Design of an Efficient Cooling Tower for Alaoji Power Plant, Aba, Abia State, Nigeria

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ABSTRACT

The work embodied in this study is to design a cooling tower that will effectively optimize the cooling effect of the condenser in Alaoji power station as a result of its heating effect. To achieve a better power efficiency output of the Combined Cycle Power Plant system existing in Alaoji power station, and to have an optimized cooling tower that could be adapted for different plants' configurations irrespective of their locations, made this study very significant. This study was carried out as a result of the problem faced by Alaoji Combined Cycle Power Plant with respect to the cooling of the condenser unit. By simply installing a well designed cooling tower, a solution was provided which effectively cooled the condenser. Also, with the introduction of the cooling tower, the heating effect of the condenser was eventually stabilized to a temperature of $30°C$ which consequently cooled the condenser. However, with the absence of the cooling tower prior to its installation, the temperature rises to about $35-40°C$. Though the overall efficiency of the steam plant calculated without the unit was actually 33.85%, an achievement and success with the introduction of the cooling tower increased the condenser's efficiency from 33.94% to 66.26% which improved the system's performance considerably. More so, an induced blower with a concrete structure was used for the design of the cooling tower.

Keywords: **Alaoji power station, combined cycle power plant, condenser unit efficiency with induced blower, cooling tower heating effect, optimizing power efficiency output**

I. INTRODUCTION

Cooling towers are very important part of many chemical plants. The primary task of a cooling tower is to reject heat into the atmosphere. They represent a relatively inexpensive and dependable means of removing low-grade heat from cooling water. The make-up water source is used to replenish water lost to evaporation, just like the hot water from the heat exchangers is sent to the cooling tower. The water exits the cooling tower and is sent back to the exchangers or to other units for further cooling. Typical closed loop cooling tower system is shown in Fig. 1 [1].
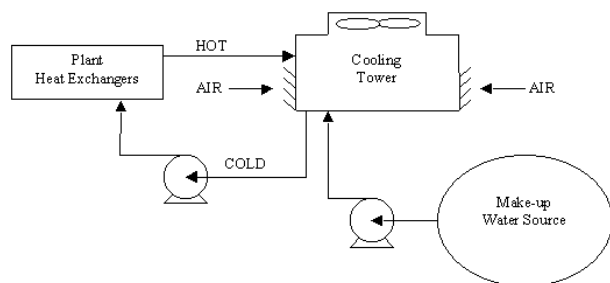

Fig. 1: Typical closed loop cooling tower system

Alaoji power plant is used as a case study for this work. It is a Combined Cycle Power Plant (CCPP) system that utilizes Wet Surface Air Cooler (WSAC) as its cooling option. Alaoji power plant is a Power Holding Company of Nigeria (PHCN) Plc and National Integrated Power Project (NIPP) facility with a stipulated output of 1074MW. The project is being handled by Rockson Engineering (RE) Company, Limited and General Electricity (GE) Company, Limited with their offices situated in Port Harcourt, Nigeria. The power plant itself is located in Aba, Abia State and is usually 5 to 8°C hotter than the neighbouring cities [2]. According to the source, Aba registers ambient of about 40°C when Port Harcourt (35km from Aba) is 32°C or less in the months of December to March. Hence, the range of temperature variation in Alaoji is usually between 24°C and 40°C. However, there are few exceptions when the ambient was 16°C and 43°C as recorded [2].

Even though the scope of this study included the initial concept of the original design (which was conceived by RE and an improvement in her design, the sourcing of materials for the plant layout in Alaoji power station, the selection of the materials for an efficient cooling tower design, and the design consideration for high effectiveness), the study however, is limited to the design of an efficient cooling tower that will effectively cool the condenser unit. This is to stabilize its heating effect for optimum performance of the system as it relates to Alaoji power plant. Also, since the degree of useful work of any engineering design is measured by the pedigrees of its economic importance, in terms of its cost effectiveness, safe operating procedure, and ease of operation, these parameters necessitated the desire to carry out the study.

II. REVIEW OF COOLING METHODS USED IN ALAOJI POWER STATION

II.1 Alaoji CCPP Cooling Solution

Steam turbine (ST) plant is optimized by the cooling method used for the condensation of the ST exhaust steam. This has a direct relationship with the back pressure on the ST exhausting steam which also affects the thermal and power efficiency of the plant [3]. There are three identified cooling methods in use in Alaoji CCPP station. These are as listed below and presented in Table 1.

    i.   Wet cooling technology-example: cooling tower.
    ii.   Dry cooling technology-example: ACC (Air Cooled Condenser); and
    iii.   Hybrid cooling technology-example: WASC (Wet Surface Air Cooler) [2].

Table 1: Consumption Rate of Raw Water for the Different Options of Cooling in Alaoji CCPP.

	Unit	Cooling tower	(WSAC)	(ACC)
Water for cooling	m^3/hr	1,475	200	Nil
Blow down	m^3/hr	98	30	Nil
Pond fill period	days	60	250	NA

From Table 1, it is evident that the first option is the most efficient of the three technologies followed by the third option, while the second option is the least efficient of the three as identified.

Alaoji is not located close to any water body (river or sea). Hence, the only water source for the plant operation is from well water. The water requirements of the cooling tower and WSAC cannot be sustained from the well water for the power plant life of 30years. Another major area of concern is the evacuation of the plant retention pond for catching the plant run-off water and the blow downs. This will not be the issue with the dry cooling technology. Without the process water, the retention pond ($189,000m^3$) will never be filled up. Hence, the issue of evacuation is completely eliminated.

II.1.1 Comparison between ACC and WSAC

Since it is obvious that water is not available for the adoption of cooling tower for Alaoji cooling solution, there was need to compare WSAC and ACC as envisaged by the company to determine the best option for water supply adoptable. These are presented as in Table 2. Based on these, it was

identified that WSAC required more equipment than ACC which implied that WSAC will demand more cost than ACC.

Table 2: Comparison between WSAC and ACC Water Supply Requirement for Alaoji CCPP.

	Unit	(WSAC)	(ACC)
Equipment footing	m^3/hr	53,035	15190
Aux power requirement	MW	22.5	7,058

II.1.2 Commercial Comparison between ACC and WSAC

  a. WSAC

Table 3: Estimated Installation Cost of WSAC for Alaoji CCPP.

	Qty	Cost ($)	Total ($)	Remarks
Water for cooling	2	8,255,000	16,510,000	
Concrete (m^3)		993.92		
Pumps				Required

  b. ACC

Table 4: Estimated Installation Cost of ACC for Alaoji CCPP.

	Qty	Cost ($)	Total ($)	Remarks
Water for cooling	0			
Concrete (m^3)				Steel frame in base price
Pumps				Included in base price

Commercially, as depicted in Tables 3 and 4, ACC appeared to be the better choice for Alaoji CCPP since the entire package handling the exhaust steam from the lower pressure (LP) ST to the condenser in the hot well, is completely handled by a vendor at a lump sum. Conversely, WSAC installation required at least three different vendors for the following sections of equipment:

- Wet section of WSAC.
- Dry section of WSAC.
- Steam surface condensers (SSC).
- Interconnecting piping from the SSC to WSAC; and
- Pumps.

Hence, in economic terms, ACC was identified to be the best option against the WSAC to be adopted for Alaoji CCPP operations for effective cooling.

II.2   ACC for Alaoji CCPP
Steam from the ST exhaust flows through the main stream duct to the roof-shaped air-cooled condenser where it is then condensed inside the heat exchangers using ambient air as the cooling medium. The cooling air is provided by axial fans, which are attached to electric motors via speed reducing gearboxes. At the bottom of the heat exchangers, there is a tank which is partially reheated with the steam coming from the main stream duct via the equalization line. The condensate from the condensate tank (hotwell) is then pumped to the boiler feed water system to complete the closed cycle.

II.2. 1   Alaoji Ambient Temperature
Ambient temperatures have direct impact on the steam turbine back pressure (Tbp), which consequently bear and affect the thermal and power efficiency of the Plant. The efficiency of ACC is extremely dependent on the ambient dry-bulb temperature (DBT).

Aba, a major commercial hub and city in Nigeria where Alaoji is located is usually $5^{o}C$ to $8^{o}C$ hotter than the neighbouring cities of other states. It registers an ambient temperature of $40^{o}C$, when Port Harcourt, Rivers State (35km from Aba) records $32^{o}C$ or less in the months of December to March [2].

Although, RE has a contractual obligation to build Alaoji CCPP at a performance guarantee ambient temperature of $32^{o}C$, studies have shown that this temperature is rarely achievable between 10.00hrs and 19.00hrs as recorded in the month of April 2009 in a study to determine the hourly temperature reading for that location [2]. Also, a similar study by RE [2] to determine the heat balance diagram (HBD) of Alaoji power plant indicated that the plant has a Tbp of 4.04 HgA (0.1368bar) at a guarantee ambient of $32^{o}C$. However, Tbp is expected to be higher when the ambient temperature increases.

II.3   Alaoji ST Performances with ACC
The variations of steam Tbp have direct impact on its thermodynamic performance, likewise on the power output [2]. This is presented as in Table 5 showing the operational limit of the ST.

Table 5: Alaoji Steam Turbine Performance with ACC

Ambient Temp (^{o}c)	Steam turbine back Press ("HgA)	Operations ability	Power output per block (MW)
40	5.9	Safe operations	270
44.2	7	Alarm	

From the Table, it is evident that at a temperature of $40^{o}C$ and a pressure of 5.9HgA, the ST is safe to be operated and will produce a power output of 270MW per block, while at $44.2^{o}C$ and 7HgA, it is very unsafe to be operated, and should be check-mated.

III.   MATERIALS AND METHODS
III.1   Design Calculations/Observations and Analyses
The materials involved in this design are the component parts of the steam power plant. These, have been methodologically, systematically and sequentially analyzed to obtain the overall condenser efficiency suitable for the cooling tower optimized performance. In making the analyses, literature materials obtained from standard steam properties tables and standard formulations (equations) were consulted and used.

The design of the cooling tower involves the analyses of the operational sequence of the steam plant as shown in Fig. 2, which presents the various stages of the steam power plant processes as utilized in Alaoji CCPP station.
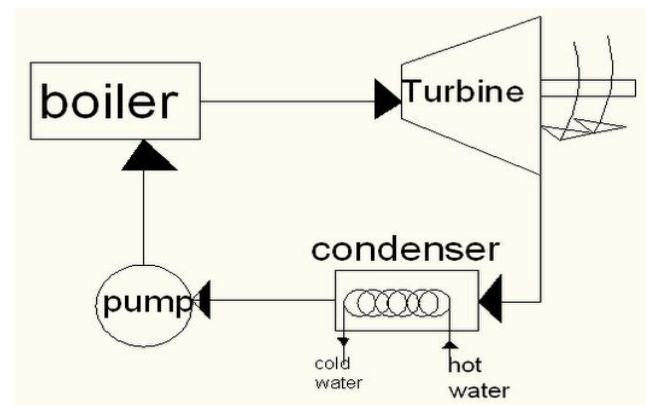

Fig. 2: Schematic diagram of the steam plant configuration in Alaoji CCPP station

III.1.1   Boiler
The boiler used in Alaoji power plant is a water- tube type. Before operation, the energy needed to start the operation is

gotten from the heat gained from the exhaust of the gas plant. This raised the pressure of the water to about 30.63 bars at a temperature of 235˚C (508K). At this point, the steam generated had enough energy to operate the steam turbine.

III.1.2 Turbine
As the turbine does work, the exhaust steam from the turbine was condensed in the condenser to a pressure and temperature of about 0.0425bar and 30˚C, respectively. At that point, the condensed steam was redirected back into the boiler by a heat pump. The major problem encountered in the operation, was that as time went on, the temperature of the condenser gradually started increasing and hence, its ability to condense the steam began to reduce. This resulted in the existence of both steam and water after the condensation process, thus reducing the performance and efficiency of the steam plant. As a result, there was a dire need for a cooling tower to be installed to maintain the temperature of the condenser to normalcy. The whole process of operation obtained for Alaoji power plant is as presented in a temperature-entropy (T-s) diagram shown in figure 3.

III.1.3 Parameters Specification and Designation
From the Steam Properties Table [4], these parameters were specified (Fig. 3).
At point 1: P = 30.63 bar; T_1 = 235˚C (508K);
      h_1 = 2803.1KJ/Kg; and
      S_g = 6.1777KJ/KgK.
At point 2´: P = 0.0563bar; $T_2^{'}$ = 35˚C (308K);
      h_f = 146.6KJ/Kg; h_g = 2564.4KJ/Kg;
      S_f = 0.5050KJ/KgK; and
      S_g = 8.3511KJ/KgK.
At point 2: P = 0.0425bar; T_2 = 30˚C (303K);
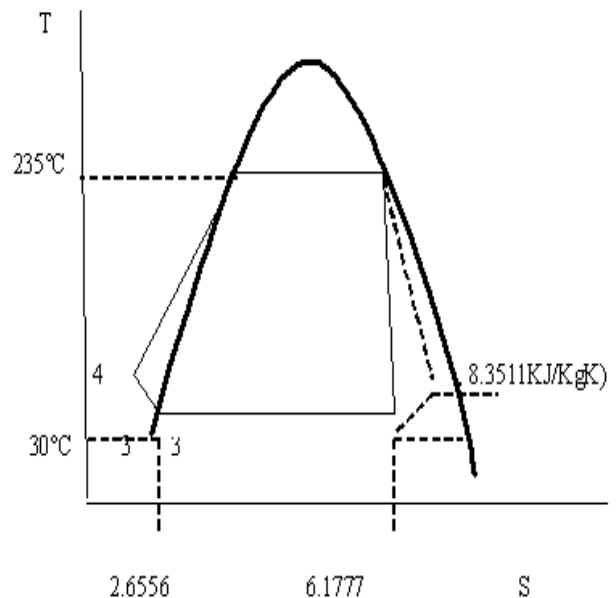 h_f = 125.7 KJ/Kg; and h_g = 2555.3KJ/Kg.

Fig. 3: Temperature-entropy (T-s) diagram of Alaoji cooling process

With these data, the efficiency of the steam plant and the designing parameters for the cooling tower were estimated. Hence, the turbine work, W_T is given by:

$$W_T = [h_1 - h_2] - W_P \quad [5] \qquad (1)$$

Where:
W_T = Work done by the steam turbine, and
W_P = Work exerted by the pump ($h_1 = h_4$ = 2803.1KJ/Kg at 30.63 bar).

Since: $S_1 = S_2$ = 6.1777KJ/KgK, then:

$$S_2 = S_f + X_2 \left(S_g - S_f\right) \quad [5] \qquad (2)$$

Thus:
6.1777 = 0.5050 + X_2 (8.3511 - 0.5050)

$$X_2 = \frac{6.1777 - 0.5050}{8.3511 - 0.5050} = \frac{5.6727}{7.8461}$$
$$\therefore \quad X_2 = 0.723 = the\ Quality\ of\ the\ fluid$$

Similarly,

$$h_2 = h_f + X_2 \left(h_g - h_f\right) \quad [5] \qquad (3)$$
$$h_2 = 146.6 + 0.723\ (2564.4 - 146.6)$$
$$h_2 = 146.6 + 0.723\ (2417.8) = 146.6 + 1748.0694$$
$$\therefore \quad h_2 = 1894.67KJ/Kg$$

III.1.4 The Pump Work of the Turbine
The pump work of the turbine, Wp is given by:
$$W_P = v\ \Delta_P \quad (pump\ work) \qquad (4)$$
Where:

v = The specific volume at 0.0425bar = 0.001004 m^3/Kg; and Δ_P = the change in pressure (P$_1$ – P$_2$). Thus:

$$W_P = 0.001004 \ (30.63 - 0.0425) \ 100$$
$$= 0.001004 \ (30.5875) \ 100$$
$$\therefore \quad W_P = 3.07 \text{KJ/Kg}$$

III.1.5   The Turbine Work, W$_T$
Recall: the turbine work, W$_T$ (1) is given by:
$$W_T = [h_1 - h_2] - W_P$$
Hence:
$$W_T = (2803.1 - 1894.67) - 3.07 = 908.43 - 3.07$$
$$\therefore \quad W_T = 905.36 \text{KJ/Kg}$$

III.1.6   Specific Steam Consumption
This is given by:

$$\text{SSC}' = \left(\frac{1}{h_1 - h_2}\right) \quad [5] \tag{5}$$

$$\text{SSC}' = \left(\frac{1}{2803.1 - 1894.67}\right) = \frac{1}{908.43}$$

$$\therefore \quad \text{SSC}' = 0.0011008 \text{Kg/KJ or } 1.1 \times 10^{-3} \text{Kg/KJ}$$

III.1.7   The Condenser Heating Load
The condenser heating load, Q´ (energy involved in heating the condenser load) is obtained as:

$$Q' = \text{SSC}' \ (h_2 - h_3) \tag{6}$$

But: h$_3$ = h$_{f2}$ = 125.7KJ/Kg
Thus:
$$Q' = 1.1 \times 10^{-3} \ (1894.67 - 125.7) = 1.1 \times 10^{-3} \ (1768.97)$$

$$\therefore \quad Q' = 1.946 \text{KW per KW output}$$
Or 1.946:1 (ratio of the heat load of the condenser to its output work).

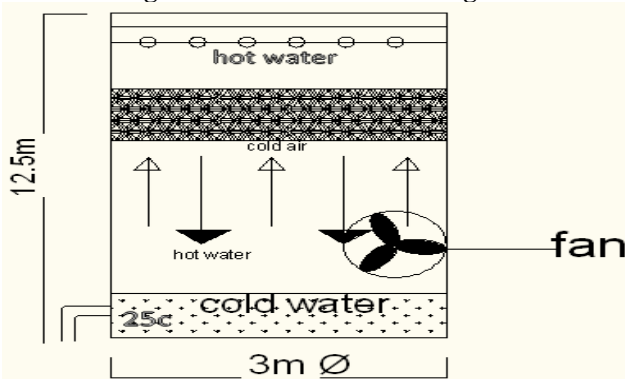### III.2   Design Parameters of the Cooling Tower

Fig. 4: Schematic of a cooling tower in Alaoji power Station

The schematic of a cooling tower existing in Alaoji power station presented in Fig. 4 enables the determination of its design parameters. This is to assist in the optimization of the condenser in order to compensate for the heating up of the condensation. By comparing the mass flow rates of the cold air needed to subdue the heat from the hot water in the cooling tower, the relations (7a) and (7b) are obtained. Hence:

Heat gained by air = Heat rejected by water   (7a)

Mathematically, it is stated as:

$$m_a \ c_a \ \theta_a = m_w \ c_w \ \theta_w \quad [6] \tag{7b}$$

Where:
m$_a$, m$_w$ = Masses of air and water;
C$_a$, C$_w$ = Specific heat capacities of air and water; and
θ_a, θ_w = Temperatures of air and water, respectively.

The cooling tower is such that the air gets to the hot water by a forced induction in which case, the forcing inducer is a discharge blower. Hence, the design takes the shape as depicted in Fig. 4 where its parameters are as specified thus:

The diameter of the tower = 3m;
The height of the tower = 12.5m;
The speed of the fan (blower) = 1800rpm;
The diameter of the blade in motion = 1m; and
The temperature of the air blown by fan = 20˚C (293K).

III.2.1   The Velocity of the Air Stream from the Blower
The velocity of the air stream from the blower is given by:
$$\text{Velocity, V} = \frac{\pi DN}{60} \tag{8}$$
Thus:
$$V = \frac{3.142 \times 1 \times 1800}{60} = \frac{5655.6}{60}$$

$$\therefore \ V = 94.26 \text{m/s}$$

III.2.2   The Area of the Cooling Tower
Since the diameter of the tower is 3m, then:

$$\text{Area, A} = \pi \ r^2 \tag{9}$$
Hence:
$$A = 3.142 \times (1.5)^2 = 3.142 \times 2.25$$
$$\therefore \ A = 7.0695 \text{ approx. } 7.070 \text{m}^2$$

III.2.3   The Discharge of the Air Stream
The discharge of the air stream is given by:

$$Q = AV \tag{10}$$
Thus:
$$Q = 7.070 \times 94.26 = 666.42 \text{m}^3\text{/s}$$

III.2.4 The Mass of the Air Stream, m_a'
This is given by:

$$m_{a'} = (\text{density x discharge}) = \rho_a Q \qquad (11)$$

But:
The density of air, $\rho_a = 1.01\text{Kg/m}^3$; thus:
$$m_{a'} = 1.01 \text{ x } 666.42 = 673.08\text{Kg/s}$$

III.2.5 The Mass Flow Rate of Water in the Cooling Tower, m_w

Invoking (7b), the mass flow rate of water, m_w is obtained as:

$$m_w = \frac{m_a \, c_a \, \theta_a}{c_w \, \theta_w} \qquad (12)$$

Where:
θ_a = the temperature difference between the ambient and the temperature of air by the blower;
θ_w = the temperature difference between the ambient and the cold water in the cooling tower; and
m_w = the mass flow rate of water in the cooling tower, respectively.

Hence:

$$m_w = \frac{673.08 \text{ x } 1.003 \text{ x } (32-20)}{4.183 \text{ x } (32-25)} = \frac{673.08 \text{ x } 1.003 \text{ x } 12}{4.183 \text{ x } 7}$$

$$\therefore m_w = \frac{8101.191}{29.281} = 276.67\text{Kg/s}$$

III.2.6 The Cooling Effect of the Condenser

Using the cold water flow rate, m_w, the cooling effect of the condenser, Q'' can be calculated thus:

$$Q'' = m_w \; x \; c_w \; x \; d\theta_C \qquad (13)$$

Where:
$d\theta_C$ = The difference between the temperature of the condenser before (T_2'), and after the installation of the cooling tower (T_2), respectively (See Fig. 3 and section 3.1.3: specification and parameters designation).
Thus:
$$Q'' = 276.67 \text{ x } 4.183 \text{ x } (35-30)$$
$$= 276.67 \text{ x } 4.183 \text{ x } 5$$
$$\therefore \quad Q'' = 5786.55\text{W or } 5.787\text{KW}$$

III.3 The Efficiency of the System

To calculate the efficiency of the system, (14) is used. Thus:

$$\text{Efficiency, } \eta = \frac{W_T - W_P}{Q_1} \quad [7] \qquad (14)$$

$$\eta = \frac{908.43 - 3.07}{Q_1} = \frac{905.36}{Q_1} \qquad (15)$$

Where: Q_1 = heat added into the system

But: $\qquad$ $h_4 = h_3 + W_P$ $\qquad\qquad$ (16)

Recall: $h_3 = h_{f2} = 125.7\text{KJ/Kg}$
Hence, from (16):

$$h_4 = 125.7 + 3.07 = 128.77\text{KJ/Kg}$$

Similarly, recall also that for pump work (W_P), $h_1 = h_4$; this implies that:

$$Q_1 = h_1 - h_4 \qquad (17)$$

Thus: $\quad Q_1 = 2803.1 - 128.77 = 2674.33\text{KJ/Kg}$

$$\therefore \eta = \frac{905.36}{Q_1} = \frac{905.36}{2674.33} = 0.3385 \text{ or } 33.85\%$$

III.4 Total Energy of the Condenser System
This is given by:

$$\text{Total energy}$$
$$= \text{work due to heat loss + output work} \qquad (18)$$

But recall that the ratio of the heat load of the condenser to its output work = 1.946: 1; hence:

$$\text{Total energy} = 1.946 + 1 = 2.946\text{KW}$$

$$\therefore \eta = \frac{1}{2.946} \; x \; 100 = 33.94\%$$

Since the cooling effect provided by the cooling tower is 5.787kw of the power, then the balance between the cooling effect and the heating load effect thus becomes:

$$(1.946 + 1){:}5.787$$
$$\text{Or } 2.946{:}5.787 = 1{:}1.964$$

Hence, the total energy of both the condenser and the cooling tower now becomes: (1+1.964) = 2.964KW.

This gives 1.964 times of cooling effect to the heating effect. Thus, the efficiency of the condenser due to the cooling tower finally becomes:

$$\eta_C = \frac{1.964}{2.964} \; x \; 100 \; = \frac{196.4}{2.964} = 66.26\%$$

This means that there is an increase in the efficiency of the condenser due to the installation of the cooling tower from 33.94% to 66.26%, respectively.

IV.   CONCLUSION

The need for cooling tower in today's industries cannot be over-emphasised. An effective cooling tower has been designed for Alaoji Power Plant, putting all the necessary conditions into play.

By simply installation a well designed cooling tower, a solution was provided which effectively cooled the condenser by stabilizing its temperature to 30°C. Prior to its installation, the temperature of the system usually rises to about 35-40°C. However, after the installation, the overall efficiency of the condenser increased from 33.94% to 66.26% from its calculated overall efficiency of 33.85%, which thus improved the system's performance tremendously. This was done utilizing an induced blower with a concrete structure.

Also, from the design, it was inferred that an efficient cooling tower should be such that the ambient wet bulb temperature is specified, since there is no initial knowledge or control over the recirculation factor. Similarly, the wet bulb temperature usually determined by the geographical location, should not exceed over 5 percent of the time in that area because the higher the wet bulb temperature, the smaller the tower required to give a specified approach to the wet bulb at a constant range and flow rate.

V.   RECOMMENDATION

Having concluded this design, it is recommend that:

- The ambient temperature of Aba, Abia State, should always be considered when making any modifications on Alaoji Power Plant.
- A combined cycle type of cooling tower is used in Alaoji. This will help check-mate the irregularities in the ambient temperatures of the site where the cooling tower is located.
- In the selection of the size, proper care should be taken so as to select a cooling tower suitable for a particular function.
- By evaluating the cost and size of the heat exchangers versus the cost and size of the cooling tower, the quantity and temperature of the cooling tower water can be selected to get the maximum economy for a particular process.
- Effective care should also be taken during CT selection, so as not to exceed the rated parameters; and A good

maintenance planning procedures should be properly prepared for the smooth running of the cooling tower.

VI.   ACKNOWLEDGEMENTS

REFERENCES

[1]   H. John, Cooling Towers System Guidance for Energy Operations, Kelcroft E & M Limited, 1988, pp.1- 6.

[2]   Rockson Engineering, Alaoji Combined Cycle Power Plant: Economic and Performance Evaluation of Heat Sink Options in Alaoji Combined Cycle Application, Aba, Nigeria, 2009.

[3]   G. Walker, Industrial Heat Exchangers, 2nd Edition, Mc Graw-Hill, 1990.

[4]   W.P. Jones, Air Conditioning Engineering, 3rd Edition, Edward Arnold, 1985.

[5]   T.D Eastop, A. Mc Conkey, Applied Thermodynamics for Engineering Technologists, 1993.

[6]   E.R. Eckret, R.M. Drake, Analysis of Heat and Mass Transfer, Taylor and Francis, 1971.

[7]   T.D. Eastop, D.R. Croft, Energy Efficiency, Longman, 1990.