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# EFFECT OF OPERATING PARAMETERS ON THE PERFORMANCE OF COUNTER FLOW TYPE COOLING TOWERS

# تأثير عوامل التشغيل على أداء أبراج التبريد المتعاكسة السريان

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## الخلاصة

يمثل هذا البحث دراسة معملية لأداء ابراج التبريد من النوع الجبري . تم إجراء هذه الدراسة على دائرة اختبار تم تصميمها في شركة مصر للزيوت والصابون بالمنصورة والتي تشمل إثنى عشر برجا من هذا النوع . تم استخدام ثلاثة أنواع من الحشو أثناء إجراء التجارب والتي تم تصنيعها من ألواح البلاستيك المعرجة (PVC) بارتفاعات تتراوح بين ٨٠٠ و ١٢٠٠مم وبأبعاد مذكورة داخل البحث.

وفي أثناء التجارب تم دراسة تأثير تغيير العوامل المختلفة على أداء برج التبريد ومنها سرعة الهواء المار خلال البرج من ١٠,٥ إلى ١٧,٥ م/ث ومعدل تصرف الماء خلال البرج من ٨٠ إلى ١٥٠ م$^3$/ساعة .

تم قياس درجة حرارة كل من الهواء والماء عند الدخول والخروج من البرج باستخدام ازدواجات حرارية ، ثم صياغة النتائج في صورة منحنيات تمثل العلاقة بين عوامل التشغيل المختلفة وأداء البرج .

وقد أوضحت النتائج أن زيادة معدل السريان النسبي بين الماء والهواء (L/G) يؤدي إلى نقص في عدد وحدات الانتقال الحراري كما يؤدي انخفاض درجة حرارة الهواء الرطبة إلى زيادة مدى البرج (Range) .

وقد تم صياغة تأثير معدل السريان النسبي بين الماء والهواء على عدد وحدات الانتقال الحراري في معادلة لا بعدية كما يلي : $NTU = \frac{K_a A_V V}{L} = 0.875\left[\frac{L}{G}\right]^{-0.12}$ والتي يمكن الاستفادة منها في تصميم أبراج التبريد المتعاكسة السريان .

## Abstract

This paper presents an experimental work, which studies the performance of a counter flow type cooling tower. The experimental results have been carried out at a test rig which designed and investigated in Misr Oil and Soap Company. It consists of 12 cooling towers from these types. Three types of film fill packing, used during experimentation, 0were made of PVC with height range 800 – 1200 mm. During the experimentation the following quantities were varied: air flow velocity in the range 10.5-17.5 m/s and water flow rate in the range of 80-150 m$^3$/h. The variation of temperature along the height of packed was measured by means of 16 appropriate placed thermocouples.

The results show that when the mass flow rate ratio decreased, the number of transfer units (NTU) were increased. Also by decreasing the inlet air wet bulb temperature, the tower range would be increased. From this study the characteristic equation is in the form: $NTU = \frac{K_a A_V V}{L} = 0.875\left[\frac{L}{G}\right]^{-0.12}$, which can be used in designing the counter flow cooling towers.

**Key words**: cooling towers, counter flow, tower range, NTU.

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## Nomenclature

| | |
|---|---|
| $A_v$ | surface area of water droplets per unit volume of the tower, $m^2/m^3$ |
| dbt | dry bulb temperature, °C |
| G | mass flow rate of dry air, kg/s |
| L | mass flow rate of water, kg/s |
| $K_a$ | combined heat and mass transfer coefficient, $kJ/m^2.s$ |
| NTU | Number of transfer units |
| R | dimensionless temperature ratio $=\frac{t_{w,i}-t_{w,o}}{t_{w,i}-t_{wb,i}}$ |
| RH | relative humidity, % |
| t | temperature, °C |
| V | volume of tower, $m^3$ |
| wbt | wet bulb temperature, °C |
| $\Delta T_w$ | difference between inlet and outlet water temperature $=t_{w,i}-t_{w,o}$, °C |

**Subscripts**

| | |
|---|---|
| a | moist air |
| i | inlet |
| o | outlet |
| w | water |
| w,i | water inlet |
| w,o | water outlet |
| wb,i | wet bulb inlet |

## 1. Introduction

The heat released from HVAC systems and/or industrial process should be rejected to the atmosphere. In the past, cooling water was supplied from tap water or river, and rejected to sewage or the river again. Recently, conventional methods cannot satisfy either economic criteria or environmental regulation because the cost of supply and disemboguement of cooling water is increasing tremendously, and the thermal pollution is regulated severely as well.

Air-cooled heat exchanger can be an alternative, but it requires high initial investment cost and high fan power consumption. Cooling tower enhances its application due to the low power consumption and, especially, low water consumption down 5% of the direct water-cooling system. Heat rejection is accomplished within the tower by heat and mass transfer between hot water droplets and ambient air [1] and [2].

The operation theory of cooling tower was suggested by Walker in 1923, [3]. However, the generally accepted concept of cooling tower performance was developed by Merkel in 1925, [4]. A simplified Merkel theory has been used for the analysis of cooling tower performance. In this model, the water loss of evaporation is neglected and the Lewis number is assumed to be one in order to simplify the analysis. Merkel's model is not accurate enough and not suitable for real applications. Baker and Shryock in 1961, [5] tried to minimize the error due to the assumption of Merkel theory. Amore rigorous analysis of a cooling tower model that relaxed Merkel's restriction was given by Sutherland in 1983, [6].

Webb in 1984, [7] performed a unified theoretical treatment for thermal analysis of cooling towers, evaporative condensers and evaporative fluid coolers. In these papers specific calculation procedures are defined for sizing and rating each type of evaporative exchanger.

Braun et al. in 1989, [8] presented effectiveness models for cooling towers and cooling coils. The models utilize existing effectiveness relationship developed for sensible heat exchangers with modified definitions for number of transfer units and the fluid capacitance rate ratio. Results of the models were compared with those of the detailed numerical solutions to the basis heat and mass transfer equations and experimental data. They also did not consider the effect of air-water interface temperature.

Vasith in 1992, [9] presented a simulation to study the effect of using packing in the force draft fan counter flow cooling tower at various operating conditions. From this study the characteristic equation is: $NTU = 0.8692\left[\frac{L}{G}\right]^{-0.1965}$ for two level of packing, and $NTU = 0.8362\left[\frac{L}{G}\right]^{-0.2543}$ for one level of packing. From the above equation it is concluded that the constant of equations is nearly constant while the power increases with packing height.

Bernier in 1994, [10] reviewed the heat and mass transfer process in cooling towers at water droplet level and analyzed an idealized spray-type tower in one dimensions, which is useful for cooling tower designers, but no much information is provided to plant operations.

Flake in 1997, [11] utilized a different regression technique to determine parameters of the cooling tower model developed by Braun and to build a predictive model for optimal supervisory control strategies.

Soylemez in 1999, [12] presented a quick method for estimating the size and performance of forced draft counter current cooling towers and experimental results were used to validate the prediction formulation. Unfortunately, this model also need iterative computation and not suitable for online optimization.

The objective of this paper is to study the performance of counter flow type cooling towers with operation parameter variation and obtains the experimental characteristic equation, which can be used in designing of counter flow cooling tower.

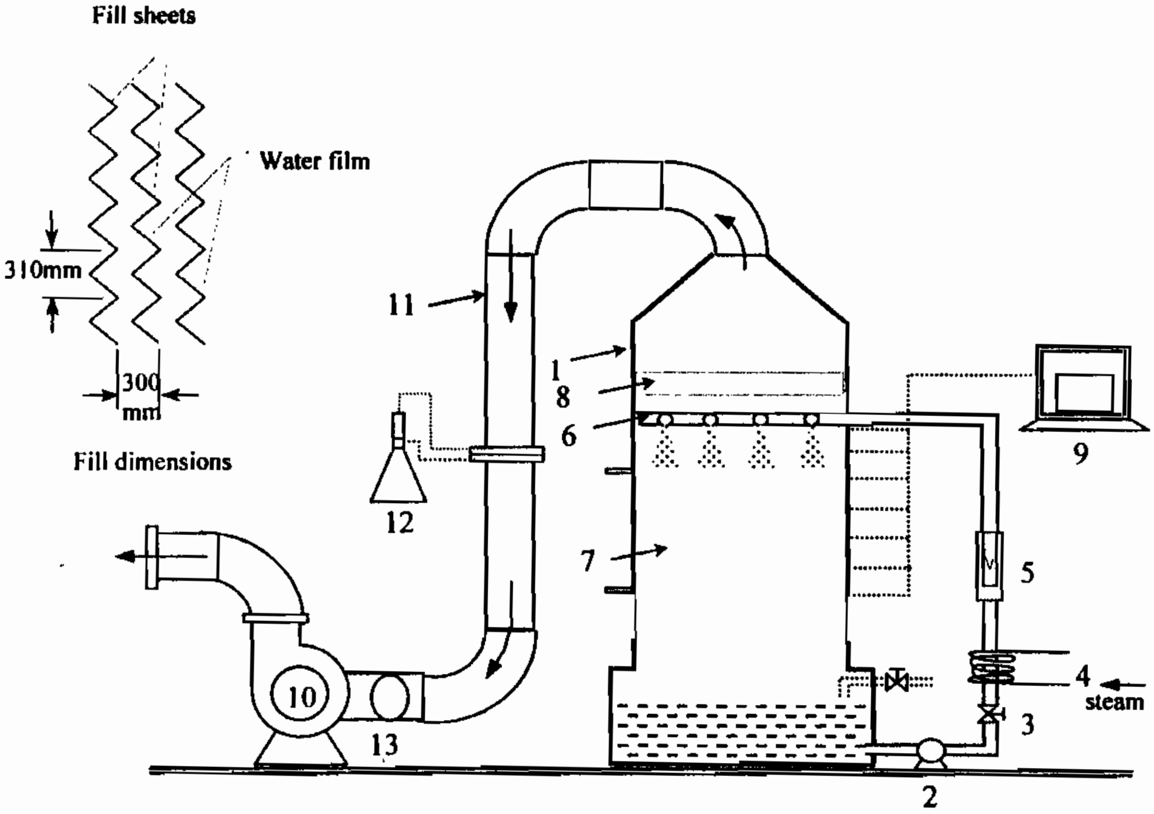
## 2. Experimental installation

A schematic diagram of the experimental apparatus is shown in Fig. 1. The main part of the installation is the cooling tower (1), 6.0 m in height and 3×3 m in cross section. The tower construction structure in made of steel beams. The sides and front side of the test section are made of sheet metal, and the rear side is transparent and is made of fiberglass plates of 5 mm thick. The rear fiberglass plate is removable, so the easy access to interior of tower is able in order to replace packing or water drops separator, as well as to enable the access of various measuring probes. The water is transported by pump (2) through flow regulated (3) to the heating load which is a steam coil (4) with adjustment of temperature is realized by thermo-regulators. The water flow rate is measured by flow meter (5) and designed system for water distribution (6). The water is distributed in the form of falling films over the plates of fill. The water distribution system consists of 16 copper injector perforated at both sides. By using this system the water is directly distributed over the plate sides to the left and right from the tube, and the films of falling water were uniform (without preferent flows and dry spots) across the whole surfaces of plates. The pressure drop at orifice meter is measured by U-tube manometer with mercury. The fill (7) is made of PVC plates having zigzag shape with characteristic dimensions as shown in Figure (1). Forty fill plates are used in this work, each having 1200 mm height and 650mm width. The fill plates are distributed inside the tower in four groups, each group consists of ten plates positioned perpendicular to tower cross section (vertically). The referent plate (8) is used as a water droplet separator.

Calibrated 0.2mm chromel-alumel thermocouples are used to measure air and water inlet and outlet temperatures. All thermocouples are connected to 24-point digital temperature recorder (9).

The relative humidity of air at tower inlet is measured by Assman psychrometer measuring both the dry bulb and the wet bulb temperature. The airflow through the tower is providing by using the fan (10); the hole test section is connected on its suction side via pipeline (11). The lengths of pipe upstream and downstream from the orifice are satisfying the conditions of flow stabilization.

Pressure drop at orifice is measured by a digital micro-manometer (12) with an accuracy of ±1Pascal. The air enters into tower, passes the rain zone, the fill and the droplet separator and leaves the tower. The adjustment of airflow rate is provided by the regulating valve (13).



1. cooling tower basis
2. Water pump
3. Flow regulator
4. Steam coil
5. Flow meter
6. Water distribution
7. PVC fill
8. Referent plate
9. Temperature recorder
10. Air fan
11. Air pipe line
12. digital micro-manometer
13. Regulating valve

**Fig. 1. Layout of experimental apparatus**

## 3. Experiment environmental conditions and ranges of operating parameters

The experimental investigations are carried out in the period June-September 2003.

- The environmental parameters have been in the ranges:
  - Environmental air temperature: 30 - 38°C
  - Relative humidity of the environmental air: 48 - 83%
- Air mass flow rate varied within the range: 54000 - 90000 $m^3/h$
- Water mass flow rate is changed in the interval: 80 - 150 $m^3/h$
- Water temperature is varied in the range: 38 - 60 °C

## 4. Experimental results and discussions

In the present experimental work many parameters affecting the performance of counter flow wet cooling towers are investigated. These parameters and their corresponding ranges as follows:

- Air velocity changes from 10.5 to 17.5 m/s;
- Mass flow rate ratio changes from 0.88 to 1.76, and
- Inlet air wet bulb temperature ($t_{wb,i}$) varied from 24 to 30 °C.

The effect of air dry bulb temperature on the performance of cooling tower is known to be negligible which is a typical characteristics of wet cooling towers [1,2]. Therefor the effect of inlet air dry bulb temperature has not been investigated in this work.

## 4.1 Effect of tower height

Figure (2) indicates the effect of tower height on the tower range at different mass flow rate ratios. From the overview of the figure one can observe that tower range increases with increasing tower height and mass flow rate ratio. There is a comparable rabid increase in tower range with tower height until tower height reaches certain values varying from 1100 to 1700 mm for mass flow rate ratio ranging from 0.88 to 1.76. After these limits tower range shows a lesser increase with proceeding tower height. This is because air humidity at tower inlet is small, depending on climatical condition, and increases while passing through the tower. This increase of air humidity decreases the ability of air to carry more water vapor. As a result heat of evaporation of water decreases and so do the heat transferred between air and water and consequently a small variation in water temperature occurs, i.e., a small variation in tower range.

## 4.2 Effect of inlet air wet bulb temperature

Figure (3) is shows the relation between tower effectiveness $(\varepsilon)$ and inlet air wet bulb temperature ($t_{wb,i}$) at different values of mass flow rate ratios. Fig. (4) is the corresponding plot between tower approach and inlet air wet bulb temperature. In this case, the values of $t_{wb,i}$ was varied from 24 to 30°C. The figure shows that tower range and effectiveness decrease with the increase of inlet wet bulb temperature. The figures show also that both tower range and effectiveness increase with mass flow rata ratios. It is interesting to note that there is no appreciable change in both approach and effectiveness with $t_{wb,i}$ particularly of high values of $t_{wb,i}$. The relation between tower range and inlet air wet bulb temperature at different values of mass flow rate ratios demonstrated in Fig. (5). It can be seen from this figure that tower range decreases with the increase of inlet air wet bulb emperature and the increase of mass flow rate ratios.

The influence of wet bulb temperature on performance of a cooling tower is studied under constant water inlet temperature and different mass flow rate ratio.

Water outlet temperature as a tower performance is represented in Fig. (6). It is seen from the figure that water outlet temperature decreases with decreasing wet bulb temperature at constant mass flow rate ratio. Also the figure shows that the effect of the wet bulb temperature becomes more sensible with increasing mass flow rate ratio (decreasing air mass flow rate). When the wet bulb temperature is too high, little effect on the performance is seen with any increase in air flow rate (decrease in mass flow rate ratio).

These trends will be different for each cooling tower and each operating condition, respectively, so it should be suggested that the analysis be done to predict .the extent of change. For example it could be suggested that increasing air flow rate be not helpful on the performance if the wet bulb temperature of initial air is above a certain value.

## 4.3 Effect of mass flow rate ratio

Figure (7) shows the relation between mass flow rate ratio (L/G) and the approach for different inlet air wet bulb temperatures. It is seen from the figure that the approach increases with increase of mass flow rate ratio. It is also seen from the figure that the increase in approach is less for $L/G \leq 1.1$ and nearly no effected with inlet wet bulb temperature. However beyond this limit the value of approach increases rapidly with mass flow rate ratio and increases with the decrease of inlet wet bulb temperature.

Figure (8) represents the relation between L/G and tower effectiveness ($\varepsilon$) for different values of inlet wet bulb temperature. This figure shows that tower effectiveness increases with mass flow rate ratio until it reaches a maximum value nearly at $L/G = 1.1$ and then still constant for $L/G > 1.1$. It is shown from the figure also that tower effectiveness increases with the decrease of inlet air wet bulb temperature (Refer Fig. 3).

Figure (9) represents the effect of mass flow rate ratio on tower range for different values of inlet air wet bulb temperature. The figure shows that as mass flow rate ratio increases tower range decreases. It is seen also that the decrease in tower range is lesser for $L/G \leq 1.1$, however beyond this point the value of tower range decreases rapidly with the increase of mass flow rate ratio. Also one can concluded from the figure that tower range increases as inlet air wet bulb temperature decreases.

Figure (10) shows a plot between tower number of transfer unit (NTU) and mass flow rate ratio (L/G) along with the experimental equation presented in Reference [9] for the case of two levels of packing in the present work and Reference [9].

An attempt was made to correlate the present experimental NTU values with mass flow rate ratio (L/G) in the following form:

$$NTU = \frac{K_a A_V V}{L} = 0.875\left[\frac{L}{G}\right]^{-0.12} \qquad (1)$$

The above correlation (1) indicates that the constant of equation is good agreement wit Reference [9] but the power of (L/G) in the present study is higher than that in Reference [9] due to the effect of packing height as mentioned earlier.

## 4.4 Effect of water outlet temperature

Figure (11) shows the relation between tower effectiveness (ε) and non-dimensional temperature ratio (R), for different values of mass flow rate ratio (L/G). As expected, the figure shows that as value of water outlet temperature ($t_{w,o}$) decreases (i.e., R increases) tower effectiveness increases. This increase of effectiveness with temperature ratio is higher for larger mass flow rate ratio. Fig. (12) is the corresponding plot between R and air approach temperature which is defined as the temperature difference between water outlet temperature and air inlet wet bulb temperature, ($t_{w,o} - t_{wb,i}$). It is important to note that this difference in temperature is a measure of the closeness to saturation condition of the cooling tower. For example, lower the temperature difference, the higher will be tower effectiveness and vice versa. When this temperature difference is equal to zero, the effectiveness of the tower is equal to 1.0. This figure clearly demonstrates the reason why for higher mass flow rate ratio, the effectiveness of the tower is approaching unity. Figure (11) shows also that for every value of R, there is on value of L/G at which the effectiveness of the tower is equal to 1.0. This value of L/G is defined as the maximum possible value of mass flow rate ratio, any value greater than this value will not increase the tower effectiveness.

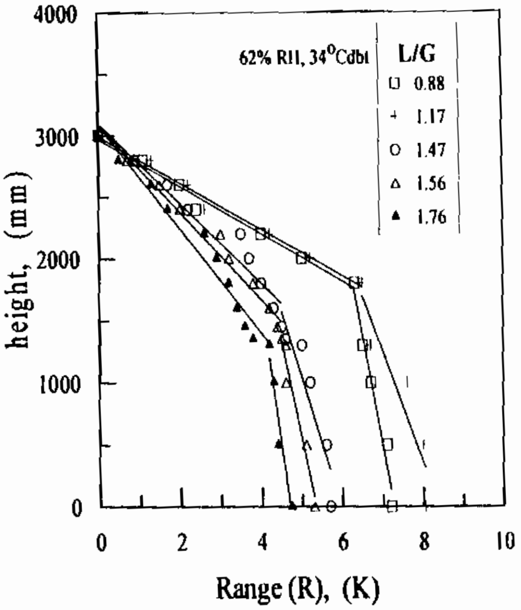


**Fig. (2) Variation of tower range along height of cooling tower.**

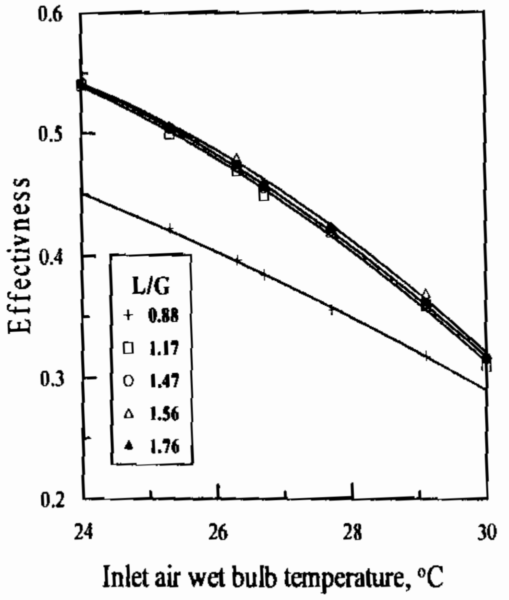


**Fig. (3) Effect of inlet air wet bulb temperature on effectivness at different water-air flow rate ratios.**

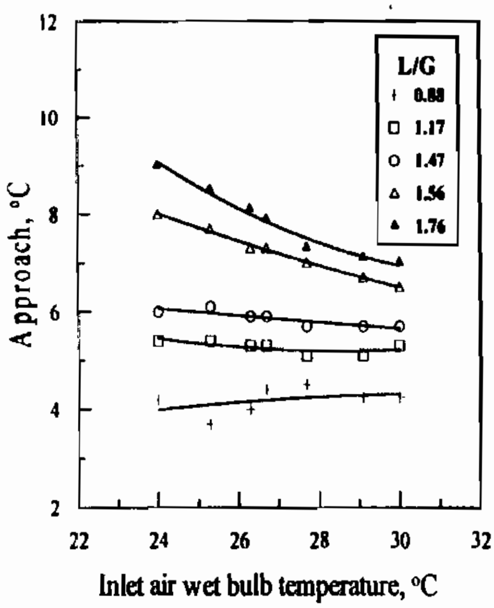


**Fig. (4) Effect of air inlet wet bulb temperature on Approach at different water-air flow ratios.**

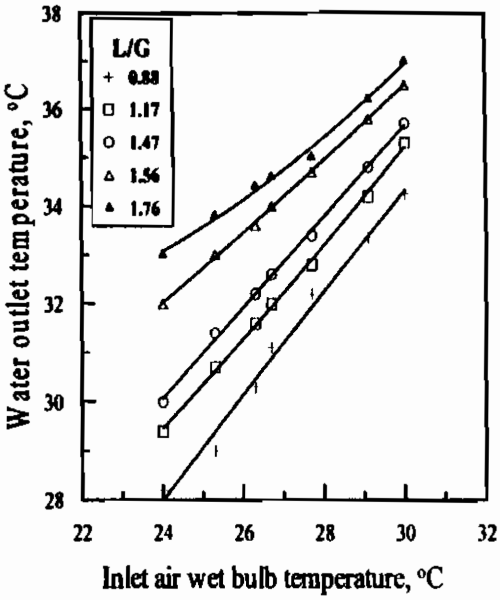


**Fig. (6) Effect of air inlet wet bulb temperature on water outlet temperature at different water-air flow rate ratios.**

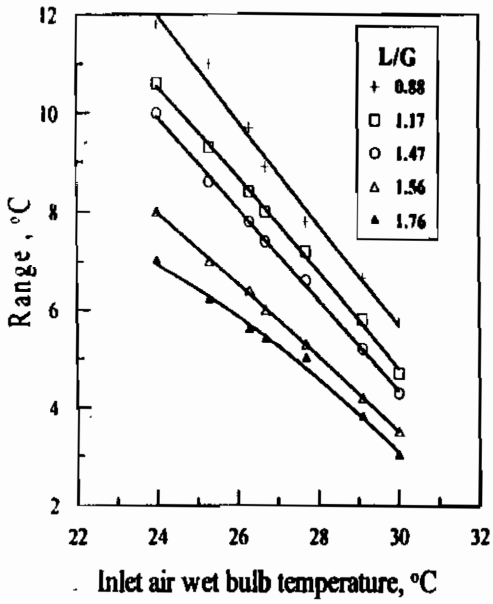


**Fig. (5) Effect of air inlet wet bulb temperature on tower range at different water-air flow rate ratios.**

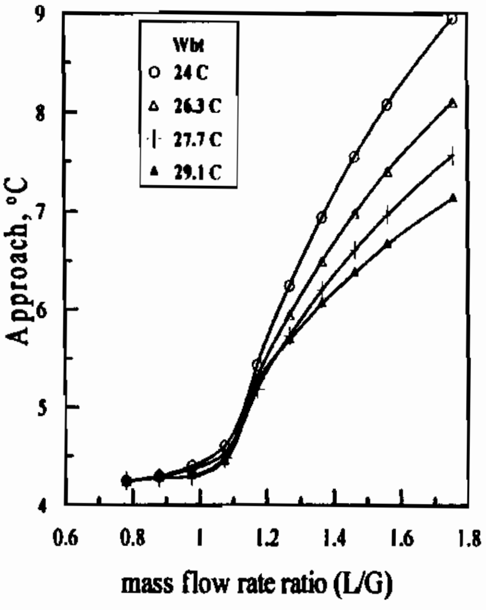


**Fig. (7) Relation between mass flow rate and approach at different wet bulb temperature.**

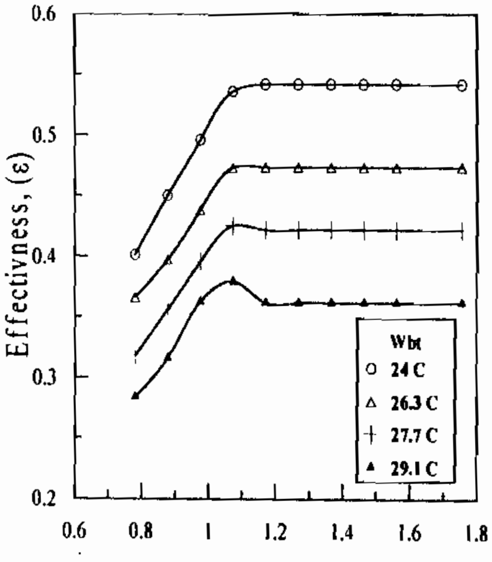


**Fig. (8) Relation between mass flow rate and effectivness at different wet bulb temperature.**

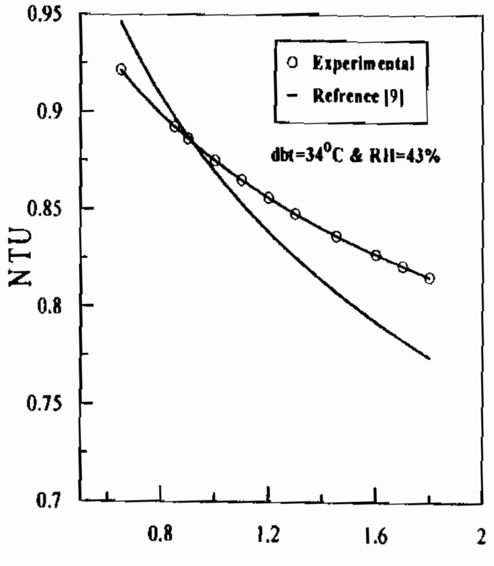


**Fig. (10) Relation between mass flow rate and number of transfer units.**

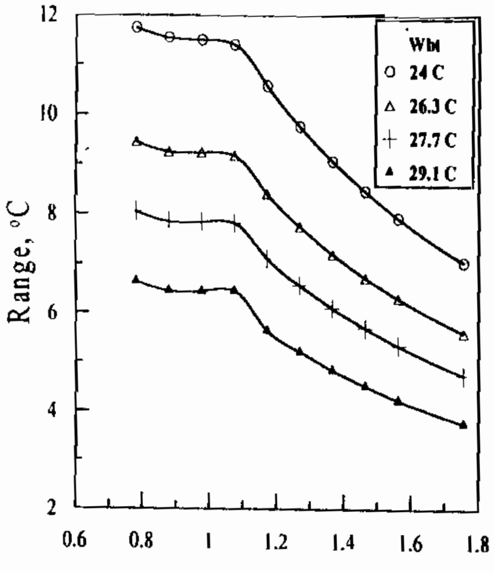


**Fig. (9) Relation between mass flow rate and range at different wet bulb temperature.**

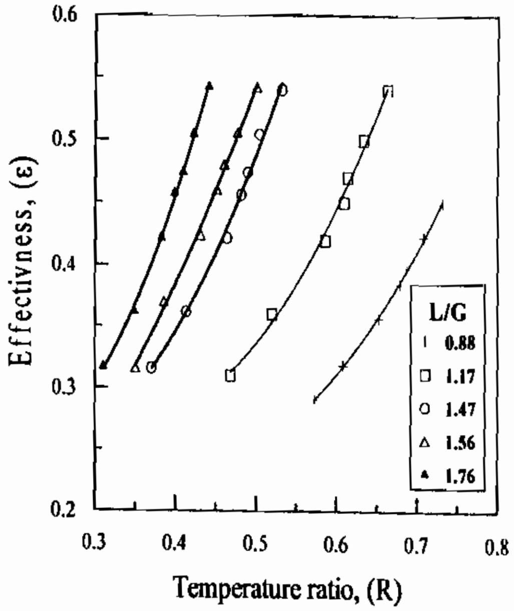


**Fig. (11) Relation between temperature ratio and tower effectivness**

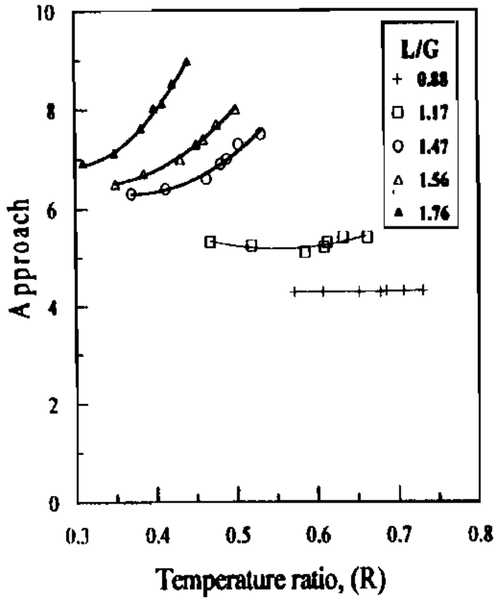


**Fig. (12) Relation between temperature ratio and approach.**

## 5. Conclusions

In this work the results of the experimental investigation of heat and mass transfer in the counter flow wet cooling tower have been presented. The cooling tower under investigation has been constructed and investigated in Misr Oil and Soap Company, Mansoura branch.

The following conclusions can be draw:

1. When the water/air flow rate ratios and inlet water temperatures decreased, the $(K_a A_V V / L)$ or NTU were increased. Decreasing the wet-bulb air temperatures, the range would be increased but decreased the NTU.
2. From this study the experimental characteristic equation is:

$$NTU_{\exp} = \frac{K_a A_V V}{L} = 0.875 \left[ \frac{L}{G} \right]^{-0.12}$$

which can be used for design counter flow wet cooling tower.

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