

# Predicting the Thermal Performance of a Mechanical Draft Counter Flow Cooling Tower of Closed Type

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## Abstract

*In this work, the enthalpy potential theory is used in conjunction with a formula derived by Uchida and a set of data available on the cooling tower of Baghdad international airport to predict the thermal performance of a mechanical draft counter flow cooling tower of closed type.*

*Computer calculations are made to determine the number of transfer units, water-cooling range and tower capacity. The computer results are presented in graphical form as performance curves showing the predictable thermal performance of the tower under different conditions of air inlet wet bulb temperature and water-to-air flow ratio, when the load on the tower, denoted by the water inlet temperature, remains unchanged.*

*The results indicated that the performance of the tower and hence its capacity are affected by the air inlet wet bulb temperature and the water-to-air flow ratio. They face a considerable decline with increase of air inlet wet bulb temperature and with increase of water-to-air flow ratio too. Then, the decline with increase of air inlet wet bulb temperature reduces with increase of water-to-air flow ratio.*

*The agreement of the present results with results of the others and with measurement would give a sufficient support to the analysis adopted in this work.*

## الخلاصة

في هذا البحث تم استخدام نظرية طاقة الأنتالبي مع معادلة مشتقة من قبل الباحث *Uchida* ومجموعة من المعلومات المتوفرة عن برج تبريد مطار بغداد الدولي لتنبؤ الأداء الحراري لبرج تبريد مروحي متعاكس الجريان ومن النوع المغلق. تم استخدام الحاسب الإلكتروني لإيجاد عدد وحدات الانتقال ومدى تبريد الماء وطاقة البرج. نتائج الحسابات تم عرضها بشكل مخططات تمثل منحنيات الأداء وهذه تظهر الأداء الحراري المتوقع للبرج تحت ظروف مختلفة من درجة حرارة رطوبة للهواء الداخل ونسبة جريان للماء إلى الهواء وذلك عندما يكون الحمل على البرج ممثلاً بدرجة حرارة الماء الداخل إلى البرج غير متغير. النتائج أشارت إلى أن أداء البرج وطاقته تتأثر بدرجة الحرارة الرطوبة للهواء الداخل وكذلك بنسبة جريان الماء إلى الهواء حيث يواجه الأداء والطاقة تدني مستمر ومحسوس في المستوى مع زيادة درجة الحرارة الرطوبة للهواء الداخل ومع زيادة نسبة جريان الماء إلى الهواء أيضاً. ثم إن هذا التدني أو الانحدار مع زيادة درجة الحرارة الرطوبة للهواء الداخل يتضاءل مع زيادة نسبة جريان الماء إلى الهواء.

التوافق الموجود بين النتائج الحالية ونتائج الآخرين يعطي دعم وإسناد كافي لأسلوب التحليل الذي تم تبنيه في هذا البحث.

## 1. Introduction

The condenser water of air conditioning systems is sometimes circulated between the condenser and the cooling tower through a closed circuit piping.

For the heat to be adequately absorbed from the condenser water in the tower, this water is being passed through a bundle of tubes inside the tower. Then, a stream of tower re-circulated water is sprayed from above on the outside of the bundle tubes which serve too as a cooling tower packing, while a stream of air is passing over the tubes from the bottom (counter-flow) or the side (cross-flow). By this means heat is transferred from the condenser water to the water spray and then to the air stream as sensible and latent heats. The closed circuit evaporative cooling tower has the advantage of keeping the condenser of the air conditioning system clean and needs not to be serviced from time to time as in the open circuit case.

In this work, a mechanical draft counter flow cooling tower of closed type is investigated. A schematic diagram of the tower is shown in **Fig.(1)**. The enthalpy potential theory is used with a formula derived by Uchida <sup>(1)</sup> and a set of data available on the cooling tower of Baghdad international airport to predict the thermal performance of the tower.

For this purpose, numerous computer calculations are made to determine the number of transfer units, the water cooling range and the tower capacity.

The results in their graphical form indicated that the tower performance and therefore the tower capacity, under conditions of constant load on the tower which corresponds to constant water inlet temperature, are affected by the inlet wet bulb temperature of air and the water -to-air flow ratio.

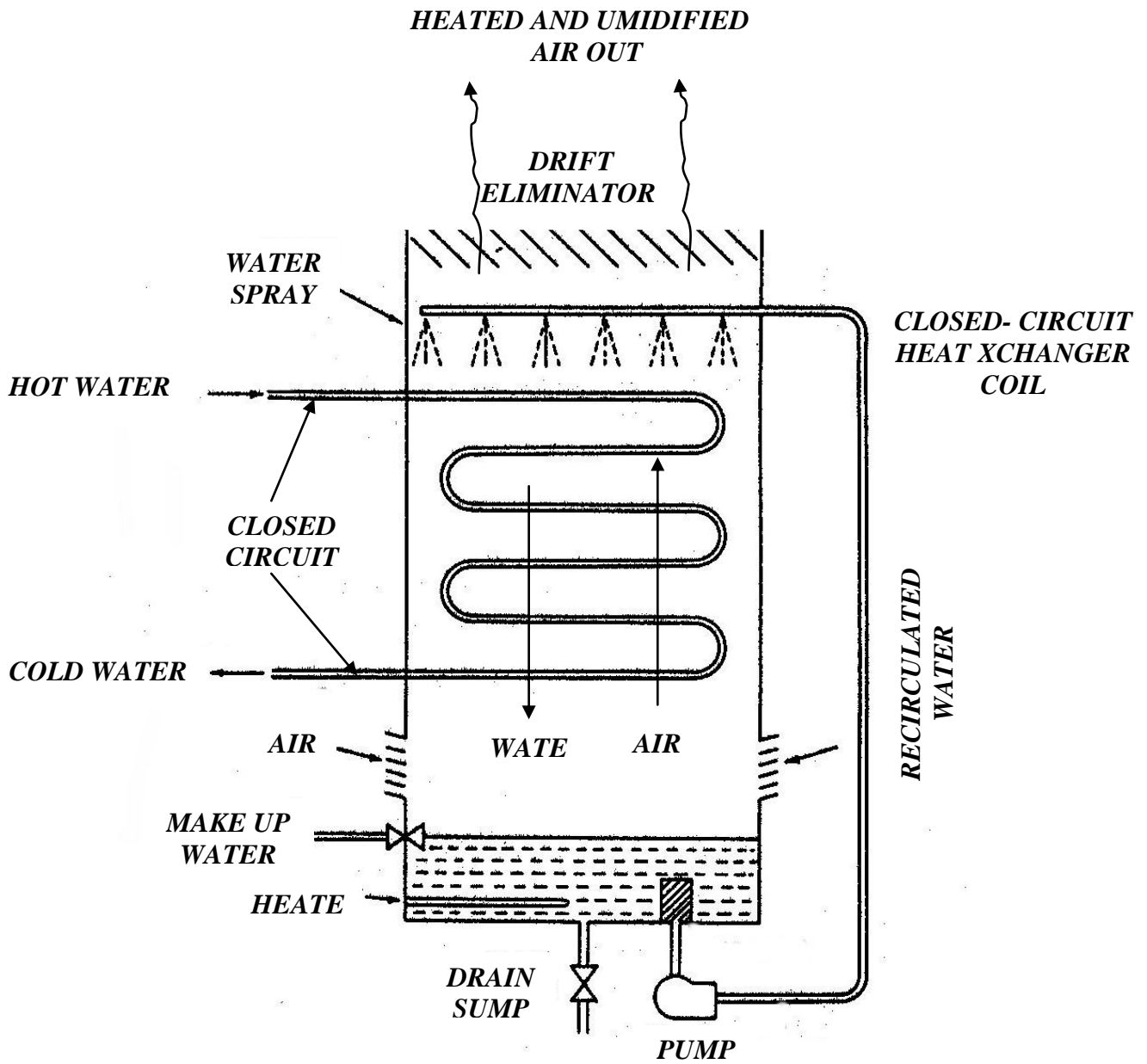


Figure (1) A Schematic Diagram for the Counter Flow Cooling Tower of Closed Type

## 2. Theory

### 2-1 Basic Equations

In this paper, the calculations are principally based on the enthalpy potential theory, which considers the enthalpy difference between saturated air at bulk water temperature and bulk air as a driving Force; and the rate of water evaporation is ignored as in usual practice. Referring to the coordinates and flow directions shown in **Fig.(2)**, basic equations are written as follows:

$$C_L (L / A)(dt_L / dz) = (G / A)(dh / dz) = -Ka(h_s - h) \dots\dots\dots (1)$$

$$C_L (dt_L / d\xi) = (1 / N)(dh / d\xi) = -NTU(h_s - h) \dots\dots\dots (2)$$

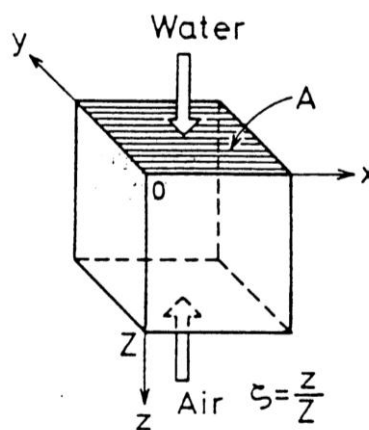
$$NTU = C_L \int_{t_{L1}}^{t_{L2}} -dt_L / (h_s - h) \dots\dots\dots (3)$$

The total heat transferred from the circulating water to the air is given by:

$$Q = C_L \times L(t_{L1} - t_{L2}) = C_L \times L \times \Delta t_L = G(h_2 - h_1) \dots\dots\dots (4)$$

That is,

$$\Delta h = C_L \times N \times \Delta t_L \dots\dots\dots (5)$$



**Figure (2) Coordinates and Flow Directions for Counter Flow Cooling Tower**

According to psychrometric tables, the enthalpy of saturated air within the temperature range,  $t = (20 - 40) ^\circ\text{C}$ , can be expressed in the form:

$$h_s = 34.60 - 1.009 t + 0.1063 t^2 \dots\dots\dots (6)$$

Uchida <sup>[1]</sup> has derived the following expression:

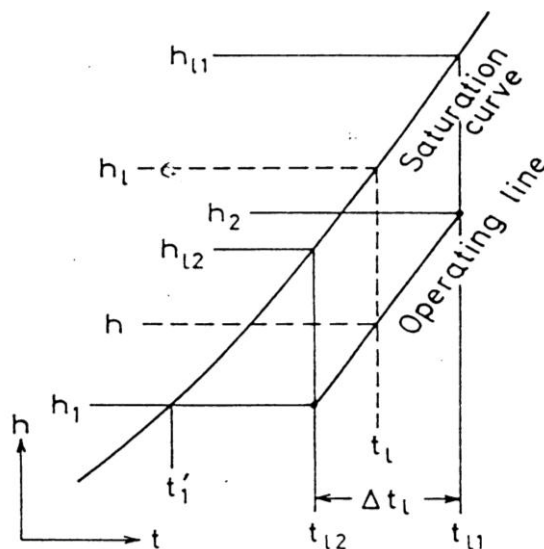
$$N(1/2) + 1/NTU = (C2/(C_L \times \Delta t_L)) (t_{Lm} - t'_1)(t_{Lm} + t'_1 - C1/C2) + C2 \times \Delta t_L / (12C_L) \dots\dots\dots (7)$$

where,  $C_1 = 1.009 \text{ KJ/Kg} \cdot ^\circ\text{C}$ ,  $C_2 = 0.1063 \text{ KJ/Kg} \cdot ^\circ\text{C}$   
 $t_{Lm} = (t_{L1} + t_{L2})/2 = t_{L1} - \Delta t_L/2 = t_{L2} + \Delta t_L/2$

Equation (7) was examined by the authors against equation (3) and data available on the cooling tower of Baghdad international airport which formed the case study, and was found to be suitable to use in this work.

### 2-2 Method of Calculations

A counter flow cooling diagram is illustrated in **Fig.(3)**. The operating line connecting the air enthalpy and water temperature has a slope of  $(C_L \times N)$ .



**Figure (3) Temperature-Enthalpy Diagram for Counter Flow Cooling Tower**

The vertical distance between the saturation curve and the operating line gives the driving force ( $h_s - h$ ).

In calculating the number of transfer units (NTU), for a given set of conditions ( $N$ ,  $t_{L1}$ ,  $t_{L2}$  and  $t'_1$ ), reciprocals  $1/(h_s - h)$  are computed at a sufficiently large number of discrete points on the operating line and the average is multiplied by the cooling range  $\Delta t_L$  and also by the specific heat of water ( $C_L$ ).

The cooling tower institute, CTI [2] recommends a simple method for the integration of equation (3), according to which, the number of transfer units approximates to the cooling range ( $\Delta t_L$ ) multiplied by  $C_L$  and also by the arithmetical mean of the reciprocals  $1/(h_s - h)$  which are evaluated at four points corresponding to the water temperatures of  $t_{L2} + 0.1 \Delta t_L$ ,  $t_{L2} + 0.4 \Delta t_L$ ,  $t_{L1} - 0.4 \Delta t_L$ ,  $t_{L1} - 0.1 \Delta t_L$ . The authors chose to use the first method of calculation rather than the CTI method for better accuracy of integration, as the first method involves smaller temperature increments especially in case of wide cooling range  $\Delta t_L$ .

On the other hand, in calculating the exit water temperature  $t_{L2}$  for a given set of conditions ( $N$ ,  $t_{L1}$  and  $t'_1$ ), a trial-and-error method is required: a value of  $t_{L2}$  is assumed iteratively until the value of NTU calculated by the above procedure coincides well with the value calculated by equation (7).

Once, the right value of  $t_{L2}$  is determined, the tower cooling capacity for the condenser water can be calculated by equation (4).

### 3. The Case Study

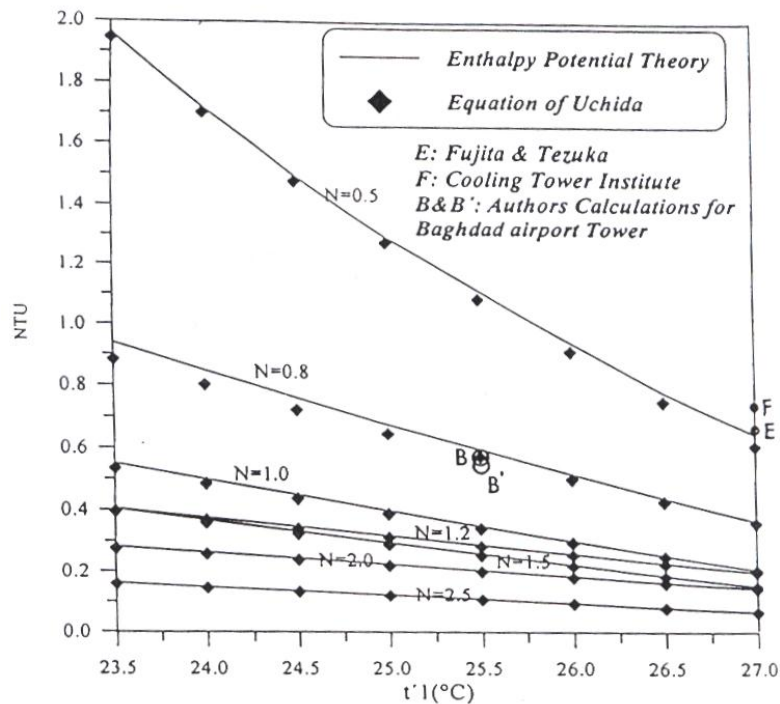
The cooling tower data of Baghdad international airport formed the basis for the case study on mechanical draft counter flow cooling tower of closed type and are as follows:

<i>Inlet air wet bulb temperature (C°)</i>	<i>25.5</i>
<i>Outlet air wet bulb temperature (C°)</i>	<i>30</i>
<i>Inlet air humidity (kg water/kg dry air)</i>	<i>1.22E-2</i>
<i>Outlet air humidity (kg water/kg dry air)</i>	<i>2.73E-2</i>
<i>Inlet air enthalpy (kJ / kg)</i>	<i>78 .64</i>
<i>Outlet air enthalpy (kJ / kg)</i>	<i>99.97</i>
<i>Capacity of chiller / tower (ton- refrigeration)</i>	<i>1000</i>
<i>Condenser water temperature at inlet to tower (C°)</i>	<i>38</i>
<i>Condenser water temperature at outlet of tower (C°)</i>	<i>32.3</i>
<i>Air mass flow rate (kg / s)</i>	<i>183</i>
<i>Condenser water mass flow rate (kg/ s)</i>	<i>148</i>
<i>Spray water volume flow rate (m<sup>3</sup> / hr)</i>	<i>250</i>

## 4. Results and Discussion

The results of computer calculations for a mechanical draft counter flow cooling tower of closed type, working under conditions of constant water inlet temperature, are presented in graphical form in **Figures (4, 5, 6)** and **(7)**.

**Figure (4)** shows the predictable effect of change of air inlet wet bulb temperature ( $t'_1$ ) and water-to-air flow ratio ( $N$ ) on the number of transfer units (NTU).



**Figure (4) Variation of the Number of Transfer Units with Inlet Wet Bulb temperature of Air for Different Water-to-Air Flow Ratios**

Two values for (NTU) appear on the diagram; one is calculated according to the enthalpy potential theory and the other is calculated from equation (7) which is derived by Uchida <sup>[1]</sup>.

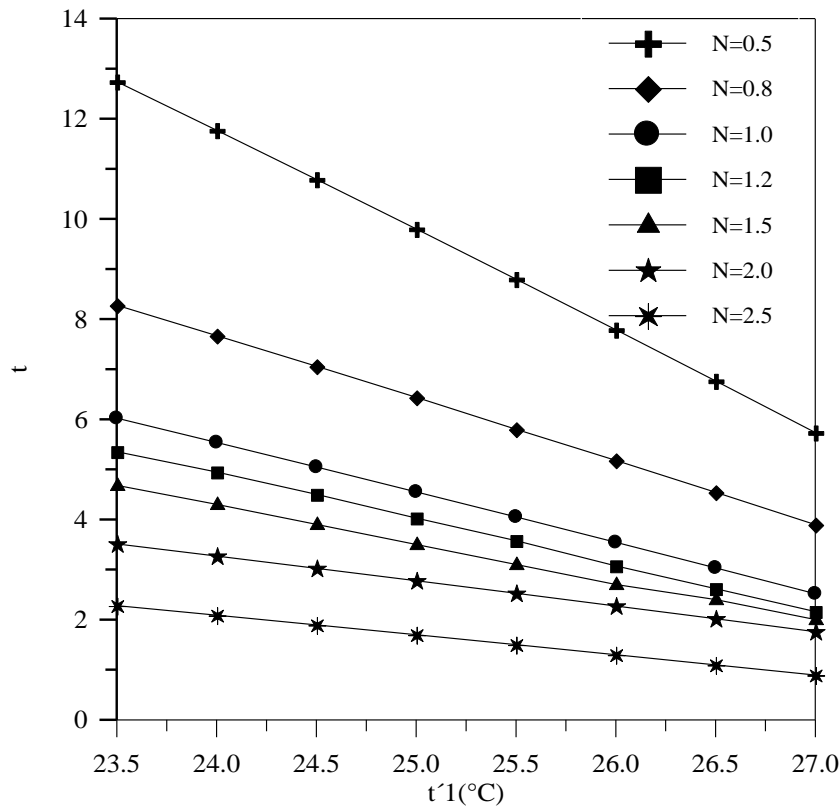
They show a perfect agreement for  $N > 1.0$  and a good agreement with discrepancy of less than 6% for  $N \leq 1.0$ .

It is obvious that the (NTU) decreases with increase of  $t'_1$  and with increase of  $N$  too. The decline in the NTU value with increase of  $t'_1$  considerably reduces with increase of  $N$ .

Points E&F on the diagram are obtained from the paper of Fujita and Tezuka <sup>[3]</sup>. Point E corresponds to their calculations whereas point F corresponds to calculations made by the cooling tower institute, CTI <sup>[2]</sup>. The agreement with the present results is fairly good.

Points B&B' correspond to the case of the cooling tower of Baghdad international airport, based on the enthalpy potential theory and the equation of Uchida <sup>[1]</sup> respectively.

From **Fig.(5)**, similar effect for  $t'_1$  and  $N$  is predictable on  $\Delta t_L$  as that on NTU seen in **Fig.(4)**; that is, the increase of  $t'_1$  and /or  $N$  is accompanied by a drop in  $\Delta t_L$ .



**Figure (5) Variation of the Water Cooling Range with Inlet Wet Bulb Temperature of Air for Different Water-to-Air Flow Ratios**

On the other hand, **Fig.(6)** predicts the value of  $N$  corresponding to the value  $t'_1$  that gives constant  $\Delta t_L$ . This is useful when it is required to run the tower under conditions of constant  $\Delta t_L$ , whilst  $t'_1$  is variable.

**Figure (7)** shows the predictable effect of change of  $t'_1$  and /or  $N$  on the tower cooling capacity per unit mass flow rate of the condenser water.

It can be noted that the tower capacity is inversely proportional to  $t'_1$  and  $N$ . Point B corresponds to the measured capacity of the cooling tower of Baghdad international airport. The evident agreement between the measured and the calculated values of tower capacity provides an additional and strong support to the analysis adopted in this work.



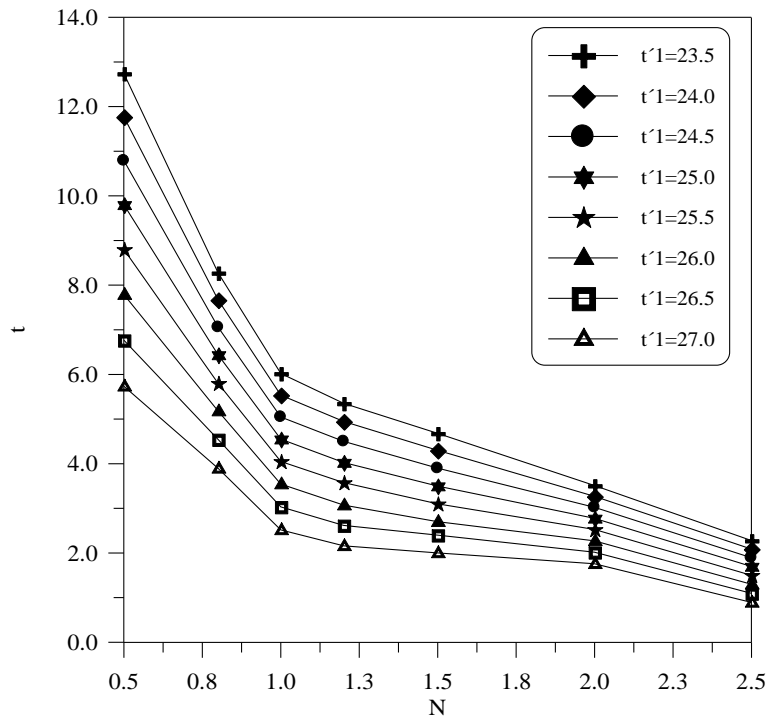


Figure (6) Variation of the Water Cooling Range with Water-to-air Flow Ratio for Different Air Inlet Wet Bulb Temperatures

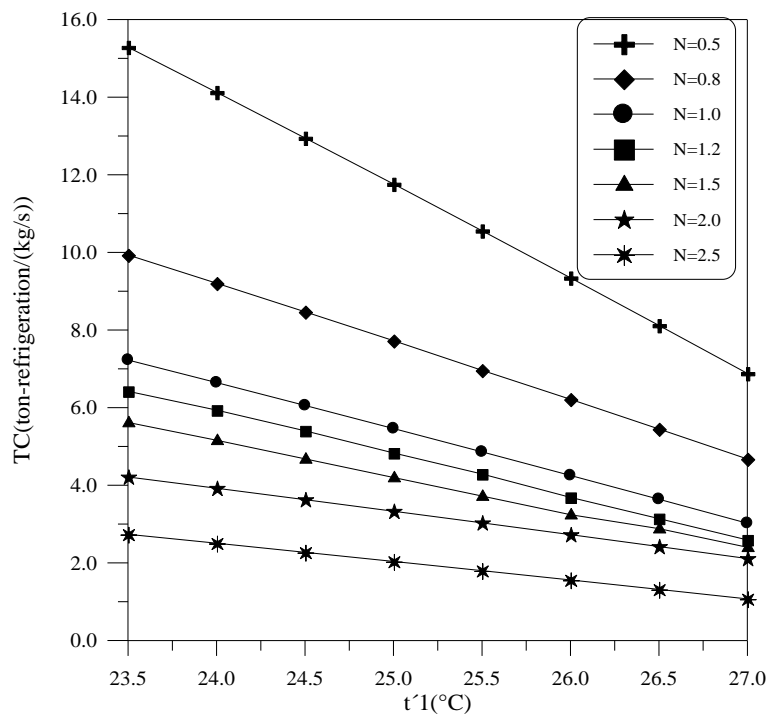


Figure (7) Variation of the Cooling Tower Capacity with Inlet Wet Bulb Temperature of Air for Different Water-to-Air Flow Ratios

## 5. Conclusions

From this work on the mechanical draft counter flow cooling tower of closed type, working under constant load, it is concluded that:

1. The thermal performance of the tower can be well predicted by relying on the enthalpy potential theory and the formula derived by Uchida <sup>[1]</sup>.
2. The number of transfer units and water cooling range which are indicative of the thermal performance of the tower and of its cooling capacity are influenced by the air inlet wet bulb temperature and by the water-to-air flow ratio. They show a considerable decrease in their values with increase of the air inlet wet bulb temperature and with increase of the water-to- air flow ratio.
3. The decline in number of transfer units and water cooling range and therefore in cooling tower capacity with increase of air inlet wet bulb temperature reduces with increase of water-to- air flow ratio.

## 6. References

1. Uchid, H., "*Prediction of Counter Flow Cooling Tower Performance*", J. Soc. Domest. Sanit. Eng., 32-2, 1985.
2. CTI Code ATC-105, "*Acceptance Test Code for Water Cooling Towers*", Houston: Cooling Tower Institute, 1982.
3. Fujita, T., and Tezuka, S., "*Calculations On Thermal Performance Of Mechanical Draft Cooling Towers*", ASHRAE Transactions, Vol. 92, Part1a, 1986, pp. 274-287.
4. Ashrae Handbook, "*Cooling Towers*", Equipment Volume, 1983, pp. 21.11-21.18.
5. Asme PTC 23-58, "*Atmospheric Water-Cooling Equipment*", p.11
6. McQuiston, F. C., Parker, J. D., and Spitler, J. D., "*Heating, Ventilating, and Air Conditioning-Analysis and Design*", John Wiley & Sons Inc., Fifth Edition, 2000, pp. 473-481.

## ***Notations***

A	Effective tower cross-sectional area normal to the direction of flow of water and air.
$C_L$	Specific heat of water.
G	Mass flow rate of air.
h	Enthalpy of air.
$h_s$	Enthalpy of saturated air.
Ka	Overall enthalpy transfer coefficient based on effective tower volume.
L	Mass flow rate of water.
N	Water-to-air flow ratio, = $L/G$ .
NTU	Number of transfer units, = $K a * V/L$
Q	Rate of heat removal from tower.
TC	Cooling tower capacity.
$t'$	Air wet bulb temperature.
$t_L$	Bulk water temperature.
$\Delta t_L$	Water cooling range, = $(t_{L1} - t_{L2})$ .
V	Effective tower volume, = $(A * Z)$ .
Z	Effective tower height.

## ***Subscripts***

- 1 Inlet of water or air
- 2 Outlet of water or air