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EXERGY ANALYSIS OFTHE CROSS CURRENT COOLING TOWER

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ABSTRACT

The cold water needs to be circulated through the steam condenser of a thermal power plant in order to carry out the waste latent heat of condensation from steam. The hot water leaving condenser needs to be cooled in order to re-circulate it through condenser. Hence the hot water is passed through a cooling tower to reject waste heat to the ambient air through convection and mass transfer. The augmented cost of energy and scarceness of water has made researchers to focus on performance investigation of cooling tower as energy conservation opportunity. The thermal efficiency is generally used to measure performance of cooling tower which is evaluated from properties of the fluids. However this method is inefficient to investigate the major causes of irreversibility inside the cooling tower. Therefore, an exergy investigation is initiated to synchronize with the energy investigation of a cooling tower. This research paper includes the investigation of the thermal performance of a cross current cooling tower through energy balance, mass balance and exergy correlations. The variation of fluid properties with flow direction of fluids and exergy loss within the cooling tower are examined and authenticated through test results. The outcomes of study have shown that the analytical exergy loss is lower than the experimental exergy loss and the exergy loss varies with length and height of the cross current cooling tower. Further the influence of variation in size of cooling tower on exergy loss is evaluated analytically and found that the increase in length of cooling tower than the height reduces exergy loss by 8.18% improving thermal efficiency of cooling tower by 3.57%.

Keywords: *Evaporative Cooling, Cross Current, Cooling Tower, Exergy*

INTRODUCTION

The cooling tower plays vital role in refrigeration, air conditioning, chemical and thermal power plants. The prime duty of the cooling tower is to discard un-useful heat to the ambient air. The water is normally circulated in as a medium to carry away un-useful heat from industrial heat exchanger or condenser. The hot water is sprinkled from top of a cooling tower in the form of small water spray, which travels down stairs exchanging mass and heat of water to the air circulated through the cooling tower. The literature review has revealed that the energy evaluation of cross current cooling tower is made by many researchers on the basis of water properties and air properties at the exit. Many researchers have analyzed the variation of properties with respect to atmospheric conditions. An energy analysis is done to evaluate the performance of the cooling tower. The various methods for the evaluation of cooling tower were devised to investigate the opportunities of technology and improvement of thermal performance through the aim of conservation of energy. The energy evaluation alone is not sufficient to discover reasons of irreversibility. The use of exergy conception explores clearly regarding exergy loss within the cooling tower that is more enlightening than energy evaluation. The exergy evaluation quantifies loss in terms of exergy loss, which gives the extent of thermodynamic inadequacy. Therefore analysis of the cross current cooling tower is experimentally evaluated to determine properties of air and water passing through a cooling tower along with flow path of fluids. The exergy evaluation of both water and air is made using experimental data and further same is used to evaluate exergy loss within the cooling tower. The experimental results are judged against analytical results evaluated from mathematical model using MATLAB.

LITERATURE REVIEW

Ren Chengqina et al. have discussed theories of exergy investigation for air conditioning and heating ventilation through logical assessment and concluded that the choice of dead state is important in assessment of moist

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air exergy [1]. Muangnoi Thirapong et al. have conducted tests over the counter current direct contact cooling tower. It was observed that the exergy of water was reduced from inlet of water to the base of a tower. It was seen that the exergy of air through convective heat transfer firstly reduced at the entrance due to negative convection and enhances a little prior to leaving tower. The exergy of air through evaporation of water was elevated and capable to absorb exergy delivered from water. They observed that the process of cooling execute poorly at the base of tower because of thermodynamic irreversibility and improve gradually with height of the cooling tower. The lowest exergy loss was obtained at the larger height of the cooling tower [2]. Bilal A. Qureshi et al. have carried out exergetic evaluation of evaporative heat exchangers and counter current cooling tower. They recorded that the exergy efficiency is influenced significantly by inlet air WBT and varies proportionately. It has been observed that dead state properties and change in dead state properties by operating at off design condition didn't influence the overall efficiency significantly [3]. Muangnoi Thirapong et al. analyzed the effect of ambient temperature and humidity over thermal performance of counter current cooling tower. They forecasted analytically air and water properties passing through a cooling tower and authenticated through experimental results. It was observed that the change in exergy of air was higher than the change in exergy of air because of evaporative heat transfer than that of change in exergy because of convective heat transfer [4]. M. Saravanan et al. obtained a mathematical correlation depending on mass and heat transfer hypothesis to find the state of water and air at the exit of a counter current cooling tower. They observed reduction in the temperature of water at the exit along with reduction in inlet air WBT, which improved water approach temperature and exergy loss thereby reducing exergetic efficiency and vice versa [5]. Hajidavalloo Ebrahim et. al. used the distinctive mathematical correlation to forecast the thermal performance of a cross current cooling tower for varying WBT and the outcomes were authenticated through test results. They found rise in the range, approach temperature and evaporative losses with the enhancement of WBT [6]. J.M.Wua et al. have theoretically investigated the mass and heat transfer among film of water and air within a direct contact evaporative cooler. It was found that the front velocity of air and padding thickness were the most significant variables for effectiveness of a direct contact evaporative cooler [7]. J.C. Santos.et.al. have evaluated analytically concurrent mass and heat transfer problems for air washers operating like evaporative air cooler. It was recorded that in dry and hot environment the air washers were more efficient and capable of producing air at the lowest temperature at the outlet. It was seen that the cooling rate was lesser at higher air flow rate because of lesser contact duration between air and water [8]. Li.Wang.et.al. investigated four kinds of exergy transfer processes occurring in the counter current cooling tower in different working circumstances. The exergy efficiency of counter current direct contact cooling tower achieved was below 25% [9]. Aravamudan Kannan.et.al. developed numerical simulation plan for a mathematical correlation for wind-assisted evaporator and experiments were carried out at various working conditions. The Numerical simulation acted as feasible prognostic instrument for design and rating of the wind-assisted evaporator [10, 12]. It is concluded from the literature review that the researchers have carried out energy evaluation of cross current and counter current cooling tower and exergy evaluation of only counter current cooling tower on the basis of fluid properties at the exit [13]. Hence the exergy evaluation of cross current cooling tower across the tower is made in this research paper which has remained unfocused.

MATHEMATICAL CORRELATIONS USED FOR ANALYSIS

The transfer of heat from water to the air in a cooling tower is achieved by means of the process of heat and mass transfer occurring in a cooling tower. The transfer of heat by the mode of evaporation dominates the heat transfer by convection; as the outer film of water absorbs the latent heat of evaporation form itself thereby cooling water. Hence, the energy balance and mass balance equations are depending up on overall mass transfer coefficient C_d. It is depending on enthalpy potential at a bulk temperature of water by ignoring the resistance of film. The heat absorbed by air is the same as heat rejected by water [10, 11] is specified by equation below.

$$m_w.C_{p,w}.dt_w = m_a.dh_a = C_d.w_a.(h_s - h_a).dV \tag{1}$$

Change in temperature of water is given by equation given below:

$$dt_w = \left(\frac{N\ T\ U}{C_{p,w}}\right).(h_s - h_{a.}) \tag{2}$$

Where, $N\ T\ U = \left(\frac{C_d.w_a.dV}{m_w}\right)$

Change in air enthalpy through mass and heat transfer in a cooling tower is specified as:

$$dh_a = N\ T\ U\left(\frac{m_w}{m_a}\right).(h_s - h_{\ a}) \tag{3}$$

Change in air humidity ratio with the path of air flow is specified as [10]:

$$\frac{\partial \omega}{\partial l} = N.T.U(\omega_s - \omega_{a.}) \tag{4}$$

The overall exergy of water for mass flow rate of water 'm_w' is specified as [7]:

$$E_w = m_w\left[\left(h_{fw} - h_{fo}\right) + v_{ft}(P - P_s) - T_o\left(s_{fw} - s_{fo}\right) - R_v.T_o.L_n\emptyset_o\right] \tag{5}$$

The $v_{ft}(P - P_s)$ term on right side of the above equation is generally ignored, when compared to $R_v.T_o.L_n\emptyset_o$. Therefore above equation is specified as:

$$E_w = m_w\left[\left(h_{fw} - h_{fo}\right) - T_0\left(s_{fw} - s_{fo}\right) - R_v.T_o.L_n\emptyset_o\right] \tag{6}$$

The air exergy on the basis of the mass of dry air ignoring pressure variation inside the cooling tower is specified as [7]:

$$E_a = m_a\left[\left(C_{p,a} + \omega C_{p,v}\right).\left(T - T_o - T_o.L_n\frac{T}{T_o}\right) + R_a.T_o\left((1 + 1.608\omega)L_n\left(\frac{1 + 1.608\omega_{oo}}{1 + 1.608\omega}\right) + 1.608\omega.L_n\left(\frac{\omega}{\omega_{oo}}\right)\right)\right] \tag{7}$$

In order to obtain the exergy loss E_D, the potential of air to recuperate exergy given by water can be achieved from the control volume exergy balance correlation. The correlation is applied at steady state conditions and goes through an adiabatic process with no work output. Presuming that the thermodynamic properties of water and air are well-known at various nodes with tower height and length, the exergy loss for each incremental tower length and height at a node (m+1, n+1) can be evaluated as.

$$Net\ exergy\ entering = Net\ exergy\ leaving + Exergy\ lost$$

$$\left[E_{w(m+1,\ n)} + E_{a(m,\ n+1)}\right] = \left[E_{w(m+1,\ n+2)} + E_{a(m+2,\ n+1)}\right] + E_{D(m+1,\ n+1)} \tag{8}$$

Rearranging correlation given above, we obtain the correlation that provides the exergy lost at (m+1, n+1) node inside cross current cooling tower.

$$E_{D(m+1,\ n+1)} = \left[E_{w(m+1,\ n)} - E_{w(m+1,\ n+2)}\right] + \left[E_{a(m,\ n+1)} - E_{a(m+2,\ n+1)}\right] \tag{9}$$

EXPERIMENTATION

The test facility for the cross current, direct contact, induced draft cooling tower is represented in Figure 1, which is built to carryout investigation. The cross current direct contact cooling tower is provided with hot water spraying facility at the top through which the warm water sprinkled homogeneously over the perforated PVC fill packing. The PVC fill packing is positioned perpendicular to flow direction of water and air in the core of cooling tower. The PVC fill packing provides sufficient wetted surface area and contact duration for transfer of heat and mass among water and air as represented in Figure 2. The fan assembly is positioned at the outlet of air to generate horizontal uniform air suction passing through PVC fill material. The tank of water is located at the base of a cooling tower fitted with immersion type water heaters for the purpose of heating of water needed to circulate to carryout actual tests. The mass flow rate of fluids can be monitored and controlled as per need of tests through control valves. The walls of tower are insulated with glass wool as insulating material to reduce heat loss from cooling tower to the environment.

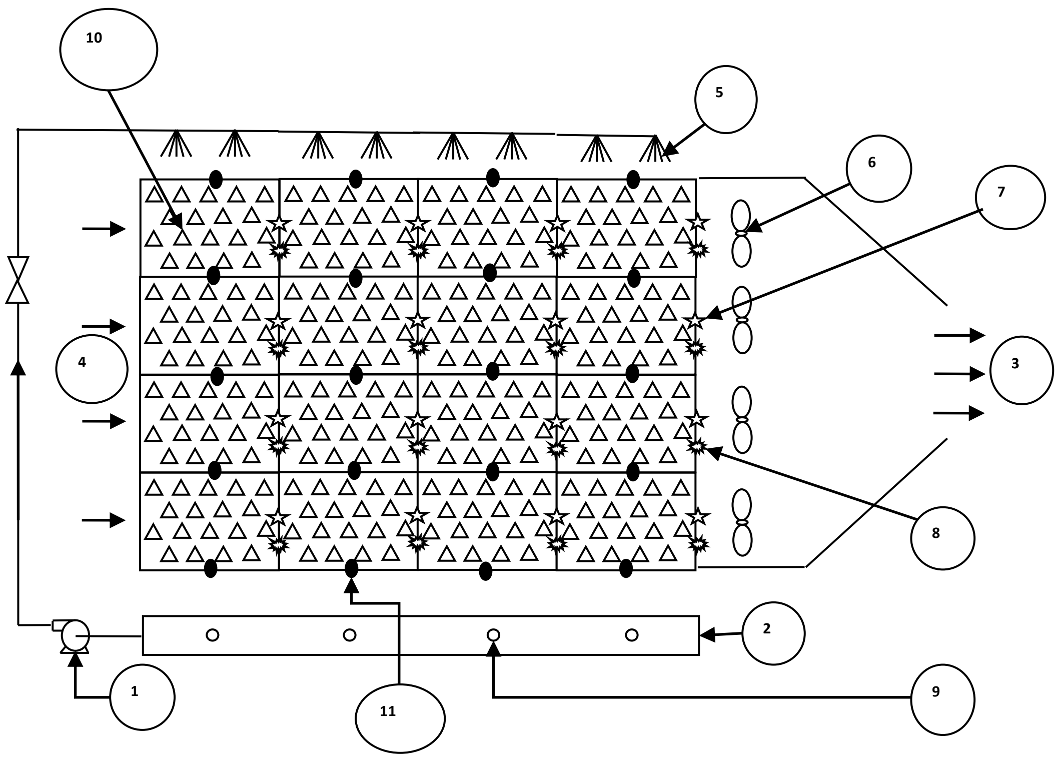


Figure 1. Schematic drawing of cross current cooling tower. 1- Water pump; 2-Warm water tank; 3-Heated air outlet; 4- Fresh air inlet; 5-Spraynozzle; 6-Air fan assembly; 7-WBT sensor; 8-DBT sensor; 9-Immersion heaters; 10- Fill packing; 11-Water temperature sensors

The PVC fill bars of 28 mm × 28 mm × 300 mm dimensions provided with holes of 0.5 cm diameter are mounted in the zigzag pattern in the core of cooling tower. The fill bars offer wetted surface area of 9.9 m2 per unit volume of the cross current cooling tower. The cooling tower is developed for the maximum water and air mass flow rate of 0.66 kg/sec each with a temperature range of 10 °C. The twenty PT100 temperature sensors have been located at identified places for recording temperature of water and sixteen sensors each for recording WBT and DBT having accuracy of ± 0.1°C inside the cooling tower interfaced with data acquisition system. Four Rota-meters are deployed for measurement of circulated water flow rate through different sections of tower having least count of 0.1 LPM. The velocity air is recorded by means of anemometer with an accuracy of ± 0.1 m/s. The water tank is built-in with four water heaters each of 6 kW fitted with temperature controller to retain constant water temperature at inlet. The technical details of test facility are provided in Table 1.

Table 1.Technical details of cross current cooling tower

Tower width	0.3 m
Tower length	2 m
Tower height	2 m
Tower active volume (V)	1.2 m^3
Maximum mass flow rate of water (m_w)	0.66 kg/s
Maximum mass flow rate of air (m_a)	0.66 kg/s
Cooling temperature range	10 ˚C

The complete cross section of the cooling tower is divided in four vertical sections V1, V2, V3 and V4 and four horizontal sections H1, H2, H3 and H4 for the actual testing and analysis purpose. The cross section of cooling tower is splitted into sixteen small unit volumes and cross current integration method is used for analysis. In addition, it is considered to be splitted in four broad regions A, B, C and D for simple demonstration, comparison and justification purpose as represented in Figure 3. The experimentations are conducted with various ratios (m_w/m_a) of fluid mass flow rate at variable environmental conditions and for different temperatures of water at the inlet. The observations were finally accepted by repeating the tests. The ratio of mass flow rate of fluids (m_w/m_a) is varied from 0.75 to 1.5 with temperatures of water 40 °C and 45 °C at the inlet for variable environmental conditions to cover up variety of ambient conditions. The air properties at inlet of a cooling tower taken at the time of test are Wet bulb temperature (WBT) = 26.7 ˚C, Dry bulb temperature (DBT) = 36.3 ˚C, Humidity ratio (ω) = 0.0182 $kg_w/kg_{d.a}$, Relative humidity (Ø) = 48.1% and Enthalpy of air (h_a) = 83.2 kJ/kg. The exergy evaluation is carried out with the standard ambient conditions P_o = 1.0132 bar, T_o = 25°C, ϕ_o = 50% and ω_{oo} = 0.009923 $kg_w/kg_{d.a.}$ The tests are performed to obtain actual properties of fluid inside the cooling tower and fluid properties are evaluated analytically using MATLAB coding.

Figure 2. Internal view of cooling tower

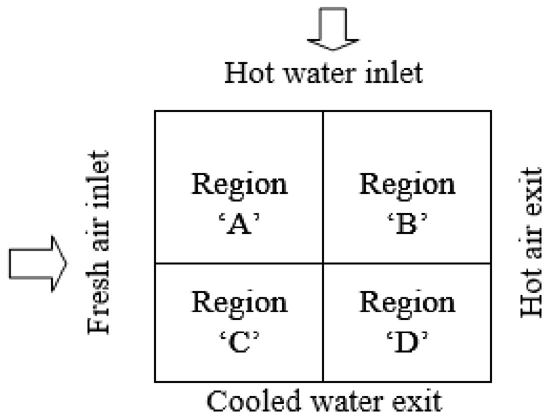
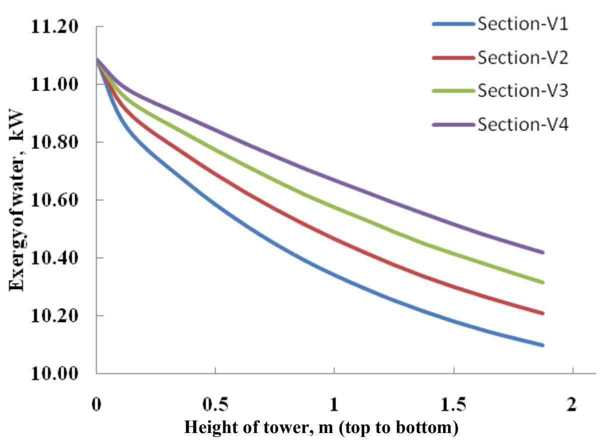


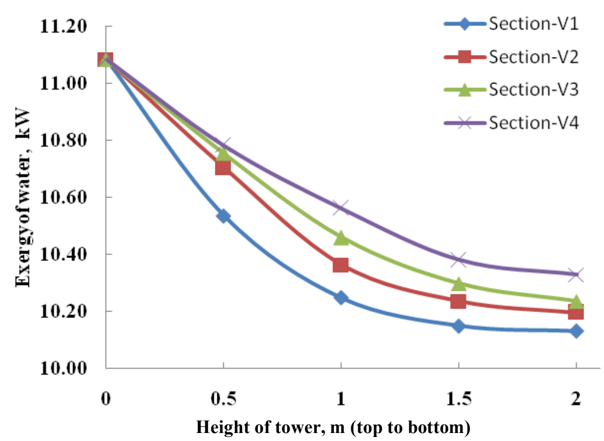
Figure 3. Line diagram of cooling tower

EXPERIMENTAL OUTCOMES AND DISCUSSIONS

The graphs plotted for variation water exergy obtained from experimental and analytical results along with height of cooling tower are represented in Figure 4 (a) and (b) respectively. The homogeneous reduction in exergy of water from top to the base of tower along height at a specified length is observed. The rate of drop in exergy of water along the height of a tower is found non-uniform at different lengths and the rate of reduction of water exergy reduces with along the length. The rate of exergy reduction of water is higher at vertical section 'V1' and 'V2' judged against vertical section 'V3' and 'V4' as seen from the test and analytical results both presented in Figure 4.



(a) Analytical



(b) Experimental

Figure 4. Water exergy variation along height of cross current cooling tower

Table 2. Exergy of water, kW

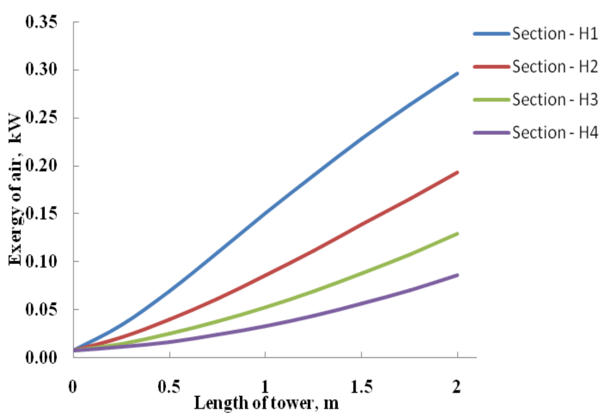
Height, (m) (top to bottom)	Analytical results				Test results			
0	11.08	11.08	11.08	11.08	11.08	11.08	11.08	11.08
0.5	10.70	10.77	10.84	10.89	10.53	10.70	10.75	10.78
1.0	10.44	10.54	10.64	10.71	10.24	10.36	10.45	10.56
1.5	10.26	10.37	10.47	10.56	10.14	10.23	10.29	10.37
2.0	10.14	10.24	10.34	10.43	10.12	10.19	10.23	10.32
Length, (m)	**0.25**	**0.75**	**1.25**	**1.75**	**0.25**	**0.75**	**1.25**	**1.75**

The water at the smallest exergy is obtained at the exit of section ‘V1’. The test results exhibit the analogous trend for reduction in water exergy as the analytical results. The reduction in exergy of water obtained experimentally is larger than reduction in exergy obtained analytically at region ‘C’ and ‘D’. The cause for larger reduction in water exergy at region ‘C’ and ‘D’ is the limit of saturation of air that occurs at a lesser rate along with length of tower at bottom of tower. The water exergy variation is summarized in Table 2. The average exergy of water at the exit obtained analytically is larger than average exergy obtained experimentally by 0.69%.

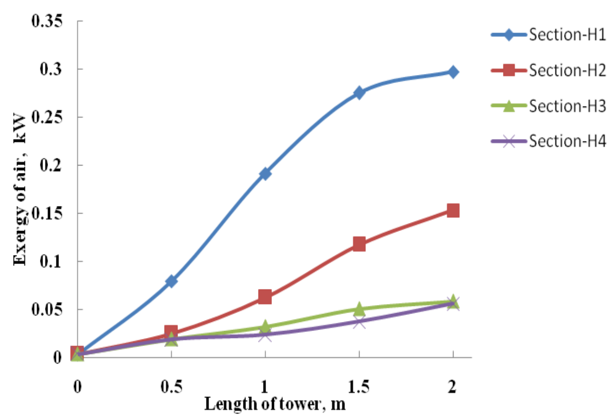
Table 3. Exergy of air, kW

Height, (m) (top to bottom)	**Analytical results**					**Test results**				
0.25	0.0029	0.0555	0.1306	0.2055	0.2723	0.0029	0.0793	0.1915	0.2751	0.2973
0.75	0.0029	0.0314	0.0749	0.1260	0.1786	0.0029	0.0249	0.0619	0.1169	0.1529
1.25	0.0029	0.0193	0.0464	0.0810	0.1203	0.0029	0.0187	0.0319	0.0501	0.0580
1.75	0.0029	0.0127	0.0295	0.0526	0.0817	0.0029	0.0186	0.0234	0.0370	0.0557
Length, (m)	**0**	**0.5**	**1**	**1.5**	**2**	**0**	**0.5**	**1**	**1.5**	**2**

The graphs plotted from analytical and experimental results for variation air exergy along with length of cooling tower are represented in Figure 5 (a) and (b) respectively. It is seen from analytical results that the exergy of air enhances with length of cooling tower homogeneously at the specified height. The maximum exergy is attained at horizontal section ‘H1’ by the air. The exergy of air enhances at higher rate at horizontal sections ‘H1’ and ‘H2’ judge against rate of rise in exergy of air at sections ‘H3’ and ‘H4’ due to the water entering at higher exergy. The air enters with lower exergy and relative humidity has got the higher potential for water evaporation which contributes to larger rate of rise in exergy of air. The results obtained experimentally show the analogous trend for variation of exergy of air obtained analytically. The rate of increase in exergy of air at region ‘C’ is the smallest as the water entering from region ‘A’ is with the smallest exergy content. The rate of increase in exergy of air enhances at the same time as passing through region ‘D’ as the water entering from region ‘B’ is with higher exergy content. The results of experimentation illustrate that the average rise in exergy of air is smaller than the results forecasted analytically. The average air exergy at the outlet is smaller by 11.9% than average air exergy forecasted analytically, which is because of lesser rate of water evaporation than the rate of evaporation forecasted analytically. The air exergy variation is summarized in Table 3.



(a) Analytical



(b) Experimental

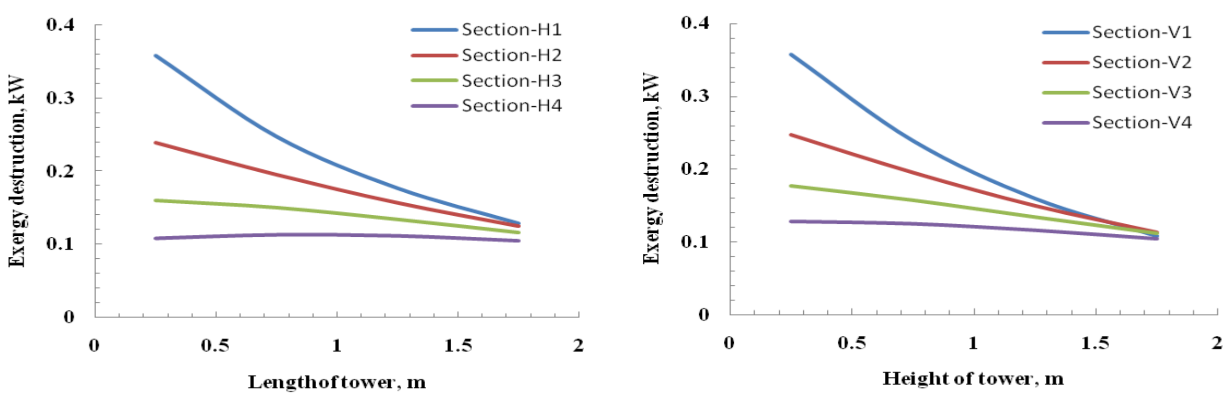
Figure 5. Air exergy variation of along length of cross current cooling tower

The graphs obtained for exergy loss based on analytical results along length and height of cooling tower are represented in Figure 6(a) and (b) respectively. The exergy loss calculated analytically demonstrates that the maximum exergy loss occurs at region ‘A’ is about 33% of net exergy lost. The minimum exergy loss of 17% occurs at region ‘D’ and moderate exergy loss of 23% and 25% occurs at region ‘B’ and ‘C’ respectively. The exergy loss reduces along diagonal joining air-water inlet corner to air-water exit corner and is more or less symmetrical about this diagonal. The exergy loss reduces along length and height, but it reduces quickly along height as compared to the length of a tower. It is seen that the exergy loss is proportional to the difference of temperature of water and air coming in contact. It is seen that the exergy loss is larger at air-water inlet corner. Hence air-water inlet region ‘A’ is recognized as a critical region for exergy loss. The graphs for exergy loss based on results of experimentation along height and length of cooling tower are shown in Figure 7(a) and (b) respectively. The experimental results show that the exergy loss at region ‘A’ is the largest as forecasted analytically. It is seen that the overall exergy loss evaluated experimentally is larger by 15% than exergy loss forecasted analytically. The exergy loss evaluated from test results at region ‘B’ is larger than forecasted analytically. The minimum exergy loss is evaluated at region ‘D’. However, the exergy loss at the lower height of a tower is smaller than at the top of a tower. The exergy loss evaluated is summarized in Table 4.

Table 4. Exergy loss, kW

Horizontal section	**Analytical result**				**Test result**			
	V1	V2	V3	V4	V1	V2	V3	V4
H1	0.3578	0.2469	0.1763	0.1281	0.4733	0.2916	0.2231	0.1886
H2	0.2390	0.1952	0.1567	0.1249	0.3505	0.2261	0.1862	0.1562
H3	0.1596	0.1499	0.1338	0.1160	0.2356	0.1762	0.1511	0.1211
H4	0.1079	0.1133	0.1117	0.1042	0.1672	0.1456	0.1211	0.1040

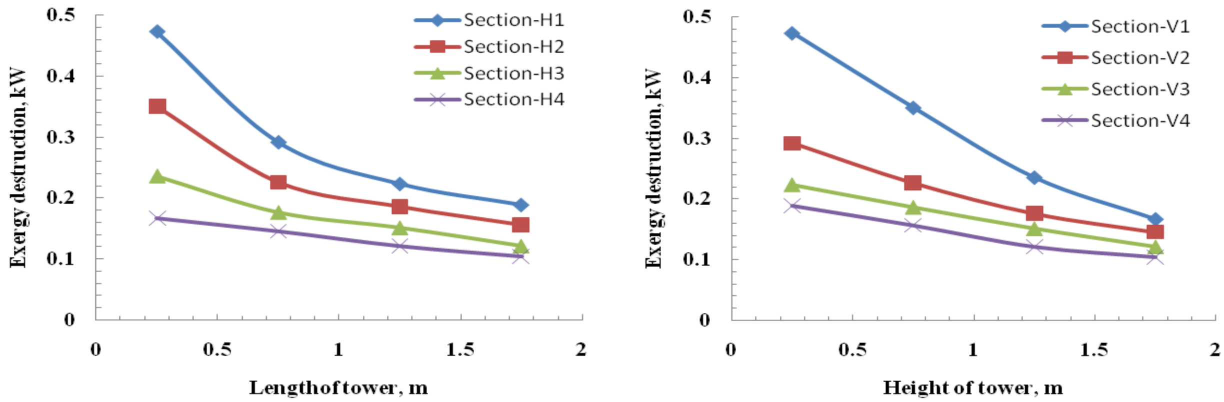
Hence the analytical results are validated with experimental results. After validating the results, the analytical method is used to carry out study of cooling tower with different sizes. The variation of exergy loss across the cooling tower with variation in length of cooling tower keeping height and width constant is analytically studied. The exergy loss along length and height for various lengths of cooling are represented in Figure 6, 8 and 9. The highest exergy loss occurring in a cooling tower for various lengths of cooling tower 1.5 m, 2.0 m and 2.5 m are 0.357 kW, 0.330 kW and 0.303 kW respectively. It is observed that the exergy loss reduces with increase in cooling tower length. However, it is seen that the exergy loss at critical region increases, but the overall exergy loss with increase in length of tower. The intensity of exergy loss reduces and gets restricted to critical region ‘A’ with increase in length of the tower. The intensity of exergy loss spreads to region ‘B’ with reduction in length of cooling tower. The efficiency of cooling tower improves with increase in length of cooling the tower; the efficiencies for the various lengths obtained are 61.08%, 68.86% and 71.32%. The average temperature of water also declines with increase in length of tower. The average temperature of water for above given set of lengths is obtained as 33.34°C, 32.11°C and 31.68°C respectively.



(a) Along length of cooling tower

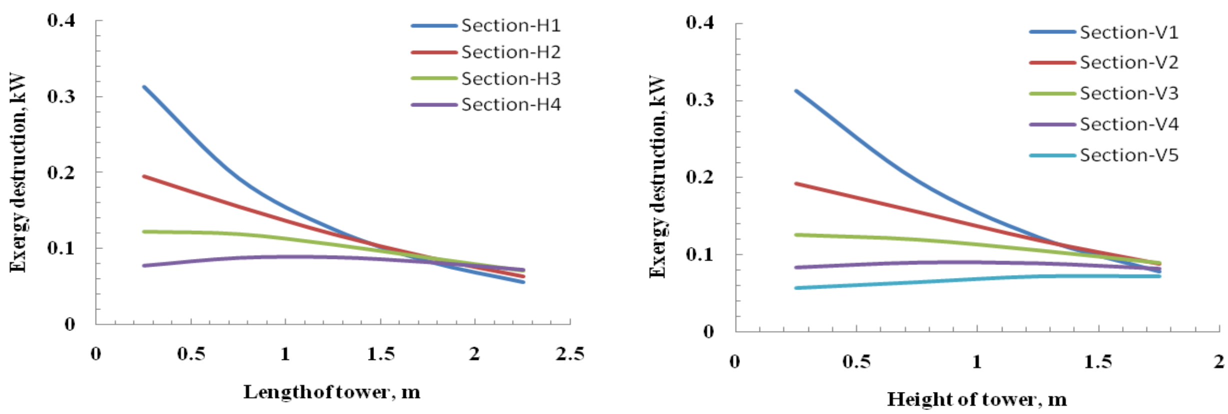
(b) Along height of cooling tower

Figure 6. Exergy loss obtained analytically



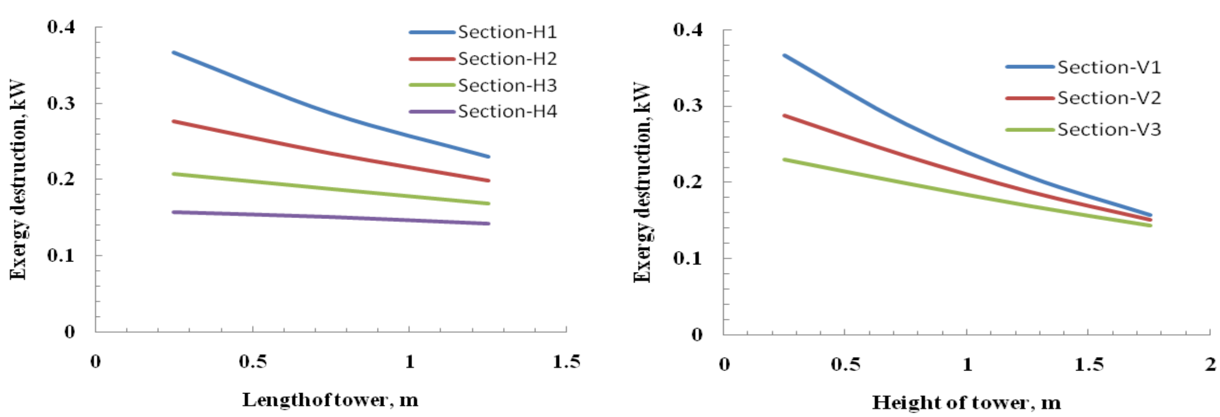
(a) Along length of cooling tower (b) Along height of cooling tower

Figure 7. Exergy loss obtained experimentally



(a) Along length of tower (b) Along height of tower

Figure 8. Variation of exergy loss for tower length = 2.5 m

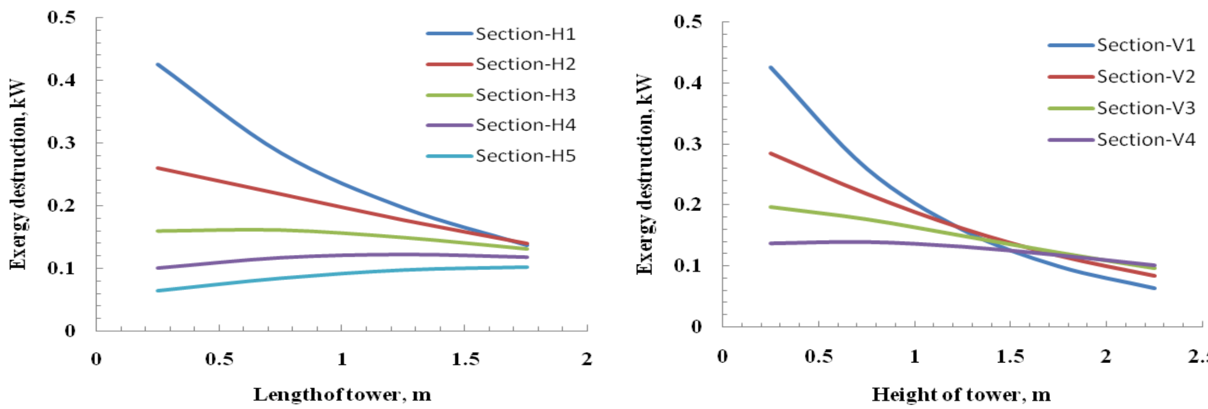


(a) Along length of tower (b) Along height of tower

Figure 9. Variation of exergy loss for tower length = 1.5 m

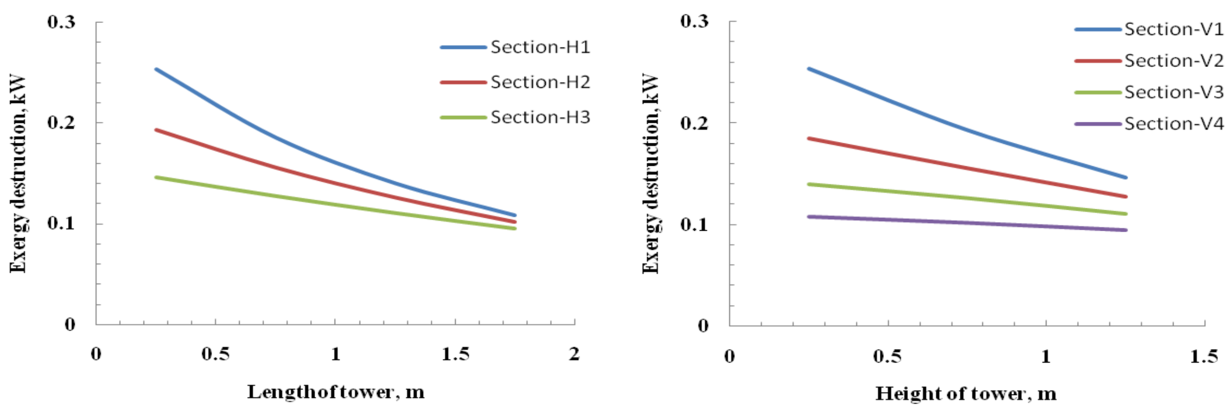
The variation of exergy loss across the cooling tower with variation in height of cooling tower is studied and represented in Figure 6, 10 and 11. It is observed that the exergy loss rises with increase in cooling tower height. The highest exergy loss for various heights of cooling tower 1.5 m, 2.0 m and 2.5 m are 0.248 kW, 0.330 kW and

0.412 kW respectively. However, it is observed that the overall exergy loss enhances with increase in height of tower. The intensity of exergy loss reduces and gets restricted to critical region ‘A’ with increase in height of tower. The intensity of exergy loss spreads to region ‘C’ with reduction in height of cooling tower. The efficiency of cooling tower improves with increase in the height of a cooling tower; the efficiencies for the various heights obtained are 46.35%, 68.86% and 89.15%. The average temperature of water obtained at outlet for the above given set of heights is 36.03°C, 32.11°C and 28.58°C respectively. With increase in height the temperature difference of fluids prolongs along the height, which introduces irreversibility and enhances exergy loss.



(a) Along length of tower (b) Along height of tower

Figure 10. Variation of exergy loss for tower height = 2.5 m



(a) Along length of tower (b) Along height of tower

Figure 11. Variation of exergy loss for tower height = 1.5 m

CONCLUSION

The exergy, exergy loss and properties of fluid inside the cooling tower are evaluated analytically and experimentally and the analytical and test results are compared. The water exergy reduces along height and the rate of reduction in exergy of water reduces with length of the tower. The exergy of air enhances with length and the rate of increase in exergy reduces with height of the tower. The exergy loss is the highest at the entrance corner of fluids at region ‘A’ and the lowest exergy loss occurs at the exit corner of fluids at region ‘D’. The exergy loss at region ‘A’, ‘B’, ‘C’ and ‘D’ obtained with reference to overall exergy loss is 33%, 23%, 25% and 17% respectively. The experimental exergy loss is seen nearly 15.05% larger than the exergy loss forecasted analytically. The improvement in thermal efficiency of cooling tower is seen by 3.6% and 29.5% with increase in length and height by 25% respectively. The overall exergy loss is less by 12.1% and thermal efficiency improves by 3.6% with increase in length of cooling tower by 25%. The overall exergy loss increases by 23.7% and thermal efficiency improves by

29.5% with increase in height of cooling tower by 25%. The reduction in height and length of tower increases exergy loss and reduces thermal efficiency of cooling tower. It is recommended that for required cooling load, designer has to evaluate length to height ratio so that the exergy loss is minimum and thermal efficiency is maximum. While designing new cooling tower one has to focus on critical region identified to reduce exergy loss. Hence the cooling tower with larger length than height yields smaller exergy loss with higher thermal efficiency is concluded. As a future scope of the work one can simulate cross current cooling tower which can help to optimize length to height ratio of cross current cooling tower in general.

NOMENCLATURE

C_d	Mass transfer coefficient, kg/m^{2}s
C_p	Specific heat, kJ/ kg K
DBT	Dry bulb temperature, °C
E	Net exergy, kW
E_D	Exergy loss, kW
NTU	Number of transfer units
P	Pressure, kPa
R	Gas constant, kJ/kg K
T	Temperature, K
V	Cooling tower active volume, m^3
WBT	Wet bulb temperature, °C
h	Enthalpy, kJ/kg
h_s	Enthalpy of saturated air at interface, kJ/kg
l	Tower length, m
m_a	Dry air mass flow rate, kg/s
m_w	Water mass flow rate, kg/s
s	Entropy, kJ/kg K
t	Temperature, °C
v	Specific volume of water, m^3/kg
w_a	Wet surface area per unit volume, m^2/m^3

Greek symbols

ϕ	Relative humidity, %
ω	Humidity ratio, $kg_w/kg_{d.a}$
ω_s	Saturated humidity ratio at water temperature, $kg_w/kg_{d.a}$

Subscripts

a	Dry air
D	Loss
f	Liquid state
o	Restricted dead state
oo	Environment
s	Saturated air
t	Water temperature
v	Water vapour
w	Water

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