DESIGN AND PERFORMANCE ANALYSIS OF A COOLING TOWER IN SULFURIC ACID PLANT

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Abstract

The capacity expansion of a sulfuric acid plant in WATA Chemicals Limited required a cooling tower to meet the increased cooling demand. Estimated water capacity of the cooling tower was 250 m^3/hr (1100 gpm) which is a medium size cooing tower with a short cooling range of 5°C. Purchasing of a new cooling tower of this size is expensive. Based on the in-house experience plus information in literature, the company designed, installed and operated a cooling tower in the plant. This paper verifies the design calculations, predicts the performance curves and analyzes the performance of the cooling tower. From this analysis it was found that the design procedure followed for the cooling tower is appropriate and the performance is satisfactory. This effort was found to be cost effective and saved foreign currency. It is an innovative adaptation leading to technological capacity building in Bangladesh.

Introduction

Water plays a notable role as a coolant in industries. Earlier small cooling requirements were catered for by 'once-through' system with warm water discharged to drain or water bodies. Today's rising water cost, limited water resource and thermal water pollution render this approach quite unsatisfactory[1,2]. Recirculation is, therefore, essential and cooling tower provides a means by which hot water is cooled with air. The cooling tower in its different forms and sizes is the cheapest way to cool large quantities of water[3,4].

Cooling towers are widely used in chemical and other plants. In Bangladesh, large cooling towers are used mainly in urea fertilizer factories and some power plants. Small and medium size cooling towers are found in a large number of small and medium industries and air conditioning of commercial buildings. Due to lack of technological capability in our country, even small size cooling towers are imported from neighboring countries. Although the technology of cooling towers is well established, ensuring its performance throughout the year with the seasonal variation in the atmospheric condition is a challenging problem.

WATA Chemicals Limited located near Dhaka city, in 2003 decided to expand the capacity of the sulfuric acid plant from 40 t/day to 60 t/day in order to meet the growing demand of sulfuric acid in its chemical complex. For the 40 t/day plant the company used the pond water to cool concentrated sulfuric acid in a trombone cooler. The hot water from the trombone cooler was discharged to the pond and recirculated to the plant after being cooled by natural evaporation process. With the increase in plant capacity to 60 t/day the cooling water requirement increased and the pond was no more sufficient for the plant.

Moreover, the presence of impurities in pond water, resulted in scale formation on the pipes of the trombone cooler and decreased the heat transfer rate. The plant therefore required a cooling tower to meet the requirement of cold water for the trombone cooler as well as to reduce the scale formation. The capacity of the cooling tower was estimated 250 m^3/hr (1100 gpm). WATA Chemicals Limited could purchase a bottle shape induced draft cooling tower of this capacity from abroad at a cost of Tk. 720,000 (US $ 12,000), instead it designed and installed a cooling tower with only one-third of that price.

In designing the cooling tower some assumptions were made to simplify its design. Major assumptions as discussed later are: design wet bulb temperature, ambient air temperature and % RH. In operating the cooling tower make up water is used to adjust evaporation loss, drift loss and blow down from the cooling tower.

This paper deals with the thermal design of the cooling tower and its performance.

Proposed Water Circulation System and Cooling Tower

In the production of concentrated (98.5%) sulfuric acid in WATA Chemicals Limited, the concentrated acid is cooled with water in a trombone cooler. As discussed previously, in order to meet the increased demand of cooling water for the capacity expansion of sulfuric acid plant, it was proposed to install a cooling tower to cool the hot water from the trombone cooler. Fig 1 shows the water circulation system comprising of the trombone cooler and a cooling tower. Heat load in the trombone cooler is 4.95 million Btu/hr. (5.22 million KJ/hr). Cooling water enters the trombone cooler at 33°C and leaves at 38°C. The flow rate of cooling water corresponding to the above heat load and the inlet and outlet temperatures of the cooling water is 1100 gpm (250 m^3/hr).

Fig.2 illustrates a schematic diagram of the proposed counter flow induced draft cooling tower which is widely used.

Cooling Tower Theory [5,6,7]

Cooling tower is a device for reducing the temperature of water by bringing it in contact with an air stream in a tower filled with packing, where a minor portion of water is evaporated and the main portion cooled. Hot water rejects heat by heat transfer to air in the form of latent heat (80%) and sensible heat (20%). The most accepted theory of cooling tower developed by Markel is based upon the potential difference as the driving force. The integrated form of Markel equation is

$$NTU = \frac{KaV}{L} = \int_{T_{w_2}}^{T_{w_1}} \frac{dT_W}{H_W - H_a} \qquad (1)$$

where,

NTU = number of transfer unit

K = mass transfer coefficient, lb/hr ft^2 (kg/hr m^2)

a = area of heat transfer per unit tower volume, ft^2/ft^3 (m^2/m^3)

V = active cooling volume per unit ground area, ft^2/ft^3 (m^2/m^3)

L = water rate, lb/h (kg/hr)

H_w = enthalpy of saturated air at bulk water temperature, Btu/lb dry air (KJ/Kg dry air)

H_a = enthalpy of air stream, Btu/lb dry air (KJ/Kg dry air)

T_{w_1}, T_{w_2} = entering and leaving water temperatures °F (°C)

The right hand side of Eq. (1) is in terms of air and water properties and is independent of tower dimensions.

Fig.3 provides water and air relationships and the driving potential (H_w-H_a) which exists in a counter flow tower. The air saturation curve AB is fixed by the inlet and outlet water temperatures T_{w_1} and T_{w_2} respectively. The air operating line is shown by line CD. The point C has an enthalpy corresponding to the wet-bulb temperature of the entering air. The equation of the air operating line is

$$H_{a_1} = H_{a_2} + L/G\,(\text{Range}) \qquad (2)$$

Where,

G = airflow rate, lb/hr (kg/hr)

Range = $(T_{w_1} - T_{w_2})$ °C

Ideally, the wet bulb temperature (T_{wb}) of the entering air is the lowest temperature to which the water can be cooled. In actual practice, cooling towers are not usually designed for approaches closer than 2.8 °C (5 °F).

The tower characteristic parameter KaV/L can be determined by integration of Eq. (1). The four-point method may be used to evaluate the integral as described by Perry[5]:

$$\frac{KaV}{L} = \int_{T_{w_2}}^{T_{w_1}} \frac{dT_W}{H_W - H_a}$$

$$= (T_{w_1} - T_{w_2})\,(1/\Delta H_1 + 1/\Delta H_2 + 1/\Delta H_3 + 1/\Delta H_4)/4 \qquad (3)$$

The intervals are at 0.1, 0.4, 0.6 and 0.9 of the cooling range[8]. The values of ΔH in Eq-3 are associated with these intervals.

NTU or KaV/L will not change due to change in the wet bulb temperature of the air or the cooling range, however, it depends on the L/G ratio[7].

Guidelines for Preliminary Design of New Tower

Cooling towers are designed according to the highest geographic wet bulb temperatures. The design Wet Bulb Temperature (WBT) should not exceed for more than 5 percent of the total hours for the summer months[6], May to October in Bangladesh. This 5% WBT will dictate the performance of the tower. As the WBT decreases, the cooling water temperature also decreases. Furthermore ambient air temperature and relative humidity need to be specified for the design of cooling towers.

The cooling tower size is a function of the following

a. Tower characteristic, KaV/L
b. Cooling range
c. Approach to wet-bulb temperature
d. Mass flow rate of water
e. Wet-bulb temperature
f. Water loading, mass flow rate per unit area
g. Air loading, mass flow rate per unit area
h. Tower height

Summary of Steps in the Cooling Tower Design[5, 9]

a. Determination of heat load to be performed by the tower, based on required water inlet and outlet temperatures and flow rates.

b. To establish the design WBT for the air at the geographical site of the tower.

c. Preparation of an enthalpy-temperature plot indicating the basic variables of the cooling tower as in Fig.3. The air operating line is to be located with a slope L/G assumed between 0.75 and 1.5. A preliminary estimate can be made from a nomograph[5], using water hot and cold temperatures and wet bulb temperature.

d. Once the water loading has been established, tower area can then be calculated by dividing the mass flow rate of water by the water loading.

e. Tower characteristic KaV/L or NTU is determined from the integral value of Markel equation.

f. Determination of the tower height, based on the tower characteristic curves supplied by manufacturers. The height of the tower must ensure the required time of contact between water and air [5].

g. If the tower height is unreasonable, the procedure must be repeated using a new assumed L/G, or a new approach, or some combination of these.

h. For the assumed L/G and known L, calculate required air flow rate G.

Typical Design Parameters of New Tower[3,5,6]

- Maximum hot water temperature of 49 °C (120 °F)
- The lowest value of approach to WBT in practice is 2.8 °C (5 °F)
- Water loading of 2 to 5 gal/(min. ft^2 ground area), 1000-2500 lb/hr.ft^2
- Air loading of 1300 to 1800 lb/(hr.ft^2 ground area), 300-400 ft/min
- L/G = 0.75 to 1.5

- Cooling Range (°C) and Typical Applications
  - Long range : (14-36 °C) Oil refineries
  - Medium range : (5.5 – 14 °C) Power plants
  - Short range : (3-5.5 °C) Refrigeration and air conditioning
- Approach to WBT:
  - Wide Approach : 8-11 °C (15-20 °F)
  - Moderate Approach : 4.5 – 8 °C (8-14 °F)
  - Close Approach : 2.2 – 4.4 °C (4-8 °F)

- Tower Characteristic : KaV/L=0.50 to 2.50
- Module or standard cell dimension [9]: 6 ft x 6ft or 8 ft x 8ft

Sizing of Cooling Tower in Sulfuric Acid Plant

Assumptions

- Design Wet-Bulb Temperature (WBT): 30 °C (86 °F)
- Ambient air temperature and % RH: 35 °C and 85 respectively

A CUFL study of the wet-bulb temperature data for a period of 10 years revealed that the 5% WBT is 29 °C in Chittagong [10]. In the present work the design WBT is assumed 30 °C for the sulfuric acid plant site near Dhaka. The wet bulb temperature and dew point of the air at 35°C and 85% RH are 32.5 °C and 31.8 °C respectively.

Design Data

- Hot water temperature (HWT) : 38 °C (100.4 °F)
- Cold water temperature (CWT): 33 °C (91.4 °F)
- Tower capacity for water, L : 250 m^3/hr (1100 gpm or 550,000 lb/hr)
- Number of cells : 2 i.e. 125 m^3/hr or 55 gpm per cell
- L/G ratio : 1.20
- Water loading or concentration: 4 gal/min. ft^2
- Air flow rate, G=L/1.2 : 458, 330 lb/hr

Thermal Design

Thermal design of an induced draft counter flow cooling water, based on above design data is presented in Fig.4. This design has been carried out according to the procedure outlined previously. Basic parameters in Fig.4 are summarized below:

- Cooling range : (38-33) °C = 5°C (9 °F)
- Approach to design WBT: (33-30) °C = 3°C(5.4 °F)
- Enthalpy of entering air at design WBT 30 °C, H_{a_2} = 50.5 Btu/lb dry air
- Enthalpy of warm air out calculated from air operating line Eq.-2, H_{a_1} = 61.3 Btu/lb dry air
- Heat rejection load (LC_{p_w} x Range): 4.95 x 10^6 Btu/hr

Enthalpy of saturated air at bulk water inlet and outlet temperatures are indicated as H_{w_1} and H_{w_2} respectively in Fig.4. The shaded area in this figure represents the tower characteristics NTU or KaV/L. Detailed calculations for determination of NTU using Eq.3, at 100% water flow rate are presented in Table 1.

In this table, water side calculations involve evaluation of the bulk water temperature (T_w) at Δ intervals within the cooling range using the following expression:

$$T_W = T_{W_2} + \Delta \times \text{Range} \quad (4)$$

Where,

Δ = intervals: 0.1, 0.4, 0.6 and 0.9.

In the third column of Table 1, H_w corresponds to the enthalpy of saturated air at bulk water temperature, T_w. For the air side, Ha is evaluated from the air operating line equation:

$$H_a = Ha_2 + L/G \times \Delta \times \text{Range} \quad (5)$$

Final result in Table 1 shows the value of NTU 1.06. For this value of NTU with L/G ratio 1.2, the total tower height was estimated, based on in-house data of WATA Chemicals as 11 ft 2 inch, Fig.2.

Tower area was determined by dividing the water flow rate (1100 gpm) by the water loading (4 gal/min. ft^2) as 275 ft^2. The tower dimensions for a rectangular geometry is about 14.7 ft x 18.5 ft. Based on this tower cross-sectional area, the air loading is 1685 lb/hr.ft^2 with corresponding air velocity 390 ft/min.

Summary of the Tower Specification

- Inner dimensions : 14.7 ft x18.5ft (4.5m x 5.6m)
- Total height (Fig.2) : 11.2 ft (3.41 m)
- Fan motor characteristics: : 10 KW, 560 rpm
- Fan diameter : 3 ft (0.915 m)
- Diameter of nozzle : 0.2 inch (5 mm)
- Distance between two nozzles : 8 inch (203 mm)
- Packing height and volume : 5ft (1.5 m), 272ft^3(7.7m^3)

Materials of construction

- Tower casing of Fiber Glass Reinforced Plastic (FRP)
- PVC honey comb fills
- Nozzle are made of plastic pipe
- Cast aluminum alloy is used for fan blade

Performance Analysis

The performance analysis of a cooling tower depends upon the seasonal variation of the atmospheric condition. In the present study the cooling tower was installed and commissioned in a sulfuric acid plant in summer of 2003. During the summer months the performance of the cooling tower was satisfactory as per design conditions. It was decided to observe the performance of the tower in winter.

In the winter the wet bulb temperature of air falls, and if the heat load and the values of water and air flow rates through the tower are maintained constant, the water undergoes the same range of cooling but the inlet and outlet temperatures will be colder than design conditions[6].

The performance curve of a cooling tower is usually presented as a plot of WBT as abscissa and CWT as ordinate with the cooling range as parameter[5]. According to Cooling Tower Institute ATC-105 (Acceptance Test Code for Cooling Tower) the curves shall fully cover the range of variables as follows[11]:

- Wet bulb temperature : ± 8.3° (15°F) from design WBT
- Cooling range : ± 20% from design range
- Water flow rate : ± 10% from design flow rate

Details for plotting of cooling tower performance curves are described elsewhere[12]. In Fig.5 performance curves are plotted for WBT 15 °C below the design WBT 30 °C for 100% water flow rate. This figure illustrates the influence of the WBT on the CWT for cooling ranges 5°C ± 20%, that is, 4°C, 5°C and 6°C. These curve show a rapid decrease in the CWT as the WBT falls below the design point.

In winter on December 8, 2003 at the plant site, dry bulb temperature (DTB) and % RH were 26 °C and 77% respectively, which correspond to WBT 23 °C, Table-2. At this WBT, the predicted CWT from Fig. 5 for 5°C range is 28°C. The actual CWT was 26.5 °C, Table-2. The difference between the predicted and actual CWT is 1.5°C. Inspite of this difference, the approach (CWT-WBT) at design condition (based on the summer weather data) and operating data in December are nearly the same, 3.0°C and 3.5 °C respectively.

Results and Discussions

The cooling tower in the present study is of close approach, short cooling range and low height when compared with literature data for industrial towers. Below is a comparison of above parameters for the lowest approach recommended by Perry[5].

<u>Approach/Range/Height</u>

Present study: 3°C /5°C /3.4m (11 ft)

Literature [3, 5]: 2.2 to 4.4°C / 14 to 19°C / 11 to 12 m (35 to 40 ft)

It is usually not economical to design a cooling tower with an approach of less than 2.8 °C (5 °F).

In the present study, the actual packing height was 1.5m (5 ft), Fig.2. Since the range was much lower than that of literature data, corresponding total tower height decreased proportionally. It is worthwhile to mention that the height of a cooling tower depends on the contact time necessary for water air flow through the tower as well as the cooling range of water. Other cooling design parameters such as water and air loadings, ratio of water to air flow rates L/G, tower characteristic NTU and cell dimension in the present study are within the guidelines in literature, Table-3.

The performance of the cooling tower in WATA Chemicals discussed in previous section has been found satisfactory throughout the year.

Finally, a comparative study of the parameters of the cooling tower in the present study and those of the cylindrical (bottle shape) commercial cooling towers available in a neighboring country were strikingly similar. Characteristic aspects of cylindrical, commercial cooling towers are: short cooling range (4°C), close approach (4°C), high water loading (5 to 6 gal/min.ft^2) and low tower height (3.2 m). In addition thermal parameters (temperature of water-air) are: HWT (36.4°C), CWT(32.2°C and WBT (28.3°C). Despite the similarity, however there was a difference in the case of tower cross sectional area. The cross-sectional area of the rectangular cooling tower in this study is about 30% higher than that of the commercial towers due to different geometry. Cylindrical cooling towers being round, air flow through the tower is more evenly distributed with improved thermodynamic efficiency. However, one of the major advantages of rectangular cooling towers is ease of construction, hence lower investment cost.

Conclusions

In the present endeavor it was found that a rectangular shaped cooling tower designed, fabricated and installed in a sulfuric acid plant operated satisfactorily throughout the year. This innovative method was also cost effective, and provided an opportunity to manufacture medium size cooling towers in the country. In spite of the constraints and unnecessary roadblocks in the technological capacity building in Bangladesh, this project has set an example of a success story.

Acknowledgement

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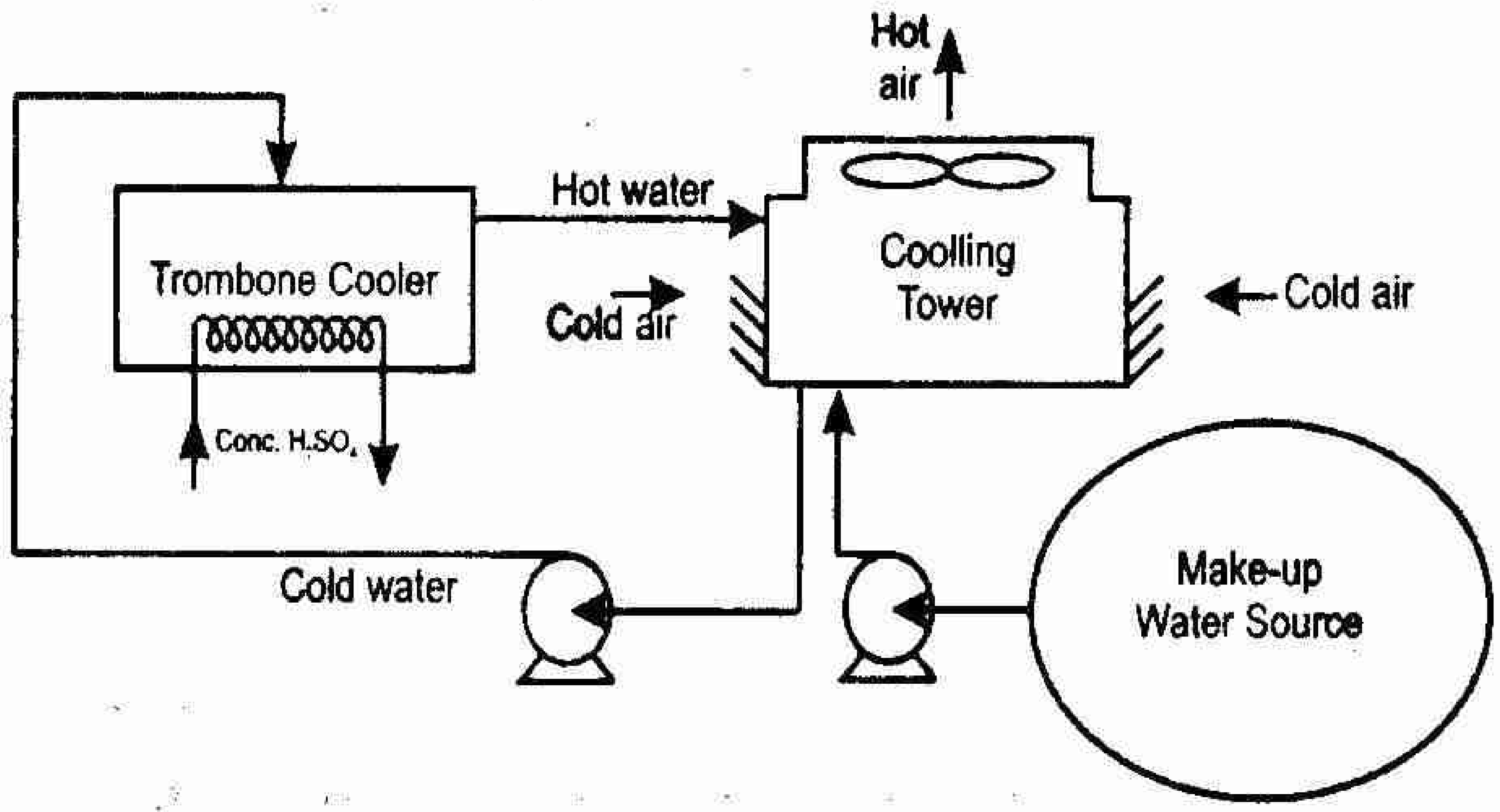

Fig 1: Water Circulation System of Sulfuric Acid Plant

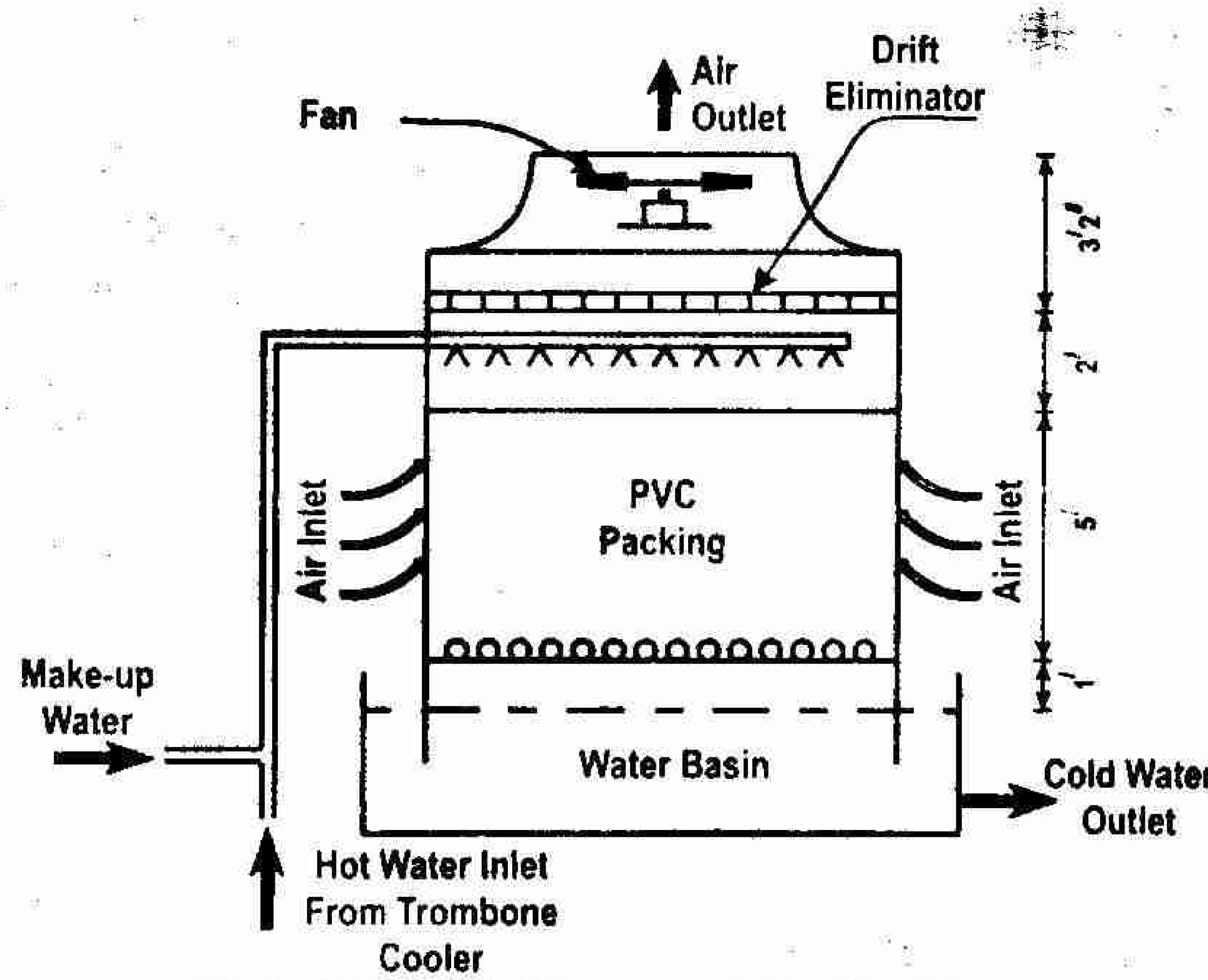

Fig 2: Schematic Diagram of Cooling Tower

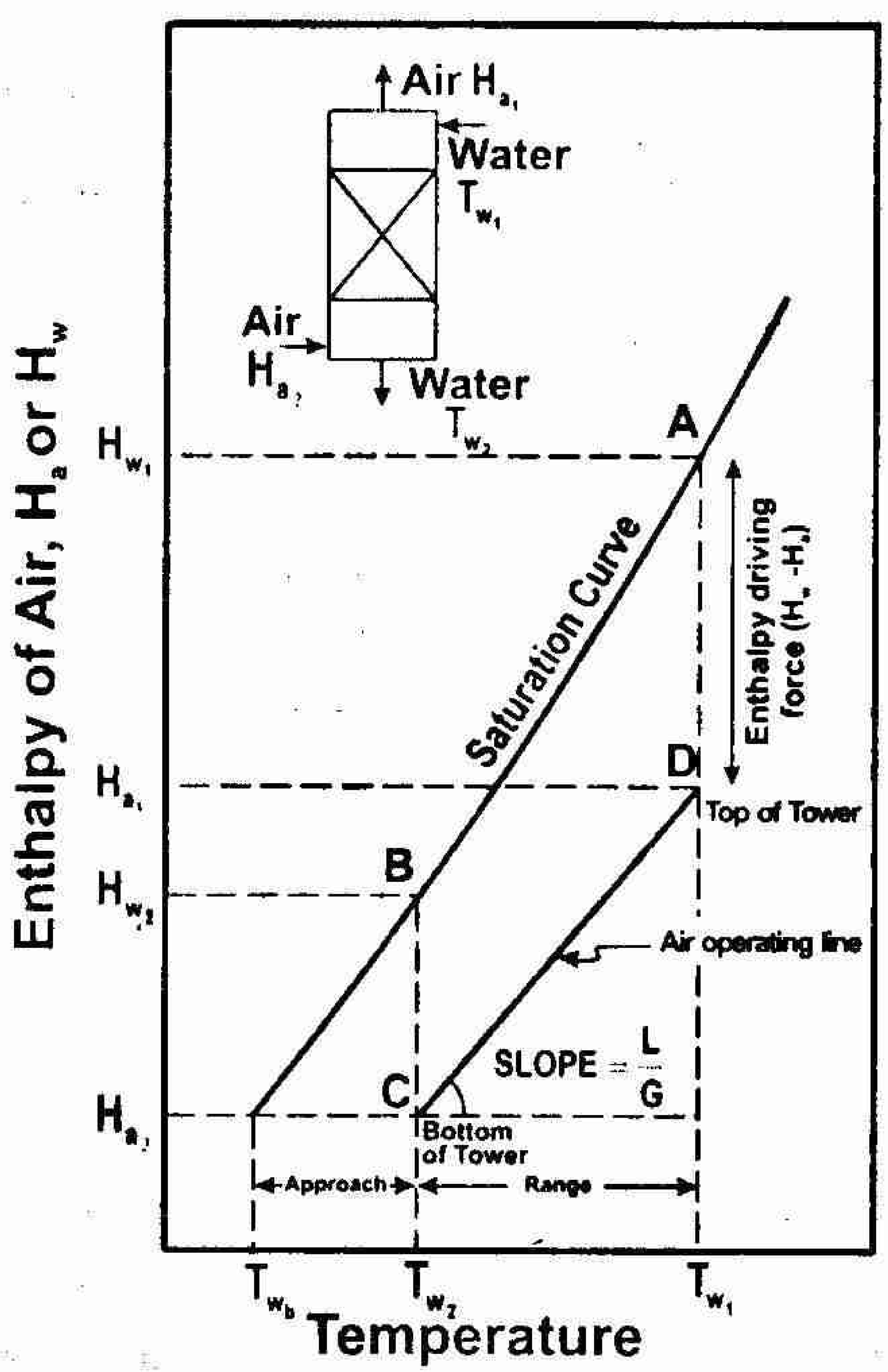

Fig 3: Basic Variables for Sizing of a Cooling Tower

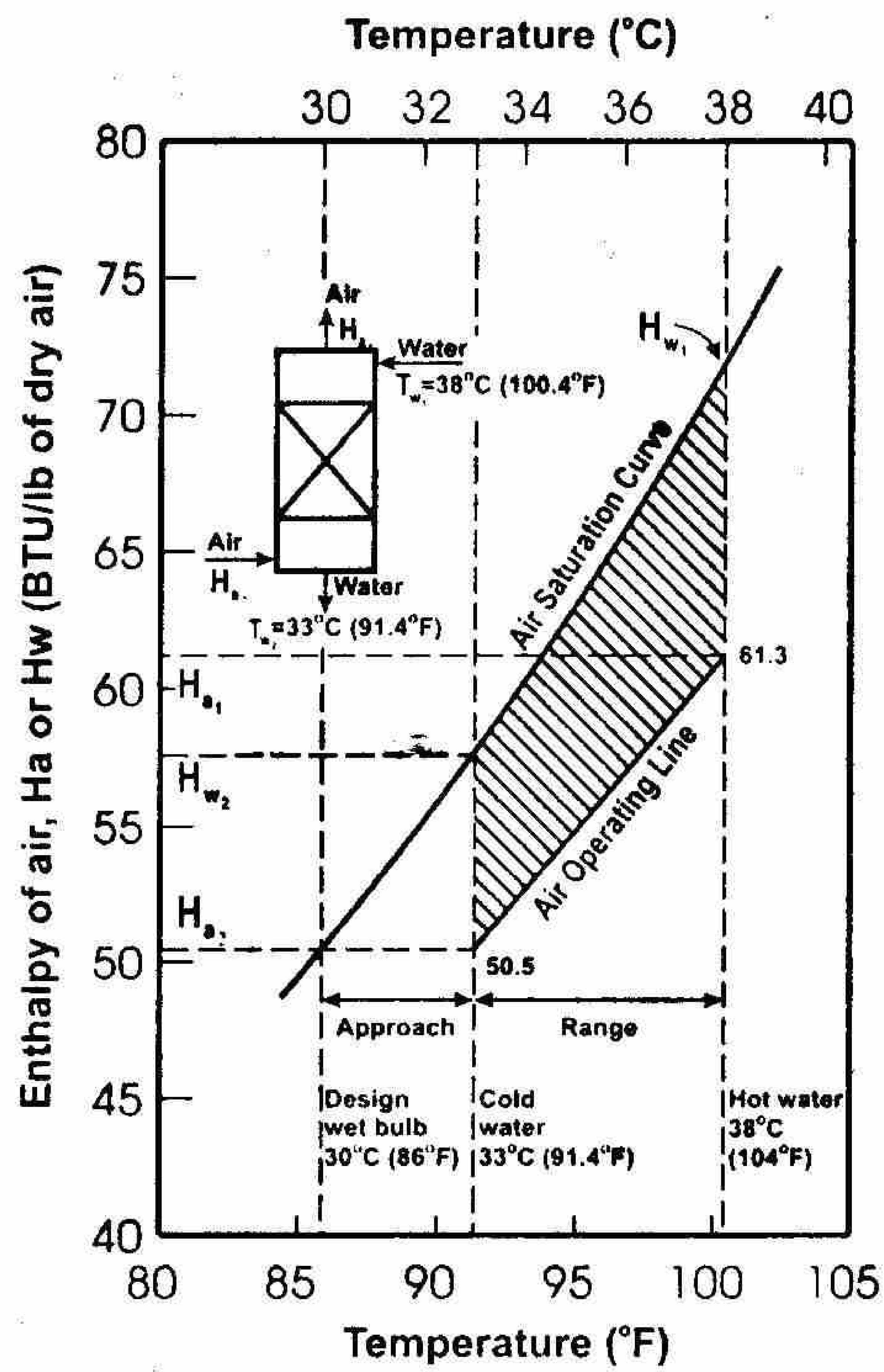

Fig 4: Design of a Cooling Tower in Sulfuric Acid Plant

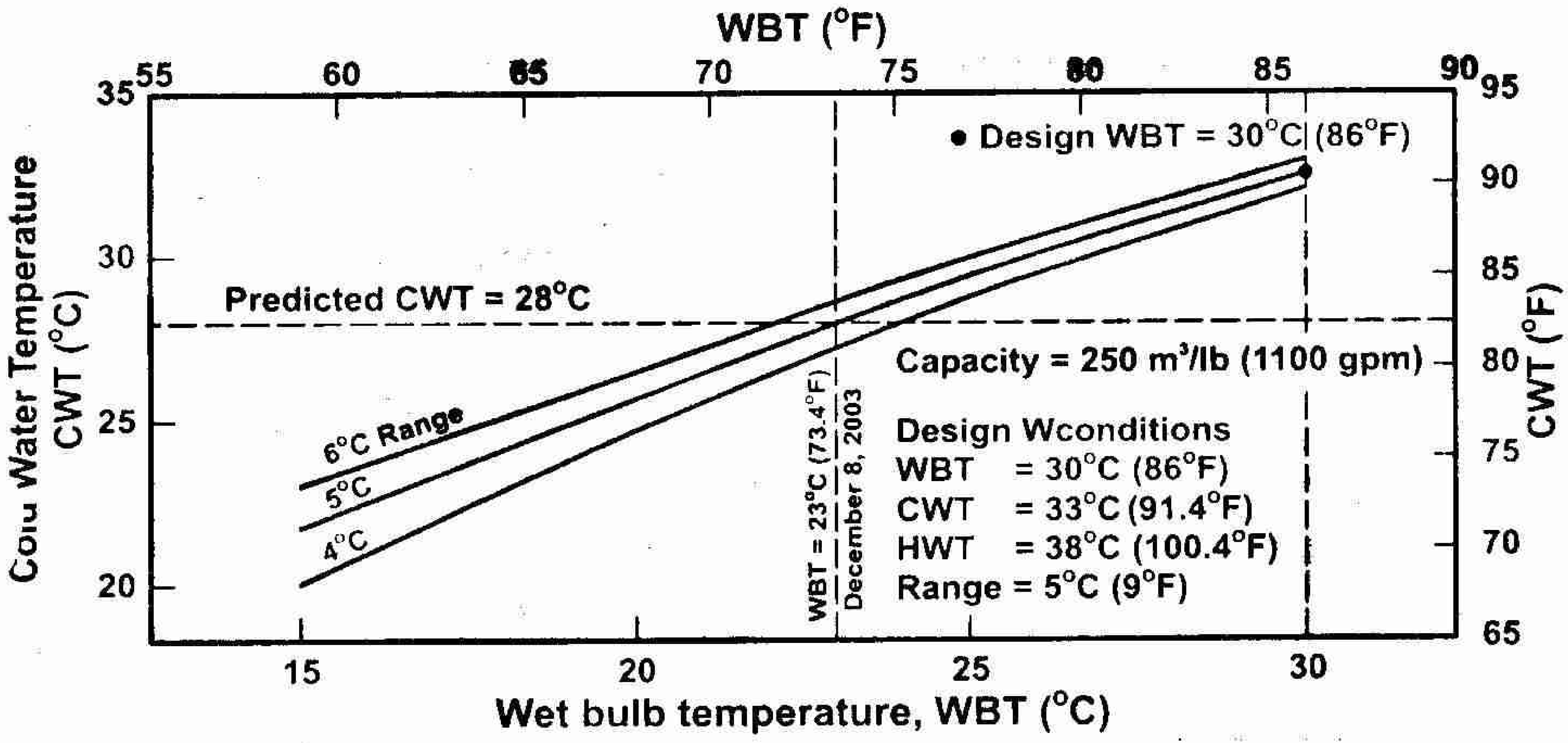

Fig 5: Cooling Tower Performance Curve for 100% Water Flow Rate

Table-1: Determination of NTU at 100% Water Flow Rate

Water side			**Air side**		**Enthalpy**
$T_{w_2} + \Delta$ x Range	T_w	H_w	Air Operating Line	H_a	$1/(H_a-H_w)$
	°F	Btu/lb	H_{a_2} +L/G x Δ x Range	Btu/lb	Btu/lb
T_{w_2} +0.1 x Range	92.3	59	H_{a_2} +L/G x 0.1 x Range	51.58	0.135
T_{w_2} +0.4 x Range	95.0	63	H_{a_2} +L/G x 0.4 x Range	54.82	0.122
T_{w_2} +0.6 x Range	96.8	66	H_{a_2} +L/G x 0.6 x Range	56.98	0.111
T_{w_2} +0.9 x Range	99.5	71	H_{a_2} +L/G x0.9 x Range	60.22	0.102
			Sum of $1/(H_a - H_w)$		0.470
Number of transfer unit (NTU)			Cooling range x $(\sum 1/H_a - H_w)/4$		1.060

T_{w_2} = 33°C (91.4°F), Range = 5°C (9°F), Ha_2 = 50.5 Btu/lb dry air, L/G = 1.2

Table-2: Performance Analysis of Cooling Tower in Winter for 100% Water Flow Rate

	Design Data		**Actual data on December 8, 2003**	
%RH	85		77	
	°C	°F	°C	°F
DBT	35	95	26	78.8
WBT	30	86	23	73.4
HWT	38	100.4	-	
CWT	33	91.4	26.5	79.7
RANGE	5	9	5	9
APPROACH	3	5.4	3.5	6.3

For December WBT of 23°C the predicted CWT from Fig. 5 is 28°C

Range = HWT-CWT; Approach = CWT-WBT

Table-3: Comparison of WATA Cooling Tower Parameters with Design Guidelines in Literature

Parameter	WATA Tower (This Study)	Literature [3,5,6]
Maximum HWT	38°C	49°C (120°F)
Cooling Range	5°C	3-5/5-14/14-36°C
Approach to WBT	3°C	2.2-4.4/4.5-8/8-11°C
Tower Characteristic, NTU=KaV/L	1.06	0.5 - 2.50
Cell dimension	8 ft x 8 ft	6 ft x 6 ft, 8ft x 8 ft
Water Loading or Concentration	4 gal/min. ft^2 (2000 lb/hr ft^2)	2-5 gal/min. ft^2 (1000-2500 lb/hr ft^2)
Air Loading	1685 lb/hr ft^2	1300-1800 lb/hr ft^2)
Air Velocity	390 ft/min.	300-400 ft/min
L/G	1.20	0.75 – 1.50
Tower height	11 ft (3.4m)	15-40 ft (4.6 – 12 m)

Table-4: Dimensional and Technical Data for WATA and Commercial Cooling Towers with Similar Capacity

Parameters	WATA Cooling Tower	Commercial Cooling Tower (India)	
Tower capacity for water	1100 gpm	1000 gpm	1200 gpm
Cooling capacity	1247 x 10^3 Kcal/hr	940 x 10^3 Kcal/hr	1125 Kcal/hr
Tower geometry	Rectangular	Cylindrical (bottle shape)	*
Dimensions	14.7 ft x 18.5 ft	Diameter = 16 ft	*
Cross-sectional area	272 ft^2	201 ft^2	*
Height	11.2 ft	11.7 ft	12.5 ft
Water loading	4 gal/min ft^2 of ground area	5 gal/min. ft^2 of ground area	6 gal/min.ft^2
HWT-CWT-WBT	38 – 33 - 30 °C	36.4 - 32.2 – 28.3 °C	*
Cooling range (HWT-CWT)	5 °C	4.2 °C	*
Approach (CWT-WBT)	3 °C	3.9 °C	*
Fan motor	10 KW	7.5 KW	9.3 KW

* Similar value as that for tower capacity of 1000 gpm