Combined Cycle Power Plant Performance Enhancement Based on Inlet Air Cooling Techniques: A Technical Review

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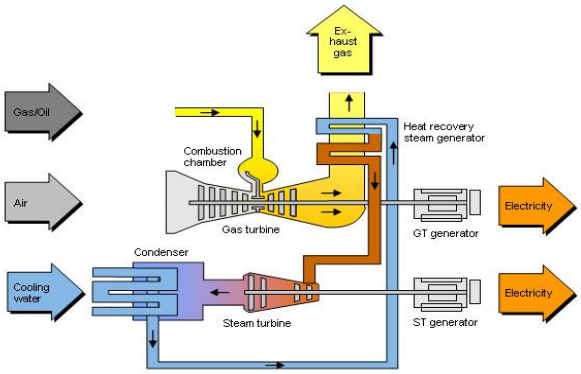
***Abstract:* - This paper is intended to review the literature on research, development and latest advancement related to combined cycle power plants performance enhancement techniques. A gas turbine and a steam turbine together called as combined cycle power plant which produces approximately 50 percent more electricity from the same fuel than a traditional simple gas turbine cycle power plant. The performance of combined cycle power plant mainly depends on the gas turbine inlet air temperature, the rate of mass flow through it and various operating parameters. This can be achieved by gas turbine inlet air cooling techniques. 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 leveling of gas turbine power output.**

Keywords: - Combined Cycle Power Plants, Performance Enhancement Techniques, Mechanical Chillers, Absorption Chillers

I. INTRODUCTION

The basic principle of the Combined Cycle power plant has a compressor, combustion chamber and a gas turbine (GT) which is coupled to generator to produce electricity and the waste exhaust heat energy is used to make steam and to generate additional electricity via a steam turbine. The gas turbine is one of the most efficient one for the conversion of gas fuels to mechanical power and in turn in to electricity using generator. A Combined Cycle Power Plant produces high power outputs at high efficiencies (up to 58%) and with low emissions. In a Conventional power plant we are getting 35% electricity only and remaining 65% as waste energy to atmosphere. By using combined cycle power plant we are getting 68% electricity.

From the diagram, First step is the same as the simple cycle gas turbine plant. An open circuit gas turbine has a compressor, a combustor and a turbine. The output temperature of flue gases is very high. This is therefore high enough to provide heat for a second cycle which uses steam as the working medium i.e. thermal power station.



1) Air Inlet: This air is drawn though the large air inlet section where it is cleaned cooled and controlled. Heavy-duty gas turbines are able to operate successfully in a wide variety of climates and environments due to inlet air filtration systems that are specifically designed to suit the plant location. Under normal conditions the inlet system has the capability to process the air by removing contaminants to levels below those that are harmful to the compressor and turbine.

2) Turbine Cycle: The air which is purified then compressed and mixed with natural gas and ignited, which causes it to expand. The pressure created from the expansion spins the turbine blades, which are attached to a shaft and a generator, creating electricity. In second step the heat of the gas turbine’s exhaust is used to generate steam by passing it through a heat recovery steam generator (HRSG) with a live steam temperature between 420 and 580 °C**.**

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3) Heat Recovery Steam Generator: In Heat Recovery Steam Generator highly purified water flows in tubes and the hot gases passes a around that and thus producing steam .The steam then rotates the steam turbine and coupled generator to produce Electricity. The hot gases leave the HRSG at around 140 degrees centigrade and are discharged into the atmosphere. The steam condensing and water system is the same as in the steam power plant.

4) Typical Size and Configuration of CCGT Plants: The combined-cycle system includes single-shaft and multi-shaft configurations. The single-shaft system consists of one gas turbine, one steam turbine, one generator and one Heat Recovery Steam Generator (HRSG), with the gas turbine and steam turbine coupled to the single generator on a single shaft. Multi-shaft systems have one or more gas turbine-generators and HRSGs that supply steam through a common header to a separate single steam turbine-generator. In terms of overall investment a multi-shaft system is about 5% higher in costs. The primary disadvantage of multiple stage combined cycle power plant is that the number of steam turbines, condensers and condensate systems-and perhaps the cooling towers and circulating water systems increases to match the number of gas turbines.

5) Efficiency of CCGT Plant: Roughly the steam turbine cycle produces one third of the power and gas turbine cycle produces two thirds of the power output of the CCPP. By combining both gas and steam cycles, high input temperatures and low output temperatures can be achieved. The efficiency of the cycles adds, because they are powered by the same fuel source. The electric efficiency of a combined cycle power station may be as high as 58 percent when operating new and at continuous output which are ideal conditions. As with single cycle thermal units, combined cycle units may also deliver low temperature heat energy for industrial processes, district heating and other uses. This is called cogeneration and such power plants are often referred to as a Combined Heat and Power (CHP) plant. The efficiency of CCPT is increased by Supplementary Firing and Blade Cooling. Supplementary firing is arranged at HRSG and in gas turbine a part of the compressed air flow bypasses and is used to cool the turbine blades. It is necessary to use part of the exhaust energy through gas to gas recuperation. Recuperation can further increase the plant efficiency, especially when gas turbine is operated under partial load.

Merits

1. Fuel efficiency: In conventional power plants turbines have a fuel conversion efficiency of 33%which means two thirds of the fuel burned to drive the turbine off. The turbines in combined cycle power plant have a fuel conversion efficiency of 50% or more, which means they burn about half amount of fuel as a conventional plant to generate same amount of electricity.
2. Low capital costs: The capital cost for building a combined cycle unit is two thirds the capital cost of a comparable coal plant.
3. Commercial availability: Combined cycle units are commercially available from suppliers anywhere in the world. They are easily manufactured, shipped and transported.
4. Abundant fuel sources: The turbines used in combined cycle plants are fuelled with natural gas, which is more versatile than a coal or oil.
5. To meet the energy demand now a day's plants are not only using natural gas but also using other alternatives like bio gas derived from agriculture.
6. Reduced emission and fuel consumption: Combined cycle plants use less fuel per kWh and produce fewer emissions than conventional thermal power plants, thereby reducing the environmental damage caused by electricity production. Comparable with coal fired power plant burning of natural gas in CCPT is much cleaner.

Demerits

1. The gas turbine can only use Natural gas or high grade oils like diesel fuel.
2. Because of this the combined cycle can be operated only in locations where these fuels are available and cost effective.

II. LITERATURE REVIEW

Alhazmy and Najjar [1] have analysed the inlet air chilling using a cooling coil and observed that the cooling coil improves the turbine output by 10 % during cold humid conditions and by 18 % during hot humid conditions. However, net power generated from the plant drops by 6.1 % during cold and humid conditions and 37.6 % during hot and humid conditions.

Amell and Cadavid [2] have examined the influence of the relative humidity on the atmospheric air-cooling thermal load of gas powered thermal station (GPTS) installed in Colombia. The inlet air cooling techniques investigated were vapour compression and ice storage based systems.

Srivastava and Yadav [3] have investigated the performance of a combined cycle using vapour compression refrigeration system. The result shows that the plant specific work of the combined cycle increases by 4 % and plant efficiency by 0.39 percentages.

Lucia et al. [4] have examined the operation of cogeneration gas turbine power plant with and without an air cooling system and concluded that in the Italian climate, the turbine power output may increase by upto19 %, if the compressor inlet air is cooled to10 °C.

Al-Ansari and Ali [5] have analyzed a hybrid turbine inlet air cooling (TIAC) system consisting of mechanical chilling followed by evaporative cooling applied to a gas turbine power plant in Saudi Arabia. An enhancement of more than 10 % power has-been reported. The cost operation analysis shows clearly that the hybrid TIAC method with wet cooling has the advantage over the other analyzed methods and it would be profitable to install it in the new gas turbine power plants.

Sanaye et al. [6] have performed a thermo economic analysis of ice thermal energy storage system for gas turbine inlet cooling application. The system comprises of a gas turbine, air cooler, and a thermal energy storage unit with vapour compression refrigeration cycle. The addition of inlet air-cooling has been reported to enhance power by 3.9- 25.7 % and efficiency by 2.1-5.2 %

Najjar [7] has analyzed an aqua-ammonia absorption chiller and reported improvement in simple cycle efficiency and power by cooling the inlet air using an absorption system.

Mohanty and Paloso [8] have used lithium-bromide, double-effect absorptionchiller which produced as much as 11 %additional electricity from the same gas turbine power plant.

Kakaras et al. [9] revealed that the absorption chiller can considerably increase the power output, although there is a reduction in thermal efficiency.

Boonnasa et al. [10] have summarized that the addition of absorption chiller could increase the power output of a gas turbine by about 10.6% and the combined cycle power plant by around 6.24%annually.

Sexton et al. [11] boosted power output of a LM-2500 engine by 34% with a spray rate of 24 g/m into the compressor inlet.

Jonsson and Yan [12] concluded that intercooling technologies are still at the experimental stage.

Nasser and El-Kalay [13] proposed the use of a simple Li-Brheat-recovery absorption system to cool the air intake of a gas turbine compressor in Bahrain to compensate for the 30 ^{0}C summer to winter variation in ambient temperature. They calculated that heat from the exhaust gases can decrease a 40 ^{0}C ambient inlet air temperature by 10 ^{0}C, giving a power increase of 10%.

Bies et al. [14] studied the use of a lithium bromide double-effect absorptionchiller to cool warm ambient air entering a gas turbine compressor.

Mohanty and Paloso[15] studied a similar system for a 100MWgasturbine in Bankok, taking the inlet temperature down to 15 ^{0}C. They achieved instantaneous power output increases of between 8 and13%, with an overall increase of 11%.

Kakaras et al. [16] developed a computer simulation a simple cycle gas turbine and a combined cycle plant. They examined the effect of ambient air temperature on output and efficiency, showed how the 40 to 45 ^{0}C ambient temperatures common in Southern Europe cause losses in excess of20%, and demonstrated the potential gains from integrating evaporative media and absorption chillers. Evaporative cooling changes physical state along the adiabatic line and limits before 100%relative humidity is achieved. The advantage of the proposed absorption system is that, independent of ambient air conditions, it can cool intake air to a specific constant temperature and consistently increase plant output.

Ameri and Hejazi[17] report that there are more than 170 gas turbine units in Iran with a combined capacity of 9500 MW, but hot weather during the summer results in 1900 MW losses. They conducted an economic analysis of a gas turbine intake air-cooling system in the Iranian Chabahar power plant. The system described uses a steam-absorption chiller and output power was increased by 11.3%.

Al-Bortmany[18] discussed the use of aqua-ammonia absorption chillers powered by heat extracted from gas-turbine exhaust gases. The inlet air of two gas turbines in Oman was cooled to 7 ^{0}C resulting in power gains of 20% and 14%.

Boonnasa et al. [19] evaluate methods of enhancing the capacity of an existing combined cycle power plant in Bangkok, Thailand. A steam-absorption chiller is proposed to cool the ambient gas turbine inlet air to 15 ^{o}C. The power gain is expected to be about 10.6% with a payback time of 3.8 years.

Dawoud et al. [20] calculated an expected gain of 19.7% in the power output of a GE Frame6B CT located in Oman if an absorption chiller was used to cool the inlet air to the CT.

Hall et al. [21] documented the performance of a 36 MW CT plant in which a chilled water-based storage refrigeration system is used to cool the inlet air. The cooling system was able to reduce the air from an ambient temperature of 35 ^{0}C to 7 ^{0}C, thus enhancing plant performance by 10%. They also showed that the size, and hence cost, of cooling systems is directly proportional to the number of hours of cooling required, and that direct cooling and thermal energy storage systems cost about the same, despite the greater capacity of direct cooling, due to the cost of the thermal storage facilities.

Andrepont and Steinmann [22] recommended the selection of chilled water as the storage medium for inlet air cooling as it requires a relatively low refrigeration capital cost compared to ice storage-based systems. However, due to its limited air-cooled temperature delivery of about 7 ^{0}C, depending upon ambient site temperatures, chilled water systems may not yield enhancements in CT performance comparable to ice storage-based systems. This is because ice has a higher thermal energy density than water.

Cross et al. [23] developed and validated a detailed model for a CTIAC system including the CT, ice harvester, chiller, and storage system. The model was used to predict the performance of a complete system using different power plant loads, and the storage system size was determined for each load profile.

Ameri et al. [24] discuss the economic design criteria behind the choice of chilled water and ice storage thermal energy storage systems for CTIAC for the Kish power plant. The plant is located in an area of Iran with humidity high enough to rule out the use of evaporative techniques. Chilled water storage was found to be economically preferable to ice storage. The proposed system was able to lower the ambient

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temperature from a high of 45 ^{0}C to 7.2 ^{0}C. The system uses off-peak power for 17 h to chill the system to provide 7 h of cooling. It has a power gain of 13.6% and an internal rate of return of 27.3%.

Amelland Cadavid [25] examines the influence of relative humidity on the thermal load of vapour compression and ice storage systems for CTIAC systems in coastal areas of Colombia. Because thermal load isa function of air mass flow, relative humidity, ambient temperature, and cooling temperature; changes in relative humidity from the region's average design criterion of 34%, to the average value at the power plant locations of 80%, result in a 94% increase in thermal load. Installed vapour compression and ice storage cooling systems are often under-designed and have higher than expected energy requirements.

Yokoyama and Ito [26] investigated how unit size and cost of gas turbine cogeneration plants are affected by inlet air cooling with ice storage. They examined capacity with and without air cooling and determined annual costs.

Behafarid and Bahadori [27] used an aquifer to store thermal energy for a CTIAC system. The aquifer water was extracted and re-injected into the aquifer throughout the year: in winter the ambient temperature cooled the water, in summer the cooled water was used to cool the turbine inlet air. The system was used for cooling for 6 h a day during the summer and increased efficiency from 31.8% to 34.2%.

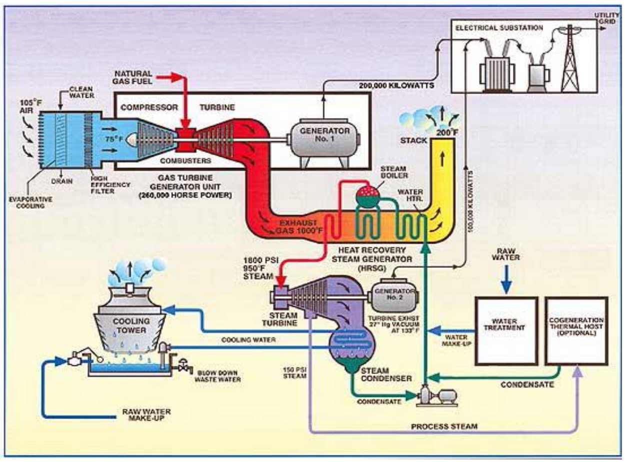
Zurigat et al. [28] evaluated the potential of ice and chilled thermal energy storage to cool gas turbine inlet air in Oman. They found the cost of chilled water and ice storage tanks to be uneconomical. They also investigated the option of partial thermal energy storage and found that reduced storage capacity does not result in a reduction of chiller size. They concluded that without a time-of-use utility rate structure the system would not be viable.

III. COMBINED CYCLE POWER PLANT INLET AIR COOLING TECHNIQUES

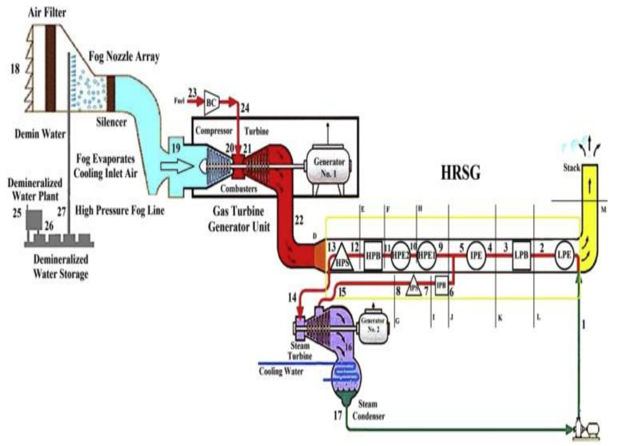
Increasing output for regions where significant power demand and highest electricity prices occur during the warm months. Inlet air-cooling increases the power output by taking advantage of the gas turbine's feature of higher mass flow rate when the compressor inlet temperature decreases. Different methods are available for reducing gas turbine inlet air temperature. There are as follows.

1. Evaporative cooler
2. Fogging system
3. Mechanical refrigeration system
4. vapour Absorption chiller

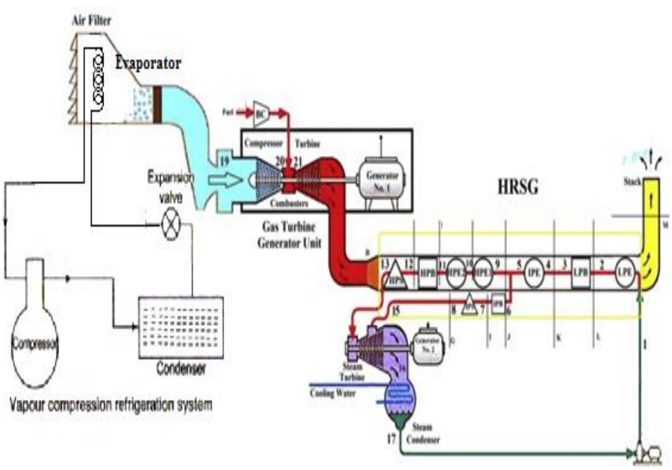
1. Evaporative cooler: In this method, in the entrance of filter chamber, a hive-shaped humid field is installed that cools the inlet air by circulating water and vaporizing it in the field of action. Generally such system is effective to go down the compressor inlet air temperature to the ideal conditions of the environment. The diagram is as shown below.



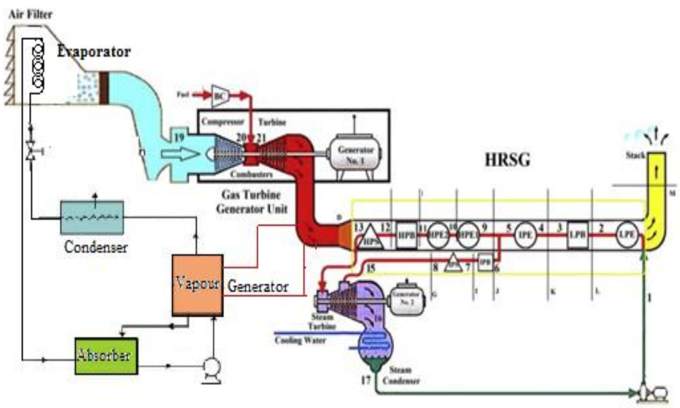
2. Fogging system: In this method, Inlet air fogging consists of spraying finely atomized water (fog) into the inlet airflow of a gas turbine. The water droplets evaporate quickly, which cools the air and increases the power output of the turbine. Demineralised water is typically pressurized to 2000 psi (138 bar) then injected into the inlet air duct through an array of stainless steel fog nozzles. Demineralised water is used in order to prevent fouling of the compressor blades.



3. Mechanical refrigeration system: This technology used mechanical devices to produce chilled water to cool inlet air at heat exchanger installed in side inlet air duct, this technology suitable for the high ambient temperature and high relative humidity.



4. Vapour Absorption chiller: This operates based on vapour absorption refrigeration cycle. This cycle consists of four major heat exchangers, (generator, condenser, evaporator and absorber) with two kinds of solution, (refrigerant and absorbent). During this cycle high pressure will prevail inside generator and condenser, while inside evaporator and absorber there will be low pressure. The cycle starts with input waste heat in the generator. As a result of this heat input, the solution in the generator will be separated into refrigerant and weak solution. The refrigerant in the vapour form will enter into condenser and will change into liquid. The solution part will enter absorber, since there is a pressure difference between condenser and evaporator; the refrigerant will flow inside evaporator and will absorb heat from cooled water that is in circulation inside evaporator. Consequently, the temperature of circulated water decreases and then it is used for air-conditioning purpose. The evaporated refrigerant will then enter absorber where it will be mixed with weak solution, the mixture will then get the liquid state and finally it will enter generator and the cycle is repeated.



IV. CONCLUSION

A review of combined cycle power plant inlet air cooling systems has been presented. Selection of best cooling method for inlet air of combined cycle power plant is a vital task and cannot be determine without several analysis and reviews. It depends on location, source of availability and energy (type of fuels). It also depends on exergoeconomic and even multi-objective optimization. After study of several research review papers we came to a conclusion that vapour absorption refrigeration cooling technique is an appropriate method for inlet air cooling of combined cycle power plant and also it is recommended by many researches.

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