)	\dot{Q}_{WJ} (kW)
20	81.2	113.6	121.2
40	161	151.1	142.7
60	240.1	202.7	176.7
80	323	266.1	219.3
100	399.6	338.3	279.3

Table 6 Optimum $S_{gen.}$ and the related T_g

	$T_{ev.} = 3 \text{ C}$				$T_{ev.} = 5 \text{ C}$				$T_{ev.} = 7 \text{ C}$			
	T_c (C)				T_c (C)				T_c (C)			
	30	35	40	45	30	35	40	45	30	35	40	45
$S_{gen,opt.}$ (kW/K)	1.07	1.13	1.18	1.26	1.06	1.12	1.17	1.21	1.05	1.12	1.17	1.21
$T_{g,opt.}$ (C)	66	77.5	89.5	100	63	75	87	99	60.5	72	84	96

Table 7 Optimum COP and the related T_g

	$T_{ev.} = 3 \text{ C}$				$T_{ev.} = 5 \text{ C}$				$T_{ev.} = 7 \text{ C}$			
	T_c (C)				T_c (C)				T_c (C)			
	30	35	40	45	30	35	40	45	30	35	40	45
$COP_{opt.}$	0.76	0.73	0.70	0.63	0.78	0.74	0.71	0.68	0.80	0.75	0.71	0.69
$T_{g,opt.}$ (C)	65.5	77.5	89.5	100	63	74.5	86.5	98.5	60.5	72	83.5	95.5

Table 8 Q_g related to the maximum T_g of Tables 5 and 6

	$T_{ev.} = 3 \text{ C}$				$T_{ev.} = 5 \text{ C}$				$T_{ev.} = 7 \text{ C}$			
	T_c (C)				T_c (C)				T_c (C)			
	30	35	40	45	30	35	40	45	30	35	40	45
Q_g (kW)	1551.1	1622.9	1677.3	1833.3	1534.8	1585.2	1638.1	1692.4	1501.0	1568.4	1620.1	1673.9
T_g (C)	66	77.5	89.5	100	63	75	87	99	60.5	72	84	96

5 Cooling and electrical loads [25]

In this study, a 10 story residential tower is considered which is used by Mohammadian Korouyeh et al. [25]. The length and the width of the tower are 40 and 20 m respectively and the height of each unit is 3 m. The northern and the southern windows are 30% of the wall surface area and both the western and eastern windows are 20%. The other detailed information is tabulated in Table 3.

The cooling load is calculated for the first, central and the last floors and these loads are summed up to calculate the tower loads. Table 4 shows the cooling load data of the tower. Tehran city has been selected as the representative city of hot-dry weather condition. These data may be shown in Fig. 11 too.

It is required to estimate the electrical demand of the building to select the proper number of the prime movers. The electrical load of the building is shown in Fig. 12.

6 Providing heating demand of the generator

The criterion of selecting the prime mover is the maximum electrical load. Since the maximum electrical demand is 1160 kW, so four prime movers with the nominal capacity of 400 kW are provided. Low heating value (LHV) of natural

Table 9 The required prime movers in the hottest month of the year Tehran

PL (%)	$Q_{g,opt.}(kW)$	$T_{ev.}=3\text{ C}$				$T_{ev.}=5\text{ C}$				$T_{ev.}=7\text{ C}$			
		$T_c\text{ (C)}$				$T_c\text{ (C)}$				$T_c\text{ (C)}$			
		30	35	40	45	30	35	40	45	30	35	40	45
20	7	7	7	8	7	7	7	7	6	7	7	7	
40	5	6	6	6	5	5	6	6	5	5	6	6	
60	4	4	4	5	4	4	4	4	4	4	4	4	
80	3	3	3	4	3	3	3	3	3	3	3	3	
100	3	3	3	3	2	3	3	3	2	3	3	3	

gas is equal to $49000 \frac{kJ}{kg}$ so nominal fuel mass flow rate is equal to $0.904 \frac{kg}{hr}$. By considering Eqs. (33)–(37), the extracted heating and the power of each prime mover may be shown in Table 5 for different partial loads.

In this study the S_{gen} and the COP are selected as the objective functions. At the optimum situation, S_{gen} is the minimum and COP is the maximum. Tables 6 and 7 show related T_g for $S_{gen,opt.}$ and $COP_{opt.}$ for various T_c . Considering the maximum T_g of Tables 6 and 7, the related Q_g for each T_c is shown in Table 8.

Considering the Q_g of Table 8, and the prime mover data in various partial loads (Table 5), the number of required prime movers is calculated and it is shown in Table 9.

7 Conclusion

In this study an analysis has been done for a single effect absorption chiller to find its optimum situation. A thermodynamic model has been developed from the first and the second laws of thermodynamics point of views to maximize the COP and minimize the entropy generation by considering permissible solution concentration range (between 0.5 to 0.65). The model is validated by the available data from the heat transfer rate point of view.

It has been found that entropy generation would be decreased by increasing the generator temperature whereas the COP is increased. The variations in the lower generator temperature are high while these variations are ignorable at higher generator temperatures. Also the minimum entropy generation may be decreased by increasing the evaporator temperature in each condensing and generator temperature but these variations are very low. To study the chiller entropy generation, it is recommended to consider only generator and condenser temperatures.

To provide required energy of generator, prime mover in the form of internal combustion engine is applied. A mathematical model is proposed to predict the performance of prime mover in partial load. In each evaporator

and condensing temperature, the required prime movers are increased by decreasing the partial load. In each evaporator temperature and partial load, the required engines are increased or constant by increasing the condensing temperature.

The important limitation of the suggested system is its size which is essential to be compacted. Also for the future work, it is suggested to study the minimum entropy generation of the prime mover and the related parameters should be evaluated.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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