Thermo- economic analysis of inlet air cooling in gas turbine plants in Basrah(Al-Rumaila gas turbine power plant case study)

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Abstract:
In the hot regions the demand on electricity increased in the hot months. Gas turbine power plant is a good solution for this problem, since it has low cost, low time of installation and stable with electricity grid variation. But the power output of gas turbine is affected by the ambient temperature, the power decrease by 18% when the ambient temperature increase to 40^{o}c. Inlet air cooling methods are used to boost the power losses in the hot days. In the present study a thermally and economically analysis was performed for Al-Rumaila gas turbine power plant located in Basrah (south of Iraq). The plant consist from five units and each unit designed to generates 296MW.The results shows that, the maximum decrease in the power developed due the increase in ambient air temperature reaches 22.97% during the month of July. The percentage of power saving due inlet air cooling increased with increasing the ambient air temperature.

Keywords: gas turbine; air cooling and evaporative cooling.

تحليل حراراي - اقتصادي لتبريد الهواء الداخل لمحطات القدرة الغازية في البصرة (محطة القدرة الغازية في الرميلة كحالة دراسية)

الملخص
في المناطق ذات المناخ الحار يزداد الطلب على الطاقة الكهربائية في الاشهر الحارة. تعتبر محطات القدرة الغازية حل جيد لهذه المشكلة، لان كلفة انشائها منخفضة ، الوقت اللازم لتشييدها قصير ومستقرة مع التغيرات الحاصلة في الشبكة الكهربائية. لكن القدرةالمنتجة من المحطات الغازية تتأثر كثيرا بدرجة حرارة المحيط الخارجي، حيث تنخفض القدرة بمقدار ١٨% عندما ترتفع درجة حرارة المحيط الخارجي الى ٤٠ درجة مئوية. تستخدم طرق متعددة لتبريد الهواء الداخل للمحطات الغازية من اجل تعزيز القدرة الخارجة منها. في هذه الدراسة تم تطبيق تحليل حراري اقتصادي لمحطة قدرة غازية في محافظة البصرة جنوب العراق. المحطة تحتوي خمس وحدات والقدرة التصميمية لكل وحدة هي ٢٩٦ ميكاواط. اثبتت النتائج ان اعظم هبوط للقدرة المنتجة بسسبب ارتفاع درجة حرارة المحيط الخارجي يصل ٢٢,٩٧% خلال شهر تموز. النسبة المئوية للتوفير في القدرة بسسبب تبريد الهواء الداخل تزداد مع ارتفاع درجة حرارة المحيط الخارجي.

1. Introduction:

Gas turbine power plants represents the most suitable solution for the problem of electricity in Iraq especially for the hot months in the year (approximately eight months in Basrah from March to October), because gas turbine has low capital cost short synchronization time which it is 30 minutes [1] (time required for gas turbine to reach the base load from zero speed), stability with electricity grid, and due to gas availability in many countries like Iraq. In the last years, in order to give quick solution for the electricity demand, different gas turbine power plants had been installed with different models and capacities. In the hot days especially in the summer the ambient temperature reaches to 50 ^{o}C this lead to total power lost from the gas turbine plants. Therefore the inlet air cooling methods is necessary to achieve enhancement in the gas turbine output.

In the literature there is a lot of studies [1,2,3,4,7,8,and 9] explained the effect of inlet air temperature on gas turbine performance and economics and also, the comparison between the available inlet air cooling methods.
Mainly there are two inlets cooling types[2]:

(i) Evaporative or fogging cooling.

(ii) Chiller cooling electrical or absorption.

In the present study, the evaporative cooling and chiller cooling are used for the inlet air cooling. Figures (1 and 2) illustrate the principles of the two methods[2].

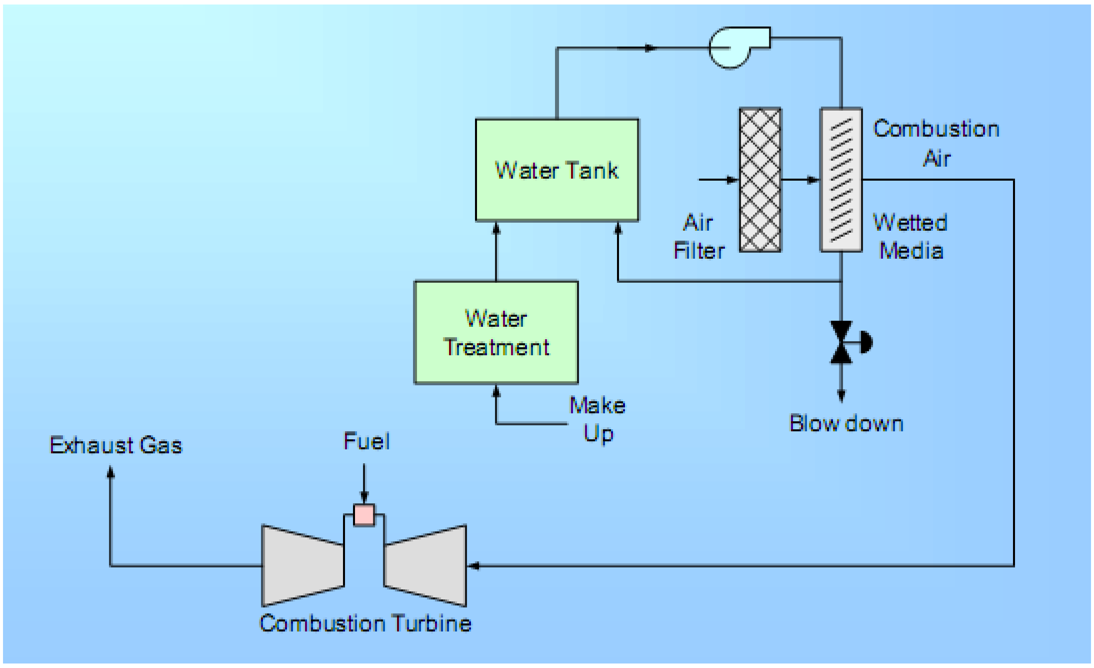

Fig.1 Evaporative cooling method[2]

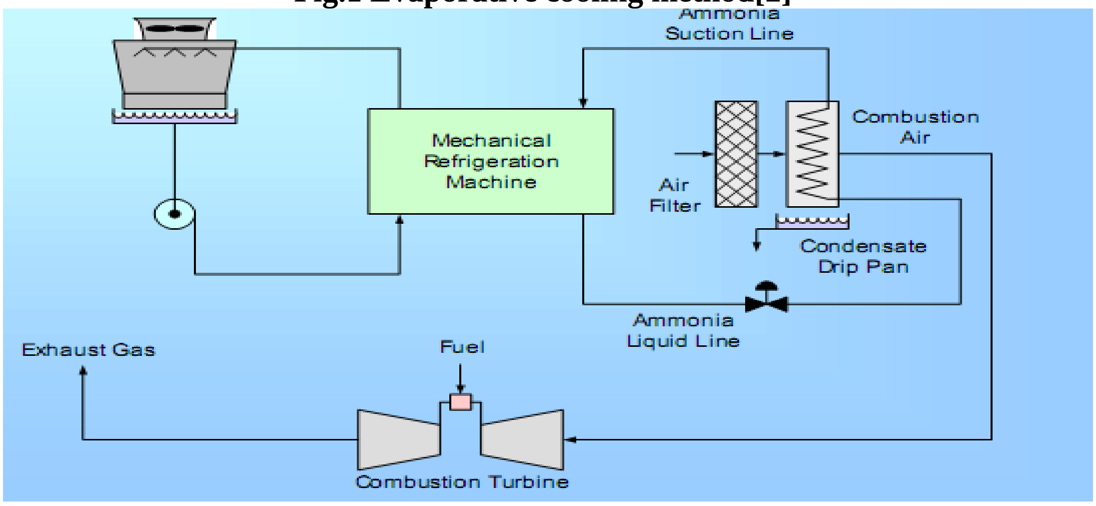

Fig.2 mechanical refrigeration method[2]

2. Aims of the present work:

In the present study, the gas turbine power plant output losses due to the increase in the ambient temperature was estimated and the economic cost for this power losses was calculated by choosing a price for the electricity cost per Mega Watt hour (MGh). Then, the power saving by using the inlet air cooling methods (evaporative and chiller) was estimated and the benefits from the power saving and the cost of the cooling methods per MWH are calculated. For each month an average temperature for the inlet air temperature was used for the power calculations.

3. Effect of Ambient Temperature on Gas Turbine Output Power:

Gas turbine can be defined as constant volume power machine[3]. So, when the ambient air temperature increased the volume of the intake air increased which results in the decreasing of the air mass flow rate and subsequently the power developed. The inlet air temperature on the power output, heat rate, exhaust flow rate and exhaust temperature are given in the figure 3 below[4].

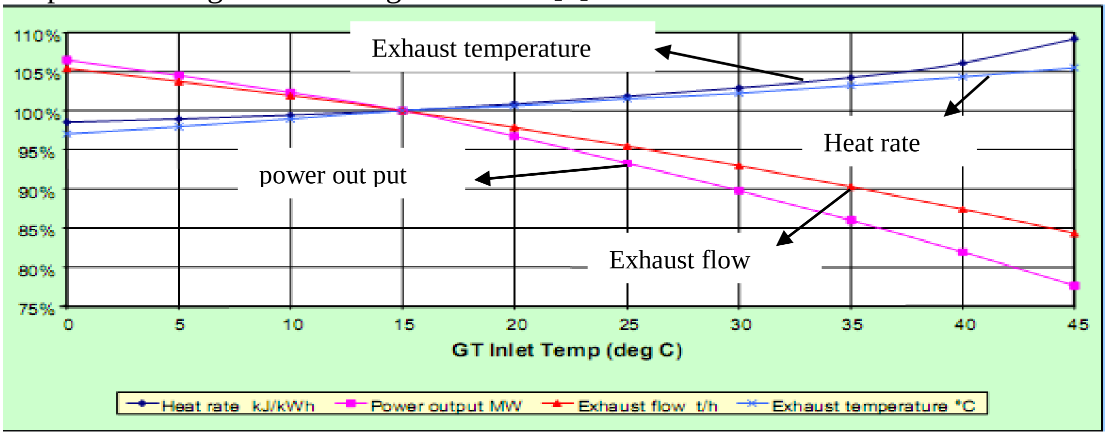

Fig.3 effect of inlet air temperature on the gas turbine[4]

In the present study, the calculations are performed for nine months (from February to October since the average temperature in these months is greater than the ISO temperature for gas turbine by more than 10 C^o). The average ambient temperature for each month is given in table1. below.

Table 1. average ambient temperature for each month[5]

Month	Temperature (^{o}C)
February	27.4
March	30.8
April	33.5
May	41.8
June	46.3
July	45.1
August	43.1
September	35
October	26.1

4. Theoretical analysis:

For an open cycle gas turbine shown in figure.4 below[6]:

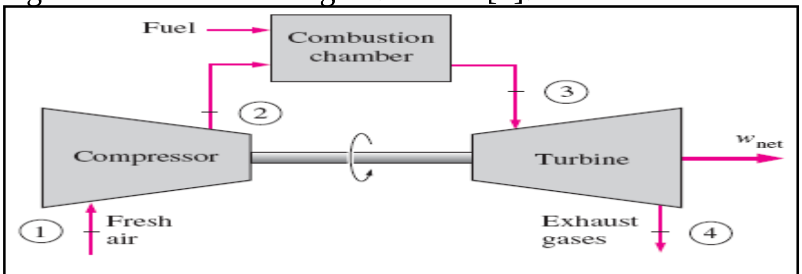

FIGURE 9–29
An open-cycle gas-turbine engine.

Fig.4 open cycle gas turbine[6]

The work required for the compressor is given by the relation;

$$W_C = \frac{\left(\dot{m}_a C_{P_a}(T_2 - T_1)\right)}{\eta_C} \qquad \ldots\ldots\ldots.1$$

The heat supplied in the combustion chamber is given by the relation;

$$Q = \dot{m}_g C_{P_g}(T_3 - T_2) \qquad \ldots\ldots\ldots..2$$

The useful work from the turbine is given by the relation;

$$W_T = \eta_T \left(\dot{m}_g C_{P_g}(T_3 - T_4)\right) \qquad \ldots\ldots\ldots..3$$

The flow rate of gases inlet the turbine is given by;

$$\dot{m}_g = \dot{m}_a + \dot{m}_f \qquad \ldots\ldots\ldots\ldots.4$$

Lastly, the net power obtained fr 4 turbine is given by;

$$W_{net} = W_T - W_C \qquad \ldots\ldots\ldots\ldots 5$$

The isentropic efficiency for compressor η_C and for turbine η_T are given by the following experimental relations[7];

$$\eta_C = \left[1 - \left(\frac{0.09 + (r_p - 1)}{300}\right)\right] \qquad \ldots\ldots\ldots\ldots 6$$

And for turbine[7];

$$\eta_T = \left[0.9 - \left(\frac{\frac{T_1}{P_1} - 1}{250}\right)\right] \qquad \ldots\ldots\ldots\ldots 7$$

The power losses due to inlet air temperature increase is given by;

$$\Delta P = W_{net}\ at\ ISO\ condition - W_{net}\ at\ a\ given\ temperature \qquad \ldots\ldots..8$$

The ISO conditions for gas turbine are (15 ^{O}C and 60% relative humidity at 1 bar)[8].

Economics losses due to power losses is given by;

$$EC = C * \Delta P \qquad \ldots\ldots..9$$

The power saving due to inlet air cooling is given by;

$$\Delta P_1 = W_{net}\ with\ cooling - W_{net}\ with\ out\ cooling \qquad \ldots\ldots..10$$

The economics benefits due to power saving is given by;

$$EC_1 = C * \Delta P_1 \qquad \ldots\ldots\ldots 11$$

The economics cost due to using inlet air cooling is given by;

$$EC_2 = C_1 * \Delta P_1 \qquad \ldots\ldots\ldots\ldots.12$$

5. Results and discussion:

The performance of the gas turbine unit is examined for a restricted set of operational and design conditions of an operating gas turbine unit taking into account real climatic circumstances prevailed during 2014 at Rumaila, South of Basrah, Iraq. The power plant consists of five units and the specifications for each unit are given in table.2 below.

Table 2. Gas turbine design data

Item	rate	Remarks
Gas turbine output	296 MW	At ISO condition
Air inlet temperature	15 ^oC	
Relative humidity	60%	
Average air mass flow rate	700.8 kg/s	
Ambient pressure	1.013 bar	
Exhaust gases temperature	600 ^oC	
Exhaust gases flow rate	718.5 kg/s	
Compression ratio	17	
Inlet temperature to turbine	1473 ^oC	
Fuel gas mass flow rate	17.76 kg/s	
Efficiency	43%	

5.1 **Effect of ambient temperature rise on power plant performance.**

The variation of net power developed, losses of power and economics cost per hour due to the temperature rise for each month and for each unit are given in table.3 below and figures (A1, A2, A3 and A4) in the appendix A.

Table.3 performance of Rumaila power plant at various ambient temperature.

Month	Ambient temperature (K)	$\dot{m}_a$ (kg/s)	W_{net} (MWh)	Power losses (MWh)	Economic cost ($/h)
February	300.4	672	258	38	9500
March	304.8	663	251	45	11250
April	306.5	659	248	48	12000
May	315.8	640	233	63	15750
June	319.3	632	227	69	17250
July	318.1	634	229	67	16750
August	316.1	638	232	64	16000
September	308	655	244	52	13000
October	299.1	675	260	36	9000

The cost of electric power generation per MWh is in the range of (80$/MWh in India to 410$/MWh in Denmark) , so on average it is taken (250 $/MWh)[9]. From the table, it is clear that, as the ambient temperature increased the losses of power and economic cost increased. This means that, the net power developed and thermal efficiency are decreased.

The given values for the power losses and economic cost are for one hour of operation, if we assumed that the power plant operate at this ambient temperatures for ten hours per day, the economic cost per day, month and for a period of nine months for one unit are given in table .4 below;

Table.4 Economic cost for one unit per day, month and for nine month.

Month	Ambient temperature (K)	Economic cost($ per day)	Economic cost($ per month)	Economic cost($ per nine month)
February	300	95000	2660000	36557500
March	304	112500	3487500	
April	306	120000	3600000	
May	315	157500	4882500	
June	319	172500	5175000	
July	318	167500	5192500	
August	316	160000	4960000	
September	308	130000	3900000	
October	299	90000	2700000	

The cost for the five units of the plant =5*36557500=182787500 ($ per nine month).

5.2 Effect of air cooling techniques on power plant performance.

In the present study the assumption that, for each month the air cooling system (evaporative and chiller) will reduce the ambient air temperature to 18^{O}C. Then for the two methods of cooling the saving in power, economical cost and economical benefits are given in tables (5 and 6) below.

The increment in the energy unit cost due to using air cooling system is taken as 32($/MWh) for evaporative cooling and 53 ($/MWh) for mechanical cooling [10].

Table.5 Thermo – economic effect of evaporative cooling method.

Month	Compressor inlet temperature (K)	Power saving (MWh)	Economic profit ($/h)	Economic cost for cooling ($/h)	Percentage of power saving
February	291	16	4000	512	42%
March	291	23	5750	736	51%
April	291	26	6500	832	54%
May	291	41	10250	1312	65%
June	291	47	11750	1504	68%
July	291	45	11250	1440	67%
August	291	42	10500	1344	65%
September	291	30	7500	960	58%
October	291	14	3500	448	39%

Table.6 Thermo – economic effect of chiller cooling method.

Month	Compressor inlet temperature (K)	Power saving (MWh)	Economic profit ($/h)	Economic cost ($/h)	Percentage of power saving
February	291	16	4000	848	42%
March	291	23	5750	1219	51%
April	291	26	6500	1378	54%
May	291	41	10250	2173	65%
June	291	47	11750	2491	68%
July	291	45	11250	2385	67%
August	291	42	10500	2226	65%
September	291	30	7500	960	58%
October	291	14	3500	742	39%

From the results of tables(5 and 6), it is clear that the percentage of the power saving increased as the ambient temperature increased. Which means that the effectiveness of air cooling method increased with increasing the ambient air temperature.

6. Conclusions:

In the hot regions the inlet air cooling techniques must be used for improving the gas turbine power plants thermally and economically. The effectiveness of air cooling methods increasing with the increasing in the ambient air temperature .

7. Nomenclature:

Symbol	Definition	Unit
C	Cost of electric power generation unit	$/MWh
C1	Cost of using air cooling techniques	$/MWh
C_{Pa}	Air specific heat	kJ/kg. K
C_{Pg}	Gases specific heat	kJ/kg. K
EC	Economic cost due to power losses	$/hour
EC_1	Economic benefits due power saving	$/hour
EC_2	Economic cost for cooling techniques	$/hour
$\dot{m}_a$	Air mass flow rate	Kg/s
$\dot{m}_g$	Inlet gas turbine flow rate	Kg/s
$\dot{m}_f$	Fuel flow rate	Kg/s
r_P	Pressure ratio	
T_1	Ambient temperature	K
T_2	Compressor exit temperature	K
T_3	Turbine inlet temperature	K
T_4	Turbine exit temperature	K
P_1	Ambient pressure	Bar
ΔP	Power losses due inlet air increase	MWh
ΔP_1	Power saving due to inlet air cooling	MWh

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[10]- From internet (shrinkthatfootprint.com).

Appendix A: Variation of air mass flow rate, net work, power losses and economic cost with ambient temperature.

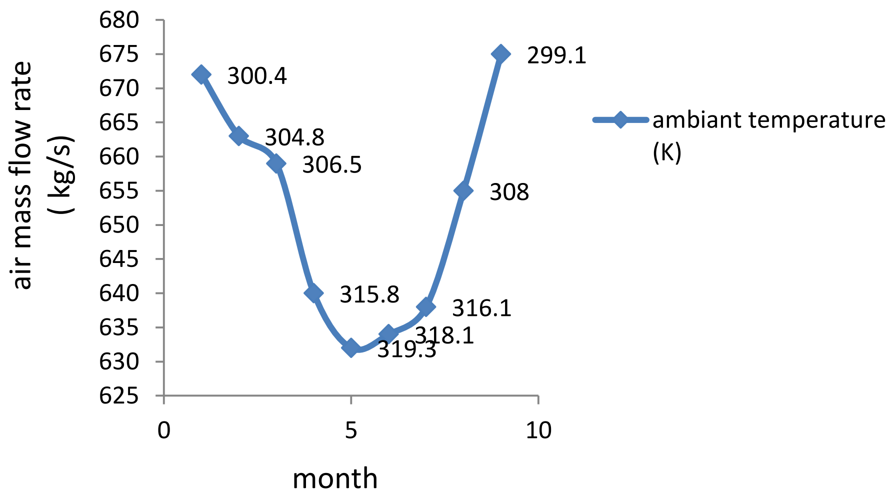

Fig.A1 Variation of air mass flow rate with ambient temperature

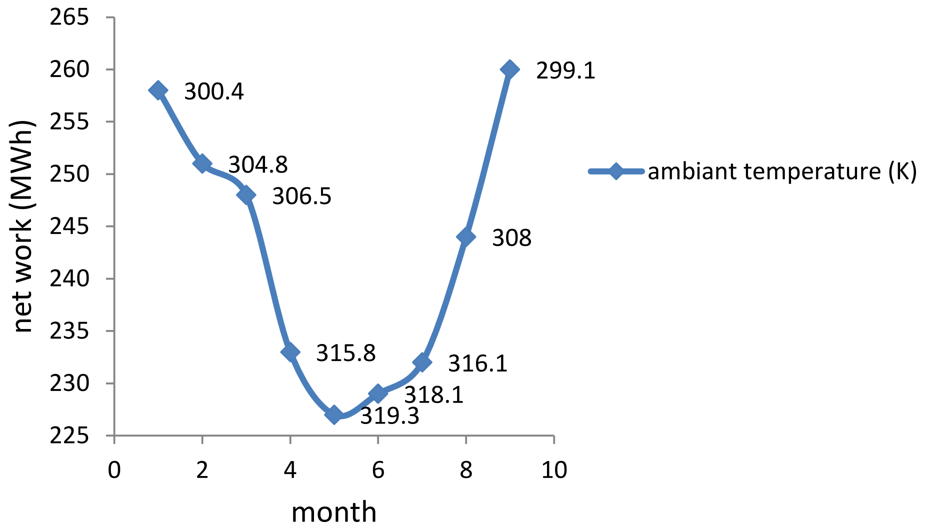

Fig.A2 Variation of net work with ambient temperature

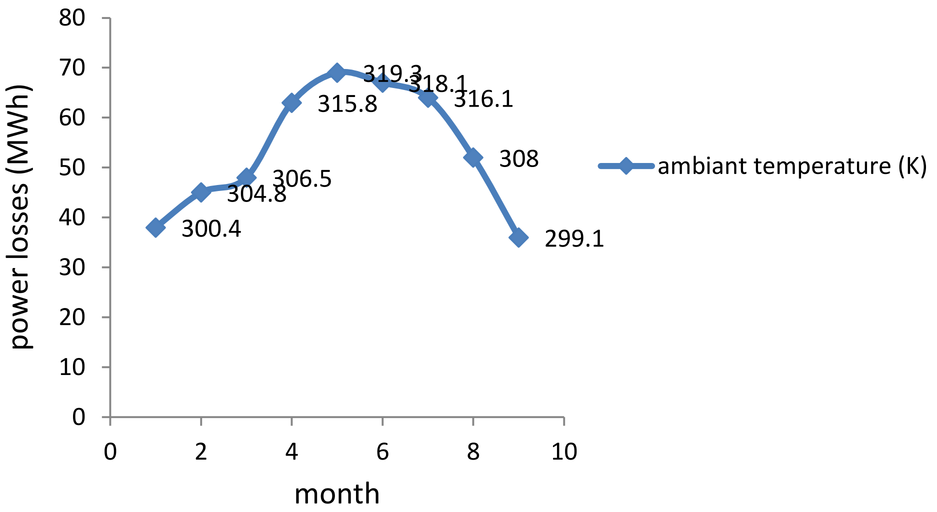

Fig.A3 Variation of power losses with ambient temperature

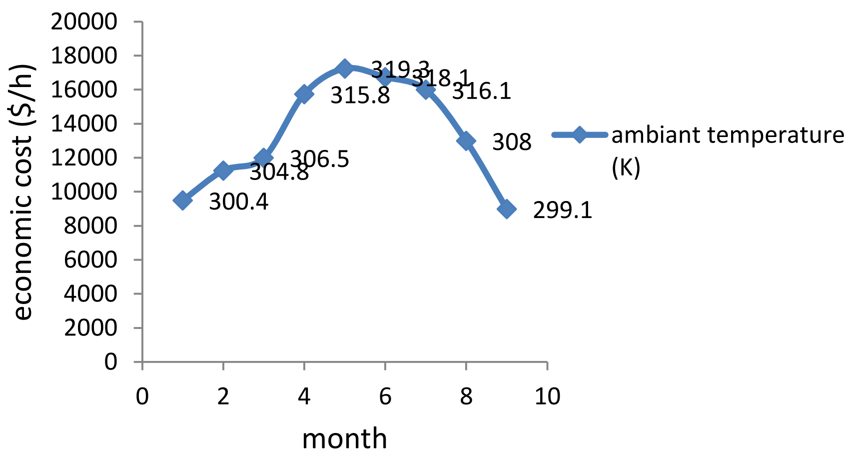

Fig.A4 Variation of economic cost with ambient temperature