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(REVIEW ARTICLE)

A review of gas turbine inlet cooling technologies

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Abstract

Gas turbine (GT) performance is primarily dependent on the inlet air temperature. The power output of gas turbine is dependent on the flow of mass through the gas turbine. This is why at hot weathers with less dense air, the power output drops, but at cold weather with high dense air, the power output rises. The inlet air cooling (IAC) technology is one of the major drivers that enhance the gas turbine performance, especially during the hot weathers. The performance of gas turbine is affected by various factors such as inlet air cooling, fuel type, fuel heating value, air temperature, turbine inlet temperature, humidity, site elevation, inlet and exhaust losses, air extraction, diluent injection, performance degradation, etc. The aim of this technical review is based on the comparative analysis of different gas turbine inlet air cooling (GTIAC) technologies and its applications based on the climate conditions. The power consumption due to inlet air cooling calls for major concern since it reduces the GT net power output. Different GTIAC has its unique benefits and challenges. The biggest gains from evaporative cooling are achieved during hot, low-humidity climates. Furthermore, the review paper showed that the efficiency of the evaporative cooler is majorly dependent on the moisture present in the air. The work also reveals that the feasibility of each GTIAC application is basically dependent on the location.

Keywords: Gas turbine; Inlet air temperature; Fuel heating value; Inlet air cooling; Evaporative cooling

1. Introduction

Gas turbines (GTs) are increasingly dominating the power generation systems as a result of its reduced cost of electricity, the ability to use a range of liquid and gaseous fuels, high specific power (power-to-weight ratio) and several other beneficial factors [1, 2]. Until mid seventies, the use of GT to achieve peak power demand suffered a lot of setback due to its low efficiency (around 30%) and poor reliability [3]. Meanwhile, low efficiency especially at part load is the main disadvantage of GT. Consequently, employing various techniques in order to improve the efficiency by using inexpensive inlet cooling technologies that are not harmful to the environment is important. The low efficiency of GT is caused by the radiation heat losses in combustion chambers and the high heat losses in the exhaust [2]. In addition, Poullikkas [4] stated that the low performance of GTs are caused by the inlet and exhaust losses, air extractions above 20% without extensive modification and the gas turbine degradation due to corrosion, erosion and fouling. However, exergy analysis of GT power plants is usually a technique for determining power plant major losses and provides means of minimizing the losses [5]. Further analysis on the performance loss of GTs in warm climates based on the size and the characteristics of the GT show that the power output decrease and that higher losses are experienced for GTs of smaller capacities [6]. Hence Amell & Cadavid [7] attributed this behaviour of smaller GTs not only to the reduction in air density with increase in ambient temperature but also due to decrease in the volumetric flow rate.

Al-Ibrahim & Varnham [8] stated that modern gas turbines run at lower airflow rates per unit of power generated and the lower flow rates reduce the cooling requirement for gas turbine inlet air cooling (GTIAC) systems and subsequently improve the GT performance. Gas turbines are constant-volume engines and their shaft power output is almost proportional to the combustion air mass flow rate [8, 9, 10]. For instance, at a particular shaft speed, gas turbines move

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the same volume of air. Since the compressor has a fixed capacity for a given rotational speed and a volumetric flow rate of air, their volumetric capacity does not change and the mass flow rate of air that flows into the GT varies with relative humidity and the compressor entry temperature [9]. Mahmoudi et al. [11] observed that since the combustion air is taken directly from the environment, their performance is greatly influenced by climate conditions. Therefore, the performance of the gas turbine power plant (GTPP) is sensible to the ambient condition. Xiaojun et al. [12] stated that the drop in ambient temperature causes rise in compression work due to the limited volume of the air increase in proportionality to the inlet air temperature. The cost of installation of GT or combined cycle power plant (CCPP) rated at ambient temperature of 45 °C is between 20% - 30% higher than that rated at 15 °C [13].

The change of power of the GTPP resulting from the change of ambient temperature is caused by change of the inlet temperature in the compressor, change of the mass flow rate of air and combustion gases, change in the internal efficiency of the machine and change of the excess air ratio [14]. Therefore, any reduction of the ambient temperature leads to the increase of flow rate of combustion gases, which resulted in the rise of power output. But if the inlet temperature is cooled below the ISO rated temperature, then the temperature of the exhaust gases flowing through the waste heat boiler become lower, which may affect the capacity of the waste heat boiler [15]. Several works [16-25] have independently analyzed the impact of the inlet air temperature on the performance of the GT in order to improve GT performance. Because of the effect of ambient temperature on the performance of GTs, in hot climates, it is recommended that the air at the inlet to the compressor is cooled. \different inlet air cooling techniques have been developed and applied. The different inlet air cooling technologies are thus reviewed in this work.

2. Inlet air cooling technologies

Gas turbine inlet air cooling is one of the techniques suggested to enhance simple and combined cycle performance, particularly in hot climate operation. The power output and thermal efficiency decrease as the ambient temperature and humidity increase. However, the compressor inlet air temperature has the highest effect on the GT performance [26]. The temperature difference between the ISO standard conditions (15 °C) and the hot climate peak periods (~40 °C), show a 20% power output reduction and the GT power outputs can be enhanced by the application of various cooling techniques [8]. In addition, if the compressor inlet air temperature is cooled to 4 °C during hot climate, a 27% rise may be achieved in specific power [8, 10]. Kolp et al. [27] analyzed IAC of a 40MW GT and revealed that a 28 °C reduction in ambient air reduced the heat rate by 4.5% and increased output power by 30%. The selection of the appropriate technique for cooling the inlet temperature of GT requires both technical and economic investigation [8, 26].

Gareta et al. [28] proposed a methodology that analyze operational costs, capital cost, utilities costs and profit analysis. In terms of vapour compression techniques, Chacartegui [29] carried out a study evaluating the energy and economic benefits of using direct expansion cooling to several commercial gas turbines. Besides the theoretical analysis of the advantages of the application of the IAC techniques that are increasingly utilized in several GT installation, especially in hot climates. Kitchen et al. [30] stated that the application of the IAC in GTs has analyzed the achievable capacity increase of the performance. A comprehensive research of the available cooling technologies and the major benefits and drawbacks of each have been examined [9, 31-33]. Before looking at the different inlet air cooling technologies, how inlet air cooling affects gas turbine performance is first presented.

2.1. The Effect of Inlet Air Cooling on Gas Turbine Performance Parameters

Inlet air cooling technology is used to control ambient temperature at the inlet of the GT [34]. The power output of the gas turbine is affected by various factors such as the ambient air temperature, relative humidity, ambient air pressure and turbine's inlet temperature. However ambient air temperature has the greatest effect [26]. Ibrahim et al. [5] stated that 1 °C increase in the inlet air temperature reduces the GT power output by 1% and Mohapatra [35] stated that an increase in each °C reduces the net power output by 6%-9%. An increase in the inlet air temperature to the compressor causes a reduction in the air density and subsequently, decreases the mass flow rate [36]. They also revealed that an increase in ambient temperature of a GT results in increase in compressor power consumption and decrease in density, power output and thermal efficiency. Besides, the compression work increases due to the increase in volume occupied by the air. The heat rate rises due to more fuel consumption needed to attain the specified TIT. Decrease in the ambient air temperature, even lesser than ISO temperature, can improve the power output for about 20% and reduces the thermal efficiency by 6% [37]. The temperature difference between the rated ISO standard condition and a typical warm climate temperature of 40 °C may lead to 20% drop in power output [38]. Thermodynamically, ambient air temperature of a GT is inversely proportional to the power output [39], while the net power output generated by GT is directly proportional to the air mass flow, which reduces when the ambient temperature increases [7]. Ameri & Hejazi [40] stated that over 170 GT units with a combined capacity of 9500 MW exist in Iran, but hot weather during the summer leads to 1900 MW losses.

2.2. Types of Inlet Air Cooling Technologies

Al-Ibrahim et al. [5] stated that the most applied IAC techniques to improve the GT performance by means of reducing the ambient temperatures are the following: wetted media evaporative cooling, high-pressure fogging, refrigerative vapour compression cooling, absorption chiller using the GT's exhaust gas and thermal energy storage. Cortes & Willems [41] also classified GT inlet cooling techniques into evaporative cooling, spray inlet coolers or fogging, refrigerated cooling, absorption chiller and thermal energy storage (TES). They further classified GTIAC into direct-contact (like evaporation method) and indirect-contact cooling methods (like cooling by compression or absorption chillers).

Dawoud et al. [23] examined the thermodynamic assessment of evaporative cooling, fogging cooling, vapour-compression cooling and absorption cooling using both LiBr–H_2O and aqua-ammonia systems for GTPPs in two different regions of Oman in south east of Saudi Arabia. These cooling technologies were compared with respect to their impact on increasing the peak capacity of the GT, as well as their electrical energy generation advancement. Meanwhile, the evaporative cooling includes spraying pressurized water (fog), wet media and spraying of water through the compressor (wet compression) or a combination of these methods [41]. In few cases, a fusion of the IAC techniques are used to achieve hybrid solutions by adopting the most effective methods based on the environmental conditions. Al-Ansary et al. [42] showed that the fusion of vapour compression cooling and fogging techniques has the capacity to achieve the requirements of both dry and humid climates and optimize the effectiveness of the IAC technique. However, high initial cost and plant complexity are the major drawbacks of this solution. The different inlet air cooling technologies are presented below.

2.2.1. Wetted Media Evaporative Cooling

Wetted media evaporative cooling is the spraying of water (droplets) into the inlet air stream in order to cool the inlet air from its dry-bulb temperature to a point near to its wet-bulb temperature. The latent heat of vaporization is absorbed from the water body and the surrounding air, leading to the cooling of the air entering the compressor. Humidity of air ensures effective evaporative cooling as evaporation only takes place when the humidity of the air is below 100%. This method is a better option for dry areas and more effective when the humidity is low. However, it is limited by wet-bulb temperature. A Schematic representation of wetted media evaporative cooling with water treatment is shown in Figure 1. The pump circulates water from the reservoir that contained the treated water into a wetted media. The filtered air and the pumped cleaned water mixed at the wetted media which in turn becomes wet and prevent dust and other airborne contaminants from impinging upon it. 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.

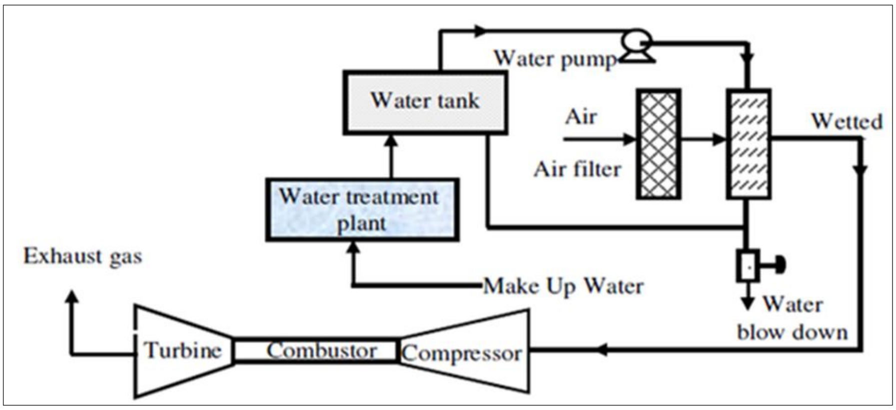

Figure 1 Schematic representation of wetted media evaporative cooling with water treatment [5]

Evaporative cooling involves heat and mass transfer, which occurs when unsaturated air-water mixture of the incoming air and the water are in contact [43]. Heat and mass transfer are both operative in the evaporative cooler due to heat transfer from air to water evaporates water, and the water evaporating into the air constitutes mass transfer [39]. Heat inflow can be described as either latent or sensible, and the term used depends on the effect. If the effect is limited to lower or raise temperature, it is sensible heat. While latent heat produces a change of state such as melting, freezing, condensing or vaporizing. Therefore, in evaporative cooling, sensible heat from the air is transferred to water, which becomes latent heat as the water evaporates. The process of exchanging the sensible heat of the air for latent heat of evaporation from water is adiabatic [44]. Such system is used as a preferred solution in dry/desert climate, which can be expected to enhance the GT power by nearly 12%. Meanwhile, for hot humid climates, the air-cooling is limited to the wet bulb temperature and the capacity of the GTPP may not be increased by more than 5 to 7% in best situations [45]. The surrounding ambient air is cooled by evaporation of the water from wet surface of the panel to the air [46]. The addition of water vapour to the air increases its latent heat and relative humidity.

Wetted media evaporative cooling is best utilized in hot dry regions as it uses the latent heat of vaporization to reduce ambient temperature from the dry-bulb to the wet-bulb temperature [8]. The benefits of this cooling technology are low capital and operational cost, minimum NOx pollution in the exhaust gases, and an average maintenance cost which is lower than other cooling methods [47]. Nabati et al. [48] reveal that parasitic power consumption is below 0.5% of the increased production, and in addition, that it minimized NOx emissions by 0.8-1.5% per ◦ 1C of cooling. However, it has limited potential in areas of hot climate humidity and installation can take as much as 10 days, which is much longer than an equivalent fogging system. Punwani et al. [49] projected additional costs to be up to $50 per kW additional capacity. The evaporative cooling technique gives a better thermal efficiency, power output, temperature drop when the inlet air temperature is lower than 20 °C (say t = 18 °C). This is as a result of greater temperature drop achieved by evaporative system when compared with absorption chiller technique that does not depend on the relative humidity (RH). Evaporative system at RH = 60% is advantageous only for low inlet ambient temperature inferior to 14 °C, when the cooling requirements are not important [36]. Also, if the sprayed water does not evaporate before entering the compressor, it will destroy the blades of the compressor. However, Chaker et al. [50] revealed that if the fog system is replaced with wet compression, the risk of damaging the compressor blades will be minimized.

2.2.2. High-Pressure Fogging

High-pressure fogging is the spraying of droplets of de-mineralized water, of about 5-20 microns in diameter, into air inlet ducts at 1000-3000 psia and fog droplets are technically less than 40 microns in diameter and remain airborne due to Brownian motion. As the fog droplets evaporate, relative humidity of 100% is produced and the air is cooled to the wet-bulb temperature which is the lowest possible temperature obtainable without refrigeration. Hence, excess fogging can be used in order for the droplets to evaporate in the compressor thereby decreasing GT compressor work and further increase turbine power output. However, the fogging droplets applied in high pressure inlet air fogging and fog intercooling does not cause erosion of turbine blades. This method is also best used in dry regions. Meher-Homji & Mee III [51] defined high-pressure fogging as the spraying of droplets of de-mineralized water, of about 5-20 microns in diameter, into air inlet ducts at 1000-3000 psia and that a typical fog system will require 15-20 hours maintenance per year. Al-Ibrahim & Varnham [8] revealed that fog droplets are technically less than 40 microns in diameter and remain airborne due to Brownian motion. As the fog droplets evaporate, relative humidity of 100% is produced and the air is cooled to the wet-bulb temperature which is the lowest possible temperature obtainable without refrigeration. Hence, excess fogging can be used in order for the droplets to evaporate in the compressor thereby decreasing GT compressor work and further increase turbine power. Hill [52] revealed that droplets of water greater than 20 microns in diameter may strike the turbine blades and cause erosion. However, the fogging droplets applied in high pressure inlet air fogging and fog intercooling does not cause erosion of turbine blades [53]. This was also buttressed via CFD studies fog droplets 10-20 microns in diameter follow the air path and do not strike the turbine blades [54].

Due to the short residence time (of a few hundredth of a second) in the compressor, compressor redesign is required for the evaporative process to provide effective cooling and to maintain pressure [55, 56]. Meanwhile, the high-pressure fogging system was preferred to other IAC techniques due to its effectiveness, pay-back period and application simplicity [29]. This technique is mainly suitable for hot and dry climates where it is possible to utilize maximally the merit of the adiabatic saturation. Conversely, it is impossible to control the temperature of the air downstream of the fogging nozzles as it is depended on the wet-bulb temperature of the ambient air. Ibrahim et al. [5] summarized the performance gain achieved by various IAC methods by stating that the power output obtained using the high pressure fogging increases within a range of 5-10% but is depended on the inlet ambient humidity and the extend of inlet air temperature reduction. White et al. [57] analyzed the cooling capability of direct spray fogging along with droplet size and water requirements. A 4.9% power increase at design conditions of 32.2 ◦ C and 60% relative humidity was expected, but difficulties in producing the required 5-10 micron droplets size at high flow rates meant that only a 3.8% power gain was obtained [8].

Hariri and Aghanajafi [58] used a mathematical model to examine the utilization of an indirect evaporative cooler to boost the power output of a gas turbine having a rated efficiency of 27.06%. It was shown that the indirect evaporative cooler may lead to a decrease in the efficiency of the turbine under investigation to 26.32% due to the increase in fuel consumption outweighs the gain attained from the reduction of the compression process work, leading to a decrease in turbine efficiency. This shows that not in all cases that inlet air cooling improves the efficiency of a gas turbine Arabi et al. [59] stated that the aim of wet compression method is to achieve isothermal compression, instead of the adiabatic process, by spraying water into a compressor. In wet compression, more fogging is added than can be evaporated in the inlet (sometimes referred to as high fogging or overspray). The excess water fog is transferred to the air stream and evaporates for compressor inlet cooling and mass flow increment. This technique can improve power by up to 25% without depending on the ambient temperature conditions [60-61]. Hurlbert [25] revealed that wet compression technique gives the maximum efficiency increase of about 2.7% when used in cooling the inlet air temperature, followed by fog and media systems which are considered as the most suitable cooling systems due to its capacity to minimize fuel consumption by 5% when compared to a normal cycle [59].

2.2.3. Absorption Chiller Cooling

This is refrigeration cooling which is an indirect-contact cooler, and the cooling is carried out by passing air over the cooling water coils. Absorption chiller extracts heat from turbine flue gases, in order to produce chilled water in a double effect lithium bromide absorption chiller as shown in Figure 2. Warm ambient air gets saturated after flowing through the inlet air cooling coils. As the air passes through the mouth of the compressor, its velocity rises and its temperature drops further as air enthalpy is transformed into kinetic energy in an adiabatic process. The use the waste heat from the GT exhaust to drive the heat-driven refrigeration system makes environment friendly technologies. Therefore, absorption and vapour compression systems are much less dependent on humidity. Chillers that are used in this method can be compression or absorption types [39].

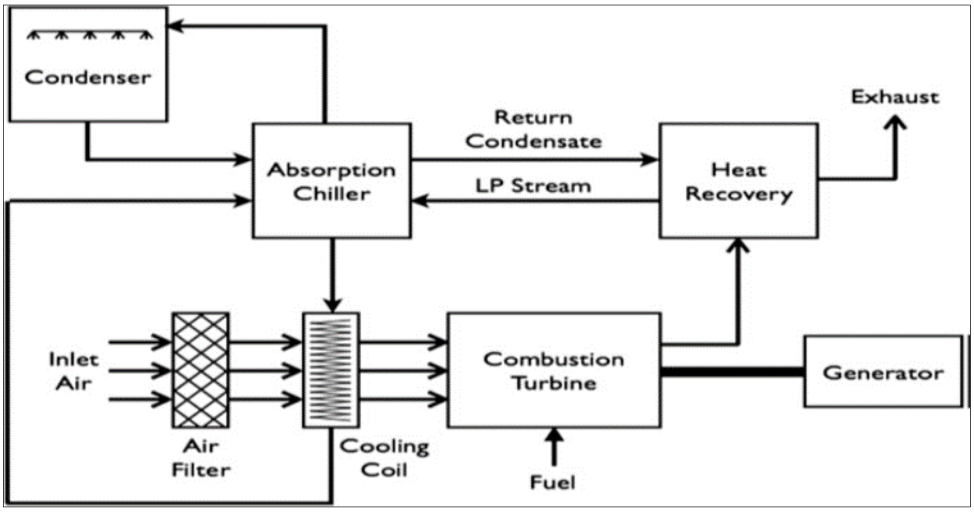

Figure 2 Schematic diagram of absorption chiller using lithium bromide [8]

When the air flows through the mouth of the compressor, its velocity rises and its temperature drops further as air enthalpy is transformed into kinetic energy in an adiabatic process. Condensate icing can occur if the temperature drops below freezing [23]. Temperature drop of not less than 5 °C is common to avoid potential icing problems [23, 25, 39]. The air will not be reduced less than 4 °C in order to prevent air from partially freezing at the compressor's inlet [62, 63]. However, the capabilities of the chiller may also affect the design inlet temperature and based on that the minimum chilled water temperature available from lithium bromide absorption chillers is 6 °C. Therefore, practical approach temperatures at the air coil will limit the design inlet air temperature to about 12 °C for these types of chillers [23].

Al-Bortmany [64] presented absorption chiller as green technique since the thermal energy required to power the absorption chiller may be easily extracted from the GT flue gases that would have been exhausted to the atmosphere and equally eliminates the need for chlorofluorocarbons (CFC) refrigeration which deplete the ozone layer. The absorption system cooling can improve the net power output. The major challenge is the quantity of heat taken by the generator and the quantity of mass flow rate of the refrigerant [18]. The major benefit of the absorption system is that, independent of ambient air conditions, the inlet air can be cooled to a specific constant temperature and consequently boost the power output of the GT [65, 8]. However, the ambient air cooling system must be designed to prevent icing at the compressor inlet or anywhere around the air intake structure. This is because ice fragments sucked into the compressor can result to serious structural damage. Icing is a potential problem anytime the ambient air temperature drops near the freezing mark. The absorption chillers produce higher net power and efficiency than the other cooling techniques since it consumes very less power than mechanical chillers [18]. A thermo-economic evaluation on the absorption chiller system and mechanical chiller revealed that absorption chiller system has the greatest capital cost, but its recovery period was found to be about 2 years in comparison with 7 years of mechanical chiller (hot and humid conditions) [18]. This disparity increases with other climates. Boonnasa et al. [66] analyzed methods of improving the capacity of an existing CCPP in Bangkok, Thailand. A steam-absorption chiller is suggested to reduce the ambient inlet air to 15 °C. The increase in power was projected to be around 10.6% with a payback time of 3.8 years. Nasser and El-Kalay [67] used a simple Li-Br heat-recovery absorption system to cool the air intake of a GT compressor in Bahrain as to compensate for the 30 °C hot climates to cold climate variation in ambient temperature. The analysis showed that heat from the exhaust gases is capable to reduce a 40 °C ambient inlet air temperature by 10 °C, giving a power increase of 10%. Bies et al. [68] analyzed the application of a lithium-bromide double-effect absorption chiller to cool warm ambient air entering a GT compressor. Mohanty & Paloso [6] analyzed a similar system for a 100MW GT in Bankok, with an inlet temperature of 15°C. They achieved instantaneous power output increases of between 8 and 13%, with an overall increase of 11%.

2.2.4. Refrigerative Cooling

Mechanical refrigeration utilizes vapour compression refrigeration equipment to cool the inlet air as shown in Figure 3.The coolant in vapour compression refrigeration is circulated through a chilling coil heat exchanger that is situated in the filter hub, downstream from the filtering stage. A droplet catcher is also installed in downstream from the coil in order to collect moisture and water drops. The mechanical chillers boost the GT performance better than evaporative coolers because they can produce any required air temperature irrespective of the weather conditions. However, the major disadvantages of mechanical chillers are their high consumption of electricity. The mechanical chillers uses mechanical or electrical vapor compression refrigeration equipment and they are independent of the ambient conditions. However, the power required to run the chiller must be put into consideration despite its power output boost [18]. The coolant in vapour compression refrigeration is circulated through a chilling coil heat exchanger that is situated in the filter hub, downstream from the filtering stage as shown in Figure 3.

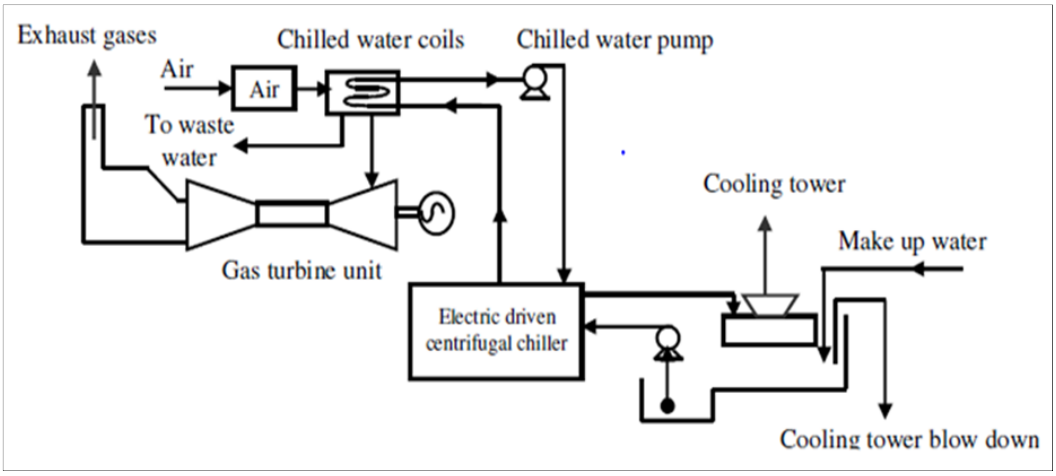

Figure 3 Schematic Representation of vapour compression refrigeration [69]

A droplet catcher is also installed in downstream from the coil in order to collect moisture and water drops. The mechanical chillers boost the GT performance better than evaporative coolers because they can produce any required air temperature irrespective of the weather conditions [69]. However, the major disadvantages of mechanical chillers are their high consumption of electricity. Hall et al. [70] stated that equipment and Operation and Maintenance (O&M) costs are less than absorption chillers, but has high capital costs and parasitic power requirements can be 30% of the power gain. Further studies include evaporative cooling and suggested that evaporative cooling can be used where a peak-power boost between 8% and 15% is needed at high temperatures, and refrigerative cooling used where a sustainable rise of 10-25% is needed [71]. The recommended air inlet cooling temperatures must not be below 7.0°C to safeguard against potential ice buildup in the compressor suction line [72]. Majority of mechanical compression chillers involve more than one chiller unit. Other options such as steam driven compression are also used in industry.

Zhang et al. [73] developed a thermodynamic model to study the performance of a GTIAC system using a vapor compression refrigeration system with pressure drop irreversibility. In their model, the combustion fluid was determined to encounter several flow resistances, which include the friction through the blades, compressor vanes and the turbines, and the cross sectional areas of the various components of the GTAIC systems encountered by the combustion fluid. They used the model they developed to identify the system operating condition that yields the optimum performance of the GTIAC system and they further varied the inlet air mass flow rate to the GTIAC system, and found that an optimum air mass flow rate exists that yields the maximum system performance. Zamzam & Al-Amiri [74] analyzed the potential use of utilizing refrigerative GTIAC systems in the United Arab Emirates by using wet-bulb and dry- bulb weather data to determine characteristic design conditions of three Emirates namely Al-Ain, inland arid which is very hot and relatively dry; Abu Dhabi, coastal Arabian Gulf which is very hot and humid; and Fujairah, coastal Oman Gulf which is hot and very humid. They used particular inlet air temperatures to find annual gross energy increase, average heat-rate reduction, cooling load requirement, and net power increase. For viability, they suggested an inlet air temperature of 15-25 °C. Mechanical chillers using centrifugal compressor with Freon refrigerant was used as an alternative inlet air cooling system in order to enhance the gas turbine power output in hot climates. The power output rises by 0.36% with each 1 °F inlet temperature reduction.

2.2.5. Thermal Energy Storage

Kakaras et al. [38] defined thermal energy storage (TES) as temporary storage of energy at high or low temperature for use when it is needed. Thermal storage could be achieved as sensible heat storage or as latent heat storage. Sensible heat storage media are oil, sand, water, 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 quantity of energy per unit mass when compared to sensible heat storage media and hence result in smaller and lighter storage devices with lower storage losses and high efficiency [38]. Typically, chillers operate during off-peak periods, and the cooled media is used to cool ambient air during peak load periods. Al-Ibrahim & Varnham [8] stated in their Saudi Electric Company review that refrigeration cooling with chilled water or ice thermal storage is the best technique and the method also requires a smaller storage volume as shown in Figure.4.

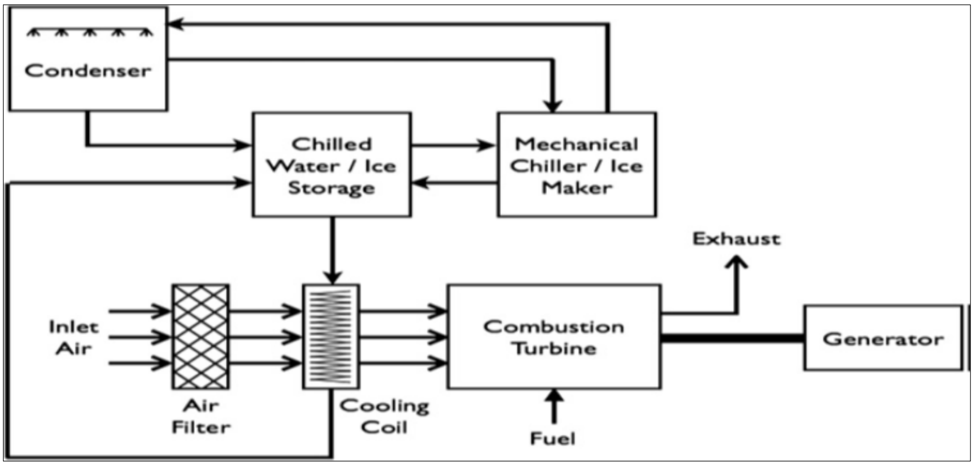

Figure 4 GTIAC using mechanical cooling with TES [8]

Ebeling & Halil [75] stated that the ice thermal storage system is charged during off-peak periods by a chiller whose capacity is strongly reduced. The available time for charging the ice storage system in their work was recorded to be 18 hours and the mechanical capacity required was reduced by 66%. This reduces the consumption to 15 kW/MWGT when compared to mechanical chillers with 50kW/MWGT [76]. It was observed that the use of such system would provide 21 to 25% increase in power output when inlet air is lowered to a temperature of 10 °C. Again, a recommendation not to drive the inlet air temperature near 0 °C 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.

Ameri et al.[77] studied the economic design criteria necessary for the choice of chilled water and ice TES systems for GTIAC in the Kish power plant, Iran. The plant was situated in a high humidity region that might not be favourable for the use of evaporative techniques. They also observed that chilled water storage was economically preferable to ice storage. The proposed system was able to cool the ambient temperature from a high temperature of 45 ℃ to 7.2 ℃ . Zurigat et al. [78] studied the potential of ice and chilled TES to reduce GTIAC in Oman and observed that the cost of chilled water and ice storage tanks were uneconomical. They further analyzed the option of partial TES and observed that reduced storage capacity does not lead to reduction of chiller size. Jolly et al. [79] analyzed the TES based on inlet air chilling systems of simple-cycle GT in Wisconsin. The inlet air is cooled for 4 hr/day in 5 days/week. Each system has a 3400tons refrigeration plant, 4,500,000 gallons of storage, and an ice producing capacity of 2600 tons. Recharge is usually at the weekends and at night. The systems produce instantaneous cooling loads of 16,200 tons for each set of 4 turbines, and were designed to lower the ambient air from 23 °C to 5.5 °C. A 17% rise in power was obtained, improving the GT power to 112 MW. Behafarid & Bahadori [80] employed an aquifer to store thermal energy for a GTIAC system and the aquifer water was extracted and re-injected into the aquifer throughout the year. In cold season, the ambient temperature cooled the water, while in hot season, the cooled water was used to cool the turbine inlet air. The system was used for cooling for 6 hours a day during the hot climate and increased efficiency from 31.8% to 34.2%. Liebendorfer & Andrepont [81] presented a case study of the 678.6 MWh TES system retrofitted to GTs in Riyadh, Saudi Arabia. The system has a 38.7MW thermal capacity chilled water plant operating for 6 hr on and 18 hr off that can provide 10.5MW simultaneous thermal cooling to each of 10 gas turbines; i.e.105 MW in total. The system increased net power by 30% and reduced capital costs by $10 million. Figure 5 presents the classification of gas turbine inlet air cooling techniques and their working fluids in order to boost the power output of the combined cycle.

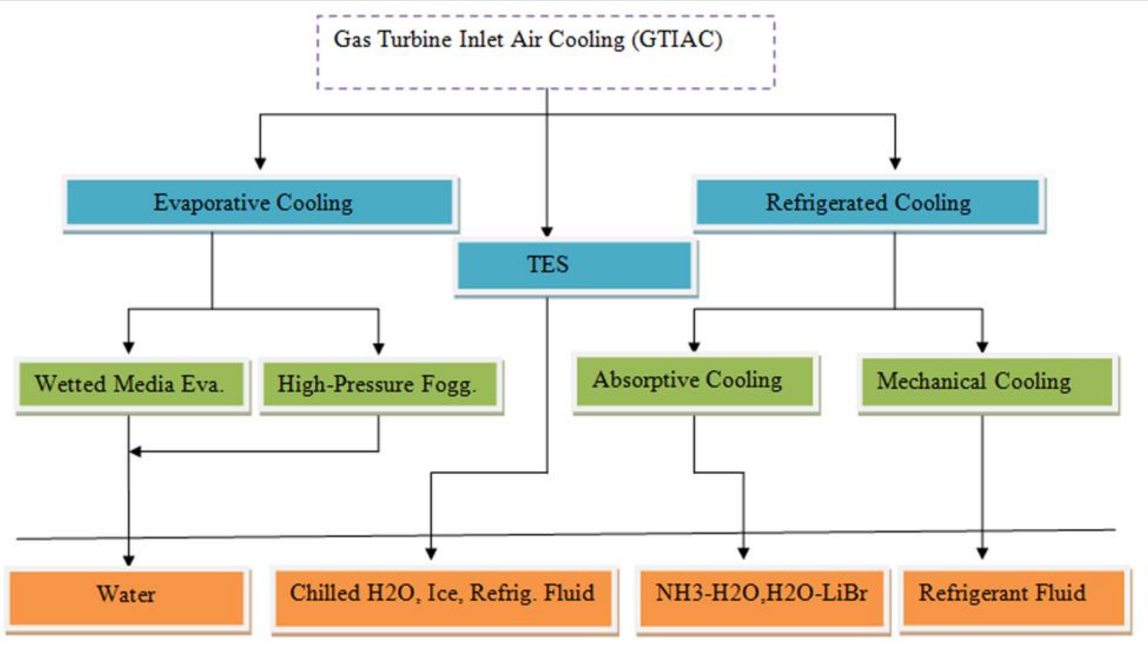

Figure 5 Schematic representation of the classification of GTIAC technologies and their working fluids

2.3. Comparative Studies

This section presents the similarities, advantages, disadvantages and differences of different gas turbine inlet air cooling technologies used in improving the power output and efficiency of the combined cycle power plant. Evaporative cooling (spray cooler) is the most cost-effective system and it uses evaporation of water to reduce the GT inlet air temperature, while the chilling (cooling coil) uses the cooling medium that flows via a heat exchanger situated in the inlet duct to remove heat from the inlet air. However, evaporative cooling is limited by wet-bulb temperature while the chilling can reduce the air intake temperatures that are lower than the wet-bulb temperature [36]. Alhazmy & Najjar [39] carried out a comparative analysis on spray coolers and cooling coils and analyzed their performance against operational and design parameters including ambient temperature, pressure ratio, relative humidity and turbine inlet temperature. Spray coolers were seen to be less costly but were majorly affected by ambient temperature and relative humidity while cooling coils give full control over inlet conditions but have large parasitic power requirements. However, absence of energy storage results to net power drop. They stated further that evaporative cooling and inlet chilling systems are the two most used cooling techniques of GT.

Jaber et al. [82] carried out an analysis of a computer simulation model for a power plant in Jordan, using evaporative and cooling coil system. They revealed that the cooling coil gives a full control of the compressor inlet conditions regardless of ambient conditions. However, it demands quite a large operational power. Najjar & Al-Zoghool [18] presented wetted media evaporative cooling and fogging systems as better option for dry areas while absorption and vapour compression systems as much less dependent on humidity. Al-Ibrahim & Varnham [8] studied the inlet air cooling technologies that can be employed to improve the power production of the Saudi Electric Company's GT during warm peak times. The results showed that fogging and wetted media cooling systems required huge quantity of water and this factor limited their application in the desert environment. Meanwhile, absorption chiller is costly and the cost of investment is not justifiable to employ it only to increase the power output in the peak hour.

Ondryas et al. [63] analyzed the use of absorption chillers operated by steam recovered from turbine exhaust, electric powered mechanical chillers, and thermal energy storage to cool the GT inlet air. The analysis showed that the economic viability of producing additional peak power does not justify the system cost, since system cost was less than the economic benefit obtained from the addition power produced. Ibrahim et al. [5] analyzed three inlet air cooling techniques including the mechanical chillers, media type evaporative coolers, and absorption chillers. They observed that the success of evaporative cooling in cooling the high air temperature depends on relative humidity of the ambient air but absorption cooling technique improved power and efficiency than evaporative cooling. Popli et al. [83] revealed that absorption chilling is a better inlet temperature cooling than either mechanical chillers or evaporative cooling since mechanical chillers require high electricity consumption and the evaporative cooling is sensitive to ambient air humidity.

Dawoud et al. [23] undertook a study on the thermodynamic analysis of power requirement for different GTIAC methods and their effects on power boost at Marmul and Fahud oil fields located in Sultante of Oman. The analysis adopted a wetted media evaporative cooling with wet-bulb temperature approximately 88% as against 98% for fogging cooling. A design compressor inlet air temperature of 14 °C was adopted for LiBr–water chilling systems and 8 °C adopted for both aqua-ammonia absorption and VC refrigerating systems in order to avoid the formation of ice fragments as the air is drawn into the mouth of the compressor. The results showed that fogging cooling offers 11.4% more electrical energy when compared with wetted media evaporative cooling in both oil fields. The LiBr–H2O cooling provides 55% and 40% more energy than fogging cooling at Marmul and Fahud, respectively. The results further revealed that annual energy production improvement of 46% and 39% is expected when compared with LiBr–H2O cooling at Marmul and Fahud respectively. Hot climates will present higher power production, but will require higher cooling loads and cooling system costs to achieve those loads if relative humidity remains constant. Drier climates lead to lower refrigeration cooling loads, but also boost the performance of evaporative or fogging cooling [23].

Najjar & Al-Zoghool [18] evaluated the merits of different cooling techniques and the following presentations were made: Wetted media technique is greatly sensitive to relative humidity, the traditional evaporative cooling can improve power output by about 15% in low humidity location, while in high humidity locations the increment is likely below 10%, approaching zero at the point of saturation (RH = 100 %). The fogging is similar to wetted media systems, However, it is more effective [84]. Vapor compression (VC) chilling which is electrically driven mechanical chillers consumes relatively high power and cools the ambient inlet air temperature by chilled fluid circulating through cooling coils. The VC chilling is not limited by humidity and can lead to over 25% improvement in power output [85, 86]. Absorption chilling is similar to VC chilling system, in which the inlet air temperature is reduced by refrigerant fluid (water) through cooling coils. However, the difference of the absorption chilling system from the VC system is that the compressor is replaced by a circulating pump that makes it to consume relatively very low power [83]. Al-Tobi [87] showed the performance of single shaft and twin-shaft GTs, with vapour compression refrigeration (VCR) and vapor absorption refrigeration VAR applied to them. The results achieved using the VCR system showed a 27% increase in power output for the single-shaft engine and about 20% increase in power output for the two- shaft engine at an ambient temperature of 50 ◦ C. Both methods of cooling were technically feasible with VCR showing better performance.

Abdalla & Adam [88] investigated technical and economic aspects of refrigerative, wetted media, and fogging inlet cooling systems for a GT in Khartoum. Useful inlet cooling degree hours of 103349, 88902 and 180275 were calculated for fogging, wetted media and refrigerative cooling respectively. The associated power increases were 51255 MWh, 44028 MWh, and 77348 MWh respectively. Hence, they deduced that the preferred technical choice was refrigerated inlet air-cooling. However, the preferred economic option was wetted evaporative media because the refrigerative system was 4-5 times more costly. Payback times are, 0.6, 0.4, and 2.2 years for, fogging, wetted media, and refrigerative cooling respectively. Ameri et al. [89] carried out a technical and economic comparison of evaporative cooling and fogging systems for GTs at a number of power plants in Iran located in hot dry areas. Mean output capacities were increased between 8.9% and 14.5%. Payback periods for the high-pressure fogging and the wetted media evaporative systems are 2 and 3 years respectively.

Meher-Homji & Mee III [51] carried out a comparative analysis on the direct type inlet air cooling systems which are evaporative cooling and high-pressure fogging. The analysis showed that neither technique is basically preferable than the other, rather the choice is dependent on the external conditions such as site and economics. They identified some potential issues with the traditional evaporative cooling such as the need for a mist eliminator on the downstream side to get rid of un-evaporated water droplets from the air before entering the compressor and the need for re-circulating evaporative coolers to have a blow-down system to avoid a build-up of minerals on the wet media. Their research also revealed the need for careful adjustment of water flow rates to avoid dry spots and water carry over and that wetted media introduces a greater differential pressure drop at the turbine entry than does a fogging system, leading to greater reductions in mass flow rate. They further analyzed the installation costs of various IAC systems. The analysis depicted that the high-pressure fogging installation costs are low when compared with other technologies such as evaporative cooling and refrigeration techniques. The high-pressure fogging installation costs are around 25% that of an equivalent evaporative cooling system and installation can take 2-3 days as opposed to an extended period of downtime. Andrepont [33] carried out a comprehensive analysis on a number of available techniques for IAC of a GT and highlighted the major benefits and drawbacks of each technique. He further proposed using technologies characterized by decoupling the operation of the refrigeration unit from the actual peak times of GTIAC. Decoupled technologies reduce the application of electric power during peak periods. He finally predicted the potential usage of ice TES systems for effectively cooling inlet air for 4 to 6 hrs/day. In earlier analyses carried out by Andrepont & Steinmann [90] and Cross et al. [91] , it was observed that the capital cost of ice TES for GTIAC systems ranged from $260 to $360 per kW of net incremental power when compared to $400 to $500 per kW for chilled water TES. Low temperature stratified fluid thermal energy storage which replaces ice or water as a storage medium in the thermal storage system, with one of aqueous fluids is another IAC technique. This Technology is capable of bringing inlet air temperature to 2 to 4 °C and requires low electric power during peak times. However, it requires a very large storage volume and limited hours of inlet air-cooling per day.

Al-Ansary [92] developed a simplified thermodynamic model to examine the performance of an ejector refrigeration system used in a GTIAC system and compared its performance against the expected performance of a vapor compression system. It was revealed that ejector refrigeration systems have low maintenance, fluid driven, heat-operated devices that can employ the turbine exhaust as the heat source for running the cooling cycle. Hence, ejector refrigeration systems are characterized by low power requirements making them superior to vapor compression systems but the large condensers associated with the ejector refrigeration systems is its main challenge. Al-Ansary [92] also revealed that the ejector refrigeration system for a range of ambient air temperature from 31 to 44°C can increase the power output from 6.8 to 7.3% which proves that power output is inversely proportional to the ambient temperature. Using his model, he predicted that the ejector refrigeration system requires 0.2-0.6% (proportional to ambient temperature) of the power gain to run the refrigeration system, whereas if a VCR system was utilized, the power needed can span from 0.6 to 0.9%. However, his simplified model has not been validated experimentally. Table 1 shows the key benefits and drawbacks of various technologies for GTIAC.

Table 1 Key benefits and drawbacks of various technologies for GTIAC

parameters	**Gas Turbine Inlet Air Cooling Technologies**				
	Wetted Media Evaporation Cooling	**High-Pressure Fogging**	**Vapour Absorption Refrigeration**	**Vapour Compression Refrigeration**	**ITES and CWTES ***
Definition	Spraying of water (droplets) into the inlet air stream, in order to cool the inlet air from its dry-bulb temperature to a point near to its wet-bulb temperature.	Cooling to wet-bulb temperature at 100% humidity by high-pressure spraying of water droplets into air-inlet ducts.	Absorption cooling uses the waste heat from the GT exhaust to drive the heat-driven refrigeration system.	Mechanical refrigeration utilizes vapour compression refrigeration equipment to cool the inlet air	temporary storage of energy at high or low temperature for use when it is needed, using ice or chilled water as a storage medium to store energy during off-peak times
Parasitic Power Consumption	Low parasitic power consumption	Low parasitic power consumption	consumes very less power than mechanical chillers	Very large electric power demand during peak times	Requires low electric power during peak times
Sensitive to ambient-air wet-bulb temperature	Sensitive	Sensitive	Not sensitive	Not sensitive	Not sensitive

Capital cost	Very Low	Low	High (greatest capital cost)	High	Low (for CWTES) and Relatively high unit cost for ITES
O&M costs	Low (M-cost Lower than other IAC)	Low,	High	High(but less than Absorption)	High (for ITES)
Installation Cost	High (Higher than high-pressure fogging)	Low	Complex system requiring expertise to operate and maintain	Relatively simple and reliable design and operation	Relatively simple and reliable design and operation (for CWTES) Complexity of the system (for ITES)
limitation on time or duration of IAC operation	No limitation	No limitation	No Limitation	No limitation	Limited hours of inlet air-cooling per day
Performance (Power output improvement)	Low(due to the ambient wet-bulb limitation on inlet air temperature)	Low(due to the ambient wet-bulb limitation on inlet air temperature)	Greater performance increase than evaporative or fogging.	Greater performance increase than evaporative or fogging.	Greater performance increase than evaporative or fogging.
Operate best	Low inlet air R.H. (arid climates)	hot and dry climates	Any Climate	Any Climate	Any Climate
Limitation /Comments	Required high water consumptions. However, water can be recovered from the condensation of flue gases in the exhaust system.	1.Required higher purified water consumptions than evaporation cooling. 2.Requires demineralized water 3.Additional filters and drainage systems required 4.Excess fogging evaporates in compressor reducing turbine compressor work and increasing turbine power	1. Not suitable for open-cycle turbines 2. Requires larger heat rejection (and cooling tower water) than other reference systems 3.Limited inlet air temperature by GT manufacturer (~9°C)	1.No practical limitation on achievable inlet air temp. 2.Requires additional chilled-water cooling circuit. 3.Higher parasitic load than evaporative or fogging.	1.Limitation of inlet air temperature (approximately 7°C) for CWTES 2.Requires a large storage volume with CWTES vol. greater than ITES) 3.For ITES-Inlet air temperature can be brought down to 4 °C and can utilize low night-time tariff to produce and store ice for peak hours operation.

* ; ITES = Ice Thermal Energy Storage ; CWTES = Chilled Water Thermal Energy Storage

2.4. Hybrid Systems

A hybrid TIAC system is a system consisting of two single gas turbine inlet air cooling technologies joined in series or parallel that is utilized to cool the inlet air temperature to the desired temperature. The hybrid approach involves using different operation modes to reduce water and energy consumption. It is best applied where water is scare or expensive.

Features such as a cross flow design help reduce maintenance and operating costs when compared with conventional evaporative fluid coolers. However, hybrid systems consisting of mechanical vapour compression and absorption refrigeration systems may be impossible and useless. This is due to the fact that both mechanical vapour compression and absorption refrigeration systems have the same principle of working and outlet air conditions. Furthermore, both systems have high capital, operating and maintenance costs when compared with other technologies. Consequently, the use of those hybrid technologies leads to rise in the payback period of the GT.

Andrepont and Steinmann [90] suggested chilled water as the storage medium for inlet air cooling as it needs a relatively low refrigeration capital cost when compared to ice storage-based systems. However, due to its limited air-cooled temperature delivery of about 7 °C , depending upon ambient site temperatures, chilled water systems may not give improvements in GT performance when compared to ice storage-based systems. This is because ice has a higher thermal energy density than water. As an alternative, Cross et al. [91] modeled a GTIAC system that consists of GT, ice harvester, chiller and storage system in order to investigate the performance of a complete system suggested the use of a hybrid ice-chilled-water thermal storage system by employing a chilled water system to achieve the bigger share of the inlet air cooling load and a smaller ice storage system to meet the 4 °C requirements. They deduced that ice storage-based systems and hybrid systems could produce 11% greater increase in plant capacity when compared to chilled water-based systems. They also compared the ice storage-based system to the hybrid system, and deduced that the hybrid system could yield the same performance benefits as the ice storage-based system, but it is 6-36% cost efficient. However, these results majorly depend on the GT load profile, and may need to be recalculated for different load profiles.

Farzaneh-Gord & Deymi-Dashtebayaz [26] carried out a comparative analysis of evaporative cooler and mechanical chiller for inlet air cooling techniques, and came up with new technique that uses turbo-expanders to increase performance of a GT situated at the Khangiran refinery (Iran). Their results revealed that turbo-expander technique has the superior cost benefit, due to its improved power and a lesser payback period. Noroozian & Bidi [93] proposed a turbo-expander connected to a mechanical chiller in order to improve GT performance in a local power plant in Iran. The turbo-expander connected to a mechanical chiller improves both the net power output and thermal efficiency by 1.138% during the hottest period.

Hybrid fogging systems can be retrofitted to cooling systems that are incapable to decrease the inlet air temperature to the wet bulb temperature [51]. The systems can be used in front of a chiller to give a colder inlet temperature, and can be used in conjunction with an evaporative cooler to reduce the inlet air to its wet-bulb temperature as the evaporative cooler cannot do so on its own. In the case of the evaporative-fogging hybrid, excess fogging can be used so that fog droplets evaporate inside the compressor and so provide intercooling. Kakaras et al. [65] analyzed the impact of ambient air temperature on output and efficiency of a model of SGT and CCPP they developed, and proved that the 40-45 °C ambient temperatures common in Southern Europe cause losses in excess of 20%, and demonstrated the potential gains from integrating evaporative media and absorption chillers. Wang & Chiou [94] examined the combination of steam injection and inlet air cooling to enhance the capacity and efficiency of GTs in peak-power generation having daily on-off usage patterns. The system used the waste exhaust heat energy from the turbine and yielded a power increase of 70% and a 20.4% heat rate improvement. Zamzam & Al-Amiri [74] developed a cooling technology using a hybrid system of an indirect evaporative (cooling tower) system and a refrigerative cooling system. The suggested hybrid system uses the cooling tower as the main source of cooling to meet the cooling load of the GTIAC system. Once the maximum capability of the cooling tower has been reached, the chiller serves to supplement the remaining cooling load.

Finally, Al-Ibrahim et al. [95] analyzed a pilot scheme in the central Qaseem region of Saudi Arabia, where six GTs with total rated power of 450 MW were retrofitted with a GTIAC system. The cooling system has a combined ammonia refrigeration plant with ice harvesting evaporators, air-cooled condensers, and storage tanks of 8000 m^3 capacity of chilled water. The system can provide cooling for a 5 hours demand period with a peak cooling capacity of 66.5 MW. Prior to the retrofit, the GTs actual power fell by 24%, reaching 342 MW in the summer mid day ambient of 50 °C. The system cooled the inlet air to 10 °C producing a 33% power increase.

2.5. Design Criteria of Inlet Air Cooling Technologies

There are certain criteria to be considered while designing the inlet air cooling technologies in order to maximize efficiency, power output, profitability and encourage environmental friendly. These design criteria are installation / O&M costs, water and fuel costs, site location, losses due to parasitic power and inlet pressure drops, and environmental hazard. The design criteria is always depended on the demand of the client and location of the plant. Chacartegui et al. [29] gave an extensive cost and parasitic load estimates for the major GTIAC systems. The deciding economic factors supporting the selection of other inlet cooling systems are identified as installation and O&M costs, water and fuel costs, losses due to parasitic power and inlet pressure drops, tariffs and power generation agreements, and environmental and legislative costs [63, 96, 97]. Guinn [96] revealed that single-point site conditions should not be applied in ascertaining plant capacity as worst case temperature and humidity are not coincidental. The highest relative humidity take place at the lowest temperature, usually early morning and the least relative humidity occurs at the highest temperature, usually noon. Thus, relative humidity is not at its highest during the hottest part of the day, even very humid locations at such times may be 10°C below the wet-bulb temperature. Wetted media evaporative cooling may not function under such conditions, but high-pressure fogging may likely be a viable choice.

The output of GTs is a function of air intake temperatures, with output power dropping by 0.5-0.9% for every 1°C rise. When ambient temperatures reach 35°C, outputs may have decreased by 20% and heat rates increased by 5%. McNeilly [98] and Chaker et al. [99] emphasized the importance for accurate climatic data at the inlet cooling design stage, since there is rarely enough suitable climatic data upon which to make design decisions. The data accessible is mainly averaged and not coincident dry and wet-bulb temperatures. Average data result in the erroneous conclusion that the cooling potential is much less than it really is. Therefore, they made a comprehensive climatic analysis of 122 locations in the US and calculated the equivalent number of hours of cooling that can be achieved by direct evaporative cooling for each month of the year and for a range of adiabatic saturation temperatures (wet bulb temperatures). Chaker & Meher-Homji [100] extended this to an additional 106 locations worldwide, including Dhahran and Riyadh in Saudi Arabia. The standards for testing the components of the refrigerative system (cooling coil, chiller loop, cooling tower, etc.) as part of the multiple components of the GTIAC system were developed by Sullivan & Giampetro [101].

Khaliq et al. [102] stated that the performance analysis of GTIAC systems based on first law of thermodynamics (net work output) alone is not sufficient, and a more meaningful analysis can be attained if the second law of thermodynamics is applied to predict the irreversibilities encountered such that the component that wastes maximum work potential is identified. Khaliq et al. [102] then applied the thermodynamic model developed by Zaki et al. [37] in order to report entropy produced as a result of heat transfer and fluid flow during the refrigeration cycle. The result of his work revealed that both the first and second law efficiencies reduce as the cooling air mass flow rate rises. Nevertheless, the rate of improvement of the first law efficiency is greater than that of the second law efficiency. Hence, the second law analysis revealed that the GT combustion chamber is responsible for 80% of the irreversibilities experienced within the cycle.

3. Conclusion

Gas turbine is a constant volume machine that the air volume that enter the CC after the compression stage is fixed for a given shaft speed. Thus the air mass flow is proportional to the density of air and the introduced volume. Since it is fixed volume machine, only the density of the air can be modified to vary air mass. The density of the air depends on the relative humidity, altitude, pressure drop and temperature. Hence, the density of the air, and by extension, the mass flow rate will vary with the relative humidity, altitude, pressure drop and temperature The IAC technology has its advantages and inconveniences according to different factors such as ambient conditions, power output enhancement, investment cost and payback time and cooling capacity. Inlet air fogging is the spraying of finely atomized demineralized water into the inlet airflow of a GTPP. This enables the droplets to evaporate quickly, and subsequently reduce the temperature of the air at the compressor inlet and enhances the power output of the GT. Demineralized water should be utilized instead of water with mineral content to prevent fouling of the compressor blades. The wetted media and high pressure fogging are dependent on the relative humidity of the inlet air and required high water consumption. However, both technologies have low capital cost, O&M costs, low performance rise and more suitable in arid climates. Fogging has low operating costs and minimizes emissions of Oxides of nitrogen (NOx) because of the additional water vapour that quenches hot spots in the combustion chamber of the gas turbine. Thermal energy is used to produce cooling instead of mechanical energy in vapour absorption chillers technology; the heat source is mainly leftover steam from combined cycle, and it is processed to reduce the inlet air temperature. Thermal energy storage has low coefficient of performance when compared with vapour compression refrigeration. However, since TES uses waste heat, it decreases the operational cost and also minimizes greenhouse effect. This technique is a viable option in greener society. The mechanical chiller can improve the GT performance better than wetted technologies due to the fact that inlet air can be chilled below the wet bulb temperature, irrespective of the weather conditions. It has higher initial capital cost, however GT power enhancement and efficiency is maximized, and the extra-cost is amortized due to increased output power. Thermal energy storage (TES) tank minimizes operational cost and refrigerant plant capacity. The production of chilled water when ambient temperature and electricity demand are low is one of the advantages of TES as it uses the excess of power generation during peak period. Other advantages of TES are increase of steam mass flow in the combustion chamber, minimization of GT emissions (SOx, NOx, CO_2), and increase in power-to-installed volume ratio. In conclusion, the literature review showed that none of the technique is basically preferable than the other, rather the choice is dependent on the external conditions such as site, economics and interest (green society).

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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