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Feasibility of Gas Turbine's Inlet-Air Cooling by Air Washing and Evaporative Cooling in the Dry and Hot Climate

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Abstract: This paper studies the effectiveness and economic feasibility of gas-turbine's inlet-air cooling by air washing (AW) and 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 WMEC 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 gas turbine model (GE PG6581B) used at Garri Power Station. 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 it is run for 4 hours daily, which can be reduced to 4 months if it is used for 8 hours. Air washing 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

Certain characteristics of gas turbines have made them the favoured engines for utility power production. These include fuel flexibility, short installation period and low initial cost, short start-up time (unlike steam turbines), wide-range of available power capacities (unlike internal-combustion engines), and low environmental pollution. However, it is well known that the performance of a gas turbine deteriorates 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 42^{o}C) the gas turbines lose about 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; which causes frequent power interrupts and blackouts.

Cooling the air entering the gas turbine's compressor is one of the most effective power augmentation methods used to avoid the loss of generation capacity. Proven inlet-air cooling technologies include the wetted media-type evaporative systems, fog-cooling systems, mechanical refrigeration systems, and absorption refrigeration systems [2-6]. The fog-cooling system can come with an option for overspray (wet compression) while the mechanical refrigeration system can be coupled with a thermal storage system. The main advantage of evaporative cooling systems over the refrigeration-based systems is their lower initial and running costs [7, 8]. These systems can also be run with minimum technical expertise, but they cannot cool the air below its wet-bulb temperature. Refrigeration systems are advantageous in that their cooling effect is not bound by the wet-bulb temperature. However, apart from their higher initial and running costs, conventional refrigeration systems have the disadvantage of placing cooling coils that obstruct the air-flow. The resulting pressure drop across the coils increases the parasitic energy requirements and reduces their benefit. A method that solves this problem which has not been applied widely so far, is by washing the air with chilled water (also called water scrubbing) [9]. The chilled water is pumped and directly sprayed in the face of the intake air after the filters and before entering the compressor. Nozzles break-up water into small particles that enhance the process of heat exchange between the cold water and air, leading to improved power augmentation effect. Unlike evaporative cooling, air-washing can produce dehumidification as well as humidification of the air flow. Dehumidification further increases the air density, which increases the benefit from air-washing in wet hot climates. Since the system requires refrigeration, it is also more expensive than evaporative coolers.

The present study evaluates the cooling effectiveness and economical feasibility of gas-turbine inlet-air cooling by air-washing and conventional wetted-media evaporative cooling under the hot and dry climatic conditions of Sudan. Under these conditions, each of the two cooling systems has certain merits that can improve its cooling effectiveness and economical feasibility. 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 by taking their advantages and limitations into consideration, a special experimental rig has been developed. Measurements were taken 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 is used at Garri Power Station.

2. THE TEST RIG

Fig. 1 shows a schematic diagram of the test rig developed for the purpose of the present study [10]. 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 air-cooler is positioned at the duct's entrance. The evaporative 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 the opposite direction of inlet air.

The water supply system consists of a container, a water pump, and the necessary piping, fittings and valves. The container stores iced water for running the experiment with air-washing by 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.

3. THE EXPERIMENTAL REESULTS

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 [11]. 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. Figs 2 and 3 show the results of the different measurements.

As shown by the figures, 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.

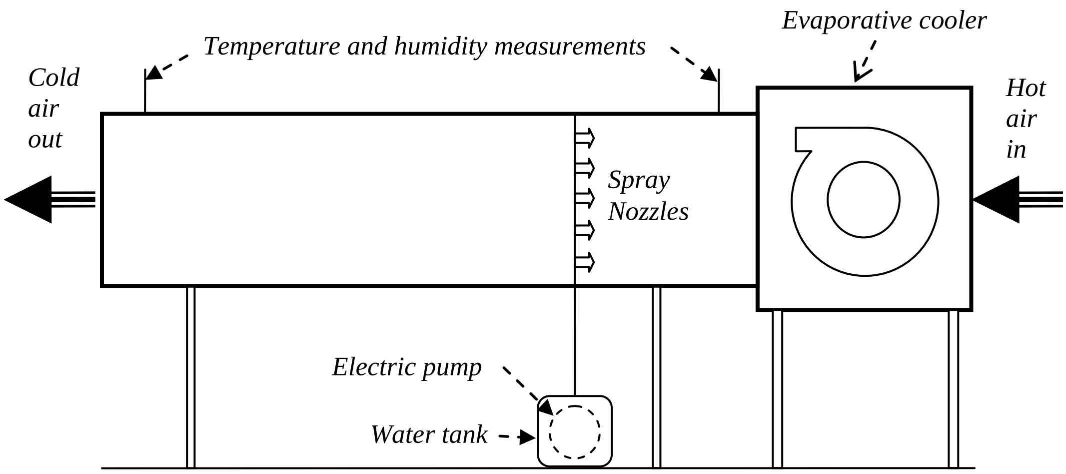

Fig. 1. A general schematic overview for the test rig

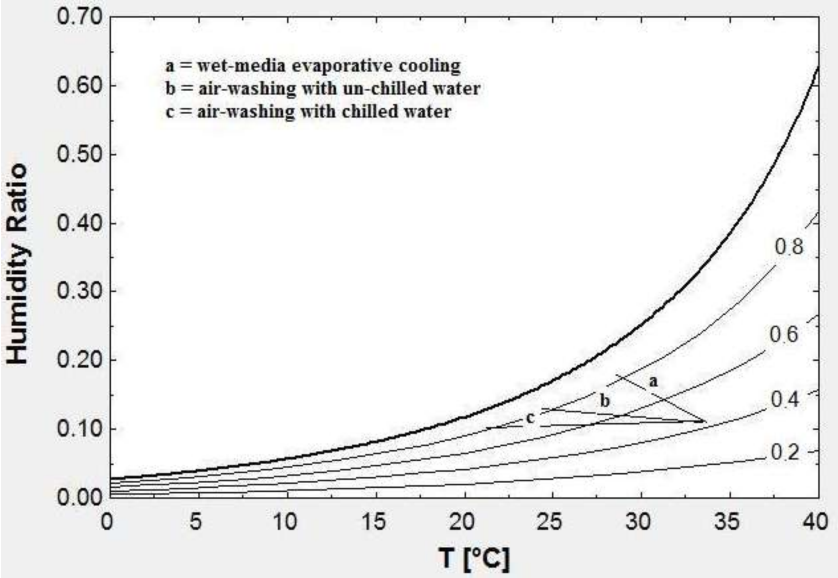

Fig. 2. Measured cooling effects in July 2010

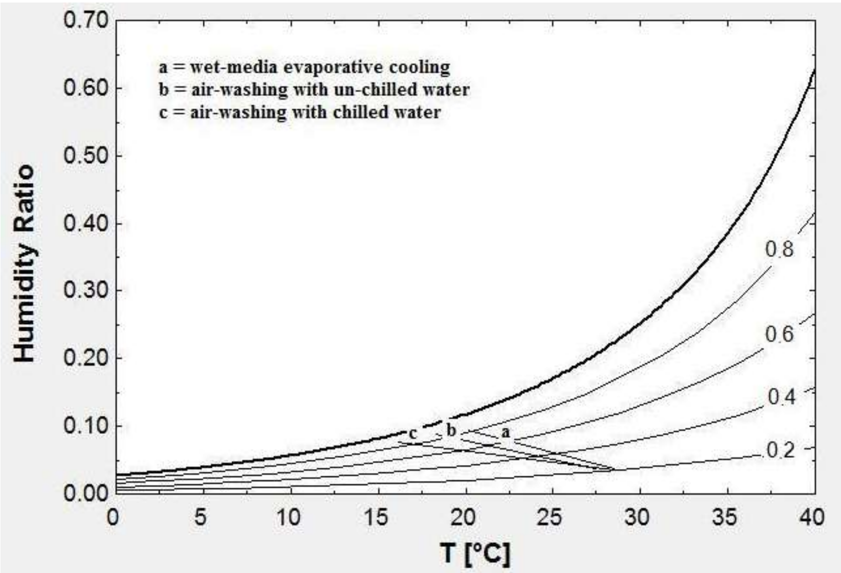

Fig. 3. Measured cooling effects in March 2011

The results obtained when the system was operated as an evaporative cooler show that the air temperature dropped in July from 33.8ºC to 28.6ºC to and in March it dropped from 28.3ºC to 20ºC. Thus, the inlet air was cooled by about 5^{o}C in July and by about 8ºC in March. When air washing was used with water at ambient temperature, the system worked as an evaporative fog-cooler. The figures show that air-washing reduced the air temperature by about 9^{o}C in July and about 9^{o}C in March. The figures also show 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 OF INLET-AIR COOLING UNDER LOCAL CONDITIONS

To meet the growing demand for electricity in the country, the national power utility has to continuously expand its generation capacity. The installation of new generation plants is expensive, and finding energy sources and trained staff for these new stations is another problem. The installation of new power stations, particularly near residential areas also raises strong concerns about environmental pollution. The need to install new power projects can be postponed by enhancing the production capacity of the existing power stations, which is very much needed considering the tough challenges facing the country today. Fortunately, the recent experience of retrofitting the gas turbines at Garri Power plant by wetted media-type evaporative cooling system is encouraging. The dry and hot conditions made the cooling system a good investment for the utility. The resulting revenues from both electricity sells and fuel savings enabled the utility to recover its investment in a few months [12,13]. However, these results also indicate that the different cooling technologies available should be evaluated carefully before a decision is made regarding future gas-turbine power plants.

Fig. 4 shows the effect of intake air-temperature on the gas turbine's output, heat consumption, exhaust flow rate, and heat rate [14]. As the figure shows, increasing the inlet-air temperature has two detrimental effects on the gas-turbine performance; (1) reducing its power and (2) increasing its heat rate. Cooling the air intake enables the gas turbine to recover its power and reduces its heat rate. Investment in an inlet-air cooling system proved to be profitable even in countries with temperate climates where it is only needed during the summer. Since the ambient temperature in Sudan is high almost all the year round, inlet-air cooling becomes a highly attractive retrofit since the payback period for the required investment will be shorter.

The choice of the cooling system to be installed must be based on its economic feasibility under local conditions. Other factors being similar, the higher the cooling effect of the system, the higher is its economic feasibility. The results obtained from the test-rig show that air washing could lower the air temperature below the limit of conventional media evaporative cooling. However, gas-turbine inlet-air cooling by air-washing, with chilled water in particular, requires refrigeration and thermal storage systems which could significantly increase the required investment. The running costs of air-washing are also higher than those of media-type evaporative cooling due to the higher energy consumption while the more stringent water requirements limit its daily hours of operation. By comparison, the wetted-media evaporative cooling, which doesn't have such stringent water quality, can be operated for longer hours; thus increasing its return. 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 come from two main sources; the revenue due to the increase in generation capacity (R_1) and that 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, these revenues can be obtained from:

$R_1 = (P_c - P_h)$ (kW) x *System operation hours per day* x *System operation days per week* x *Weeks per year* x *Price of electricity* (\$/kWh) (1)

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

In addition to a number of operational parameters, Eqs 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. 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 1 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 [12]. 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 Figs 2 and 3.

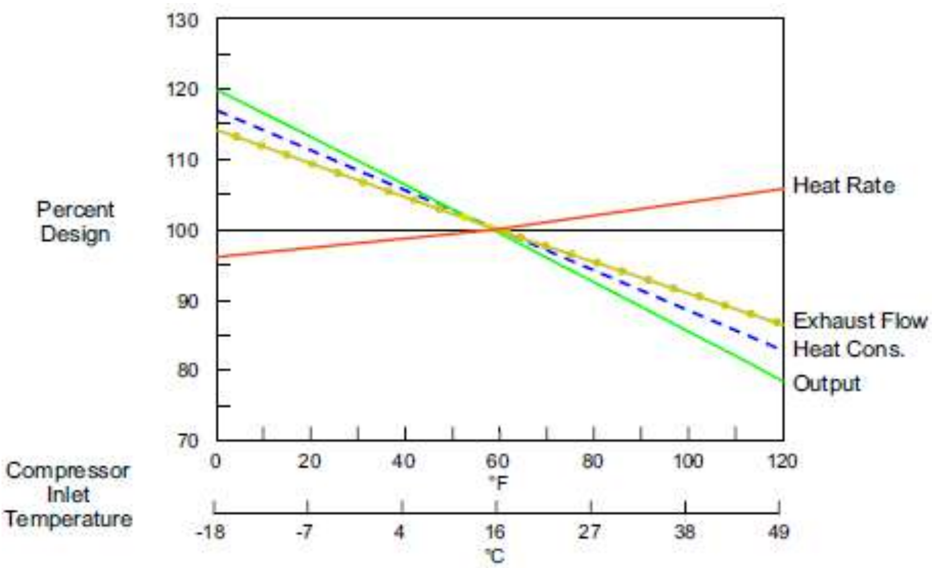

Fig. 4. Effect of ambient temperature on the gas-turbine's performance [14]

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 1 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%. Eq.s 1 and 2 require the number of operation hours per day of the cooling system to be specified. For 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 43,000 kJ/kg.

To calculate the systems' payback periods, the initial costs of the alternative systems are required. The required investment (C) for a given system is obtained from:

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

The conventional wetted media evaporative cooling system can be installed for $50/kW of capacity enhancement [8]. The air-washing system with water at ambient temperature can also be installed for this cost, but the electric chilling costs 400$/kW of capacity enhancement. Table 2 shows the estimated revenues and payback periods for the cooling systems based on these 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. This drops to about 5 months and 4 months if the system is used for 6 and 8 hours per day, respectively. The figures are in good agreement with earlier estimations made locally [12,13]. 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 economic benefits of the alternative cooling systems over an extended period of time, Table 2 also shows the net revenues of the systems over 10 and 20 years. According to the figures, the wetted-media evaporative cooling system returns more revenues than both air-washing options if it is used for more than 6 hours per day. It should be noted that the actual cost of a given cooling system cannot be estimated accurately since it depends on the actual site

Table 1. 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 2. 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

and size of the gas turbine [8,15]. The costs used here are those given by Wang and Braquet [8] 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) [15] 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.

5. CONCLUSIONS

The present study gives clear advantage to the wetted-media evaporative cooling over the air-washing system under the hot and dry conditions of Sudan. 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. Apart from its economic feasibility, the selection of this type of cooling systems is also supported by the fact that it does not require a high level of technical expertise to operate. The availability of water makes evaporative cooling even more attractive in Sudan than in many other areas with similar hot and dry conditions. To apply the present results to similar climatic conditions in other countries, the local fuel cost and electricity tariff must also be taken into consideration. Of these two factors, the electricity tariff is more influential since a higher fuel cost will reduce the payback period by a smaller margin compared to a higher electricity tariff.

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REFERENCES

[1] C.D. McCracken, Off-peak air conditioning: a major energy saver, ASHRAE Journal (1991) 12-13.

[2] R.S. Johanson, The theory and operation of evaporative coolers for industrial gas turbine installations, Gas Turbine and Aeroengine Congress and Exposition, June 5-9, Amsterdam, The Netherlands (1988), Paper No. 88-GT-41.

[3] M. Chaker and C.B. Meher-Homji, Inlet fogging of gas turbine engines: climatic analysis of gas turbine evaporative cooling potential of international locations, Proceedings of ASME Turbo Expo 2002, June 3-6, 2002, Amsterdam, The Netherlands (2002), GT-30559.

[4] S.M. Hasnain, S.H. Alawaji, A.M. Al-Ibrahim, M.S. Smiai, Prospects of cool thermal storage utilization in Saudi Arabia, Energy Conversion & Management 41 (2000) 1829-1839.

[5] Q.M. Jaber, J.O. Jaber, M.A. Khawaldah, Assessment of Power Augmentation from Gas Turbine Power Plants Using Different Inlet Air Cooling Systems, Jordan Journal of Mechanical and Industrial Engineering, 1 (1) (2007) 7 – 15.

[6] K.N. Abdalla and Z.A.M. Adam, Enhancing gas turbine output through inlet air cooling. Sudan Eng. Soc. J. 52(4-6) (2006) 7-14.

[7] T.K. Ibrahim, M.M. Rahman and A.N. Abdalla, Improvement of gas turbine performance based on inlet air cooling systems: A technical review, International Journal of Physical Sciences, 6(4), (2011) 620-627.

[8] T. Wang and L. Braquet, Assessment of inlet cooling to enhance output of a fleet of gas turbines, Proceedings of Industrial Energy Technology Conference IETC 30th, New Orleans, May 6-9, 2008.

[9] M. S. El-Morsi, Optimization of direct-contact-spray-coolers, A dissertation submitted in partial fulfilment of the requirements for the degree of doctor of philosophy (Mechanical Engineering) at the University of Wisconsin, 2002.

[10] A.A. Tahanna, A.N.Y. Ahmed, Design and fabrication of a test rig for inlet air washing for gas turbine power augmentation, Final-year project report, Mechanical Engineering Department, Faculty of Engineering, University of Khartoum, 2010.

[11] Internet: http://www.climatetemp.info/sudan/khartoum.html (accessed 3/8/2011).

[12] M.M. El-Awad and O.H.M. El-Hassan. Gas-turbine power augmentation by media-type evaporative cooling for at Garri Power Station, Proceedings of the International Engineering Conference on Hot Arid Regions, Al-Ahsa, Saudi Arabia, May, 1-2, 2010.

[13] M.A.E. Eldoud, The performance improvement in Garri combined cycle power plant by inlet air media type evaporative cooling, a thesis submitted in partial fulfilment of the degree of M.Sc. in Electrical Power Engineering, Department of Electrical Engineering, Faculty of Engineering, University of Khartoum, 2010.

[14] F. J. Brooks, GE Gas Turbine Performance Characteristics, GER-3567H, GE Power Systems, Schenectady, NY. Internet: http://ncad.net/Advo/CinerNo/ger3567h.pdf, (accessed on 3/8/2011).

[15] Annual Gas Turbine Handbook 2010, Gas turbine world, Pequot Publishing Inc, CT, USA, 2010.