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Review

Improvement of gas turbine performance based on inlet air cooling systems: A technical review

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Performance of a gas turbine is mainly depends on the inlet air temperature. The power output of a gas turbine depends on the flow of mass through it. This is precisely the reason why on hot days, when air is less dense, power output falls off. A rise of 1°C temperature of inlet air decreases the power output by 1%. The aim of this paper is to review up to date techniques that were developed to cool inlet air to gas turbine. The techniques including the mechanical chillers, media type evaporative coolers and absorption chillers have been reviewed. It is found that the power consumption of the cool inlet air is of considerable concern since it decreases the net power output of gas turbine. In addition, the mechanical chiller auxiliary power consumption is very high compared to media type evaporative coolers. Furthermore, the reviewed works revealed that the efficiency of evaporative cooler largely depends on moisture present in the air. The gas turbine power augmentation through inlet air chilling is effectively used to boost power during high ambient temperature usually synchronous with on-peak power generation, allowing levelling of gas turbine power output.

Key words*:* Gas turbine, absorption cooler, evaporative cooler, chiller.

INTRODUCTION

Gas turbine air cooling has been studied recently to raise the performance to peak power level during hot seasons when high atmospheric temperatures cause a significant reduction in its net power output. Gas turbines are constant volume machines; at a given shaft speed, they always move the same volume of air. In gas turbines, since the combustion air is taken directly from the environment, their performance is strongly affected by weather conditions (Mahmoudi et al., 2009). Power rating can drop by as much as 20 to 30%, with respect to international standard organization (ISO) design conditions, when ambient temperature reaches, 35 to 45°C. One way of restoring, operating conditions is to add an air cooler at the compressor inlet (Sadrameli and Goswami, 2007). The air cooling system serves to raise the turbine performance to peak power levels during the warmer months when the high atmospheric temperature cause the turbine to work at off-design conditions, with reduced power output (Kakaras et al., 2004).

The performance of a gas turbine power plant is sensible to the ambient condition. As the ambient air temperature arises, less air can be compressed by the compressor since the withdrawing capacity of compressor is given, and so the gas turbine output is reduced at a given turbine entry temperature. Additionally, the compression work increases because the limited volume of the air increases in proportionality to the intake air temperature (Xiaojun et al., 2010). Inlet air cooling and intercooling are two important methods for rising power output of gas turbine cycles. Many researchers have focused on three different inlet air cooling methods including the evaporative cooling with or without pre-compressed air and refrigeration cooling. However, gas turbine intake air cooling may cause a small decrease in efficiency because a lot of fuel is needed to bring compressor exhaust gas equal to the same

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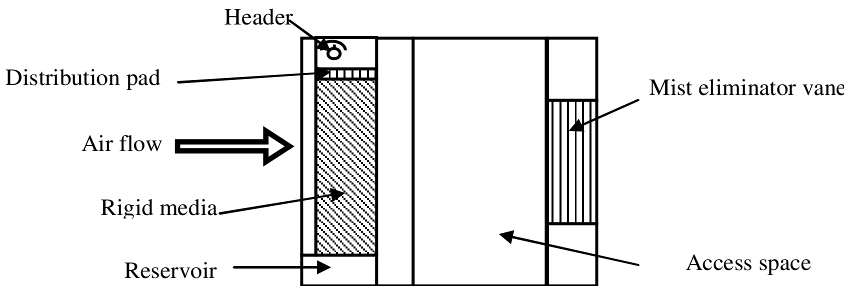


Figure 1. Rigid media evaporative cooler (Johnson, 1989).

gas turbine entry temperature.

This paper introduces technical review for inlet air cooling system that is used to improve the performance of the gas turbine power plants. The gas turbine inlet air cooling system describes and compared in detail the evaporative cooler, indirect mechanical refrigeration system, mechanical refrigeration with ice storage, direct mechanical refrigeration system, refrigeration system with chilled water storage and absorption chiller inlet air cooling system.

GAS TURBINE INLET AIR COOLING SYSTEM

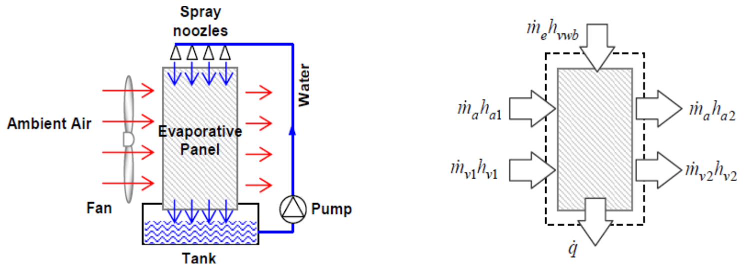
The gas turbine inlet air cooling methods can be divided into five categories including the evaporative cooler, indirect mechanical refrigeration system, direct mechanical refrigeration system, mechanical refrigeration system with chilled water storage and absorption chiller inlet air cooling system (Kamal and Zuhairm, 2006). The detail review will be presented subsequently.

Evaporative cooler

In an effort to boost the performance of gas turbine engine, the rigid media evaporative coolers were used with gas turbine to increase the density of the combustion air; thereby increasing the power output. Figure 1 shows the schematic diagram of rigid media evaporative cooler. The evaporation surface is a saturated porous pad. Water introduced through a header at the top of media and sprays into the top of an inverted half-pipe and is deflected downward onto a distribution pad on top of the media (Johnson, 1989). Water drains through the distribution pad into the media, by gravity action downward through it, and wets enormous area of media surface contacted by air passing through the cooler (Beshkani and Hosseini, 2006). According to Johnson (1989), the increase of air density accomplished by evaporating water into the inlet air, which decrease its temperature and correspondingly increase its density. The water vapour passes through the turbine, causing negligible increase in fuel consumption. Water used with evaporative coolers often contain dissolved salts such as sodium and potassium chlorides, which, in combination with sulfur in the fuel, form principle ingredients in hot gas path corrosion. For this reason, water quality and the prevention of water carry-over are important considerations in the use of evaporative coolers.

The direct evaporative cooling process works essentially with the conversion of sensible heat in latent heat. The surrounding ambient air is cooled by evaporation of the water from wet surface of the panel to the air (Zadpoor and Golshan, 2006). The addition of water vapour to the air increases its latent heat and relative humidity. If the process is adiabatic, this increase of the latent heat is compensated by a reduction of the sensible heat and consequent reduction of the dry bulb temperature of air when the process is adiabatic. Figure 2 shows the schematic diagram and control volume of direct evaporative cooler. The model used for the evaporative panel based on mass and energy balances as well as in available empirical correlations for commercial evaporative panels. The modelling of the gas turbine cycle based in non-dimensional numbers obtained from performance maps reproducing actual performance of the compressor and turbine. Simulation results from the analysis of the influence of evaporative conditioning of air supplied to a gas turbine power plant allow both confirming and quantifying the expected gains in power production. Besides, the performance of improvement is an important aspect related to *NOx* reduction in emissions from the combustion chambers (Marcos and João, 2005).

For the gas turbine inlet air system, it is recommended that the evaporative cooler is placed after the inlet air filter not before it, which is shown in Figure 3. This arrangement protected the media from the dust and other airborne contaminants that would otherwise impinge upon it. Evaporative cooling involves heat and mass transfer, which occurs when water and the unsaturated air-water mixture of the incoming air are in contact (Hosseini et al., 2007). This transfer is a function of the differences in temperatures and vapour pressures between the air and water. Heat and mass transfer are both operative in the evaporative cooler because of heat transfer from air to water evaporates water, and the water



(a) (b)

Figure 2. Direct evaporative panel: (a) Schematic diagram, (b) Panel control volume (Marcos and João, 2005).

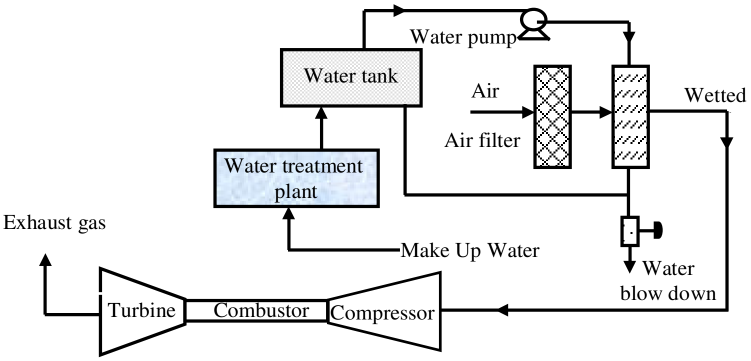


Figure 3. Schematic of evaporative air cooling with optional water treatment.

evaporating into the air constitutes mass transfer (Alhazmy and Najjar, 2004). Heat inflow can be described as either latent or sensible; the term used depends on the effect. If the effect is only to raise or lower temperature, it is sensible heat. Latent heat on the other hand, produces a change of state, e.g. freezing, melting, condensing or vaporizing. In evaporative cooling, sensible heat from the air is transferred to water, which becomes latent heat as the water evaporates. The water vapour becomes part of the air and carries the latent heat with it. The air dry-bulb temperature decreases because it gives up the sensible heat. The air wet-bulb temperature is not affected by absorption of latent heat in the water vapour because the water vapour enters the air at air wet-bulb temperature. Theoretically, the incoming air and water in the evaporative cooler considered as isolated system due to no heat is added to or removed from the system. The process of exchanging the sensible heat of the air for latent heat of evaporation from water is adiabatic (Bhargava and Meher-Homji, 2005). Such system is used as a preferred solution in dry/desert climate, which can be expected to boost the gas turbine power by nearly 12%. Meanwhile, for hot humid climates, the air-cooling is limited to the wet bulb temperature and the capacity of the gas turbine generator may not be increased by more than 5 to 7% in best cases (Johnson, 1989).

Indirect mechanical refrigeration system

Ondryas et al. (1991) investigated the various options for cooling the inlet air including mechanical vapour compression and aqua-ammonia absorption refrigeration. Figure 4 shows a schematic diagram of gas turbine with mechanical chiller of centrifugal compressor type. In this sort of inlet air cooling system, the air is cooled by a cooling coil served by a mechanical compressor, which draws its electricity supply from the generation unit itself. This means that the mechanical chiller needs only electricity and condenser water to provide all chilled water requirements, there is no need to provide steam or another thermal energy sources. The mechanical chillers increase the gas turbine performance better than evaporative coolers because they can produce any required air temperature irrespective of the weather conditions (Kamal and Zuhairm, 2006).

However, the main disadvantages of mechanical chillers are their high consumption of electricity. Such air cooling systems require an electric capacity for the cooling compressor of between 40 to 50 kW/MWGT; which will reduce the potential output of the power plant. The possible power output elevation of 20%, one third of which is to be used by the cooling system itself. Such penalty and the high cost, primary plus operation cost, of

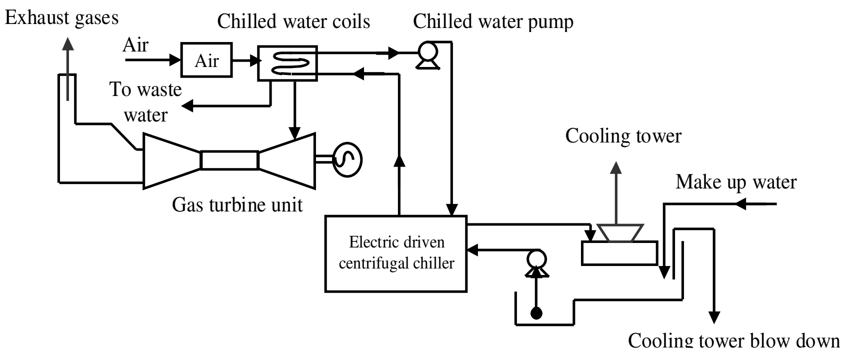


Figure 4. Gas turbine with mechanical chiller (Kamal and Zuhairm, 2006).

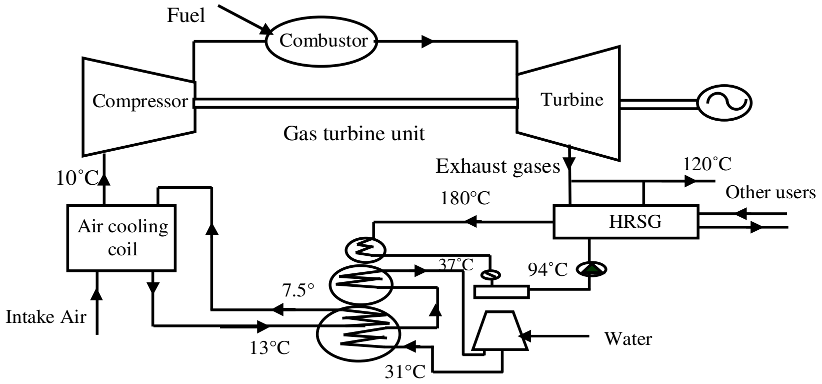


Figure 5. Schematic diagram of gas turbine with aqua-ammonia absorption unit.

mechanical compression systems inhibits their use (Sadrameli and Goswami, 2007).

Ondryas et al. (1991) also studied the possibility of using aqua- ammonia absorption chilling systems for inlet air cooling below 10℃. The examined air cooling plant is schematically illustrated in Figure 5. It was reported that only a fraction of thermal energy recoverable from the gas turbine exhaust flow, 10% is used to cool the air from 35 to10℃, a value that decreases proportionally with temperature. The power boost was reported to be approximately 19 to 21%, and as a result of that, the adoption of the aqua- ammonia absorption chilling system was documented as the most suitable option. However, the authors were warned against cooling the inlet air below 4℃ to prevent ice formation at the compressor suction, but no knowledge about the economic benefit of using either type of air cooling systems were given. Malewski and holldroft (1986) analyzed the performance of the gas turbine engine fitted with an aqua-ammonia absorption system to cool the inlet air. In their system, the generator received the required heat from the exhaust gases by a direct contact heat exchanger. The author found that the gas turbine power can be boosted by 21% when the inlet air cooled down to 8℃. However, cooling the inlet air to a temperature below 5℃ was not recommended to prevent ice build up in compressor suction.

Mechanical refrigeration with ice storage

According to Ameri et al. (2005), the gas turbine can take advantage of off-peak and mid-peak energy cost by using mechanical chillers and thermal energy storage systems. Thermal energy storage, TES, may be defined as temporary storage of energy at high or low temperature for use when it is needed. Thermal storage could be accomplished as sensible heat storage or as latent heat storage. Sensible heat storage media includes water, sand, oil, etc. In latent heat storage, storage is accomplished by change in the physical state of the storage medium with or without change in its temperature. Latent storage media can store relatively large amounts of energy per unit mass compared to sensible heat storage media and hence result in smaller and lighter storage devices with lower storage losses and high efficiency (Kakaras et al., 2006). The study of the use of mechanical indirect cooling where air is cooled using chilled water supplied by an ice thermal storage system. The storage is charged during off-peak periods by a chiller whose capacity is strongly reduced. The

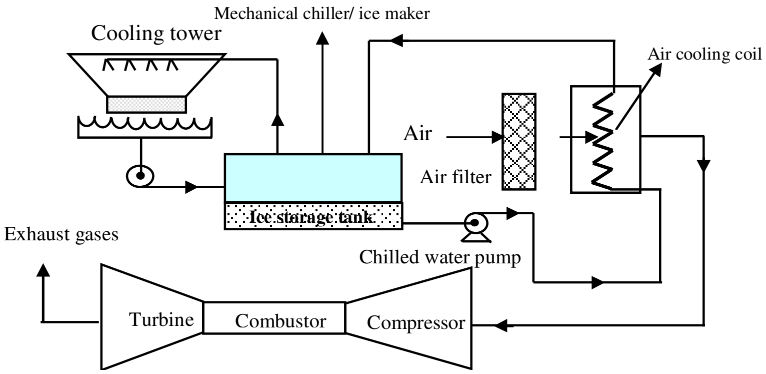


Figure 6. Gas turbine with mechanical indirect cooling (Ameri et al., 2005).

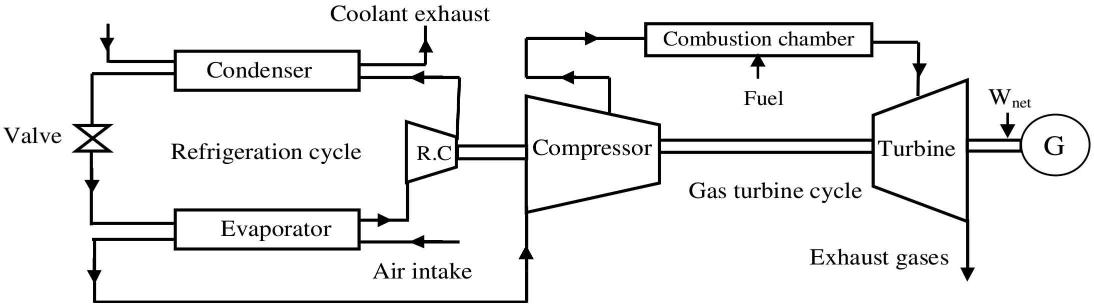


Figure 7. Schematic diagram of a gas turbine with refrigerated air to the compressor inlet (Lucia et al., 1994)

available time for charging the ice storage system was reported to be 18 h and the mechanical capacity required was reduced by 66% (Ebeling and Halil, 1992). This reduces the consumption to 15 kW/MWGT as compared to 50 kW/MWGT (Ondryas and Wilson, 1993). Furthermore, the efficiency of the system was not affected because the chiller is stopped during peak periods. Direct external melting system was used in the study due to the low temperature (~ 0℃) it can provide. The author concluded that using of such system would provide 21 to 25% increase in power output when inlet air is cooled down to a temperature of 10℃. Figure 6 shows the schematic diagram of the plant. Again, a recommendation not to drive the inlet air temperature near 0℃ was made to prevent ice build up on the compressor blades, since the chilled inlet air shall be at 100% relative humidity due to moisture condensation during the chilling process.

Mechanical chillers utilizing centrifugal compressor with Freon refrigerant was used as an alternative inlet air cooling system in order to increase the gas turbine power output in hot seasons. The power output would increase by 0.36% with each 1℉ inlet temperature reduction. Based on 35℃ and 20% relative humidity for the ambient air, the power boost has been estimated at 15.5%. Air cooling temperatures have been recommended not to reach values below 7.0℃ to safeguard against potential ice build up in the compressor suction line (Lucia et al., 1994).

Direct mechanical refrigeration system

Lucia et al. (1994) examined the operation of cogeneration gas turbine power plant with and without an air cooling system. The air cooling plant examined, is similar to that which is illustrated in Figure 7, it cools the compressor inlet air to a temperature of 10℃. Gas turbine data were obtained from three general electric heavy-duty gas turbines between 26 and 150 MW. Actual performances were examined according to Italy climate to evaluate the feasibility and cost effectiveness of the cooling system. The authors stated the possibility of coupling a conventional mechanical cooling unit and a thermal storage unit especially when high peak demands must be met. With coupled solution, the two types of cooling systems were used together despite increase in the plant's cost, complexity and management. The author concluded that, in the Italian climate, the turbine power output may increase by 18 to 19% if the compressor inlet air is cooled to 10℃. Even greater energy and economic benefits can be envisaged for sites where average

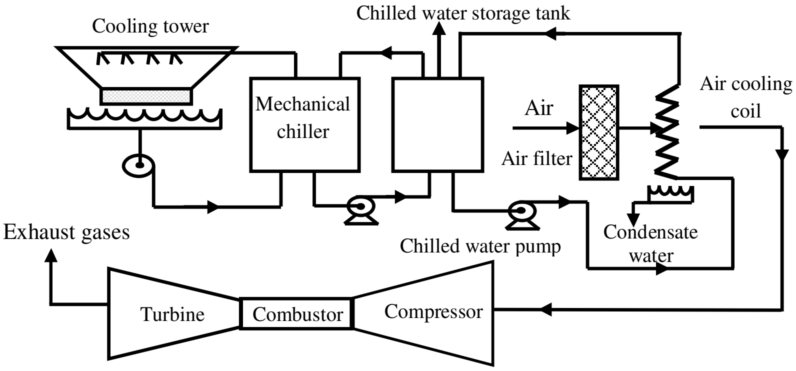


Figure 8. Mechanical chiller with water storage system (Ameri et al., 2005).

temperatures are relatively higher.

Kamal and Zuhairm (2006) had not indicated whether the installed refrigeration capacity is optimum, given the parameters of gas turbine cogeneration power plant. The optimization of such system could be solved first without any constraints, in order to determine the global optimum, and then in a second stage, compare the induced loss of power against the cost of removing the constraint, which is the cost of preventing ice formation. Such an approach has been used recently to conduct a similar work in which the overall specific energy of compressing and dehumidifying air is minimized. It had been found that the overall specific energy increase with mild refrigeration temperature, then decrease with low refrigeration temperature, as the coefficient of performance deteriorates very rapidly. These results suggest that the net power of gas turbine cycle with refrigerated air inlet would first increase with refrigeration, and then decrease after a certain refrigeration temperature is exceeded for which the refrigeration power exceeds the power gain from refrigeration.

A conceptual Brayton-Joule gas turbine cycle was investigated by Ait-Ali (1997) where the air and products of combustion specific heats are considered as temperature dependent parameters. The overall net power per m^3/s and specific net power per kg/s of induced air are maximized as unconstrained two-degree-of-freedom problem, first with respect to the pressure ratio, then with respect to the refrigeration inlet air temperature. The author assumed the overall net power delivered by a conceptual gas turbine cycle with refrigerated air supply to the compressor is equal to the net power delivered by the gas turbine minus the power supplied to the refrigeration cycle. A vapour compression refrigeration cycle with Joule-Thompson expansion valve was considered whose schematic diagram of this cycle is represented in Figure 7 (Ait-Ali, 1997) concluded that the overall net power output is a function of two independent variables. The first is the pressure ratio, which does not affect the refrigeration power. The second variable is the compressor inlet temperature, which affects the turbine net power as well as the refrigeration power. Boonnassaa et al. (2006) also suggests that the system performance will improve by compressor intercooling which will further increase the optimum compressor ratio.

Paepe and Dick (2001) studied the influence of ambient temperature on the operational indices of the gas turbine set. Calculations have been made for the gas turbine set comprising the compressor, the combustion chamber, the gas turbine and the waste heat boiler. The influence of the air charge at ambient temperature on the mass output of the compressor, its compression ratio, mechanical power and energy efficiency of the gas turbine set as well as on thermal power was studied. Polyzakis et al. (2008) concluded that the change of power of the gas turbine set resulting from the change of ambient temperature is due to the following reasons:

1. Change of the inlet temperature in the compressor.
2. Change of the mass flow rate of air and combustion gases.
3. Change of the air excess ratio.
4. Change in the internal efficiency of the machine.

The lowering of the ambient temperature leads to the increase of flow rate of combustion gases, which resulted in the increase of power output. But if the inlet temperature is reduced below the ISO rated temperature of 15°C, then the temperature of the exhaust gases entering the waste heat boiler become lower, which may influenced the capacity of the waste heat boiler (Paepe and Dick, 2001).

Refrigeration system with chilled water storage

Ameri et al. (2005) studied the turbine performance with optional power booster including mechanical chillers with thermal storage system, which is shown in Figure 8. During the off-peak hours, the operation can take advantage of the lower electrical rates by operating mechanical chillers which produce chilled water for the

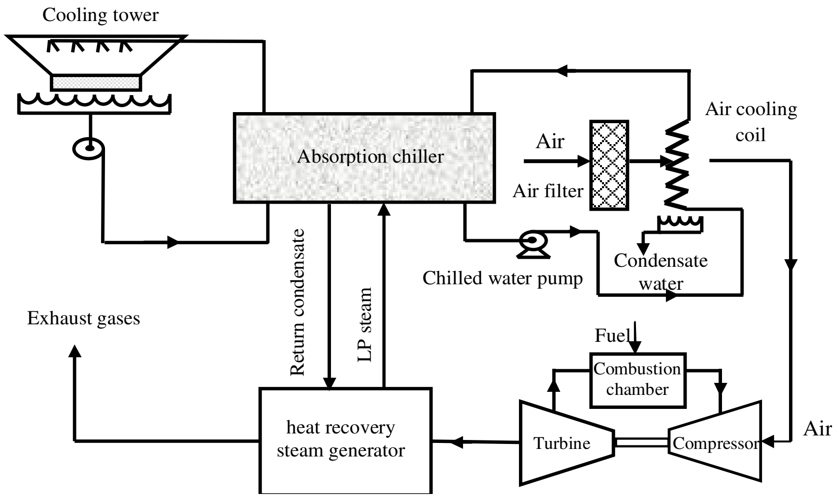


Figure 9. Absorption chiller inlet air cooling system (Kakaras et al., 2004).

thermal storage system. Paepe and Dick (2001) recommended that a full size thermal storage would reduce the overall size of the peak cooling load profile and levelize the production of chilled water over the off-peak period. A significant improvement of power output by more than 20% is reported.

Absorption chiller inlet air cooling system

Cooling of the compressor inlet air using two-stage LiBr absorption chiller was expected to result in boosting the gas turbine power output. Figure 9 shows the absorption chiller inlet air cooling system. Absorption chiller requires a low-grade thermal source to drive the refrigerant off the lithium bromide in the generator. The heat source in their study was a low-grade steam from existing heat recovery steam generators, HRSGs, in cogeneration (Ameri and Hejazi, 2004; Boonnassaa, et al., 2006). The value of the extracted steam must be compared to the value of power augmentation during peak hours. The cost of two-stage LiBr absorption chiller is twice the cost of mechanical chiller (Mohanty and Paloso, 1995; Maria and Jinyue, 2005). However, the economical calculation have considered 17% for the domestic interest rate, 7% for the foreign interest rate and 20 years for the equipment life (Ameri and Hejazi, 2004 ; Liu and Wang, 2004).

DISCUSSION

From the forgoing review of literature, various available technologies of gas turbine inlet air cooling system were studied including the evaporative coolers, mechanical chillers with and without thermal energy storage systems. Furthermore, in cogeneration gas turbine generators, aqua-ammonia and two-stage LiBr absorption system were explored as booster for the gas turbine power output without affecting the thermal efficiency of the cogeneration unit. All the aforementioned technologies can be used in conjunction with gas turbine generators to boost the power output in hot months with various degrees of effectiveness. The evaporative cooler is an old system used to cool down the gas turbine inlet air temperature. However, it is simple in design, have a short installation time and low capital and maintenance cost. Unfortunately, this technique is limited by the wet bulb temperature of the inlet air and the gas turbine generator capacity may not be increased by more than 12% in best cases even in dry climates. Water carry-over is another problem associated with the use of evaporative coolers.

Mechanical chillers increase the capacity of gas turbine generators better than evaporative coolers because they can produce any air temperature required by the designer. However, the main disadvantage of this technique is not associated with high capital cost nor with the space required, but it is associated with its high consumption of electricity which reduces the potential power output increase of the gas turbine generator. Mechanical chillers with thermal energy storage systems such as water and ice storage systems can be used as inlet air cooling system to boost the gas turbine generator power in hot months in countries which adopts variable price for selling electricity, off-peak and on-peak, and have no shortage of electricity production. The exhaust gases of gas turbines carry a significant amount of thermal energy which can be used as a heat source to drive the generator of a vapour absorption chiller such as: aqua-ammonia absorption chiller, two-stage LiBr chiller and single stage LiBr chiller that serves as a cooling system to cool the inlet air during hot periods before admitting to the gas turbine compressor. However, the COP of aqua-ammonia chiller is relatively lower than that of LiBr chiller for the same operating conditions, require high capital cost of refrigeration and large plot space while the two-stage LiBr chiller is mainly used when high COP is required and boost the power output in cogeneration gas turbines. The effort to boost the power output during hot periods for a simple gas turbine unit without cogeneration, a single stage LiBr absorption chiller seems a feasible solution to be investigated thermally and economically due to its relatively high COP and low capital cost of refrigeration. As per author's knowledge, a very little work has been undertaken in previous work.

CONCLUSIONS

In the present review, the development occurred in the inlet air cooling system that is used to improve the performance of the gas turbine power plants had been classified. The following list summarizes the conclusion drawn:

1. The diversity used of system to achieve the cooling function reflects the necessity of this technique in improving the performance of the gas turbine power plants.
2. The success of evaporative cooling in reducing the high air temperature depends on relative humidity of the ambient air. These types of systems are economical and suitable for hot and dry climates rather than hot and humid ones.
3. Absorption systems are similar to vapour-compression air conditioning systems except the pressurisation stage. The absorption cooling technique demonstrated a higher gain in power output and efficiency than evaporative cooling for a simple cycle gas turbine, independent of the ambient conditions.
4. The absorption chiller system for inlet air cooling of the gas turbine increases the peaking capacity of the gas turbines during the hot ambient operation.

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