

Technical, Economic Evaluation and Determining Appropriate Method of Cooling of Inlet Air of Combined Cycle Power Plant with Multi-Criteria Techniques

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Abstract

In hot seasons of year, due to increase in inlet temperature to compressor, production power of gas turbines decreases. Gas turbine inlet air cooling is a technology that improves gas turbine performance, in which gas turbine power per kilowatt is increased by spending less. In this study, three gas turbine inlet air cooling methods including fog, media and absorption chiller have been technically and economically evaluated in order to improve performance of Kashan combined cycle power plant. In this article, by using multi-criteria technique according to decision criteria, prioritization of inlet air cooling method for use in Kashan power plant has been done and prioritization of methods has been determined using TOPSIS methods. Considering technical and economic conditions and environmental conditions of Kashan region, using multi-criteria techniques, Media cooling system is selected and introduced as a suitable system to improve performance in this power plant. By using media system in Kashan power plant, net power output from power plant increases by 5.166%, energy efficiency and exergy of gas cycle increases by 2.26% and 2.25%, respectively.

Keywords: Gas turbine, energy, exergy, simulation, inlet air cooling, thermoflow.

1. Introduction

So far, many methods have been presented to improve performance of combined cycles, and each of these methods has different effects on output power, efficiency and specific fuel consumption, water consumption or recovery. choice of a specific method is made according to type of power plant, climatic conditions of working area, how it affects cycle performance and economic equipment of plan. Some of most important parameters affecting gas turbine performance are:

- Pressure ratio
- Inlet temperature to compressor
- Compressor efficiency
- Compressor work
- Turbine inlet temperature
- turbine efficiency
- The output work of turbine
- fuel to air ratio
- Mass flow rate of passing fluid

By presenting a series of methods and changing each of mentioned parameters, performance of gas turbine can be improved.

The types of effective methods in improving gas turbine performance are:

- Intermediate cooling
- Evaporative cooling (media and fog)
- Cooling by energy storage (cold water ice storage)
- Refrigeration cooling (using absorption chiller and compression chiller)

- Water or steam injection into combustion chamber
- Heating air coming out of compressor
- Steam production by recovery boiler

Since cooling of air entering compressor is an independent process, it is practical in gas turbines and has a simpler design and implementation.

Gas turbine inlet air cooling is a well-known technology used to improve gas turbine performance, where gas turbine power is increased at a low cost per kW [1]. Different methods have been used to cool turbine inlet air. Gas turbines are sensitive to ambient temperature, in which both capacity and efficiency decrease as ambient temperature increases. power demand of compressor is proportional to absolute temperature of incoming air. mass flow rate capacity of compressor is proportional to air density at compressor inlet, which is inversely proportional to absolute temperature. Therefore, high temperature of environment has a negative effect on capacity and efficiency of turbine. Various approaches have been used to cool turbine inlet air.

Hamdani et al. studied performance of an inlet air cooling system for a 157 MW gas power plant located in Asalouye in southern Iran. They proposed a new hybrid cooling method, combined cooling systems (indirect evaporative cooling system + absorption chiller). Then, with functional and thermal-economic analysis of increase in output power, they showed net income from increase in electricity sales and payback period [2].

Zaytoon investigated cooling of inlet air of two-stage evaporative gas turbine for GE 7001EA gas turbine model in climatic conditions of city of Riyadh, Saudi Arabia. two-stage evaporation system consists of indirect and direct evaporation stages. By simulating gas turbine using Thermoflex software, a comparison of different performance parameters of gas turbines was made and added annual profit and payback period for different inlet air cooling systems were estimated [1].

Deng et al. conducted extensive investigations of gas turbine inlet air cooling systems [3].

Dizaji et al investigated hybrid inlet cooling systems. They reported that hybrid inlet cooling systems typically require lower amounts of make-up water than conventional evaporative cooling systems because amount of water that must be added initially is significantly lower. Compared to mechanical vapor compression, hybrid system cools air to moderate temperatures, significantly reducing required cooling/cooling capacity. Therefore, required chillers can have a lower relative capacity and consume relatively less power[4]. Mishra et al analyzed a gas turbine cycle in terms of first law using compressor inlet air cooling. gas turbine was examined in various operational and environmental parameters and their effect on specific work and efficiency of gas turbine cycle power plant was studied [5]. Kamal et al evaluated effect of turbine inlet air cooling using electric chillers on performance of LM6000PD gas turbine generator in Malaysian climate using GT Pro software. They showed that net output power of gas turbine and heating rate are significantly improved, and cooling of turbine inlet air using electric chillers is effective as a power increasing technology in Malaysia [6]. Gang studied application of a double-effect lithium bromide absorption chiller for gas turbine inlet cooling based on actual climatic data and gas turbine technical parameters, and annual fuel savings were analyzed as criteria. results showed a fuel consumption saving of 26359.2 grams per 1 kW of unit output power and a total annual fuel saving of 354.6 tons throughout year [7]. Andrey Radchenko et al. proposed an innovative cooling system design for temperate climates: intake air cooling is implemented in two stages depending on cooling temperature. This method is divided into a high temperature cooling stage and a low temperature cooling stage. results of this study showed that annual fuel savings of a combustion turbine using a combined absorption-injection air cooling system is 50% more than a combustion turbine that only uses a single-effect lithium bromide absorption chiller system [8]. Tolba et al proposed a new hybrid air cooling system using a refrigeration cooling system before fog cooling system to reduce size of cooling system and improve gas turbine performance. Exergy destruction, net power and all efficiencies (first law and second efficiency) were investigated in different conditions and theoretical model was validated using actual performance data of a 25 MW gas turbine power plant (GE GT-TM) built by GE, Heliopolis-Egypt power plant. became. results showed that maximum output power increase at maximum ambient temperature (313 K) is about 14.3%, while change of first law efficiency and second law efficiency is very small and can be ignored. Their proposed multi-stage cooling system reduces return period cost if a chiller system is used. This means lower initial investment costs and lower total annual costs [9]. In his article, Ahmadi discussed thermodynamic and exergetoeconomic modeling of a gas cycle power plant and obtained best design parameters by using multi-objective optimization. design parameters included inlet temperature to gas turbine and combustion chamber, compressor pressure ratio, turbine and compressor isentropic efficiency. results showed that using obtained parameters, exergy efficiency of power plant increases up to 33.5% [10]. Carmona conducted thermodynamic and economic research using evaporative cooling in hot and humid regions. According to his research, evaporative cooling can improve performance of gas

turbines even in tropical regions[11]. Arabi et al presented a detailed evaluation of a gas turbine that used inlet air cooling. In this study, authors used GE type F5 gas turbines for energy analysis [12].

Barigozzi et al did an economic and technical evaluation of a combined cycle power plant with gas turbine inlet air cooling for different weather conditions[13].

Koditovako calculated effect of inlet air cooling and estimated performance of inlet air cooling in Kalanitisa gas turbine power plant[14].

According to past articles and studies, one of most important problems related to gas turbines in gas and combined cycle power plants is reduction of their production power and efficiency in summer season. As ambient air temperature increases, inlet temperature to compressor increases. This increases temperature of compressor outlet and subsequently increases temperature of inlet to turbine. This problem is much greater for countries located in tropical regions. Due to fact that in our country this problem plagues gas power plants, therefore, a detailed and scientific investigation of this issue is of particular importance.

In this work, performance improvement of Kashan combined cycle power plant has been evaluated. For this purpose, in present work, cycle modeling and analysis is discussed using Thermoflow software. In this work, effect of cooling incoming air to compressor on performance of Kashan gas power plant will be investigated. In this study, three methods of gas turbine inlet air cooling; Fog, media and double-effect absorption chiller are studied technically and economically and are ranked according to presented valuation criteria and best method is selected according to TOPSIS decision criteria. In multi-criteria decision-making, meaning of criteria is factors that decision-maker considers in order to increase desirability and satisfaction of choice. In decision-making problems, final results of used model are reliable only if criteria of problem are well identified. In this article, aim is to identify these influencing factors well and to choose best method of cooling turbine inlet air by considering all influencing factors.

2. Thermodynamic modeling of gas cycle of Kashan power plant

In this section, thermodynamic modeling of gas cycle of Kashan power plant is discussed using thermodynamic relations. Figure (1) shows a schematic picture of gas cycle of Kashan power plant.

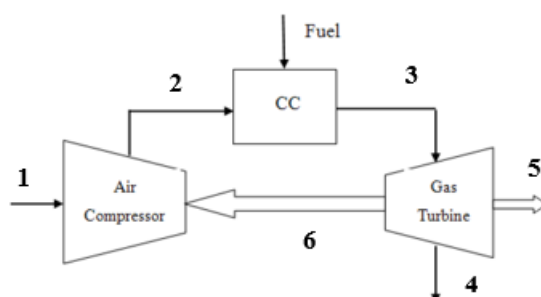


Figure 1. gas cycle

2.1. Thermodynamic analysis of compressor

Figure (2) shows diagram of real and isentropic compression processes in compressor. reversible adiabatic process is called isentropic where following relationship holds.

$$\frac{T_{2s}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \quad (1)$$

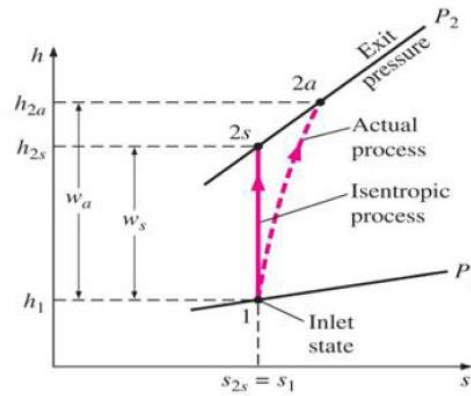


Figure 2 Real and isentropic compression processes in compressor

The actual or useful work and power consumption of compressor is obtained from following relationships.

$$w_{AC,u} = w_{AC,a} = h_2 - h_1 \quad (2)$$

$$W_{AC,u} = W_{AC,a} = \dot{m}_{air}(w_{AC,a}) \quad (3)$$

The work and power consumption of isentropic compressor is obtained from following relationships.

$$w_{AC,s} = h_{2s} - h_1 \quad (4)$$

$$W_{AC,s} = \dot{m}_{air}(w_{AC,s}) \quad (5)$$

The isentropic efficiency of compressor is obtained from following equation.

$$\eta_{AC} = \frac{w_{AC,s}}{w_{AC,a}} \quad (6)$$

The reversible work and power consumption of compressor is obtained from following equation.

$$w_{AC,rev} = ex_2 - ex_1 \quad (7)$$

$$W_{AC,rev} = \dot{m}_{air} \times w_{AC,rev} \quad (8)$$

Irreversibility and intensity of irreversibility in compressor are obtained from following relationship.

$$i_c = w_{cu} - w_{c,rev} \quad (9)$$

$$I_c = W_{cu} - W_{c,rev} \quad (10)$$

The exergy efficiency (second law) of compressor is obtained from following equation.

$$\eta_{II,AC} = \frac{W_{AC,rev}}{W_{AC,u}} \quad (11)$$

2.2. Thermodynamic analysis of combustion chamber

An auxiliary concept that expresses amount of thermal energy input to cycle in form of amount of fuel consumed per work done is specific fuel consumption. This quantity is usually expressed in kg/kWh.

$$\text{SFC} = \frac{3600}{\eta_{\text{th}} \text{LHV}} \quad (12)$$

LHV indicates calorific value of fuel. term calorific value or heat of reaction expresses heat produced during combustion or reaction at a constant temperature. In constant pressure combustion with steady flow, heat transfer is equivalent to combustion enthalpy. Calorific value is defined in two ways. High calorific value is heat transferred with liquid water in combustion products and low calorific value is heat transferred with water vapor in combustion products. ratio of air to fuel based on mass and molar is expressed as follows.

$$\overline{\text{AFR}} = \frac{n_a}{n_f} \quad (13)$$

$$\begin{aligned} \text{AFR} &= \frac{\dot{m}_{\text{air}}}{\dot{m}_{\text{Fuel}}} = \frac{n_{\text{air}} M_{\text{air}}}{n_{\text{Fuel}} M_{\text{Fuel}}} \\ &= \overline{\text{AFR}} \frac{M_{\text{air}}}{M_{\text{Fuel}}} \end{aligned} \quad (14)$$

The intensity of irreversibility of combustion chamber is obtained from following equation.

$$I_{\text{CC}} = \dot{E}x_F + \dot{E}x_2 - \dot{E}x_3 \quad (15)$$

The exergy efficiency of combustion chamber is equal to:

$$\eta_{\text{II,CC}} = \frac{\dot{E}x_3}{\dot{E}x_F + \dot{E}x_2} \quad (16)$$

2.3. Thermodynamic analysis of gas turbine

Figure (3) shows diagram of real and isentropic expansion processes in gas turbine.

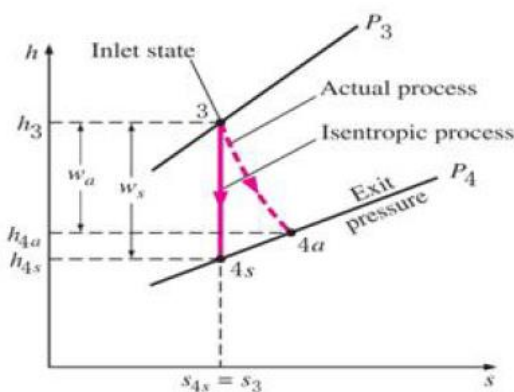


Figure 3. Real and isentropic expansion processes in gas turbine

The real or useful power of gas turbine is obtained from following equation.

$$W_{GT} = W_{GT,a} = \dot{m}_3 \times h_3 + \dot{m}_{Coolant} \times h_{Coolant} - \dot{m}_4 \times h_4 \quad (17)$$

$\dot{m}_{Coolant}$ is air flow rate leaving compressor and entering gas turbine for cooling blades. isentropic power of gas turbine is obtained from following equation.

$$W_{GT,s} = \dot{m}_3 \times h_3 + \dot{m}_{Coolant} \times h_{Coolant} - \dot{m}_{4s} \times h_{4s} \quad (18)$$

The isentropic efficiency of gas turbine is obtained from following equation.

$$\eta_{GT,s} = \frac{W_{GT}}{W_{GT,rev}} \quad (19)$$

The reversible power of gas turbine is obtained from following equation.

$$W_{GT,rev} = \dot{E}X_3 + \dot{E}X_{Coolant} - \dot{E}X_4 \quad (20)$$

The intensity of irreversibility in gas turbine is obtained from following equation.

$$I_{GT} = W_{GT,rev} - W_{GT} \quad (21)$$

Exergy efficiency of gas turbine is obtained from following equation.

$$\eta_{II,GT} = \frac{W_{GT}}{W_{GT,rev}} \quad (22)$$

2.4. Thermodynamic analysis of gas turbine power plant

The net power output from gas cycle of power plant is obtained from following equation.

$$W_{net} = \eta_{Gen} \times (W_{GT} - W_{AC,u}) \quad (23)$$

The thermal efficiency (first law efficiency) and exergy efficiency of gas cycle of power plant are obtained from following equation.

$$\eta_{th} = \frac{W_{net}}{\dot{m}_F \times LHV} \quad (24)$$

$$\eta_{II,p} = \frac{W_{net}}{\dot{E}_{XF}} \quad (25)$$

The heat rate and intensity of irreversibility of gas cycle of power plant are obtained from following equation.

$$HR = \frac{3600}{\eta_{th}} \quad (26)$$

$$\dot{I}_p = \dot{E}_{XF} - W_{net} \quad (27)$$

The thermal efficiency of gas cycle in an ideal state is equal to:

$$\eta_{th} = 1 - \frac{T_{4s} - T_1}{T_3 - T_{2s}} \quad (28)$$

$$T_{4s} = T_3 \left(\frac{P_4}{P_3} \right)^{\frac{\gamma-1}{\gamma}} \quad (29)$$

3. Introducing combined cycle of Kashan power plant

Kashan combined cycle power plant is one of Iran's combined cycle power plants with a production capacity of more than 470 MW, which includes 2 gas units of 162 MW and 1 steam unit.

The Kashan gas power plant project includes two gas units with a capacity of 162 megawatts (324 megawatts in total) in ISO conditions, in which V94 Niam design gas turbines have been used.

The fuel of this power plant is natural gas and oil backup fuel (diesel), which is stored in two tanks of 20,000 cubic meters.

The consultant of employer, Qods Niro Engineering Company and Iran Power Plant Project Management Company (MAPNA) as a contractor, is responsible for construction of this power plant.

- Geographical location: Kashan combined cycle power plant is located at km 20 of Kashan-Ardestan road.
- Environmental conditions: relative humidity: 20%
- Average maximum ambient temperature: 43 degrees Celsius
- Average minimum ambient temperature: -12 degrees Celsius
- Height above sea level: 937 meters

4. Simulation of Kashan combined cycle power plant in Thermoflow software

In this section, simulation of gas and combined cycle of Kashan power plant in Thermoflow software is discussed. way it works is that a combined cycle block that includes two gas turbines, two recovery boilers and a steam turbine, by choosing gas turbine that is available in default turbine list of software, in normal load and in software environment, it is simulated.

In this section, first, in GT Pro module, a combined cycle block that includes two gas turbines, two recovery boilers and a steam turbine is simulated in maximum load mode and in Kashan weather conditions. To simulate combined cycle, first, information related to air conditions of Kashan, which is specified in table (1), is entered into software, and then desired turbine is selected

from list of default turbines of software.

Table 1. information about environmental conditions of Kashan

parameter	temperature	pressure	relative humidity	sea level altitude
value	43C	0.905 bar	20%	937m

5. Parametric study

5.1. Investigating effects of ambient temperature change on power plant cycle performance

Predicting gas turbine performance in different atmospheric conditions leads to its correct use, saving energy, improving performance and increasing its useful life. To predict performance of gas turbine, effect of environmental parameters on performance of its components should be investigated. Among environmental factors affecting performance of turbine, we can mention pressure, temperature and relative humidity of ambient air.

To investigate effects of changing ambient temperature, temperature is considered in range of 5 to 40 degrees Celsius, then changes are checked for every 5 degrees of temperature increase and results are compared. In this case, other specifications are considered as basic state of Kashan power plant (ambient pressure 0.9057 bar, relative humidity 20.14% and loading 100%). Also, in each step, a comparison is made between results of different temperatures and base state.

Air mass flow rate entering compressor

Gas turbine is a power generation system in constant volume. As ambient air temperature increases and ambient air pressure remains constant, in a constant volume, air flow density decreases and as a result, mass flow rate of incoming air to compressor decreases. Figure (4) shows changes in mass flow rate of air entering compressor against changes in ambient temperature. For one-degree centigrade increase in temperature, mass flow rate of incoming air to compressor decreases by an average of 0.8 kg/s.

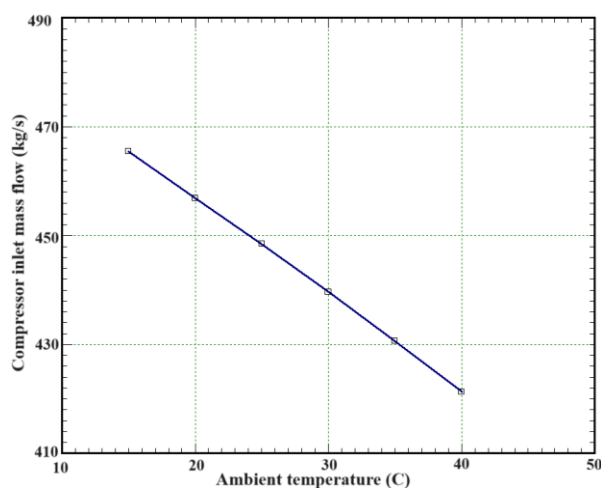


Figure 4. Changes in mass flow rate of air entering compressor with ambient temperature

Power and efficiency of power plant

As ambient air temperature increases, power of gas turbine and compressor decreases, but because slope of gas turbine power decrease is greater than that of compressor, gross output power of gas cycle decreases. For one-degree centigrade increase in ambient air temperature, gross power output from gas cycle will decrease by 920 kW on average, and gross power of cycle will decrease by 2120 kW.

These changes can be seen in figure (5) and (6).

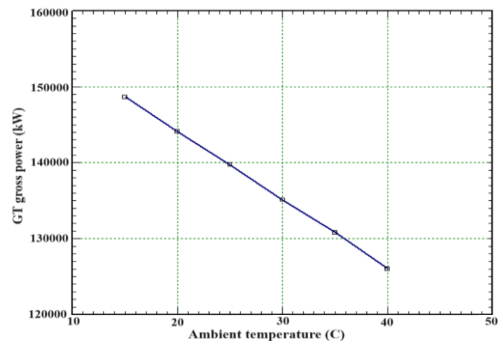


Figure 5. Changes in net power output of gas cycle with ambient temperature

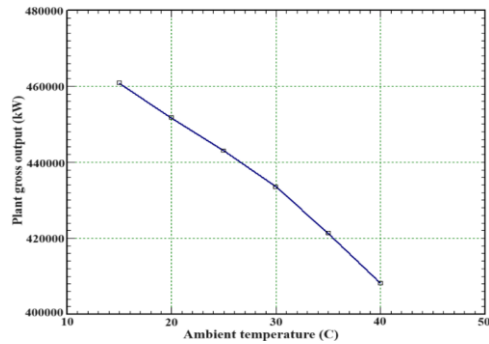


Figure 6. Changes in net output power of unit with ambient temperature

Figure (7) shows that as ambient air temperature increases, energy efficiency of gas cycle decreases. For one-degree centigrade increase in ambient air temperature, gas cycle efficiency decreases by 0.064% on average, and unit efficiency also decreases by 0.048% for each degree of temperature increase.

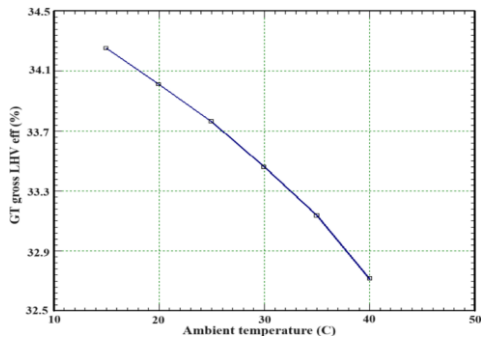


Figure 7. Gas cycle efficiency changes with ambient temperature

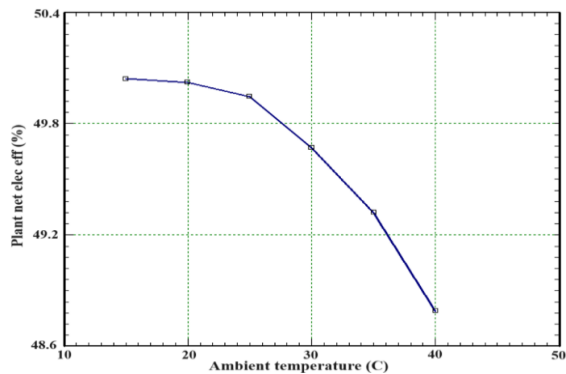


Figure 8. Unit efficiency changes with ambient temperature

6. Improving gas cycle performance of Kashan power plant by cooling inlet air

In previous section, effect of ambient temperature changes on performance of gas cycle and entire power plant was investigated. results show that increase in ambient temperature has a great effect on power output from gas cycle and power plant, so that at constant pressure and relative humidity, for one-degree Celsius increase in temperature, on average 0.63% of power of gas cycle (approximately equal to 688 kW) and 0.53% of power plant power (approximately equal to 1637 kW) is reduced. Also, for one-degree Celsius increase in temperature, on average 0.26% of gas cycle energy efficiency and 0.14% of power plant energy efficiency decrease. Kashan power plant is located in a region of Iran that has a warm and semi-arid climate. average temperature in this type of weather is 14 to 19 degrees Celsius. Figure (9) shows average of highest and lowest temperatures during day and night and for each month of year, for city of Kashan.

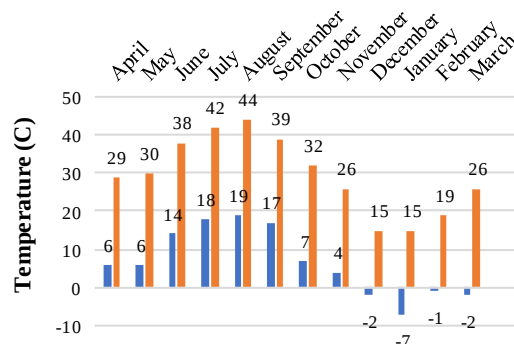


Figure 9. Average highest and lowest ambient temperature in Kashan city in degrees Celsius

Figure (10) shows average relative humidity during day and night for each month of year and for city of Kashan.

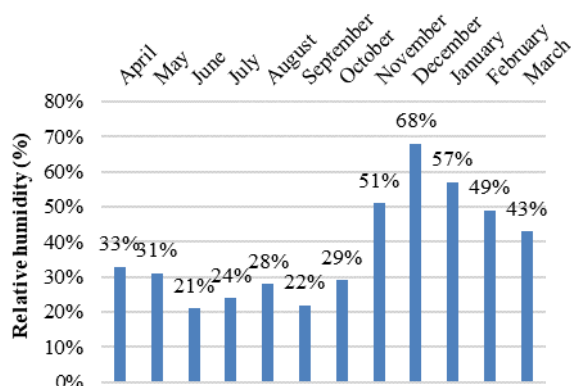


Figure 10. Average relative humidity in Kashan city

With heating of air during summer and as a result high use of cooling equipment in homes and offices, amount of electrical energy consumption will increase sharply and decrease in output power of power plants may cause problems in providing necessary electrical energy in country. Therefore, main priority in power plants is to produce more power to supply country's electrical energy. sum of mentioned factors has caused necessity of cooling air entering compressor to increase output power of gas cycles. In following, technical and economic analysis of use of three conventional cooling systems in country including media and fog evaporative cooling systems and double-effect absorption chiller cooling will be discussed. For this purpose, three cooling systems with a combined cycle are simulated in Thermoflow software. Figure (11) shows simulation of cooling systems.

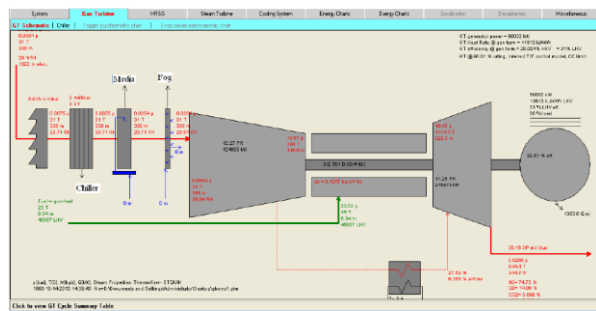


Figure 11. Simulation of cooling systems in ThermoFlow

Using cooling systems for all hours of day and all year round is technically and economically not suitable, so they will be used only in months with highest average temperature and lowest humidity. cooling systems will be used from first of May to end of October. Figures (12) and (13) show average temperature and relative humidity during day and night in month of August and for city of Kashan.

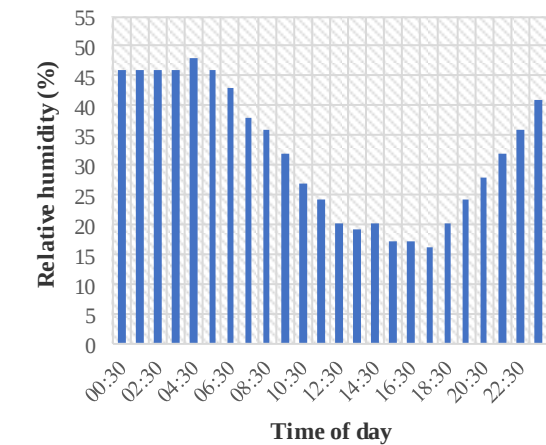


Figure 12. Average relative humidity during day and night in August

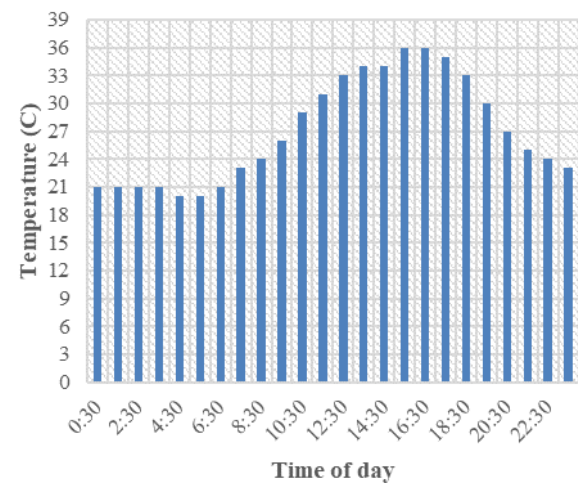


Figure 13. Average temperature during day and night in August

According to figures (12) and (13), cooling systems will be used in hours between 12:30 p.m. and 18:30 p.m., which have highest temperature and lowest relative humidity.

6.1. Economic analysis of using three types of cooling systems in Kashan power plant

One of most important factors in deciding whether to reject or accept an industrial plan, after technical evaluations of plan, is economic review of plan. A suitable industrial plan is a plan that, in addition to having a technical justification and taking into account all limitations in construction, maintenance and operation, also has a proper justification from an economic point of view. One of important parameters in evaluating economic justification of an industrial plan is return on investment. return on investment is obtained by dividing amount of investment to complete project by amount of periodic income and savings due to implementation of project [15].

$$PB = \frac{CC}{AS} \quad (30)$$

In above relationship, CC represents initial investment required to complete project, PB represents investment return period in years, and AS represents annual income or savings resulting from project. In technical and economic justification of cooling systems, following parameters should be considered.

- The initial investment cost includes cost of purchasing and installing equipment
- Annual maintenance and operation costs
- Water consumption costs
- The cost of additional fuel consumption for increasing production power
- Income from increasing electrical power output from power plant by cooling systems

To obtain increase in electric power produced by power plant, with addition of cooling system, first average temperature, pressure and humidity of ambient air, between hours of 12:30 PM and 18:30 PM, for each of warm months of year. It is calculated by information obtained from meteorological sites. This information is given in table (2).

Table 2. Average temperature, pressure and humidity of environment in 6 warm months of year for Kashan city

humidity %	wet bulb temperature (C)	dry bulb temperature (C)	month
20	10	23	May
14	13	30	June
17	16	33.5	July
18	16	34	August
14	14	32	September
18	11	25	October

Next, using Thermoflow software, a combined cycle block including two gas turbines, two recovery boilers, one steam turbine and two cooling systems for both modes, combined cycle alone and combined cycle with cooling system, similar to an average power produced by gas cycle and power plant in one hour and for 6 months of year and for both modes is calculated. results of calculations for fog cooling system are shown in table (3) and for media cooling system and absorption chiller in table (4).

Table 3. average power produced in one hour and for 6 months of year for fog cooling

fog		without cooling		month
Combined cycle power (kW)	Gas cycle power (kW)	Combined cycle power (kW)	Gas cycle power (kW)	
454962	304912	433234	282972	May

443212	296532	417179	270230	June
435444	291170	408693	264136	July
434074	290144	407492	263280	August
439502	294204	412286	266702	September
451828	302418	429144	279508	October

Table 4. average power produced in one hour and for 6 hot months of year for media cooling and absorption chiller

absorption chiller		media		month
Combined cycle power (kW)	Gas cycle power (kW)	Combined cycle power (kW)	Gas cycle power (kW)	
457157	307132	455034	304904	May
438056	291322	443319	296536	June
429520	285174	435556	291172	July
428302	284300	434189	290148	August
433173	287802	439611	294200	September
451395	301982	451924	302428	October

Table (5) shows power increase of a combined cycle block of Kashan power plant using fog cooling, for one hour and each of hot months of year. Table (6) shows power increase of a combined cycle block of Kashan power plant using media cooling and absorption chiller for one hour and each of hot months of year.

Table 5. Power increase of a combined cycle block using fog cooling

Increasing power of combined cycle		month
Total month (kWh)	one hour (kWh)	
4041408	21728	May
4842138	26033	June
4975686	26751	July
4944252	26582	August
5062176	27216	September
4083120	22684	October
27948780	amount of power increase in 6 months	

Table 6. Power increase of a combined cycle block using media cooling and absorption chiller

Increasing power of combined cycle				month
absorption chiller		media		
Total month (kWh)	one hour (kWh)	Total month (kWh)	one hour (kWh)	

4449678	23923	4054800	21800	May
3883122	20877	4862040	26140	June
3873822	20827	4996518	26863	July
3870660	20810	4965642	26697	August
3884982	20887	5082450	27325	September
4005180	22251	4100400	22780	October
23967444		28061850	amount of power increase in 6 months	

Table (7) shows total increase in electric power for a combined cycle block and for entire Kashan power plant using cooling systems.

Table 7. increase in electrical power using cooling systems

absorption chiller	media	fog	
23967.444	28061.850	27948.780	power plant)MWh(

6.1.1. income from increasing electric power output from power plant

If we consider price of each kilowatt hour of electricity purchased from power plant equal to 0.008\$, total income from increasing power of power plant by cooling systems is given in table (8).

Table 8. Income from increasing electric power using cooling systems

absorption chiller	media	fog	
0.19174	0.22449	0.22359	million\$

6.1.2. initial investment cost of cooling system

According to previous calculations, maximum increase in electric power in a gas cycle is equal to 12 MWh, and if average cost of buying and installing equipment in this case according to reference [18] for fog and media system is equal to \$47/kWh and for chiller If absorption of two effects is considered equal to 125 \$/kWh, initial investment cost is calculated for 2 units with different cooling systems, which is given in table (9).

Table 9 initial investment cost of cooling systems

absorption chiller	media	fog	
3.0	1.128	1.128	million\$

6.1.3. annual costs of cooling system

The annual costs are equal to total costs of excess fuel, water consumption and maintenance costs, which are given below for different cooling systems.

6.1.3.1. cost of annual water consumption

Fag system:

The water treatment unit of Kashan power plant has daily production capacity of 1000 cubic meters of tap water and 250 cubic

meters of domestic (soft) water [19]. Demin water means pure water that does not have roughness or corrosiveness, in addition to being free of ions (both positive and negative ions), but domestic water does not necessarily have ions, and it is enough that this water does not have corrosive properties. amount of demining water required for hot months of year and for a fog cooling system is calculated using Thermoflow software and is specified in table (10). total cost of each cubic meter of Damin water, including costs of raw water and purification processes, is considered equal to 0.264\$ [19]. cost of water consumption for 6 hot months of year and for 2 fog system units is equal to:

$$(10032.012 \times 2) \times 0.264 = 5296.9\$ \quad (31)$$

Table 10. Amount of water consumption in fog system

Water consumption		month
in one month (liter)	in one hour (liter)	
1353261.6	7275.6	May
1773100.8	9532.8	June
1819303.2	9781.2	July
1806580.8	9712.8	August
1855461.6	9975.6	September
1424304	7912.8	October
10032012	Water consumption in 6 months	

Media system:

The amount of water required for hot months of year and for a media cooling system is calculated using Thermoflow software and is equal to 10659268.8 liters for one unit. cost of each cubic meter of water is equal to 0.01\$ [19]. cost of water consumption for 6 hot months of year and for 2 media system units is equal to:

$$(10659.269 \times 2) \times 0.01 = 213.185\$ \quad (32)$$

Table 11. Media system water consumption

Water consumption		month
in one month (liter)	in one hour (liter)	
1434952.8	7714.8	May
1882915.2	10123.2	June
1931796	10386	July
1918404	10314	August
1969293.6	10587.6	September
1511784	8398.8	October
10659268.8	Water consumption in 6 months	

6.1.3.2. annual additional fuel consumption cost

The amount of fuel consumed for a combined cycle block and for both modes, combined cycle with cooling and combined cycle without cooling and for each of 6 hot months of year, is specified in Table (12).

Table 12 Fuel consumption of a combined cycle block

Fuel consumption (kg/s)				month
absorption chiller	media	fog	without cooling	
9.598	9.561	9.525	9.028	May
9.235	9.381	9.341	8.72	June
9.089	9.254	9.215	8.584	July
9.069	9.23	9.192	8.565	August
9.15	9.325	9.286	8.639	September
9.485	9.508	9.469	8.943	October

The amount of extra fuel consumed during a month, using cooling, for a gas cycle unit and for each of 6 months of year is specified in table (13).

Table 13. Amount of extra fuel consumed using cooling and for a gas cycle unit

amount of excess fuel consumed			month
absorption chiller	media	fog	
381672	356896.8	332791.2	May
344844	442605.6	415821.6	June
338148	448632	422517.6	July
337478.4	445284	419839.2	August
342165.6	459345.6	433231.2	September
351216	366120	340848	October
2095524	2518884	2365049	amount of excess fuel consumed in 6 months

Considering price of each cubic meter of natural gas equal to 0.0014\$ in Iran [20], cost of additional fuel consumption by 2 cooling system units for 6 months for different systems is given in table (14).

Table 14. additional fuel consumption cost of cooling systems

absorption chiller	media	fog	
0.007855	0.009442	0.008865	million\$

6.1.3.3. annual maintenance cost

According to manufacturers, these costs are 2% of investment cost for fog and media systems [16] and 5% of investment cost for absorption chiller system [17], so annual maintenance cost is 2 units for different systems are given in table (15).

Table 15. annual maintenance cost of cooling systems

absorption chiller	media	fog	
0.15	0.02256	0.02256	million \$

Now, total annual costs, which are equal to sum of costs of excess fuel, cost of water consumption, and cost of maintenance, are calculated for different systems, which can be obtained in form of following table.

Table 16. annual cost of cooling systems

absorption chiller	media	fog	
0.15785	0.03221	0.03672	million\$

6.1.4. return period of cooling system investment

By dividing initial investment cost by annual net income of cooling system, investment return period is obtained according to table (17).

Table 17. investment return period of cooling systems

absorption chiller	media	fog	
88.53	5.87	6.03	Year

As you have seen, longest time required for return on investment due to use of cooling systems is related to double-effect absorption chiller and shortest time is related to media evaporative cooling. use of double-effect absorption chiller cooling is completely uneconomical. As can be seen, dollar price has a great influence on economic or uneconomical use of cooling systems. Also, due to fact that use of cooling systems produces a lot of extra power, price of electricity purchased from power plant has a great impact on economic or non-economical nature of plans.

6.1.5. price of extra production power per kilowatt hour of production

The price of extra production power of power plant due to use of cooling systems and without taking into account initial investment cost is obtained according to following table:

Table 18. price of additional power produced by power plant with different cooling systems

absorption chiller	media	fog	
0.006586	0.001148	0.001314	\$/kWh

6.2. Technical analysis of using three types of cooling systems in Kashan power plant

After calculations and thermodynamic analysis by software, simulation results are obtained for weather conditions of Kashan. To analyze performance improvement using Thermoflow software, three different methods of fog, media and absorption chiller are investigated. For a better comparison, different output performance parameters are compared and checked.

6.2.1. Net output power

As can be seen in table (19), biggest increase in net power output of power plant is related to combined cycle with absorption chiller cooling system and then fog.

Table 19. amount of power increase in power plant using cooling systems

	power plant	Percentage of power increase%
absorption chiller	443170.3333	6.020427204
fog	443272.1667	6.044788974
media	439600.5	5.166409625

6.2.2. Energetic efficiency

According to Figure (14), by cooling air entering compressor, energetic and exergetic efficiency of gas cycle increases. highest energetic and exergetic efficiency of gas cycle occurs in combined cycle with absorption chiller and after that in combined cycle with fog.

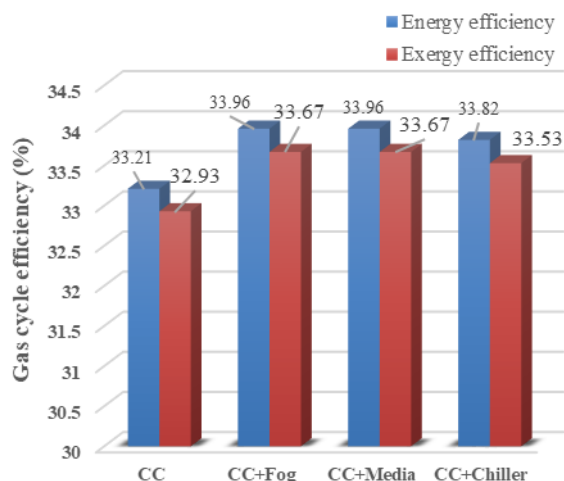


Figure 14. Comparison of energetic and exergetic efficiency of gas cycle in different combined cycles

6.2.3. Thermal rate

As can be seen in table (20), by cooling air entering compressor, heating rate of gas cycle decreases. lowest heating rate occurs in gas cycle using fog and media.

Table 20. Heat rate of gas cycle in different cycles

	Gas cycle thermal rate		
	value kJ/kWh	amount of reduction kJ/kWh	percentage reduction%
without cooling	10840	-	-
absorption chiller	10645	195	1.8%
fog	10600	240	2.21%
media	10600	240	2.21%

6.2.4. temperature of inlet and outlet gases from gas turbine

According to figure (15), with cooling of air entering compressor, temperature of gases leaving gas turbine decreases, lowest of which is related to cooling with absorption chiller. combined cycle with absorption chiller has highest temperature of gases entering gas turbine.

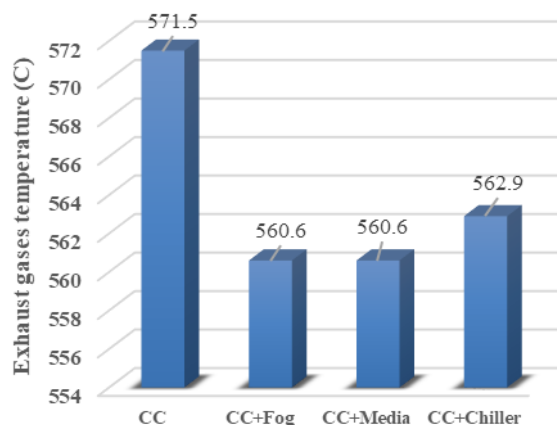


Figure 15. Comparison of temperature of gases exiting gas turbine in different combined cycles

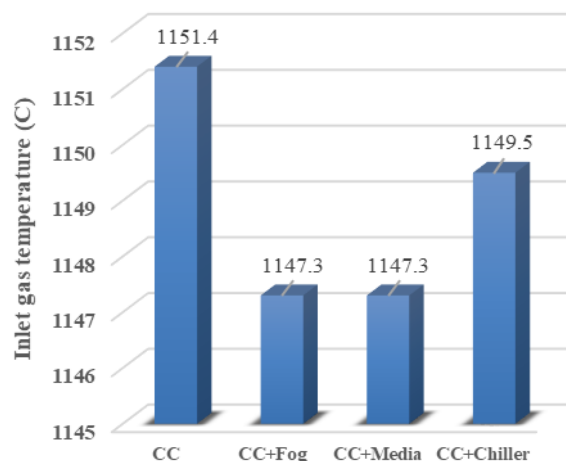


Figure 16. Comparison of temperature of gases entering gas turbine in different combined cycles

6.2.5. Fuel consumption and air-fuel ratio

According to figure (17), by cooling air entering compressor, fuel consumption increases and air-to-fuel ratio decreases. highest fuel consumption and lowest air-to-fuel ratio are related to combined cycle with an absorption chiller.

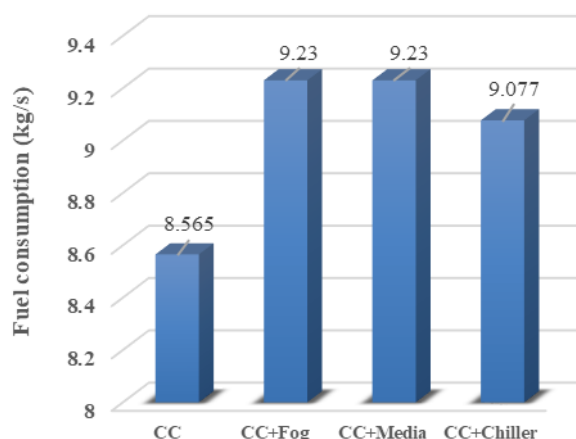


Figure 17. Comparison of fuel consumption in different combined cycles

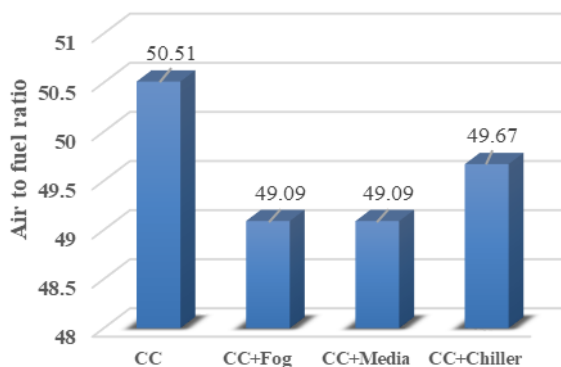


Figure 18. Comparison of air-fuel ratio in different combined cycles

6.2.6. Temperature and relative humidity of air entering compressor

As can be seen in figure (19), fog and media cause greatest temperature reduction, followed by absorption chillers in air entering compressor, as well as highest and lowest relative humidity in air entering

the compressor, respectively, in fog cooling (equal to media) and absorption chiller happens.

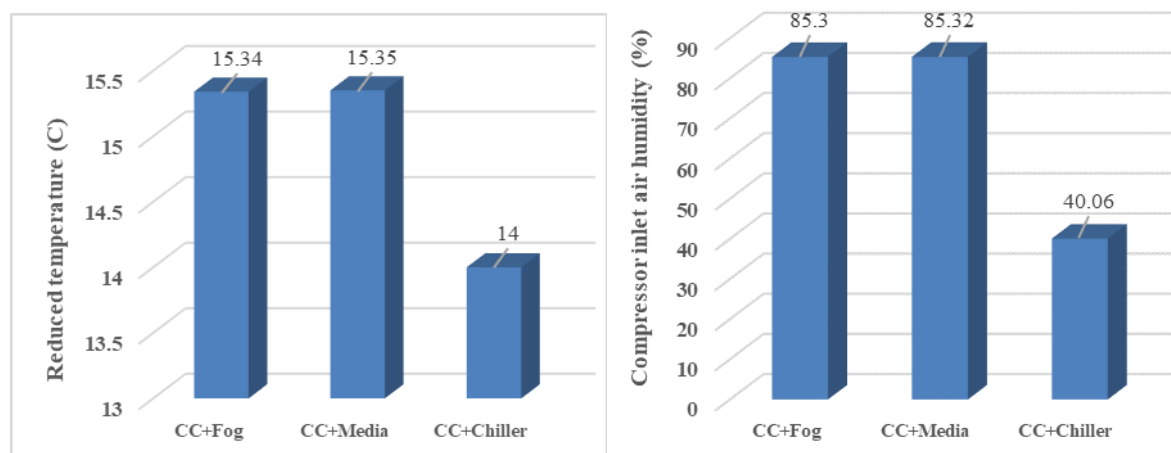


Figure 19. Average relative humidity and reduced temperature of air entering compressor in different cycles.

7. Introducing most suitable method for cooling air entering compressor

In multi-criteria decision-making, meaning of criteria is factors that decision-maker considers in order to increase desirability and satisfaction of choice. criterion in decision-making may be presented as an index or goal. Indicators are features, qualities or performance parameters that are relevant for choosing decision options. In decision-making issues, if a decision is made based on several indicators, it is called a multi-indicator decision. Only if final results of used model are reliable if problem criteria are well identified. In this article, factors affecting prioritization of inlet air cooling method to be used in Kashan power plant have been described. These influential factors are problem evaluation indicators in multi-criteria decision-making method.

In this article, data related to decision making criteria include: net output power, energetic efficiency, exergetic efficiency, heat rate, fuel consumption, return on investment, price of excess production power, initial investment cost, unit vulnerability risk, changes in unit, consumption Water, access to spare parts, operation and maintenance of unit and ease of project implementation are stated and then results of prioritizing methods are specified using TOPSIS methods. sensitivity analysis on weight of criteria will be done using four defined scenarios.

Tables (21) and (22) compare effect of using three types of fog, media and absorption chiller cooling systems on some important parameters in gas cycle and power plant.

Table 21. comparing effect of using three cooling systems on power plant

parameters	absorption chiller	fog	media
Net output power of gas cycle (MW)	284.300	290.144	290.148
Net output power of power plant (MW)	428.302	434.074	434.189
Gas cycle energy efficiency (%)	33.82	33.96	33.96
Gas cycle exergy efficiency (%)	33.53	33.67	33.67
Gas cycle heating rate (kJ/kWh)	10645	10600	10600
fuel consumption (kg/s)	9.069	9.192	9.23
Return on investment (years)	88	6	5
price of extra production power (\$/kWh)	0.006586	0.001314	0.001148

Table 22. Comparison of three cooling systems according to evaluation criteria of cooling designs

absorption chiller	fog	media	parameters
2	1	1	Initial investment cost
1	2	3	Vulnerability risk of unit
2	1	1	Minimum changes
1	3	2	Minimum water consumption
1	3	2	Ease of access to spare parts
3	2	1	Ease of operation and maintenance of unit
3	1	2	Ease of project implementation

7.1. decision options

The options examined in this article are 3 methods of cooling gas turbine inlet air; Fog, media and absorption chiller are two effects.

7.2. Decision criteria

The defined criteria are shown in Table 23. criteria of a multi-criteria problem are divided into two categories, positive and negative, according to their influence. Positive criteria are those criteria that have a positive effect on decision-making process and goal is to maximize them, and on other hand, negative criteria are criteria that should be minimized.

Table 23. evaluation criteria and their type of impact

Criterion type	Criterion	Row
Positive	Net power output	1
Positive	Energy efficiency	2
Positive	Exergetic efficiency	3
negative	Thermal rate	4
negative	Fuel consumption	5
negative	return on investment	6
negative	The price of additional production capacity	7
negative	Initial investment cost	8
negative	Vulnerability risk of unit	9
negative	Changes in unit	10
negative	Water consumption	11
negative	Access to spare parts	12
negative	Operation and maintenance of unit	13
negative	Ease of project implementation	14

7.3. Decision matrix

Information about options and criteria is recorded in decision matrix. In this decision, 3 options are evaluated by 14 criteria. All information obtained for options according to criteria are in table (24). This table is actually decision matrix whose rows are criteria and its columns are decision options. In this table, indicators 1, 2, 3 are positive and rest are negative. In other words,

decision matrix displays all information necessary to make a decision in a centralized manner.

Table 24. Formation of decision matrix

Index3	Index2	Index1	index
absorption chiller	media	fog	
284.3	290.15	290.14	Net power output
33.82	33.96	33.96	Energy efficiency
33.53	33.67	33.67	Exergetic efficiency
10645	10600	10600	Thermal rate
9.07	9.23	9.19	Fuel consumption
88	5	6	return on investment
3293.1	573.99	656.95	The price of additional production capacity
150000	56400	56400	Initial investment cost
1	3	2	Vulnerability risk of unit
2	1	1	Changes in unit
1	10.66	264.85	cost of water consumption
1	2	3	Access to spare parts
3	1	2	Operation and maintenance of unit
3	2	1	Ease of project implementation

7.4. Implementation of TOPSIS method

Considering that information recorded in decision matrix has been measured with different scales, so they cannot be compared with each other, and at beginning of TOPSIS method, decision matrix obtained from previous step (Table (24)) using We convert de-scaling methods into a matrix whose elements are comparable to each other. Table 25 shows unscaled decision matrix. terms of this matrix are all numbers in range (0 and 1) that can be easily compared to each other. In soft method of descaled matrix derivations, according to formula, values of each element of decision matrix are divided by square of sum of squares of elements of same column.

Table 25. Unscaled matrix using soft method

Option 3	Option 2	Option 1	
absorption chiller	media	fog	index
0.569517	0.581231	0.581223	Net power output
0.57576	0.578144	0.578144	Energy efficiency
0.575747	0.57815	0.57815	Exergetic efficiency
0.578981	0.576533	0.576533	Thermal rate
0.57137	0.581513	0.579119	Fuel consumption
0.996085	0.056596	0.067915	return on investment
0.966656	0.168489	0.192841	The price of additional production capacity

0.882935	0.331983	0.331983	Initial investment cost
0.267261	0.801784	0.534522	Vulnerability risk of unit
0.816497	0.408248	0.408248	Changes in unit
0.000377	0.040214	0.999191	cost of water consumption
0.267261	0.534522	0.801784	Access to spare parts
0.801784	0.267261	0.534522	Operation and maintenance of unit
0.801784	0.534522	0.267261	Ease of project implementation

7.4.1. Allocating weight of criteria

The weight of criteria can be calculated by different methods. In this section, criteria's weight is calculated using special vector method obtained from matrix of pairwise comparisons by questionnaire from experts in energy, technical, economic and social fields, and weighting scenario is considered as follows.

Table 26. weight of criteria

Weight	index	
0.05	Net power output	Index1
0.05	Energy efficiency	Index2
0.05	Exergetic efficiency	Index3
0.05	Thermal rate	Index4
0.075	Fuel consumption	Index5
0.1	return on investment	Index6
0.1	The price of additional production capacity	Index7
0.1	Initial investment cost	Index8
0.05	Vulnerability risk of unit	Index9
0.075	Changes in unit	Index10
0.075	cost of water consumption	Index11
0.075	Access to spare parts	Index12
0.1	Operation and maintenance of unit	Index13
0.05	Ease of project implementation	Index14

7.4.2. weighted scaleless decision matrix

In next step, after assigning weights of criteria, weighted scaleless decision matrix according to table (27) will be obtained by multiplying weights vector in scaleless matrix.

Table 27. Forming weighted scaleless matrix

Option 3	Option 2	Option 1	
absorption chiller	media	fog	index
0.028476	0.029062	0.029061	Net power output

0.028788	0.028907	0.028907	Energy efficiency
0.028787	0.028908	0.028908	Exergetic efficiency
0.028949	0.028827	0.028827	Thermal rate
0.042853	0.043613	0.043434	Fuel consumption
0.099608	0.00566	0.006791	return on investment
0.096666	0.016849	0.019284	The price of additional production capacity
0.088293	0.033198	0.033198	Initial investment cost
0.013363	0.040089	0.026726	Vulnerability risk of unit
0.061237	0.030619	0.030619	Changes in unit
0.000028	0.003016	0.074939	cost of water consumption
0.020045	0.040089	0.060134	Access to spare parts
0.080178	0.026726	0.053452	Operation and maintenance of unit
0.040089	0.026726	0.013363	Ease of project implementation

7.4.3. Positive ideal solution and negative ideal solution

The ideal positive vector solution consists of largest value for positive indices and smallest value for negative indices. In other words, positive ideal solution contains best values for each criterion. negative ideal solution is also defined by same expression. Table (28) shows, in order to calculate positive ideal solution for each criterion, maximum element is selected in each column. It should be noted that maximum value is considered in profit criteria and minimum value is considered in cost criteria. It is done in a similar way for negative ideal solution. In table, criteria 1 to 3 are profit and rest are cost.

Table 28. ideal solutions in TOPSIS method

Negative ideal	Positive ideal	index
0.028476	0.029062	Net power output
0.028788	0.028907	Energy efficiency
0.028787	0.028908	Exergetic efficiency
0.028949	0.028827	Thermal rate
0.043613	0.042853	Fuel consumption
0.099608	0.00566	return on investment
0.096666	0.016849	The price of additional production capacity
0.088293	0.033198	Initial investment cost
0.040089	0.013363	Vulnerability risk of unit
0.061237	0.030619	Changes in unit
0.074939	0.000028	cost of water consumption
0.060134	0.020045	Access to spare parts
0.080178	0.026726	Operation and maintenance of unit
0.040089	0.013363	Ease of project implementation

7.4.4. Calculating Euclidean distance of each option to positive and negative ideals

In next step, after calculating positive and negative ideal solution, Euclidean distance of each option is calculated from positive ideal solution and negative ideal solution, and set of these distances for each option is recorded under terms d_i^+ and d_i^- in table (29) has been Finally, relative proximity of each option under Cl_i term is calculated and ranking is done based on larger Cl_i .

Table 29. results of implementing TOPSIS method

Option 3	Option 2	Option 1	Option number
absorption chiller	media	fog	System name
0.150804	0.036113	0.090107	d_i^+
0.089071	0.166676	0.142068	d_i^-
0.371323	0.821918	0.611902	Cl_i
3	1	2	rank

The media system with relative proximity of 0.81918 is first priority, and fog options with 0.611902 and double-effect absorption chiller with 0.371323 are second and third priorities in methods of cooling air entering gas turbine.

8. Conclusion

Cooling air entering gas turbine increases mass flow rate and increases output power of turbine. use of media system, fog and absorption chiller is one of ways to reduce inlet air temperature. By using these systems, temperature of incoming air can be reduced, which increases efficiency of cycle. Although cooling method is not very effective in cold months of year, use of these methods can increase efficiency during hot months of year.

In this article, modeling and analysis of energy and exergy of gas cycle using Thermoflow software was done to investigate effect of cooling air entering compressor on performance of Kashan gas power plant. In continuation of technical and economic evaluation of use of three types of air-cooling systems entering compressor in six hot months of year and effect of their use on performance of gas cycle was investigated, which was finally determined according to technical, economic and environmental conditions. In Kashan region, a suitable cooling system was selected and introduced to improve performance in this power plant. From results of this article, following can be mentioned:

- Technical analysis of use of three types of cooling systems in Kashan power plant was done, and results of use of three cooling systems on power plant were compared with each other.
- comparison of three cooling systems was done according to evaluation criteria of cooling plans, and results of three cooling systems were compared according to evaluation criteria of cooling plans.
- According to technical and economic studies and also according to above two tables of media cooling system, both from point of view of energy and possibility of improving performance of turbine, increasing efficiency of power plant from point of view of first and second law of thermodynamics and also in terms of Economically, it is best and most suitable plan for cooling air entering compressor for gas cycle of Kashan power plant.

9- List of signs and abbreviations

English signs

mass air to fuel ratio (-)	AFR
Air to fuel molar ratio (-)	AFR
Specific exergy (kj/kg)	ex
Specific enthalpy (kj/kg)	h
Thermal rate (kj/kWh)	HR
Irreversibility (kj)	i
Irreversible intensity (kW)	I
Heating value of fuel (kj/kg)	LHV
Molecular mass (kg/kmol)	M
Mass flow rate (kg/s)	m
Molar percentage (%)	n
Pressure (Pa)	P
Specific fuel consumption (kg/kWh)	SFC
Temperature (C or K)	T
Work (kj)	w
Power (kW)	W
Greek symbols	
efficiency	η
Specific heat ratio	γ
Subtitles	
Compressor inlet	1
Compressor output	2
Turbine inlet	3
Turbine output	4
Second law	II

Air	a
Related to compressor	Ac
Related to air	air
Compressor	c
Combustion chamber	cc
Cooling flow	Coolant
Fuel	f
Fuel	Fuel
Gas turbine	GT
Real gas turbine	GT,a
Generator	Gen
Entire of power plant	P
Reversible	rev
Isentropic	s
Thermal	th
Useful	u
Superscripts	

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