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Effectiveness and Economic Feasibility of Gas Turbine Inlet-Air Cooling by Air Washing in the Hot and Dry Climate of Sudan

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Abstract: This paper studies the effectiveness and economic feasibility of cooling the gas-turbine's inlet-air by air washing (AW) compared to wetted-media evaporative cooling (WMEC) in the hot and dry climatic conditions of Sudan. Measurements were made on an experimental test rig to determine the cooling effect of the WMEV and that of AW with water at ambient temperature and with chilled water. Taken at two seasons of the year with different ambient temperature and humidity levels, the experimental results were used to estimate the revenues that the systems can generate as a result of increased megawatts and reduced heat rate of a typical gas turbine model (GE PG6581B). The calculations indicate that the WMEC system can increase the gas turbine output by 12% and reduce its heat rate by 1.6%. Using un-chilled water, the AW system can increase the output by 16.7% and reduce the heat rate by 2.2%, while with chilled water it can increase the power by 23.3% and reduce the heat rate by 3.1%. Based on these estimates, the WMEC system requires a payback period of 8 months if run for 4 hours daily, which reduces to 4 months if used for 8 hours. AW with un-chilled water has a payback period of about 8 months, but the pay-back period for the chilled-water AW system is about 5 years.

Keywords: *Gas turbine; Power augmentation; Inlet-air cooling; Hot and dry climate.*

1. INTRODUCTION

It is well known that the generation capacity of a gas turbine diminishes with increased air temperature. High inlet-air temperature reduces the air density, leading to a reduction in the power generated from the turbine and a higher heat rate. According to Cracken [1], gas turbines produce 25-35% more power in winter than in summer and at 5-10% lower heat rate (kJ/kWh) which means less fuel consumption by an average of 6% saving in fuel. Since the ambient temperature in Sudan is high almost all the year round, gas turbines have lower power output and higher heat rate compared to their design values particularly in summer time when they are mostly needed. Due to high ambient temperature in summer (average of 42oC) the gas turbines lose 25% of their rated capacity at the standard design conditions. Moreover, the highest temperatures occur during the hot midday hours when the demand is high; thus causing frequent power interrupts and blackouts. Cooling the air entering the gas turbine's compressor is one of the most practiced power augmentation methods used to avoid loss of generation capacity.

There are a number of proven inlet-air cooling technologies that include the wetted media-type evaporative systems, fog-cooling systems, mechanical refrigeration systems, and absorption refrigeration systems [2-7]. Johnson [2] presented a discussion of the theory and operation of evaporative coolers for industrial gas turbine installations. Chaker and Meher-Homji [3] presented a detailed climatic analysis of 106 major locations over the world to provide the hours of cooling that can be obtained by direct evaporative cooling. Their data helps gas turbine operators in assessing the economics of evaporative fogging. Hasnain et al [4] looked into the prospects of thermal storage systems in Saudi Arabia which has similar climatic conditions to Sudan's. They estimated that the use of ice storage systems with gas turbines for inlet air cooling would increase the turbine's output by 30% and reduce its heat rate by 10% at a mere fraction of the cost of installing additional capacity for power generation in order to meet the summer peak demand. Jaber et al [5] presented a theoretical study on the influence of intake air cooling on the gas turbine performance by evaporative cooling and refrigeration coil cooling. A computer simulation model was developed in order to evaluate the performance of the PG5341 gas turbine unit at Marka Power Station, Amman, Jordan. Their results showed that the evaporative cooling system was capable of boosting the power and enhancing the efficiency of the gas turbine unit in a way much cheaper than the cooling coil system. Due to the high power consumption required to run the vapour-compression refrigeration unit, the payback period of the coil system was 5 years while that for the evaporative cooler was 2 years.

The present study compares the cooling effectiveness and economical feasibility of gas-turbine inlet-air cooling by air-washing and by conventional wetted-media evaporative cooling under the climatic conditions of Sudan. The advantage of the air washing system over the wetted-media system is that it enables the use of chilled water, which greatly increases its cooling effectiveness. However, the system requires the water to be de-mineralised, which increases its initial cost and limits its operation time. On the other hand, the cooling effectiveness of the wetted-media evaporative system is bound by the wet-bulb temperature, but as its water quality requirement is less stringent, it can be used for prolonged hours. The longer operating hours increase its daily revenues and decrease its payback period. In order to compare the two cooling systems taking their advantages and limitations into consideration, a special experimental rig has been developed. Experimental tests were performed on the test rig to determine the cooled-air temperature with the two systems at two times of the year with different climatic conditions. The measurements were then used to estimate the expected increase in the gas-turbine's power and thermal efficiency and the resulting revenues from increased generation capacity and fuel savings. By estimating the required installation costs, the study determines the payback periods of the systems for the gas turbine model PG6581B, which exists at Garri Power Station.

2. The Test Rig

Figure (1) shows the test rig developed for the purpose of the present study [8]. The rig consists of a circular duct 0.6 m in diameter and 3.0 m long which is raised on a structure to a height of about 1.2 m above the floor. A conventional 3000 cfm evaporative cooler is positioned at the duct's entrance. The evaporative air-cooler serves two purposes; the first of which is to assess the effectiveness of traditional evaporative cooling. When testing the effectiveness of air-washing, the cooling pads were removed and the fan of the evaporative cooler was used to circulate air through the duct. Spray nozzles (18 nozzles) were put in the duct to spray water in opposite direction of inlet air. The water supply system consists of a container, a water pump, and necessary piping, fittings and valves. The container stores iced water for running the experiment with air-washing using chilled water. Water is added manually to the containers to compensate for the water sprayed into the air flow. The measurements taken were temperature and humidity at different locations along the duct.

Figure (1). A general view of the test rig.

3. The Experimental Results

Experiments were performed on the test rig so as to assess the effectiveness of air washing compared to traditional evaporative cooling under different ambient conditions. The climate of Sudan is influenced by the north-south movement of dry northerly winds and moist southerly winds that produce a wet summer and a dry winter [9]. The area passes through three main seasons, summer (March – July), autumn (July – October) and winter (November – March). To represent different ambient conditions, two sets of experiments were performed on the test-rig; one set was carried out in July 2010 and the other in March 2011. Each set consisted of three experiments. The first experiment evaluated the cooling effect of the wetted-media evaporative cooler. The second and third experiments evaluated the performance of air washing at different water temperatures. Tables (1) to (3) summarise the results of the different experiments.

Table (1). Performance of evaporative cooling.

		July 2010	March 2011
Air-Side	Inlet dry-bulb [ºC]	33.8	28.3
	Inlet wet bulb temperature [ºC]	22.8	14.4
	Inlet humidity (%)	42	21
	Exit dry-bulb [ºC]	28.6	20
	Exit humidity (%)	81	83

Table (2). Performance of air washing with water at ambient temperature.

		July 2010	March 2011
Air-Side	Inlet dry-bulb [ºC]	32.8	27.3
	Inlet wet bulb temperature [ºC]	22.7	14.4
	Inlet humidity (%)	42	22
	Exit dry-bulb [ºC]	23.7	18.3
	Exit humidity (%)	82	89
Water Side	Inlet temperature [ºC]	34	25.5
	Exit temperature [ºC]	37	26

Table (3). Performance of air washing with chilled water.

		July 2011	March 2011
Air-Side	Inlet dry-bulb [ºC]	33.8	28.3
	Inlet wet bulb temperature [ºC]	23.8	11.9
	Inlet humidity (%)	42	21
	Exit dry-bulb [ºC]	21.2	15.7
	Exit humidity (%)	81	91
Water Side	Inlet temperature [ºC]	7.5	7
	Exit temperature [ºC]	11	10.5

The figures on the tables indicate that the ambient temperature in July was higher than that in March by about 5^{o}C. However, the relative humidity in March was lower by about 20%; which makes evaporative cooling an effective cooling method even at times of the year when the ambient temperature is relatively low. Table (1), which shows the results obtained when the system was operated as an evaporative cooler, shows that the air temperature dropped in July from 33.8ºC to 28.6ºC to and in March it dropped from 28.3ºC to 20ºC, respectively. Thus, the inlet air was cooled by about 5^{o}C in July and by about 8ºC in March. Table (2) shows the results when air washing was used with water at ambient temperature. In this case, the system works as an evaporative fog-cooler. The figures on the table show that air-washing reduced the air temperature by about 9^{o}C in July and by about 9^{o}C also in March. Table 3 shows the results when chilled-water, at about 7^{o}C, was sprayed instead of water at ambient temperature. In this case, the air temperature could be reduced by about 12.5^{o}C in both July and March.

4. Feasibility of Gas Turbine Inlet-Air Cooing under Local Conditions

In this section, the feasibilities of the alternative cooling methods are compared by their payback periods. The simple payback period of any investment is obtained by dividing its installation cost (C) by its annual revenue (R). The revenues and installation costs of the alternative cooling options are estimated on the basis of the experimental results described in the previous section. The revenues come from two main sources; the revenue due to the increase in generation capacity (R_1) and the revenue due to reduced heat rate and fuel saving (R_2). Taking the turbine's power and heat rate before cooling as P_h and HR_h, respectively, and those after cooling as P_c and HR_c, respectively, then these revenues can be obtained from:

$$R_1 = (P_c - P_h)\ (\text{kW}) \times \text{System operation hours per day} \times \text{System operation days per week} \times \text{Weeks per year} \times \text{Price of electricity (\$/kWh)} \quad (1)$$

$$R_2 = P_c\ (\text{kW}) \times \text{System operation hours per day} \times \text{System operation days per week} \times \text{Weeks per year} \times (HR_h - HR_c)/(\text{Calorific value of fuel} \times 1000) \times \text{Price of fuel (\$/ton)} \quad (2)$$

The required investment (*C*) for a given system is obtained from:

$$C = (P_c - P_h)\ (\text{kW}) \times \text{Cost of inlet-air cooling system (\$/kW)} \quad (3)$$

In addition to a number of operational parameters, Equations 1-3 require specific values for P_h, P_c, HR_h and HR_c. These values depend on the particular gas-turbine model in use and on its characteristic response to the ambient air temperature. In what follows, these are determined based on the characteristics of the gas-turbine model GE PG6581B [13]. This model is used in a combined-cycle arrangement at Garri Power plant, which is the largest gas-turbine based thermal power station in the country. Table 4 shows the power and heat rate of this turbine at design conditions and at the local operating conditions. Due to the high ambient temperature, the power of the turbine drops by more than 10 MW [10,11]. The table also shows the increase in turbine power and decrease in heat rate that can be achieved by the alternative cooling methods as obtained from the data shown on Tables (1)-(3). The wetted-media evaporative system was assumed to reduce the air temperature by an average of 6.6^{o}C. Air-washing with water at ambient temperature was assumed to cool the air by 9^{o}C, while air-washing with chilled water was assumed to cool it by 12.5^{o}C.

Table 4: Effects of alternative cooling options on the GE PG6581B performance.

	Design (15^{o}C)	Ambient (36^{o}C)	Change per ^{o}C	Media-type evaporative cooler	A/W with normal water	A/W with chilled water
Power (kW)	41,160	30,000	-558	33,627	35,022	36,975
Heat rate (kJ/kWh)	11,318	11,909	29.55	11,716.9	11,643.1	11,539.6

Table 4 indicates that wetted-media evaporative cooling increases the gas turbine output by 13% and reduces its heat rate by 1.7%. Air-washing with tap water increases the output by 16.7% and reduces the heat rate by 2.2% while air-washing with chilled water increases the power by 22.3% and reduces the heat rate by 3.0%. To calculate the systems' payback periods, Equations 1 and 2 require the number of operation hours per day of the cooling system to be specified. For the air-washing, which requires water demineralisation, a short duration peak operating period of four hours per day is assumed. Since the evaporative cooling does not require such measures, it can be used for longer hours per day. The alternative systems are assumed to run for 5 days per week, 52 weeks per year. The revenues are based on the local residential tariff of 0.2 SDG/kWh (0.07 $/kWh) and fuel cost of 600 SDG/ton (200 $/ton). The calorific value of the fuel used, which is light-diesel oil, is taken as 43000 kJ/kg. The conventional wetted media evaporative cooling system can be installed for $50/kW of capacity enhancement **[**12**]**. The air-washing system with water at ambient temperature can also be installed for this cost, but the electric chilling costs 400$/kW of capacity enhancement.

Table 5 shows the estimated revenues and payback periods for the cooling systems based on the costs and the operational data given above. For the wetted-media evaporative system, the revenue and payback period are shown with 4, 6 and 8 hours of operation per day. With 4 hours of operation, the investment in the evaporative cooling system can be returned in less than 8 months, which drops to about 5 months and 4 months if the system is used for 6 and 8 hours per day, respectively. These figures are in good agreement with earlier estimations made locally [11,13]. The payback period of the air-washing system using water at ambient temperature is also 8 months, but the payback period of the system with chilled water just exceeds 5 years. In agreement with the present estimation for the electric chilling system, Jaber et al [5] also estimated a payback period to be around 5 years. The simple payback method is deficient in that it doesn't take into consideration the revenues over the whole lifetime of a given project. To compare the economical benefits of the alternative cooling systems over an extended period of time, Table 5 also shows the net revenues of the systems over 10 and 20 years. According to these figures, the wetted-media evaporative cooling system returns more revenues than both air-washing options if used for more than 6 hours per day.

Table (5). Annual revenues and pay-back periods for the cooling systems

	Evaporative cooling			Air washing	
	4 hours per day	6 hours per day	8 hours per day	with un-chilled water	with chilled water
Power increase revenue ($)	251,472	377,208	502,944	348,192	483,600
Fuel saving revenue ($)	31,243	46,865	62,486	45,054	66,065
Total revenue ($)	282,715	424,073	565,430	393,246	549,665
Enhancement (KW)	3,627	3,627	3,627	5,022	6,975
Enhancement cost ($/KW)	50	50	50	50	400
Investment ($)	181,350	181,350	181,350	251,100	2,79,000
Payback period (years)	0.64	0.43	0.32	0.64	5.1
Net revenue over 10 years ($)	2,645,801	4,059,376	5,472,952	3,681,363	2,706,649
Net revenue over 20 years ($)	5,472,952	8,300,102	11,127,253	7,613,825	8,203,297

5. Conclusions

The present study gives a clear advantage of the wetted-media evaporative cooling over the air-washing system under the hot and dry conditions of Sudan. Moreover, the present payback period estimation for the evaporative cooling system, which is less than a year, is much shorter than the value obtained by Jaber et al [5] who estimated a period of 2 years. Apart from the system's short payback period, it can also generate more lifetime's revenues than the air-washing system if used for more than 6 hours per day. The selection this type of cooling systems is also supported by other operational considerations in addition to its economical feasibility which include its low running cots and that it does not require a high level of technical expertise to operate. A factor that makes evaporative cooling even more attractive in Sudan than in other areas with similar hot and dry conditions is the availability of water.

However, it should be noted that the actual cost of a given cooling systems cannot be estimated accurately since it depends on the actual site and size of the gas turbine [12,14]. The costs used here are those given by Wang and Braquet [12] for the 50 – 100 MW gas turbines in a simple cycle plant, which are closest to the range used in Sudan. The costs given by the Annual Gas Turbine Handbook (2010 edition) [14] for larger sizes (F-class combined cycle) are as low as $15/kW for wetted-media and fogging systems and 185$/kW for electric chilling. The same reference gives 830$/kW as the cost of a new gas turbine, which exceeds by far the cost of any cooling system per kW. To apply the present results to similar climatic conditions in other countries, the local fuel cost and electricity tariff must be taken into consideration.

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