Performance Investigations of a Cross-Flow Induced Draft Cooling Tower Employed in a Water Cooled Condenser of 900 TR A/C Plant

B.Kiran Naik and P.Muthukumar

Abstract: Water cooled condensers are generally used in large – scale air-conditioning plant for con-verting the refrigerant from gaseous phase to liquid phase typically by removing the latent heat of refrigerant by using water as a coolant. Then, the sensible heat gained by the cool-ing water is rejected (evaporative cooling) in the cooling tower of either natural or me-chanical draft. While rejecting the heat from the water in cooling tower, considerable amount of water in the form of droplets (drift) and evaporation is carried away along with the circulated air. In the present paper, the performances of a standard cross flow induced draft cooling tower employed in the water cooled condenser of a A/C plant in terms of water loss, range, approach and cooling tower efficiency have been investigated. Extensive experimental studies have been carried out in three cooling towers employed in 900 TR refrigeration capacity A/C plant over a period of 4 months. Daily variation of average wa-ter loss and cooling tower performance parameters have been plotted for some selected days. It was observed that an average 3,564 lit/hr of water has been evaporated from 3 cooling towers. The estimated average water loss per TR per hr was about 3.3 litres in the ambient temperature range between 28^{0}C DBT - 35^{0}C DBT (26 ^{0}C WBT - 32 ^{0}C WBT). The water loss at peak hours (1 - 2 pm) was about 3.71 lit/hr-TR corresponding to 32^{0}C DBT and 30 ^{0}C WBT. The efficiency of cooling towers varied between 25 % and 45%.

Keywords: *Water Cooled Condenser, Cooling Tower, Efficiency, Performance Analysis, Drift Loss.*

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1. Introduction

Currently the temperature of earth is predominantly increasing day by day because of global warming, industrialisation, deforestation, air pollution, etc. Due to continuous raise in the ambient temperature, the need for refrigeration and air-conditioning are becoming more essential when compared to previous generations for the comfort of mankind. The local climatic condition of the north-eastern regions of India, particularly in Assam, due to high relative humidity (70% to 85%), most frequent occurrence of sand storm in the month of January –

March, etc. differs from other regions of India. Hence in order to sustain these type of typical environmental conditions, water cooled condenser are more effective when com-pared to air cooled condenser for large scale A/C plants. Generally water cooled condens-ers are used to convert the refrigerant from gaseous phase to liquid phase typically by re-moving its latent heat by using water as a coolant. Then the sensible heat gained by the cooling water is rejected (evaporative cooling) in the cooling tower of either natural or mechanical draft. While rejecting the heat from the water in cooling tower, considerable amount of water in the form of drift and evaporation is carried away along with the circu-lated air. Hence, the loss of water occurs due to drift and evaporation.

The basic theory of cooling tower operation was first proposed by Walker et al. [1]. How-ever, the first practical use of differential equations was developed by Merkel [2]. But the theory used by Merkel [2] neglected the water loss by evaporation and assumed the Lewis number for air/water vapour system as unity. Merkel's differential equation for cooling tower was redeveloped by Nottage [3] and converted to a graphical method of solution by Lichtenstein [4]. Another graphical procedure for determining the air process line in a cooling tower, which was suggested by Mickley [5]. Simpson and Sherwood [6] carried out the experimental studies on several small scale cooling towers and examined the de-pendence of the mass transfer coefficient on the various air and water properties. Later, some theoretical investigations on cooling towers were carried out by Berman [7], Ther-lkeld [8], Yadigaroglu and Pastor [9] and Whillier [10]. Nahavandi and Serico[11] developed a method for including the evaporation losses in the cross flow cooling tower analy-sis by extending the technique employed in the counter flow study. Then analysis of cool-ing tower design and performance of a mechanical draught counter flow air/water cooling towers were carried out by Sutherland [12]. Bernier [13, 14] explained the performance of a cooling tower by examining the heat and mass transfer mechanism from a single water droplet to the ambient air. However, the author did not consider the effect of air tempera-ture as it moved from the bottom to the top of the tower. Nimr [15] presented a mathemati-cal model to describe the thermal behaviour of cooling towers that contain packing materi-als and the model has taken into account both sensible and latent heat effects on the cool-ing tower performance. Jose [16] defined a new parameter ''thermo fluid dynamic effi-ciency'', to quantify the performances of cooling t ower and concluded that it was inde-pendent of the cooling tower height. Khan et al. [17] investigated the variation of air and water temperatures along the height of the tower using psychometric charts. Fisenko et al. [18] developed a mathematical model of a mechanical draft cooling tower. This model has allowed to optimize the performance of the mechanical draft cooling tower under changing atmospheric conditions.

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It is observed from the reported works that there is lack of information on the estimation of water loss based on the Indian weather conditions particularly related to the north-east regions of India. Here in the present paper, the performance of a cross-flow induced draft cooling tower used in a standard water cooled condenser of a A/C plant which is located inside the IIT Guwahati campus has been presented. During this analysis, cooling tower range, approach and efficiency variation from June to September, 2013 has been analysed. Also the water loss variation for the months of August and September has been observed. Further, a thermodynamic cum economic analysis on condensation of the evaporated water drift has been presented.

2. Water cooled condenser A/C Plant

2.1 Working procedure

Figure 1 shows the schematic of the 900 TR capacity A/C plant and the circulation of wa-ter from the condenser to the cooling tower and from cooling tower to condenser. Initially the hot water coming out of the condenser enters into the cooling tower. In the cooling tower, heat has been removed from water by evaporating a small portion of it. The heat which is removed from the hot water is called as latent heat of vaporisation. During this process of vaporisation, water in the form of drift will be carried away by the humidified air. Hence, in order to maintain constant water level in the cooling tower water collection tank, make up water has been added. Then, the cold water coming out from the cooling tower is sent to the pot strainer where the dust particles have been removed. Then it is sent to the condenser through the centrifugal pumps.

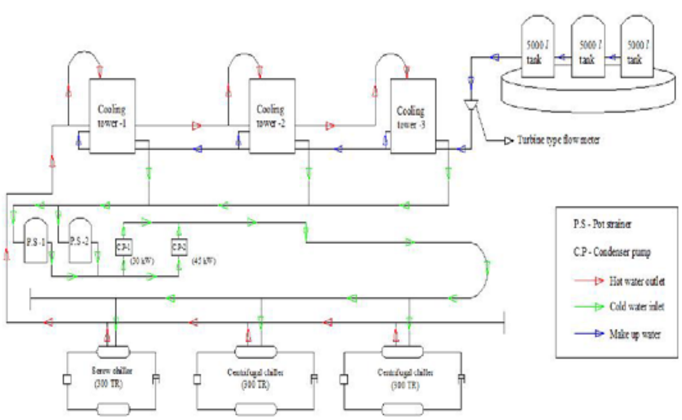

Figure 1 Schematic diagram of a plant layout

2.2 Performance parameters

2.2.1. Cooling tower efficiency

The performances of the cooling tower are defined in terms of range, approach and cooling tower efficiency. These parameters are defined in the following section.

Range(R)

The temperature difference between hot water entering into the tower (Tw,in) and cold water leaving from the tower (Tw,out) is said to be the range of a cooling tower.

$$R = (T_{w,in} - T_{w,out}) \ (°C) \quad (1)$$

Approach (A)

Approach can be defined as the difference between the temperature of cold water leaving from the tower (Tw,out) and the wet bulb temperature of the ambient air (T1).

$$A = (T_{w,out} - T_{wbt}) \ (°C)$$

$$\eta = \frac{R}{(R+A)} \quad (3)$$

From the definition it is understood that the cooling tower efficiency reaches its maximum value if the approach approaches to zero.

2.2.2 Water loss

From operational point of view, the amount of water loss per TR of refrigeration is also an important parameter which needs to be given more importance than that of the cooling tower efficiency. The theoretical water loss per TR is calculated based on the specific hu-midity difference of air between the inlet and outlet of the cooling tower. It can be found using Eq.(4)

$$\text{Theoretical water loss} = \frac{\dot{m}_w}{\alpha Q_e \phi} \quad (l/\text{hr-TR}) \quad (4)$$

Where is the mass of water vapour which can be calculated (l/hr) using Eq.(5).is the correction factor (1.2 for cooling tower calculation), Qe is the designed cooling capacity of the chiller (TR) and is the percentage of load acting on the chiller w m

$$\dot{m}_w = \rho A v(\omega_1 - \omega_2) \quad (l/\text{hr}) \quad (5)$$

where A, ρ and v are effective air flow area (m2), density of the humidified air at the outlet of the fan (kg/m3) and velocity of the air (m/s). Specific humidity (ω1) at air outlet and specific humidity (ω2) at air inlet are measured from the psychometric chart.

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Overall theoretical water loss (OTWL) for the three cooling towers can be calculated using Eq. (6);

$$OTWL = \frac{\dot{m}_{w1} + \dot{m}_{w2} + \dot{m}_{w3}}{\alpha(\varphi_1 Q_{e1} + \varphi_2 Q_{e2} + \varphi_3 Q_{e3})} \; (l/\text{hr-TR}) \qquad (6)$$

where mw1, mw2 and mw3 are the mass of water vapour leaving out from the cooling towers 1, 2 and 3, respectively. Qe1 is the cooling capacity of screw chiller (300 TR) and Qe2 and Qe3 are the cooling capacities of the centrifugal chillers (300 TR).

Actual water loss (AWL)

Actual water loss (l/hr-TR) can be calculated based on the amout of water (m) entering into the cooling towers from make up water tank. The amount of water is measured using turbine flow meter at regular intervals (every 1 hr) of time in order to obtain actual water loss.

$$AWL = \frac{m}{\alpha(\varphi_1 Q_{e1} + \varphi_2 Q_{e2} + \varphi_3 Q_{e3})} \; (l/\text{hr-TR}) \qquad (7)$$

3. Results and discussion

In order to determine the cooling tower performance, a detailed investigation has been carried out by calculating cooling tower range, approach and efficiency over a period of four months (June, July, August and September, 2013) on some selected days during 8 am

– 6 pm. Theoretical and actual water losses have be en also calculated for the months of August and September, 2013. Graphs are drawn with respect to time during some selected days to show the variation of theoretical water loss, actual water loss, range, approach and efficiency.

3.1 Variation of cooling tower range and efficiency

From Figs. 2, 3, 4 and 5, it was observed that the cooling tower range varies from 1.6 °C to 3.3 °C with an average value of 2.6 °C. Cooling ran ge is an important factor which has a major influence on the cooling tower efficiency along with the approach. From these ob-servations, it was observed that if cooling range decreases, the efficiency of the cooling tower increases and vice versa. The maximum values of range reported were fluctuated between 3 to 3.3 °C during the test period. It was maximum during 3 pm to 4 pm of each day.

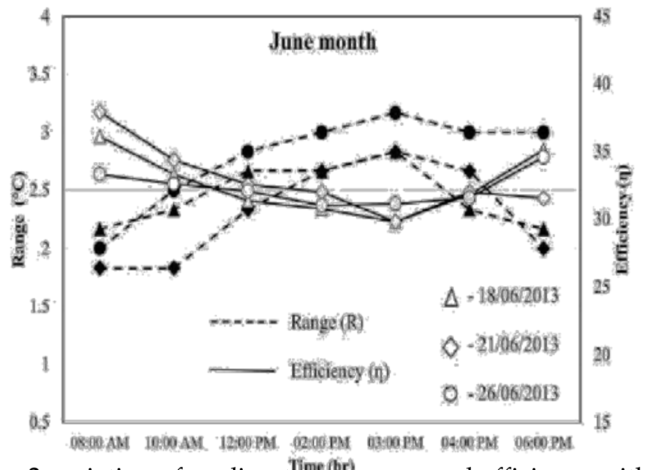

Figure 2 variation of cooling tower range and efficiency with time during June, 2013

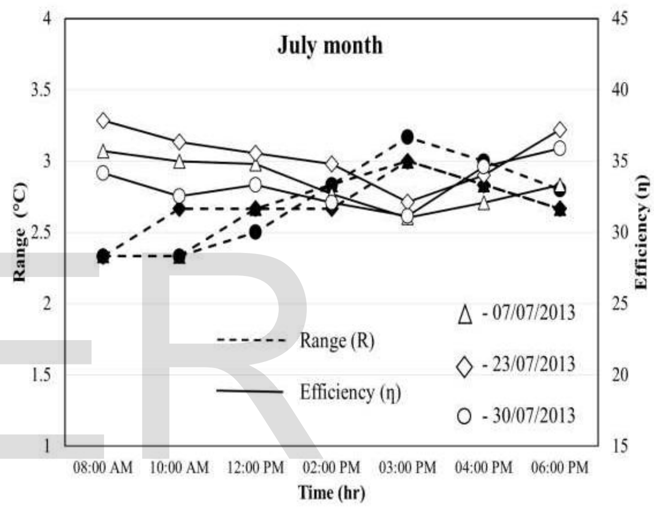

Figure 3 variation of cooling tower range and efficiency with time during July, 2013

3.2 Variation of cooling tower approach and efficiency.

Approach is a most important parameter used for determining the cooling tower size and cost. The variations of cooling tower approach with time during June 2013 to September 2013 are illustrated in Figs. 6, 7, 8 and 9. From Figs. 6, 7, 8 and 9, it is observed that the approach varies from 3°C to 7°C and the efficiency varies from 25% to 45%. The average values of approach and efficiency are about 4.6°C a nd 35%, respectively. When the water loss is high, the amount of water present in the cooling tower decreases and hence the sup-ply of water from the make-up tank increases. As the temperature of water present in the make-up tank is low when compared to water present in the cooling tower, the change in cooling water temperature is high. Hence, during the peak hours (2-3 PM) the cooling tower efficiency is minimum because of higher range and approach when compared to non-peak hours (8 AM and 6 PM). It has been observed from Fig.6 that the efficiency at peak hour (2 pm) was about 31% corresponding to 7 ° C approach on 22/06/2013. Also during non-peak hours (06:00

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pm), the efficiency was about 35 % corresponding to 5.8 °C approach on the same day. For maximum cooling tower efficiency, the approach should be minimum, i.e., the cooling tower outlet water should approach the wet bulb temperature of the ambient air.

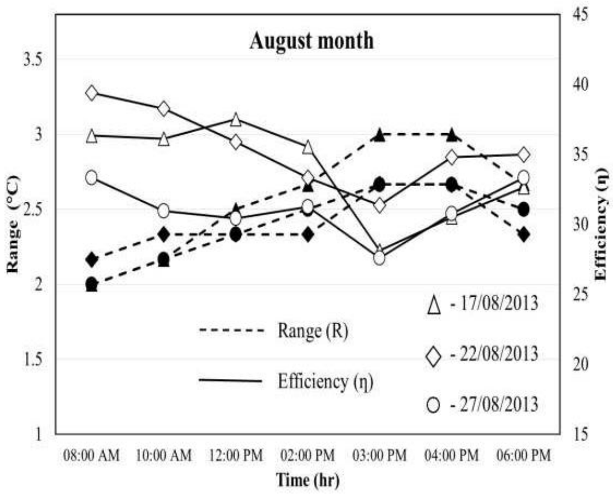

Figure 4 Variation of cooling tower range and efficiency with time during august, 2013

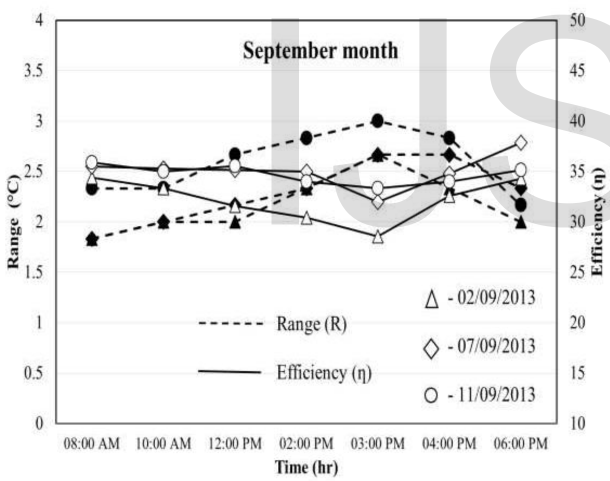

Figure 5 variation of cooling tower range and efficiency with time during September, 2013

3.3 Variation of water loss

Systematic experiments were conducted in order to determine the water loss from the cool-ing tower over a period of four months. From Figs. 10 and 11, it was observed that theo-retical water loss is marginally higher than actual water loss measured during August – Septermber 2013. From Fig. 11, it has been observed that the theoritical water and actual water loss were about 3.65 l/hr-TR and 3.48 l/hr-TR, respectively at 2:00 pm on 11/09/2013. The gap between the theoretical and actual water loss is just mariginal at 0.17 l/hr-TR. This reveals the closeness of the experimental results with the theoretical one.

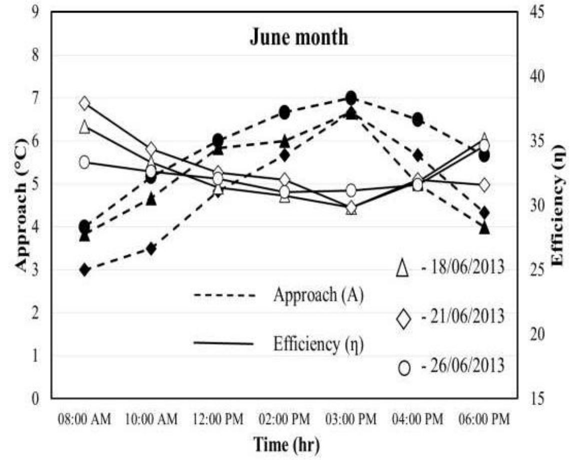

Figure 6 variation of cooling tower approach and efficiency with time during June 2013

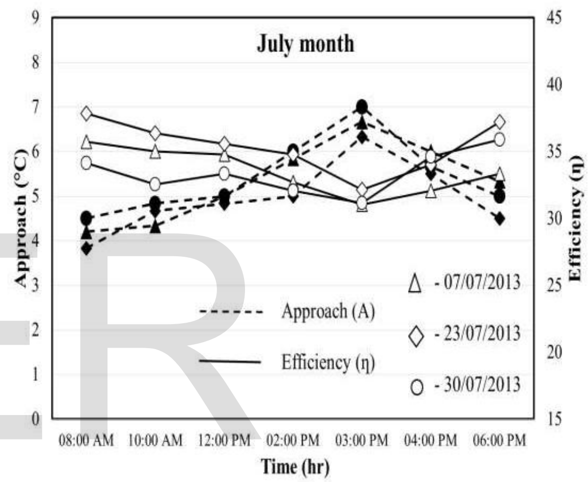

Figure 7 variation of cooling tower approach and efficiency with time during July 2013

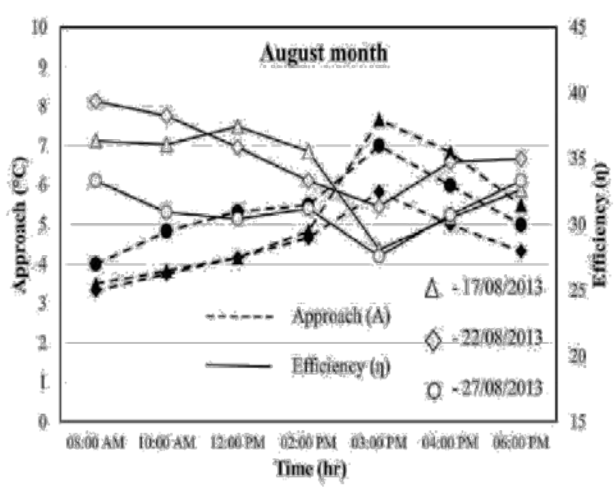

Figure 8 Variation of cooling tower approach and efficiency with time during August 2013

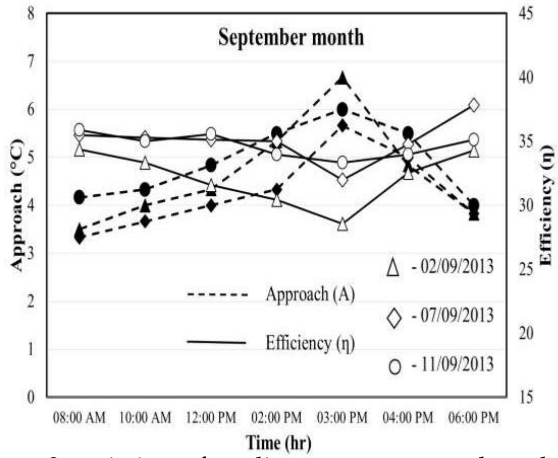

Figure 9 variation of cooling tower approach and efficiency with time during September 2013

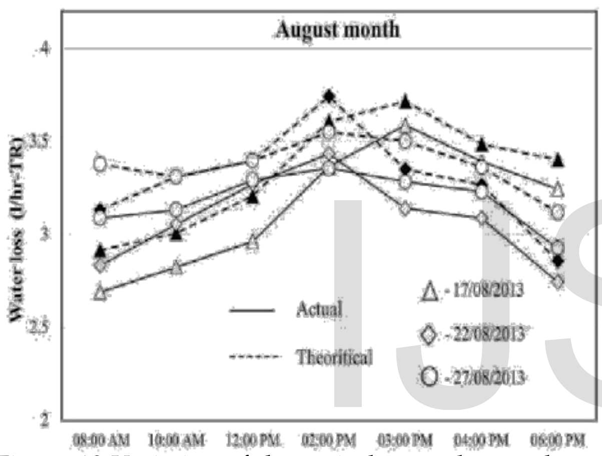

Figure 10 Variation of theoretical water loss and actual water loss with respect to time dur-ing August, 2013.

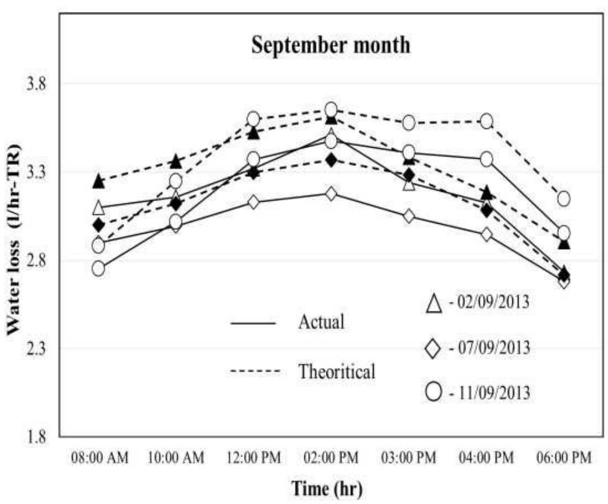

Figure 11 Variation of theoretical water loss and actual water loss with respect to time during September, 2013

Figures 12 and 13 show the variation of water loss, ambient dry bulb temperature (DBT) or air inlet temparature and ambient wet bulb temperature (WBT) for the regular intervals of time during some selected days. It was observed that as the air inlet temperature increases, the water loss also increases and reaches to a maximum at the peak hours and after that the water loss decreases. It has been observed from Fig.12 that the water loss at peak hour (2 pm) was about 3.4 lit/hr-TR corresponding to 34 °C DBT and 31.5 °C WBT on 22/08/2013. Also at non-peak hours (08:00 am, 06:00 pm) the water loss was about 2.7 lit/hr-TR corresponding to 31 °C DBT and 29 °C WBT on the same day.

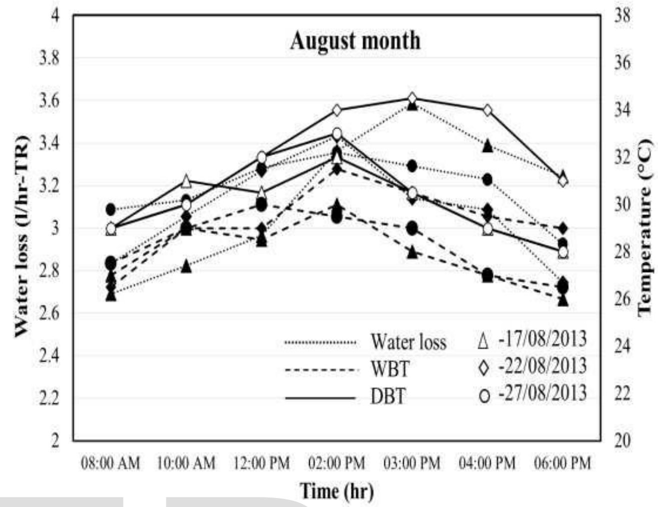

Figure 12 variation of water loss, WBT, DBT with time during August 2013

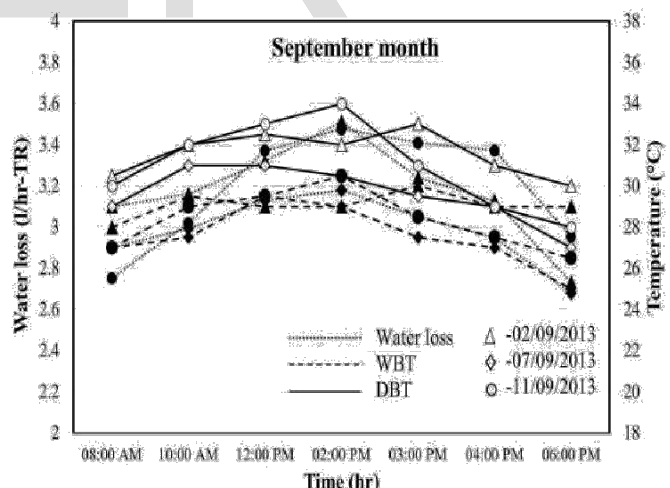

Figure 13 variation of water loss, WBT, DBT with time during September, 2013

3.4 Converting the water vapour into useful drinking water

It was observed from the Fig. 10 that about 3.4 l/hr-TR of water loss has been reported during 1 – 2 pm on 22nd August 2013. The correspond ing specific humidity of air at inlet and outlet of the cooling tower were 0.024 and 0.033 kg/kg of dry air, respectively. The estimated total water loss on 22nd August 2013 was about 3,672 lit/hr. In order to recover the amount of water which has been carried away by the cooling air in the form of drift and evaporation, a cooling unit with a dew point temperature of about 8-12 C has been proposed. It should be noted that using the above mentioned arrangement of cooling coil system, outlet air temperature can be further reduced to about 22 C (DBT) and the cor-responding specific humidity is 0.016 kg/kg of dry air. Therefore, the amount of water which can be condensed within the range of 0.016 - 0.033 kg/kg of dry air (total air flow rate of 80 kg/s) is about 4100 lit/hr. The net cooling effect required to condense 4100 lit/hr of water is estimated to be 1144 TR. Assuming a normal A/C plant power consumption rate @ 1 TR = 1 kW-hr, the electrical power required to produce (condense) 1 lit of water is about 0.27 kW-hr. Considering the electricity cost of Rs. 3 per kW-hr, the average pro-duction cost is Rs. 0.834 per lit. If the plant operates for a minimum period of 10 hr per day, the total amount of water which can be produced is about 41,000 lit. This is more than sufficient to fulfil the drinking water re-quirement of the whole IIT Guwahati student com-munity.

4. Conclusions

Performances of the water cooled towers employed in a 900 TR air-conditioning plant in terms approach, range and effi-ciency have been presented over a period of four months. Av-erage water loss per hr per TR refrigeration capacity has been estimated according to the North-eastern regions of India. It was observed that the peak hour (2 pm) water loss was about 3.4 lit/hr-TR corresponding to 34 °C DBT and 31.5 °C WBT recorded on 22/08/2013. The average values of cooling tower range, approach and efficiency during the test period were about 2.6 °C, 4.6 °C and 35% r espectively. Employing a simple cool-ing coil arrangement of having a dew point temperature of about 8-12 C, the average cost of condensing per lit of water is estimated to Rs.0.83.

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References

[1] Walker, W.H., Lewis, W.K., and McAdams, W.H., Principles of Chemi-cal Engineer-ing, McGraw-Hill, New York, 1923.

[2]Merkel,F.,"Verdunstungskiihlung," VDI Forschungsarbeiten, No.275, Berlin,1925.

[3] Nottage, H.B., "Merkel's Cooling Diagram as a Performance Correla-tion for Air-Water Evaporative Cooling Systems," ASHVE Transactions, Vol.47, 1941, pp.429-448.

[4] Lichtenstein, "Performance and Selection of Mechanical-Draft Cooling-Towers," ASME Transactions, Vol.65, No.7, 1943, pp.779-787.

[5] Mickley, H.S., "Design of Forced Draft Air Conditioning Equipment," Chemical Engi-neering Progress, Vol.45, No.12, 1949, pp.739-745.

[6] Simpson, W.M., and Sherwood, T.K., "Performance of Small Mechani-cal Draft Cool-ing Towers, "Refrigerating Engineering, Vol.52, No.6, 1946, pp.535-543, 574-576.

[7] Berman, L. D., Evaporative Cooling of Circulating Water, ch.2, Per-gamon, Oxford, 1961.

[8] U Threlkeld, J.L., Thermal Environmental Engineering, Prentice-Hall, Inc., ch.11, NewJersey, 1970.

[9] Yadigaroglu, G., and Pastor, E.J., "An Investigation of the Accuracy of the Merkel Equation for Evaporative Cooling Tower Calculations," ASME Paper No.74-HT-59, Pro-ceedings of the AIAA/ASME Thermophysics and Heat Transfer Conference, Boston, 1974.

[10] Whillier,A.," A fresh Look at the Calculation of Performance of Cool-ing Towers," ASHRAE Transactions, Vol.82, pt.I, 1976, pp.269-282.

[11] A.N. Nahavandi, R.M. Kershah, B.J. Serico The effect of evaporation losses in the analysis of counter flow cooling towers Nuclear Engineering and Design, 32 (1) (1975), pages 29–36.

[12] Suthedand, J. W. Analysis of mechanical draught counterflow air/water cooling tow-ers Trans. ASME, J Heat Transfer (1983), Pages 105, 576-583.

[13] Bernier MA. Cooling tower performance : theory and experiments. ASHRAE Trans 1994;100 (2):114–21.

[14] Bernier MA. Thermal performance of cooling towers. ASHRAE J 1995;37(4): 56–61.

[15] Nimr MA. Modeling the dynamic thermal behavior of cooling towers containing packing materials. Heat Transfer Eng 1999;20(1):91– 6.

[16] Jose AS. The use of thermo-fluid dynamic efficiency in cooling towers. Heat Transfer Eng 2002;23:22–30.

[17] J.R. Khan, S.M. Zubair Performance characteristics of counter flow wet cooling tow-ers Energy Convers Manage, 44 (2002), pp. 2073–2091 .

[18] S.P. Fisenko, A.A. Brin, A.I. Petruchik Evaporative cooling of water in a mechanical draft cooling tower International Journal of Heat and Mass Transfer, 47 (2004), pp. 165– 177