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Experimental and Theoretical Study for a Counter Flow Water Cooling Tower by Using (clear P.V.C.) Packing

دراسة تجريبية ونظرية لبرج تبريد ذو جريان ماء متعاكس باستعمال حشوة (P.V.C)الصافية

Assistant Lecturer Hayder J.Kurji
Mechanical Engineering Department, College of Engineering, University of Karbala

الخلاصة :

تم في هذا البحث دراسة الأداء لبرج تبريد ذو جريان ماء متعاكس باستعمال حشوة (P.V.C.) الصافية بميلان 45°عن المحور العمودي.وقد تم تحليل العلاقة التجريبية والنظرية بين تَبريد الحملِ ومدى التبريد لنِسَبِ تدفقِ ماءِ مختلفة .حيث وجد إن زيادة تدفقالماء تؤدي إلى نقصان مدى التبريد بحيث عندما كان تدفق الماء(0,3 كغم\ثا) كان معدل التبريد (11 درجة حرارية) وعندما كانتدفق الماء(0,5 كغم\ثا) كان معدل التبريد (6 درجات حرارية).تم اختبار أربعة ارتفاعات مختلفةِ للحشوة (0.12, 0.24, 0.36, 0.48)متر بتَغيير نِسَبِ تدفقِ الهواء، ونسب تدفق الماء في ثلاث خطواتِ لكُلّ مِنْ الارتفاعات الأربعة,ووجد إن عدد وحداتالانتقال(معامل الأداء) NTU أو (KaV/L) تزداد بزيادة تدفق الهواء.إن العلاقة لعددِ وحدات الانتقال مَع(L/G) (نسب تدفقالماء بوحدة المساحة إلى نسب تدفق الهواء بوحدة المساحة) درستْ تجريبيا ونظريا. بالإضافة إلى تلك الحسابات ,تمحساب (KaV/L) نظرياً باستعمال طريقة Tchebycheff,واستعملت طريقة(least square method) لرَبْط النَتائِجِ التجريبيةِللعدد (NTU)مَع نسبةِL/G. في هذا البحث وجد أن الأداء الأفضل لبرج التبريد يتمثل في تجهيز اقل نسبة من (L/G),حيث لوحظعند ثبات نسبة تدفق الهواء بوحدة المساحة إن عدد وحدات الانتقال تصل 1,9 عندما (L/G) تساوي 0,435 وعدد وحداتالانتقال تصل 0,42 عند(L/G) تساوي **0,87**.ووجد أن درجة حرارة الماء الداخل أذا زادت فان عدد وحدات الانتقال NTUتقل والعكس بالعكس .النتائج العملية المستحصلة في هذا البحث متوافقة بصورة معقولة مع النتائج النظرية.

ABSTRACT:

In this paper we study the performance of a counter flow water cooling tower by employing (clear PVC) packing with inclined 45^o from the vertical axis. For different flow rate of water the cooling load are studied experimentally and theoretically .It is found that an increase in water flow rate leads to a decrease in cooling range, whereas when the water flow rate was (0.3kg/s) the cooling range was (11 C^o) and when the water flow rate was (0.5kg/s) the cooling range was (6 C^o).Four different packing heights (0.12, 0.24, 0.36 , 0.48)m are tested by varying the air flow rates, and the water flow rates in three steps for each of the four packing heights, it is observed that the number of transfer units (performance coefficient) (NTU) or (KaV/L) increases by increasing air flow rate. The relation of NTU with (L/G) (water flow rate per unit area to air flow rate per unit area) are studied experimentally and theoretically. Moreover, the calculation for (KaV/L) is theoretically computed by using Tchebycheff method, and the least square method is used to correlate the experimental results for NTU in terms of (L/G). We conclude that best performance for tower packing is represented in providing minimum water to air ratio (L/G),where it is noticed that when the air flow rate per unit area constant then the NTU reaches to 1.9 with (L/G) equals 0.435 and NTU reaches to 0.42 with (L/G) equals 0.87.We also conclude that when the inlet water temperature increases the (NTU) decreases and vice versa. The experimental results obtained in this paper reasonably agree with the theoretical results.

Nomenclature

NTU Number of transfer units
K Mass transfer coefficient per unit plan area(kg/ m^3.s).
a Surface area per unit volume (m^{-1}).
V Cooling tower volume(m^3).
L Water flux(kg/ m^2. s).
G Air flux(kg/ m^2. s).
P Power(W).
H Enthalpy rate(W).
h Specific enthalpy(J/kg).
w Specific humidity(kg. kg^{-1}).
t Temperature (K).
x Orifice differential (mm H_2O)
v Specific volume (m3/kg).
Z Packed height(m).
A Inlet low humidity air (figures 1,2)
B Leave high
C Inlet warm water humidity air (figures 1,2)
(figure 2)
D Leave cool water (figures 2)
E Make up (figures 1,2)
C_p Specific heat(kJ / kg. K).
C_w Specific heat of water(kJ / kg. K).
$\dot{m}$ Mass flow rate(kg/ s).
$\dot{Q}$ Heat transfer rate(W).

1. Introduction

Cooling towers are commonly used to dissipate heat from water needed for condensers, and other process equipments. Economic and safety operations for an unit is greatly influenced by outlet water temperature of cooling tower. Thermal efficiency of the unit is increased because of the outlet water temperature of cooling tower is decreased.

The water consumption rate is only about 5% from that which is used, and making the cooling tower least expensive system to operate with purchased water supply[1]. It is used in power stations, chemical engineering processes and air conditioning equipments. Many theories have been developed to describe the heat and mass transfer phenomenon, which is take place in water cooling towers. Jaber and Webb [2] they develops the effectiveness NTU design method for cooling towers. The definitions effectiveness and NTU are totally consistent with the fundamental definitions used in heat exchanger design. Hasan [3] studied the theoretical and experimental parameters that effect on the performance of cooling tower such as air flow rate, water flow rate , inlet water temperature and height of packing.

The e-NTU method is based on the same critical assumptions as the Merkel method. Due to its simplicity, the e-NTU is especially useful in the solution of the cross flow cooling tower fills [4] where the heat and mass transfer problem is described by partial differential equations. Bedekar et al, [5] studied experimentally the performance of a counter flow packed bed mechanical cooling tower, using a film type packing. Their results were presented in terms of tower characteristics, water outlet temperature and efficiency as functions of the water-to-air flow rate ratio, *L*/*G*. They concluded that the tower performance decrease with an increase in the *L*/*G* ratio, however they did not suggest any correlation in their work.

Söylemez [6] performed theoretical and experimental analyses of cooling towers. He presented a method for estimating the size and performance of forced draft counter flow cooling towers. The author used an iterative technique for the calculation and compared the theoretical results with experimental results obtained for this purpose. Goshayshi et al. [7] presented an investigation using measurements of the mass transfer rates and pressure drops for a comprehensive range of PVC plastic packing. In order to produce an economic comparison to find the best geometry and range, mass transfer and pressure drop for turbulent conditions in fills used in the modern cooling tower had been studied. The authors introduced a new method of comparison of existing cooling tower packing. It was also indicated that the mass transfer coefficients of corrugated packing vary in proportion to the 0.41 power of pressure drop per unit height. Goshayshi and Missenden [8] studied experimentally the mass transfer and the pressure drop characteristics of many types of corrugated packing, including smooth and rough surface corrugated packing in atmospheric cooling towers. Kloppers and Kröger [9] studied experimentally the transfer characteristics of wet cooling tower fills. They reported that the transfer characteristic correlations for wet cooling tower fills are functions of the air and water mass flow rates, the inlet water temperature and fill height but not of the air dry bulb and wet bulb temperatures.

The main contribution of this paper is summarized in the following four points:-

1- We develop mathematical relationship between performance coefficient (NTU) and (L/G) (water flow rate per unit area to air flow rate per unit area). furthermore, this relation was verified by the experimental results obtained in this paper.

2-We find the relationship between the (NTU) and (L/G)for (clear P.V.C. **)** packing.

3- We present the relationship between the cooling range and cooling load for the same (clear P.V.C. **)** packing

4- We find out the effect of the inlet water temperature on the (NTU).

2. Analysis and Formulation

The heat and mass transfer characteristics of the counter flow water cooling tower can be determined by the conservation equations of energy and mass. The mathematical model is based on the main following assumptions:-

Assumption 1: Film type, counter flow, direct contact cooling tower of constant cross section.

Assumption 2: The air and water property are constant across any cross section but varies vertically.

Assumption 3:Heat and mass transfer coefficients are constant throughout the tower.

Assumption 4: The liquid side heat transfer resistance is negligible then the interface condition will be considered saturated at the bulk water temperature.

2-1 Application of Steady Flow Energy Equation

For the system shown in figure (1), which represent the model without outside system [10]. Heat (Q) is transferred at the load tank, i.e. the process load, and possibly a small quantity to surrounding. Work(P) is transferred at the pump. Low humidity air enters at (A).High humidity air leaves at (B).Make-up m_e (equal to the increase of moisture in the air stream) enters at E.

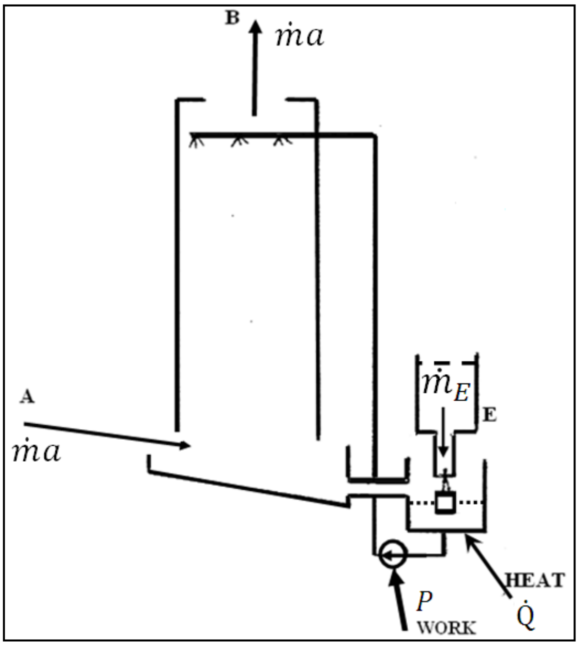

Figure (1).Model without outside system

From the steady flow equation[10]:

$$\dot{Q} - P = H_{Exit} - H_{Entry} \quad (1)$$

$$\dot{Q} - P = (\dot{m}_a h_{da} + \dot{m}_s h_s)_B - (\dot{m}_a h_{da} + \dot{m}_s h_s)_A - \dot{m}_E h_E \quad (2)$$

If the enthalpy of the air includes the enthalpy of the steam associated with it, and this quantity is expressed per unit mass of dry air (2) may be written

$$\dot{Q} - P = \dot{m}_a (h_B + h_A) - \dot{m}_E h_E \quad (3)$$

Where the mass flow rate of dry air($\dot{m}_a$) through a cooling tower is a constant**,** whereas the mass flow rate of moisture air increases due to the evaporation of some of water. The term $\dot{m}_E h_E$ is usually small compared with the other terms and is often neglected.

2-2Mass Balance

For the system shown in figure (2), which represent the model with outside system [10]. by conservation of mass, under steady state conditions, the mass flow rate of dry air and of H_2O (as liquid or vapor) must be the same at inlet and outlet to any system.

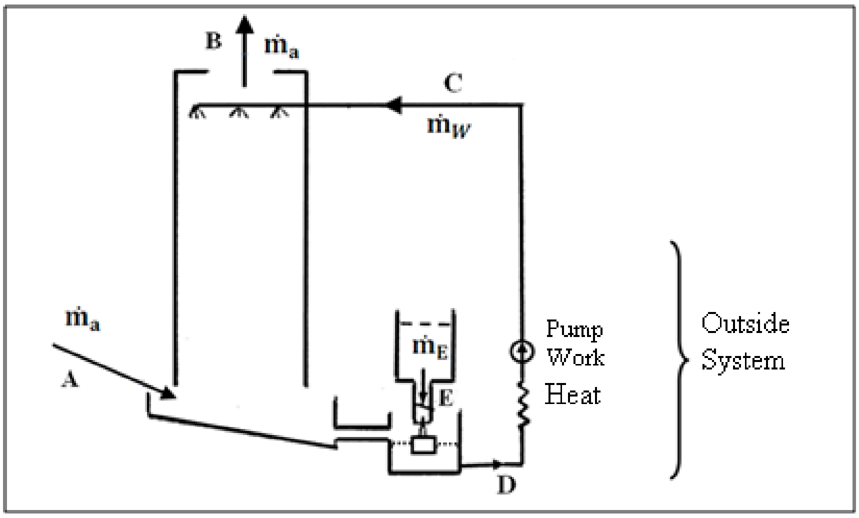

Figure (2).Model with outside system(pump work and heat)

Thus, $(\dot{m}_a)_A = (\dot{m}_a)_B$ (4)

And $(\dot{m}_s)_A + \dot{m}_E = (\dot{m}_s)_B$ (5)

$\dot{m}_E = (\dot{m}_s)_B - (\dot{m}_s)_A$ (6)

The ratio of steam to air (w) is known for the initial and final state points on the psychrometric charts.

$(\dot{m}_s)_B = \dot{m}_a w_B$ (7)

$(\dot{m}_s)_A = \dot{m}_{a_A}$ (8)

$\dot{m}_E = \dot{m}_a(w_B - w_a)$ (9)

In this case the process heat and pump work does not cross the boundary of the system, but we now have warm water entering the system at C and cool leaving at D.

Applying the steady flow energy (1) [10], pump work P=0; may have a small value due to heat transfer between the unit and its surroundings.

$\dot{Q} = \dot{m}_a h_B + \dot{m}_w h_D - (\dot{m}_a h_A + \dot{m}_w h_{C+} \dot{m}_E h_E)$ (10)

$\dot{Q} = \dot{m}_a(h_B - h_A) - \dot{m}_w(h_D - h_C) - \dot{m}_E h_E$ (11)

$\dot{Q} = \dot{m}_a(h_B - h_A) - \dot{m}_w C_p(t_D - t_C) - \dot{m}_E h_E$ (12)

As stated earlier the term $\dot{m}_E h_E$ is usually small compared with the other terms .

2-3 The Heat Transfer Coefficient KaV/L

The Tchebycheff method for numerically evaluating the integral $\int_b^a y dx$ uses values of y at predetermined values of x within interval (a) to (b). It can be selected that the sum of these values of y multiplied by a constant times the interval (b- a) gives the desired value of integral. In its four-point form, the values of y are taken at selected values of x of 0.102673, 0.40620, 0.59379, and 0.89732 of the interval (b-a). For the determination of KaV/L, rounding off these values to the nearest tenth is entirely adequate. The approximate formula becomes [11]:

$\int_b^a y dx = (b-a)/4(y_1 + y_2 + y_3 + y_4)$ (13)

Where y_1= value of y at x=a+0.1(b-a)

y_2= value of y at x=a+0.4(b-a)

y_3= value of y at x=a+0.6(b-a)

y_4= value of y at x=a+0.9(b-a)

The water temperatures on the divided cross section of packing can be calculated in 4 positions. Each position can be determined from bottom to top of the packing as $T2$+0.1($T1$-$T2$),$T2$+0.4($T1$-$T2$), $T2$+0.6($T1$-$T2$), and $T2$+0.9($T1$- $T2$), respectively. So, the enthalpy difference at each position can be calculated and the value of *KaV/L* can be evaluated as

$$\frac{KaV}{L} = \frac{C_W(T_1 - T_2)}{4}\left[\frac{1}{\Delta h_1} + \frac{1}{\Delta h_2} + \frac{1}{\Delta h_3} + \frac{1}{\Delta h_4}\right] \quad (14)$$

Where Δh_1=saturated air and moist air enthalpy difference at T_2+0.1(T_1-T_2)

Δh_2 = saturated air and moist air enthalpy difference at T_2+0.4(T_1-T_2)

Δh_3 = saturated air and moist air enthalpy difference at T_2+0.6(T_1-T_2)

Δh_4 = saturated air and moist air enthalpy difference at T_2+0.9(T_1-T_2)

C_w = specific heat of water

T_1 = hot water temperature

T_2 = coldwater temperature

3. EXPERIMENTAL WORK

Schematic diagram of the experimental set up is shown in Figure (3)[12]. The tower's column has a parallel form of dimensions 150 mm × 150 mm × 600 mm, and manufactured from clear plastic to allow viewing of water flow through the system. It is filled with the (clear PVC). type packing having a surface area of 1.19 m^2, height of 0.48 m and consists of (8) decks , every deck consists of 10 plates. The considered measurements which were taken consist of the temperatures increase (dry and wet) of the air at the entry and exit of the tower, as well as the inlet and outlet water temperatures.

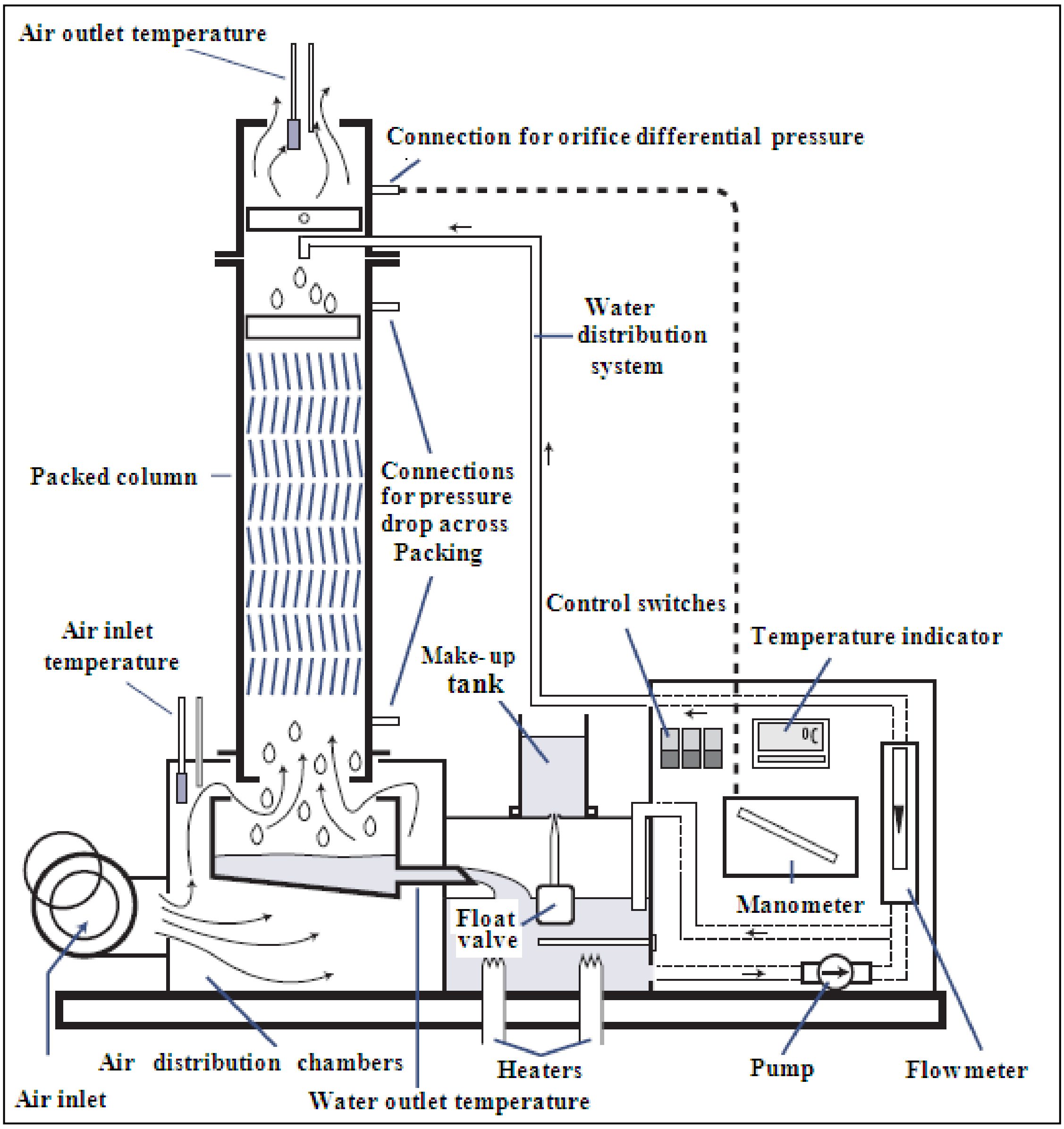

Figure (3). schematic diagram for experimental counter flow cooling tower

The testing procedure is described:-
Warm water is pumped from the lead tank through the control valve and water flow meter where its rate is adjusted and arrive to the top of the tower. After its temperature T_5 (water entering tower)is measured, the water is uniformly distributed over the packing elements and exposed to the air stream. During its downward passage through the packing, the water is cooled largely by evaporation of a small portion of the total flow. The cooled water falls from the packing into the basin, where its temperature T_6 (water leaving tower) is again measured and then passes into the load tank where it is reheated before recirculation. Air from the atmosphere, enters the fan at a rate which is controlled by the intake damper setting. The fan discharges into the distribution chamber and the air passes wet and dry bulb sensors, where its wet and dry temperatures t_1 (air inlet dry bulb) and t_2 (air inlet wet bulb) are measured before entering the packing zone. As the air flows upward through the packing elements, its moisture contents increases and the water is cooled. On leaving the top of the tower, the air passes through the drift eliminator, which traps the entrained droplets and returns them to the packing zone. The air is then discharged to the atmosphere via the air

measuring orifice and further wet and dry bulb sensors, where the wet and dry temperatures t_3 (air outlet dry bulb)and t_4 (air outlet wet bulb) are again measured.

3-1 Air Mass Flow Rate

Air mass flow rate passing through the packing inside the cooling tower was determined by measuring orifice differential in (mmH_2O) with an inclined manometer, determining specific volume of the air at the exit of the tower utilizing dry temperature (t_3) and specific humidity, and substituting them into the following equation [13]:

$$\dot{m}_a = 0.0137\sqrt{(x/v_B)} = 0.0137\sqrt{(x/(1+w_B)v_{ab}} \qquad (15)$$

$\dot{m}_a$ = dry air mass flow rate (kg/s)

x = orifice differential (mm H2O)

v_B = specific volume of steam and air mixture leaving top of column (m^3/kg)

v_{ab} = specific volume of dry air leaving top of column (m^3/kg)

w_B = specific humidity of air leaving top of column (kg water/kg dry air)

3.2. Performance characteristics of the cooling tower

In the present study, the important parameters are used in investigating the performance characteristics of the cooling tower, namely the cooling load and number of transfer units (NTU) cooling tower.

3.2.1 Cooling Load and Cooling Range

Cooling load where represent the rate at which heat is removed from the water cooling load we could got from apparatus directly. and cooling range described the difference between the water temperature at entry to and exit from the tower.

3.2.2 Number of Transfer Units (NTU)

Cooling tower data are most often plotted in the form of KaV/L versus L/G Common practice is to neglect the effect of air velocity and develop the tower correlation in the form of a power law relation:

$KaV/L = \lambda[L/G]^n$

Where λ, n are constants for a particular packing

4. Results

The performance of a cooling tower depends on several parameters such as the range of cooling temperature, the inlet water temperature and the (L /G) variation ratio. Six cases are studied; three for air flow rate and three for water flow rate. The packing height is (600 mm) . The various affecting parameters are plotted in figures (4) to (12).In figures (4, 5, 6) a comparison is made between cooling load and cooling range for different water flow rates[$\dot{m}w$ (0.03, 0.04, 0.05) Kg/s] and constant air flow rate $\dot{m}_a = 0.057Kg/s$. These figures show that the influence of increase of the water mass flow rates leads to decreasing the cooling range with constant air mass flow rate. This behavior is attributed to the fact that the increase in water flow rate leads to an increase in heat load. The theoretically calculated temperature values of the water entering the tower , the water leaving tower and air inlet wet bulb are found to be close to the experimental results with small deviations.

Each figure(7, 8, 9) represents the performance (NTU) with height of packing; each one corresponds to one value of air mass flow rate. Four heights of packing were investigated (0.12, 0.24, 0.36 , 0.48) m, where these values are measured from the top of tower.

These figures show that for each fixed height of packing, when the water flow rate is increased then the performance coefficient (NTU) is decreased. This is due to the decreasing of (K.a) (Volumetric mass transfer coefficient). In other words the performance coefficient definition is (K.a.z/L)(Performance coefficient (NTU) based on L), so it is inversely proportional with L. Physically, as the water flow rate increases the heat load increases. Therefore, the capability of the packing for dissipating heat load is decreased. That is the duty is become harder to be accomplished. It is also noted that as the packing height increases the performance coefficient increases approximately with the same slope.

Figures. (10, 11, 12) showed a comparison between theoretical NTU and experimental NTU ,where a good agreement between the experimental and theoretical results is observed . It is clear from the figures that as the water to air flux ratio (L/G) increases the performance coefficient decreases. This is due to the decreased of (K.a). By the least square method we can found the following equations:

1. $KaV/\dot{m}_w=0.43[L/G]^{-1.64}$,for inlet water temperature =34.4C° (16)
2. $KaV/\dot{m}_w=0.48[L/G]^{-0.81}$,for inlet water temperature = 30C° (17)
3. $KaV/\dot{m}_w=0.43[L/G]^{-0.95}$,for inlet water temperature = 27.9C° (18)

5. Conclusions and Scope for Future Work

Maximum performance in a given volume of tower packing may be obtained with minimum water to air ratio (L/G) .The cooling range is increased by the addition of a cooling load , where it is noticed from figure (4) that when cooling load is (0.5 Kw) the cooling range becomes about ($4C^o$). But when a cooling load is (1.5 Kw) the cooling range is about ($12C^o$). It is observed that the inlet water temperature has a significant effect on performance coefficient, i.e, if inlet water temperature increases the (NTU) decreases. To correlate the results, using least square method, the independent variable (NTU) is correlated primarily with water and air flow ratio (L/G). The theoretical and experimental results have a good agreement. For future work, researchers can study the performance of a counter flow cooling tower by using Aluminum packing .It is recommended to use the (CFD) codes and compare these results with experimental data.
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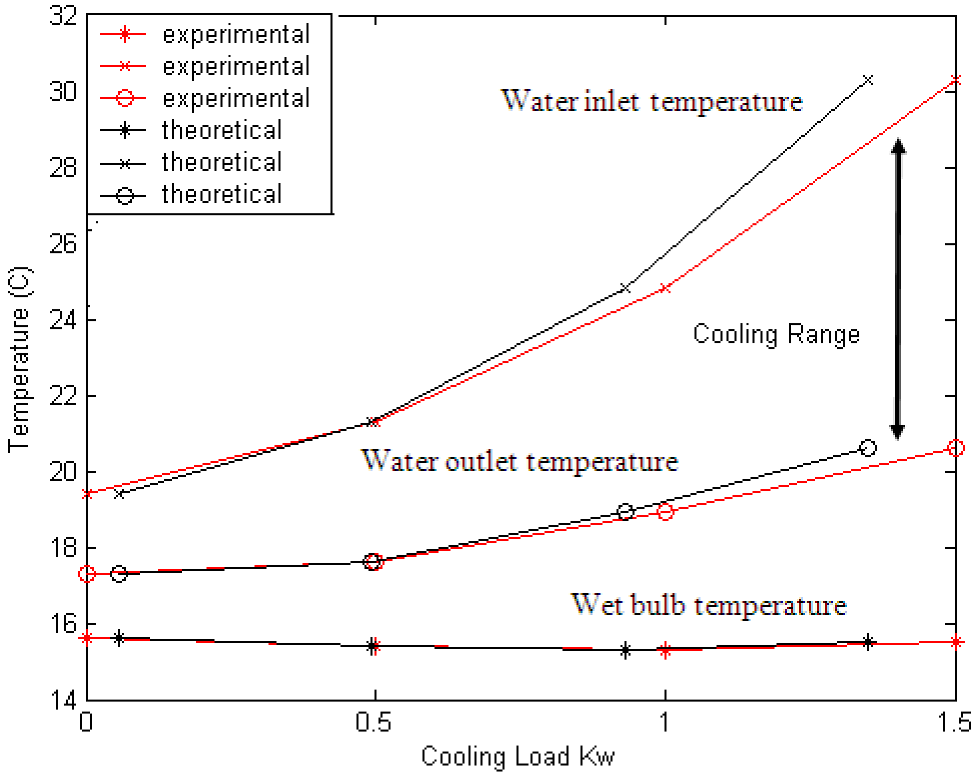

Figure (4)relationship between cooling load and cooling range for water flow rate $(\dot{m}w = 0.03Kg/s)$

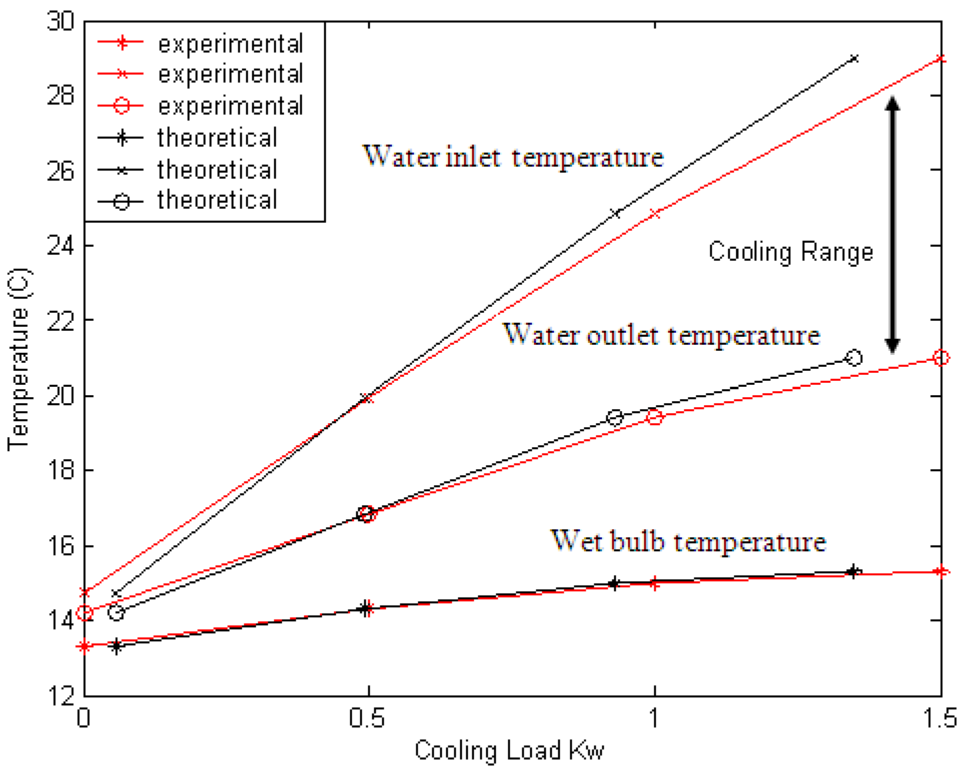

Figure (5).relationship between cooling load and cooling range for water flow rate $(\dot{m}w = 0.04Kg/s)$

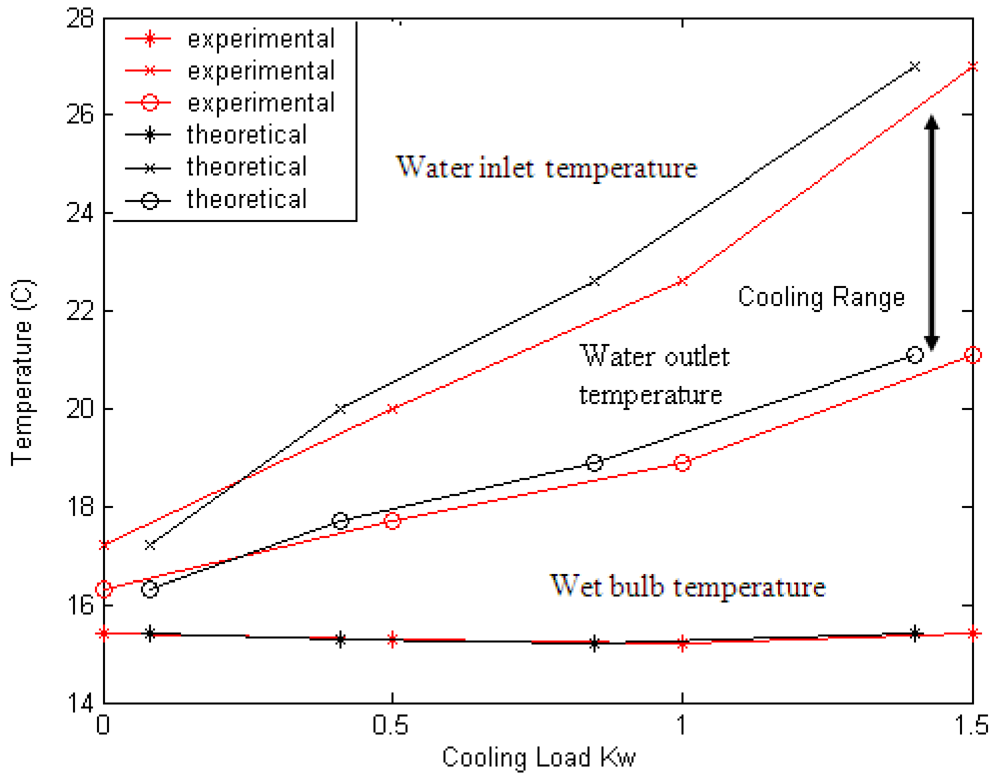

Figure (6).relationship between cooling load and cooling range for water flow rate $(\dot{m}w = 0.05Kg/s)$

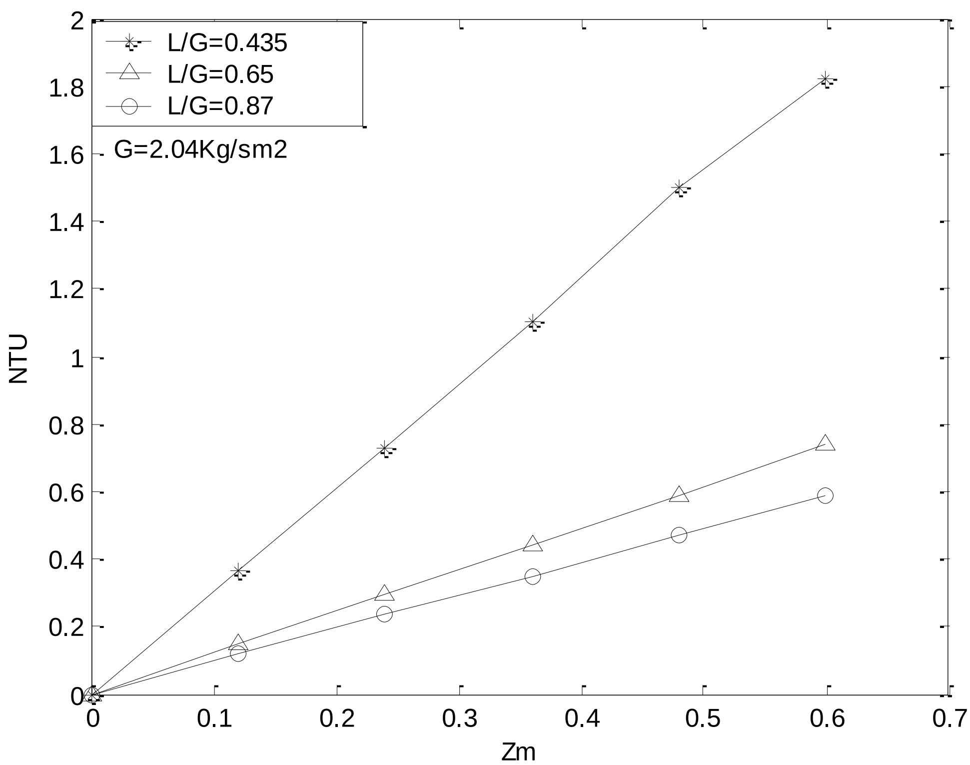

Figure (7). NTU with packing height for air flow rate $(G = 2.04Kg/m^2s)$

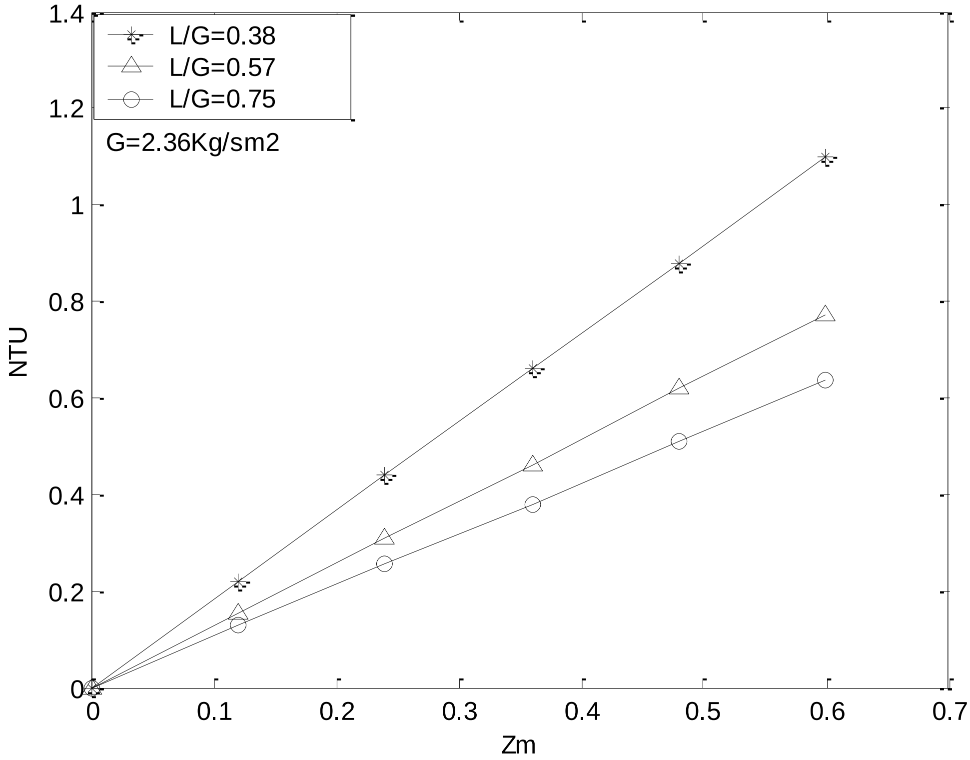

Figure (8). NTU with packing height for air flow rate $(G = 2.36Kg/m^2s)$

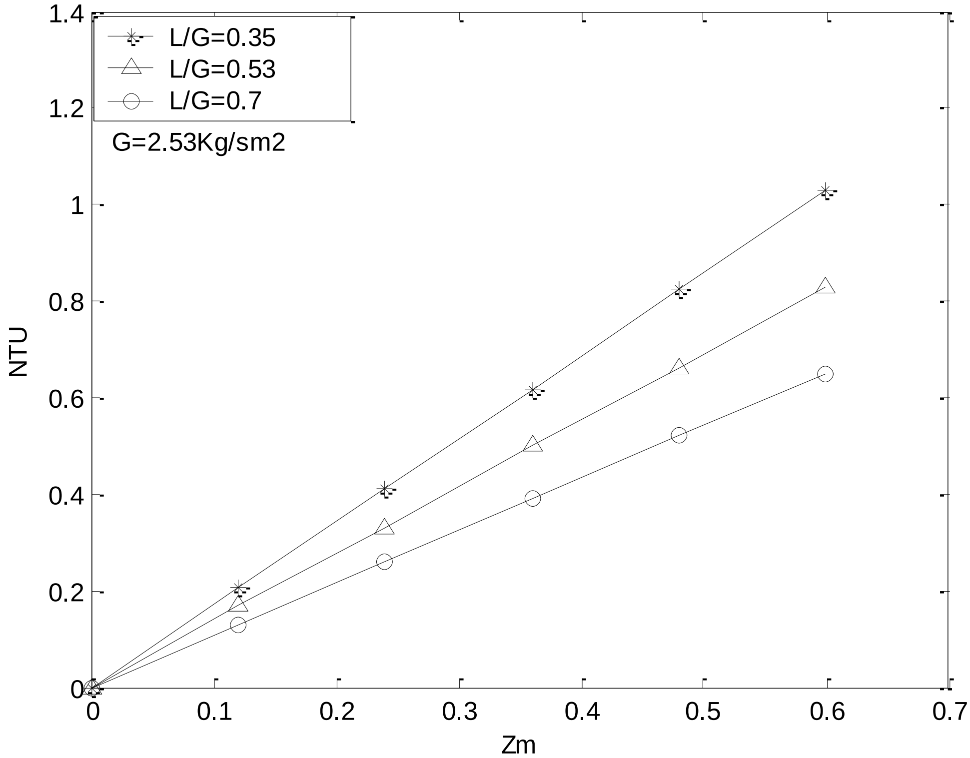

Figure (9). NTU with packing height for air flow rate $\left(G = \frac{2.53Kg}{m^2s}\right)$

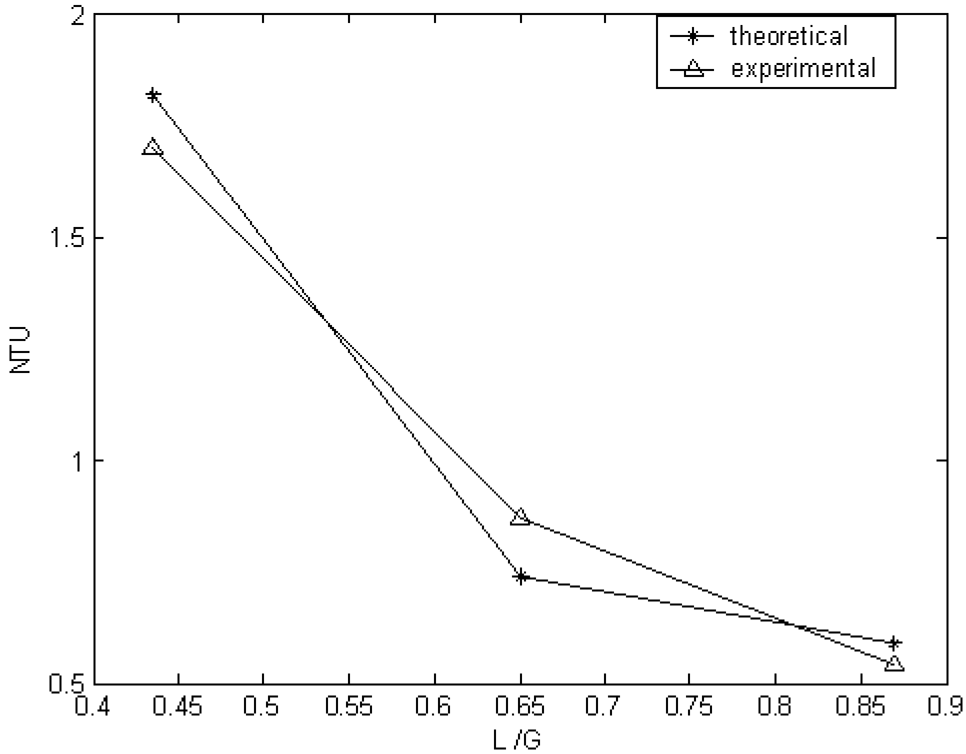

Figure (10). NTU with L/G for (water entering tower)= 34.4C°

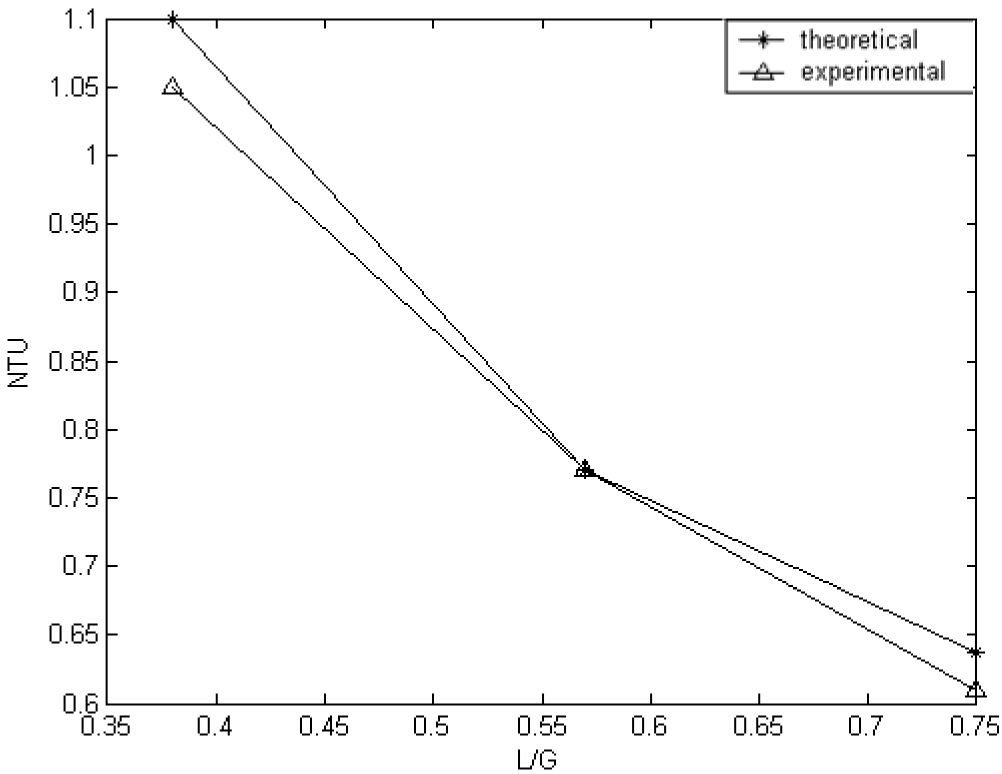

Figure (11). NTU with L/G for (water entering tower)= 30C°

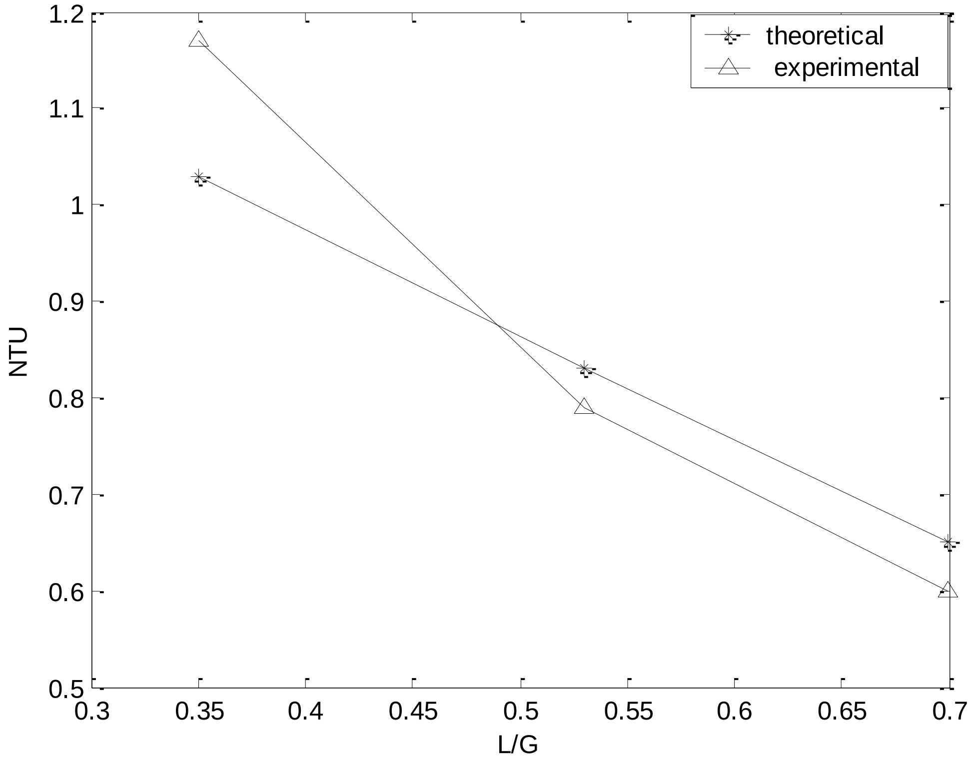

Figure (12). NTU with L/G for (water entering tower)= 27.9C°