OPTIMIZATION OF COUNTER FLOW WET COOLING TOWERS CHARACTERISTICS PERFORMANCE

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Abstract:

A theoretical and experimental investigation was carried out to optimize counter flow wet cooling tower performance characteristics. The Taguchi optimization method was adopted at different thermal loads, different packing density, and wide range of water to air mass flow rate ratios for two different packing materials. The governing factors for the optimization process are the Number of Transfer Units, packing density, packing material and the tower effectiveness. Taguchi method is clearly established with the advantage of specifying the effect of the governing factors on the performance; the interaction between different factors, as well as it specify the optimum combination of all factors and their levels.

An experimental investigation for an existing counter flow wet cooling tower was carried out. Series of experiments were conducted to study the effect of packing density, packing materials, thermal loads, and water to air mass flow ratios and also, weather conditions. A full analysis of the experimental results is presented.

Based on both the experimental analysis and the Taguchi analysis, the two important parameters in the cooling tower performance characteristics are the thermal load, the mass flow ratio and their interaction (i.e. the temperature range and water to air mass flow ratio). However, the packing density and the packing material have less contribution effect on the characteristics performance of the cooling tower.

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Nomenclature

A	area, m^2
$a_0,..a_{10}$	coefficients in Eq. (3)
A_p	wet bulb temperature approach
C_w	specific heat of water, kJ/kg K
E	optimization error analysis
$F_1, \ldots, F_3$	interaction contribution factors
f	saturated air enthalpy function, kJ/kg
f'	slope of saturated enthalpy vs. temperature, kJ/ K
G	mass velocity of gas (air), kg/s. m^2
H_{fw}	enthalpy of liquid water at t_w, kJ/kg
H_a	enthalpy of moist air kJ/kg
H_{gw}	enthalpy of water vapour at t_w, kJ/kg
h_m	mass transfer coefficient, kg/s. m^2
H_{si}	enthalpy of saturated air at water/air interface temperature, kJ/kg
H_{sw}	enthalpy of saturated moist air at t_w, kJ/kg
L	mass velocity of liquid (water), kg/s. m^2
m_a	air mass flow rate, kg/s
M_r	mass flow ratio (water/air); (L/G)
M_w	water mass flow rate, kg/s
m_w^+	water side capacity rate, kg/s
NTU	number of transfer units (NTU)
P_d	packing density = tower cross sectional area / tower volume, m^{-1}
P_m	packing material
Q	thermal load, kW
q	heat transfer rate, kW
t_w	water temperature, °C
t_{wb}	air wet bulb temperature, °C
V	cooling tower volume, m^3
W	exponent in Eq. (8)
X	constant in Eq. (7)
Y	exponent in Eq. (7)

Z constant in Eq. (8)

Greek Symbols

ε tower effectiveness

Additional Subscripts

1	inlet	2	outlet
a	air	act	actual
max	maximum	min	minimum
s	saturation	w	water

1-INTRODUCTION

In many domestic and industrial processes, water is commonly used as a heat transfer medium, which absorbs the heat load from thermal processes. This heat can be dissipated by the use of air-cooled condenser or by rejecting heated water to its natural source and supplying new charge. In the case of using air-cooled condenser the initial cost is high and consequently, higher fan power consumption is required. Also, in the case of rejecting water to the natural source and supplying new charge, this has a bad effect on the ecology of water source due to the rise of the discharge temperature and high cost for supply and withdrawal of water ASHRAE, 1996.

The problem of dissipating heat from water can be overcome by using cooling towers. In cooling towers the water consumption rate is very small at a lower operating cost. Also, no environmental impact of cooling towers exists. Because of the mentioned above, cooling towers are the largest mass and heat transfer devices in common use, El-Dessouky et al, 1997. Cooling towers are used in many industrial power generation units, space conditioning process, chemical and petrochemical and petroleum industries.

Katipamula, 1997 utilized mini cooling tower to a vapor compression refrigeration system to remove heat from the vapor in the condenser before its expansion. An increase of refrigerant sub-cooling is noticed and consequently the cycle efficiency increased. Al-Juwayhel et al 1997, used the cooled water discharged from cooling tower to sensibly pre-cool ambient air in an indirect water-air heat exchanger and then the air is cooled by passing through a direct contact evaporative cooler. A method of aerodynamics and thermodynamics characteristics analysis of cooling tower performance was presented by Sirok et al, 1998, to attain the optimum operation after upgrading the cooling tower. Also, Burger, 1996, recommended an improvement of cooling tower by upgrading with minimum structural and mechanical equipment changes.

Majumdar et al, 1983, reevaluated the thermal performance of the cooling towers through the introduction of a mathematical model for mechanical and natural draft cooling towers. The model is based on two-dimensional analysis and computed the air velocity, temperature, pressure, moisture content and the water temperature. Sadasivam and Balakrishran, 1995, introduced a new definition for driving potential available for the net heat transfer rate in counter current cooling towers based on the apparent enthalpy.

Higazy and Saykr, 1999, employed a new model for cooling tower calculation methods to compute the tower effectiveness and thermal loads based taking into consideration the water evapouration and the thermal resistance of water/air interfaces film.

The optimization methods, as shown by Ranjit, 1990, added mainly: the classical method (full factorial process); Taguchi method (fractional factorial process); Shinin methods and Generic Algorithm (optimization by means of mutation role). The Taguchi method is clearly established with the advantage of specifying the effect of each governing factor on the performance, as well as presenting the optimum combination of factors and their levels as discussed by Peace, 1994.

2- EXPERIMENTAL APPARATUS

The present cooling tower test rig is an open system through which two streams of fluid flow (water and air) where both mass and heat transfer from one stream to the anther take place. It has the same configuration as a full size forced draught cooling tower. The tower column is made of clear PVC and has the dimensions of 150x150x600 mm high. The tower contains eight decks and having plates inclined to the horizontal by an angle of 60°. The material used for the tower fills was either laminated plastic or galvanized steel and they have a rectangular cross section. Experimental runs were carried out for different number of wet laminated, plastic, or galvanized steel, plates for each deck having values of 5, 10 and 15 corresponding to total surface area to volume ratio (tower packing density P_d) equal to 55, 110 and 165 m^2/m^3, respectively.

The components of the tower shown in Fig. (1) include air distribution chamber. A tank equipped with electrical heaters to simulate heating load of 0.5, 1.0 and 1.5 kW. There are also a make up tank with gauge mark, floating operated central needle valve, and centrifugal fan with intake damper to give a maximum air flow of 0.06 kg/s, bronze and stainless steel gladness circulating pump driven by 100 W motor and water collecting basin. Warm water is pumped from the load tank through the control valve and the water flow meter to the column cap. The water' is uniformly distributed over the top packing deck. Air from the atmosphere enters the tower by the fan at a rate, which is controlled by the intake damper setting. Flow through the column may be observed through the transparent PVC casing. Six-point digital temperature indicator with K-type thermocouple sensors is used to measure terminal water temperatures, wet and dry bulb air temperature.

The accuracy of the digital temperature indicator is 0.1 °C. Pressure tappings are also provided with inclined manometer of range (0-40 mm of H_2O) that is used to measure air flow rate and the packing resistance. Also the water mass flow rate, which enters the tower, is controlled by a valve and measured through a flow meter of range (0-50 gm/s). The experimental runs are carried out for water mass flow rate of 0.018, 0.030, 0.040 and 0.0475 kg/s and a wide range of water to air mass ratios (L/G) varying from 0.3 up to 1.35. These runs are carried out for different thermal loads of 0.1, 0.6, 1.1 and 1.6 kW. The case of 0.1 kW corresponding to water pump load only.

3- MATHEMATICAL ANALYSIS

Thermal Analysis

In the present work, a modified analysis based on the mass and energy conservation given by Higazy and Sakr, 1999, is applied to predict both water and air properties at any level of the tower. Also from the analysis of the cooling tower by Jabber and Webb,1989, gives the NTU, the numbers of transfer units, as:

$$NTU= \int \frac{d(H_{si} - H_a)}{H_{si} - H_a} = \frac{h_m A}{m_{min}} \tag{1}$$

where: m_{min} is the minimum value of either m_w^+ or m_a and m_w^+ is given by:

$$m_w^+ = \frac{M_w C_w}{f} \quad , f = \frac{dH_{si}}{dT_w} \tag{2}$$

Where $H_s = f\,(t_w)$ is given by a polynomial of $10^{\underline{th}}$ order for a temperature range of (10-60 °C), Higazy and Sakr, 1999. The polynomial constants are as follows: -

$$H_s = a_0 + \sum_{n=1}^{10} a_n\, t^n \tag{3}$$

$a_0 = 8.36537$, $a_1 = 2.0482$, $a_2 = -0.016547$, $a_3 = 0.202296$, $a_4 = 2.0848 \times 10^{-5}$, $a_5 = -5.7473 \times 10^{-6}$ $a_6 = 2.9383 \times 10^{-7}$, $a_7 = -7.585238 \times 10^{-9}$, $a_8 = 1.1162486 \times 10^{-10}$, $a_9 = -8.8796 \times 10^{-13}$, and $a_{10} = 3.00468 \times 10^{-15}$, where (t) is substituted in °C.

It is necessary to define cooling tower effectiveness (ε). So,it will be defined identically to that used for heat exchanger design;

$$\varepsilon = q_{act}/q_{max} \tag{4}$$

where; $q_{max} = m_{min} (H_{si} - H_{a1})$ (5)

Definition of the parameters used in the present cooling water analysis is illustrated in Fig. (2).

Taguchi Analysis

The fundamental goal of the optimization process is to determine the objective of the experiments. Also, it is important to realize that defining the objective is not to solve the whole world's problems in one experiment. Focusing on a specific attainable aim is important and moving step by step at a time. The objectives of the present experiments is: to determine the effect of tower packing density variation and the effect of tower packing materials on the tower characteristic performance parameters such as: Number of Transfer Units, tower effectiveness, wet bulb temperature approach and thermal load or water temperature range.

Since the experimental objectives goal have been established and plans are put to reach this goal, a single experiment is considered to be sufficient for the governing factors that affect the performance parameters. Thus, the single experiment strategy is considered where concerning the number of levels for the control factors, more levels will give a greater choice of settings for improving the process. Peace, 1994 indicated that the use of three levels as opposed to two setting would allow detecting nonlinear relationships between factors and the quality characteristic. Low, middle and high values of input parameters are considered. They in fact may have a significant effect on the output. Factors and their level setting within a single experiment strategy is based on the present objectives are given in the Table I.

A suitable orthogonal array of experiments in addition to the interaction between the factors and overall experimental matrix structure is obtained with the proper degree of freedom. Matrix of array is given in Peace 1994, corresponding to four factors. These four factors are packing material, packing density, thermal load, water to air mass ratio. The packing material has two levels and the reset of factors have three levels as shown in Table I.

Table I: Factors and their level settings

Materials of packing	level 1 plastic			level 2 galvanized steel		
	level 1	level 2	level 3	level 1	level 2	Level 3
Packing density m^{-1}, P_d	55	110	165	55	110	165
Thermal load kW, Q	0.6	1.1	1.6	0.6	1.1	1.6
Mass ratio: water/air (L/G) M_r	0.5	0.7	1.1	0.5	0.7	1.1

Thus, the analysis is based on combining the data as sociated with each level for each factor or interaction. The difference in the average results for each level is the measure of the effect of that factor. Those factors with the greatest effect or difference are the ones that can be used to improve the design process or determine the significance of each factor. So, level average analysis gets its name from determining the average response for factor and interaction levels and analyzing the importance of factors and interaction based on either the concept of smaller is the better or the larger is the better and attributed characteristics.

4- RESULTS AND DISCUSSIONS

4.1 Experimental Results

Cooling Tower Performance Characteristics

Figures 3 and 4 show the relationship between water cooling range temperature verses wet bulb temperature approach for different water/air mass flow ratios (L/G), different packing densities and two different materials. Plastic packing materials are giving less wet bulb approach than the galvanized steel. This is may be due to two reasons: plastic have less thermal conductivity than the galvanized steel; and plastic plates surfaces are more wettable than the galvanized steel plates. The packing density of 110 m^{-1} for plastic gives the smallest approach of all curves. It is also, noticeable that as the ratio L/G increases the approach increases for the same thermal load. This is due to the fact of increasing L/G ratio mean reducing the thermal resistance of the air/water interface.

Figures 5 and 6 show the Number of Transfer Unit (NTU) effect on the mass flow ratios L/G. The relationship between the NTU and the water to air mass flow ratios are given by the cooling tower characteristic equation:

$$NTU = X\left(\frac{L}{G}\right)^{Y} \tag{7}$$

Where X is constant depends on the packing density and Y depends on the packing materials. For plastic material Y may be equal to 0.57 and for density equal to 110 m^{-1} and X is equal to 1.2. However, for galvanized steel, Y is equal to 0.68 and X is equal to 0.64 and for also, density equal to 110 m^{-1}.

Figures 7 and 8 show the behavior of the tower effectiveness against the mass flow rate ratio (L/G). A relationship similar to the cooling tower characteristic equation is found between the tower effectiveness and the mass flow ratio L/G. This relation is proposed in the form:

$$\varepsilon = Z\left(\frac{L}{G}\right)^{W} \tag{8}$$

Where Z is constant depends on the packing density and W is independent of the packing materials. But, for plastic material Z may be equal to an average value of 0.27 and for galvanized steel equal to an average value of 0.25 and W is equal to -0.42.

Effect of packing density on the wet bulb temperature approach, on the Number of Transfer Units (NTU, and on the tower effectiveness is shown in Fig. 9-a, b & c, respectively.
Also, effect of varying inlet air conditions is given in Fig. 10, for two values of inlet wet bulb temperature and for the same mass flow ratio L/G.

4.2 Results of Taguchi Methods

Level average analysis gets its name from determining response for factor and interaction levels and analyzing the importance of factor and interactions based on these computed values. The goal behind level average is to identify the strong effects and to determine the combination of factors and interactions investigated that can produce the most desired results. The calculation matrix based on the average response for corresponding levels of factors in the orthogonal array is given in Table II below.

Table II Orthogonal Array

RUN	P_m	Q	M_r	F_1	P_d	F_2	F_3	E	ε	NTU	A_p
1	1	1	1	1	1	1	1	1	0.63	1.16	5.3
2	1	1	2	2	2	2	2	2	.58	1.37	4.2
3	1	1	3	3	3	3	3	3	0.53	0.82	3.0
4	1	2	1	1	2	2	3	3	0.83	2.04	5.6
5	1	2	2	2	3	3	1	1	0.65	0.99	6.4
6	1	2	3	3	1	1	2	2	0.51	1.11	6.4
7	1	3	1	2	1	3	2	3	0.63	1.03	12
8	1	3	2	3	2	1	3	1	0.58	1.15	8.4
9	1	3	3	1	3	2	1	2	0.99	2.01	3.9
10	2	1	1	3	3	2	2	1	0.44	0.61	5.9
11	2	1	2	1	1	3	3	2	0.71	1.25	4.8
12	2	1	3	2	2	1	1	3	0.60	0.95	3.7
13	2	2	1	2	3	1	3	2	0.62	0.87	8.2
14	2	2	2	3	1	2	1	3	0.54	0.89	6.8
15	2	2	3	1	2	3	2	1	0.82	1.30	5.1
16	2	3	1	3	2	3	1	2	0.52	0.56	11.5
17	2	3	2	1	3	1	2	3	0.92	1.46	5.8
18	2	3	3	2	1	2	3	1	0.73	1.33	6.5

where $F_1=m_r/Q$, $F_2=P_d/Q$ and $F_3=P_d/M_r$.

The converging lines in the interaction graph, not shown for brevity, indicate that there is a strong interaction between thermal load and the mass flow ratio L/G, also, the percentage contribution of factors affecting cooling tower performance are given in Fig. 11 a, b and c. Therefore, the recommended factor levels are: packing density in level 2, mass ratio in level 3, and thermal load in level 3, based on the minimum cooling tower volume or in other words minimum NTU Number of Transfer Units. But for maximum tower effectiveness, the recommended factor levels are: packing density in level 3, mass ratio in level 3, and thermal load in level 3, while for minimum wet bulb approach they are: density is level 2, mass ratio is level 2, and thermal load in level 3.

5- CONCLUSIONS

From the presented analysis and results, the following conclusions can be drawn:

1-This paper presents a series of experimental data on counter flow wet cooling tower for different working conditions based on different packing materials, with different packing density, operating under different thermal loads and mass flow ratios (L/G)..

2- A relationship relating the mass flow ratio with the Number of Transfer Units (NUT) is also, suggested. This relationship takes the form: $NTU = X\left(\frac{L}{G}\right)^{Y}$.

3- Another relationship relating the tower effectiveness with the mass flow ratio is also proposed in the from: $\varepsilon = Z\left(\frac{L}{G}\right)^{W}$.

4-Graph for cooling tower performance based on the cooling range and the wet bulb temperature approach is given for mass flow ratio varying range from 0.3 up 1.35.

5-Based on both the experimental analysis and Taguchi analysis; the two important factors in the cooling tower design are the mass flow ratio (L/G) and the thermal load, i.e. the water temperature range, whereas, the packing density and the packing material are having minor effect on the tower design.

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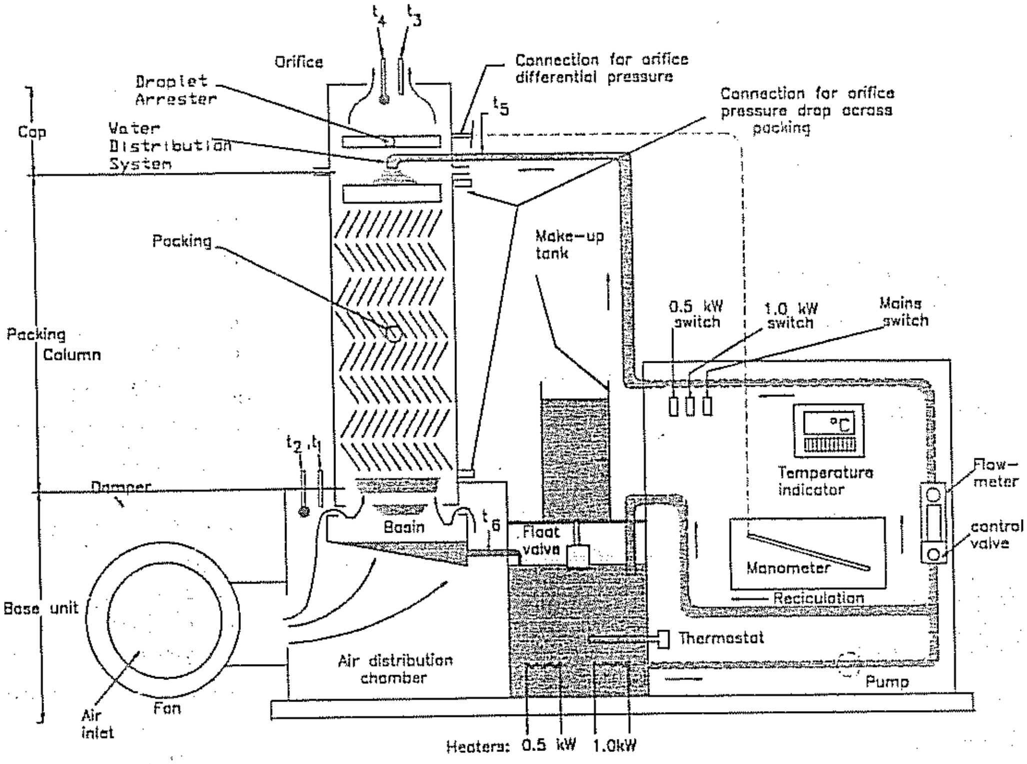


Fig 1 Cooling tower schematic diagram with full details

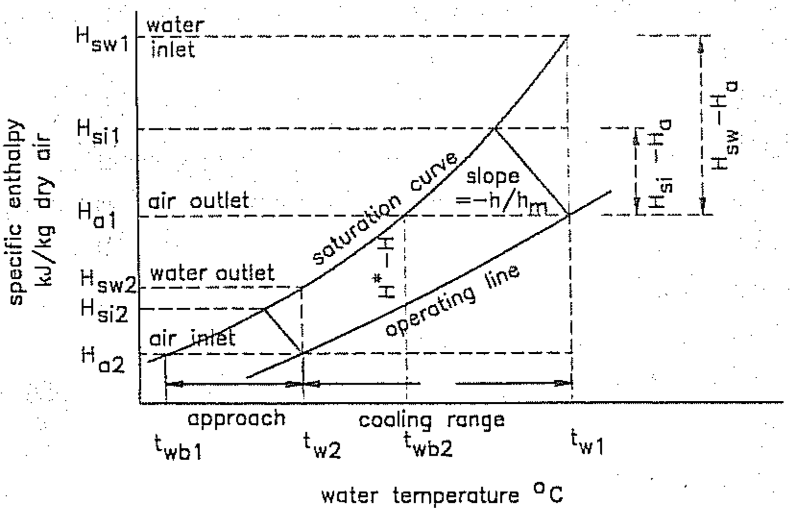


Fig. 2 General performance diagram for cooling tower with definitions of the parameter used .

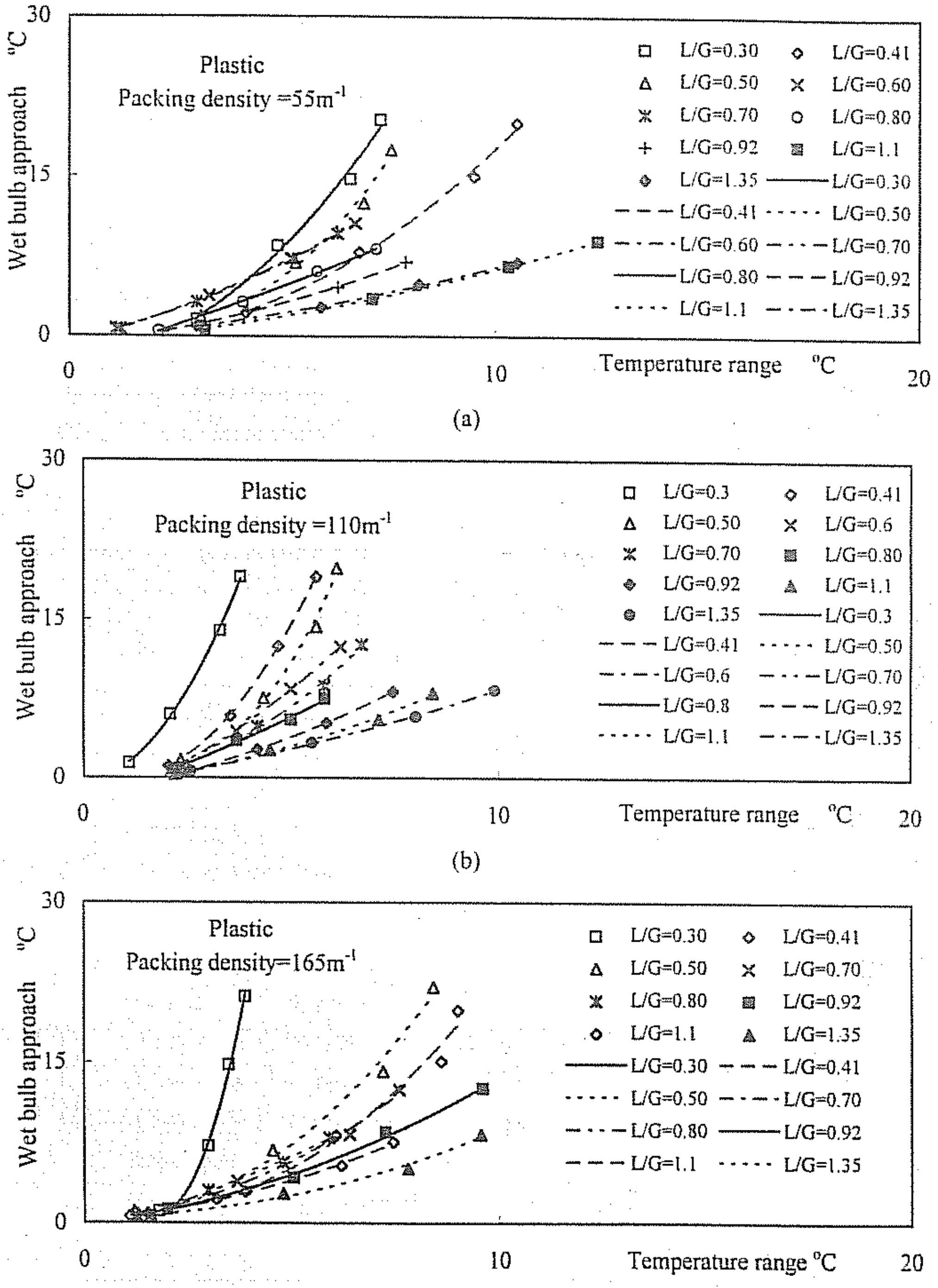
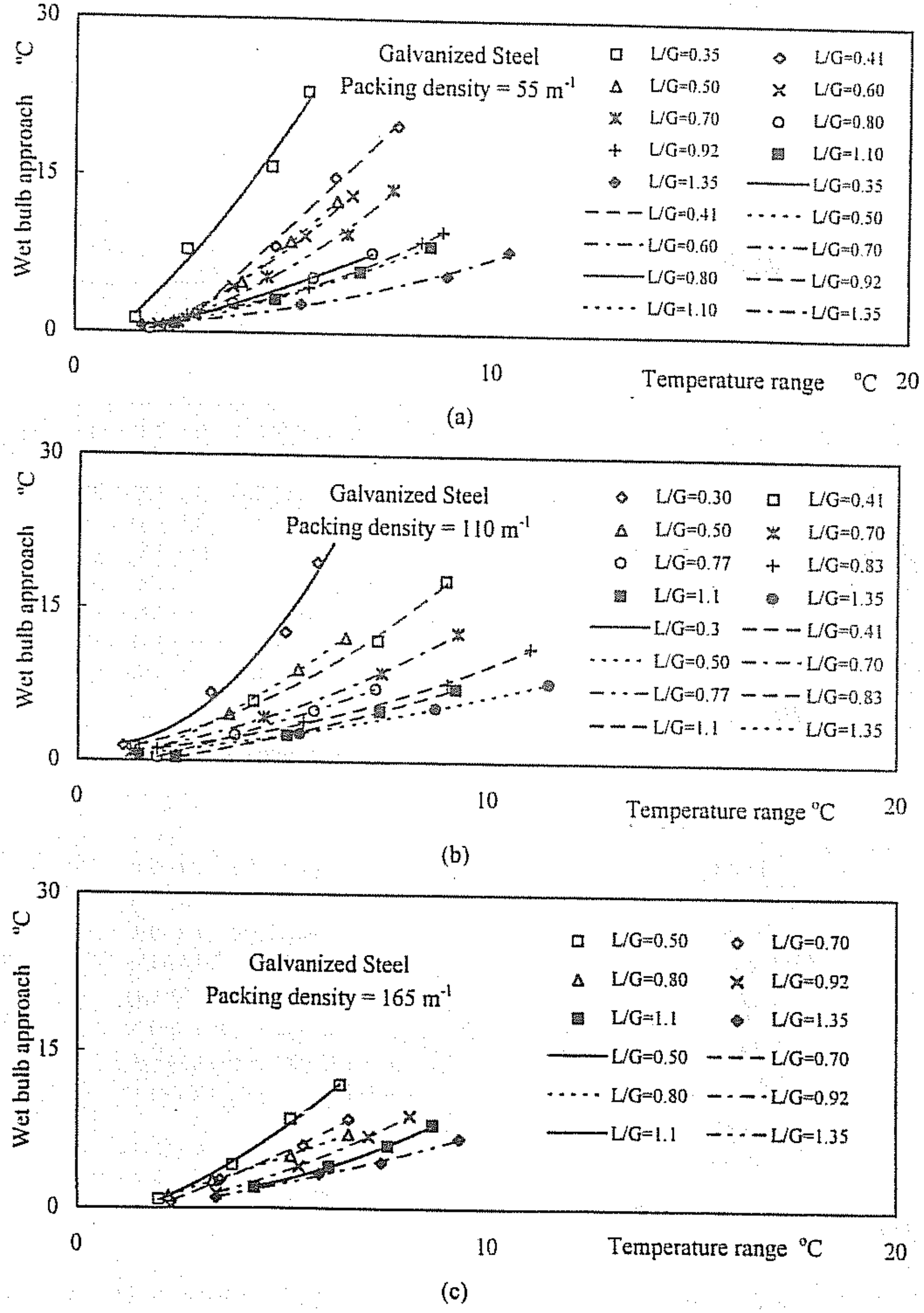


Fig. 3 Relationship between tower wet bulb approach and thermal load (temperature range), for plastic with different packing densities

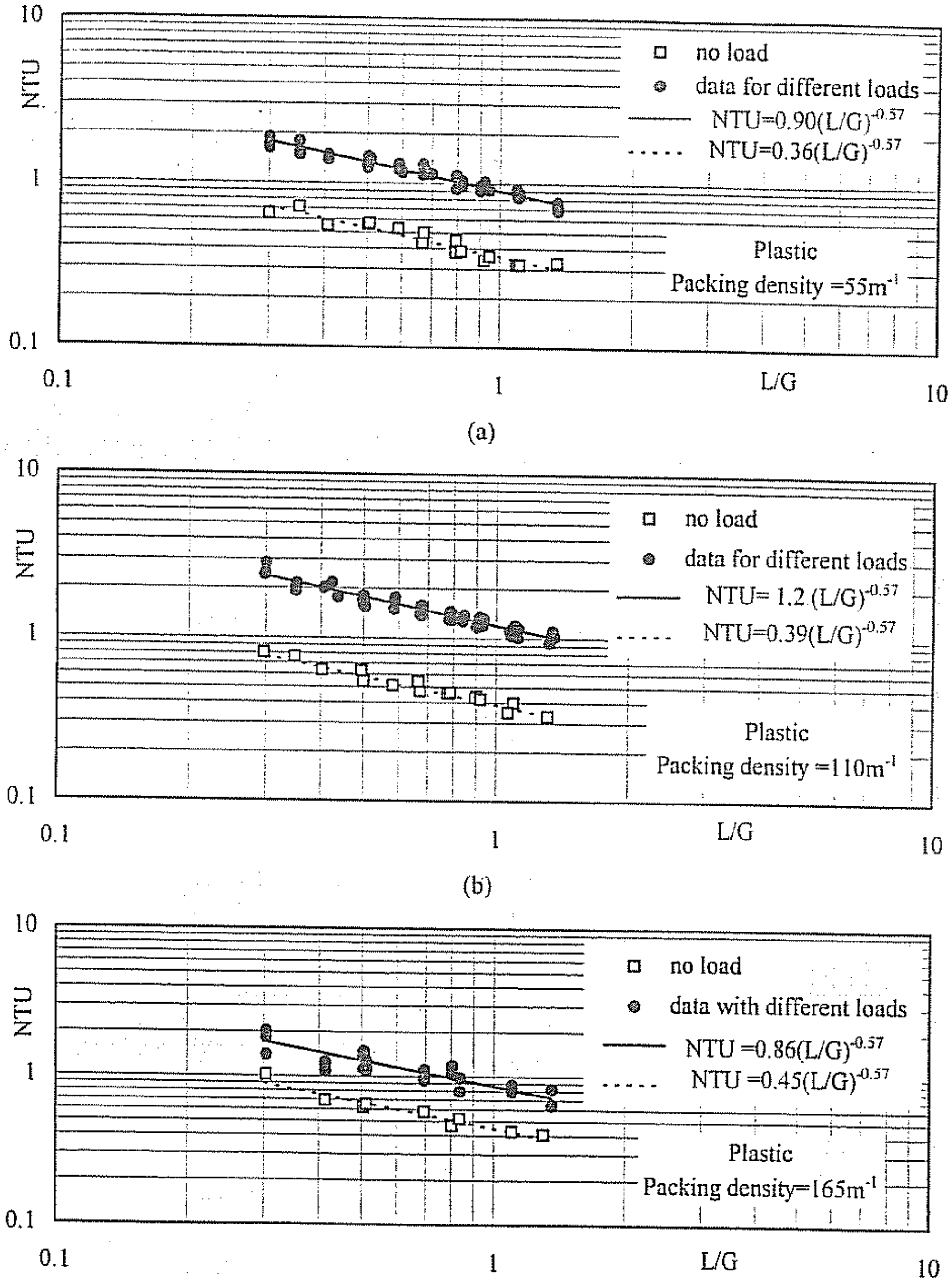


(a)

(b)

(c)

Fig. 4 Relationship between tower wet bulb approach and thermal load (temperature range), for plastic with different packing densities



(a)

(b)

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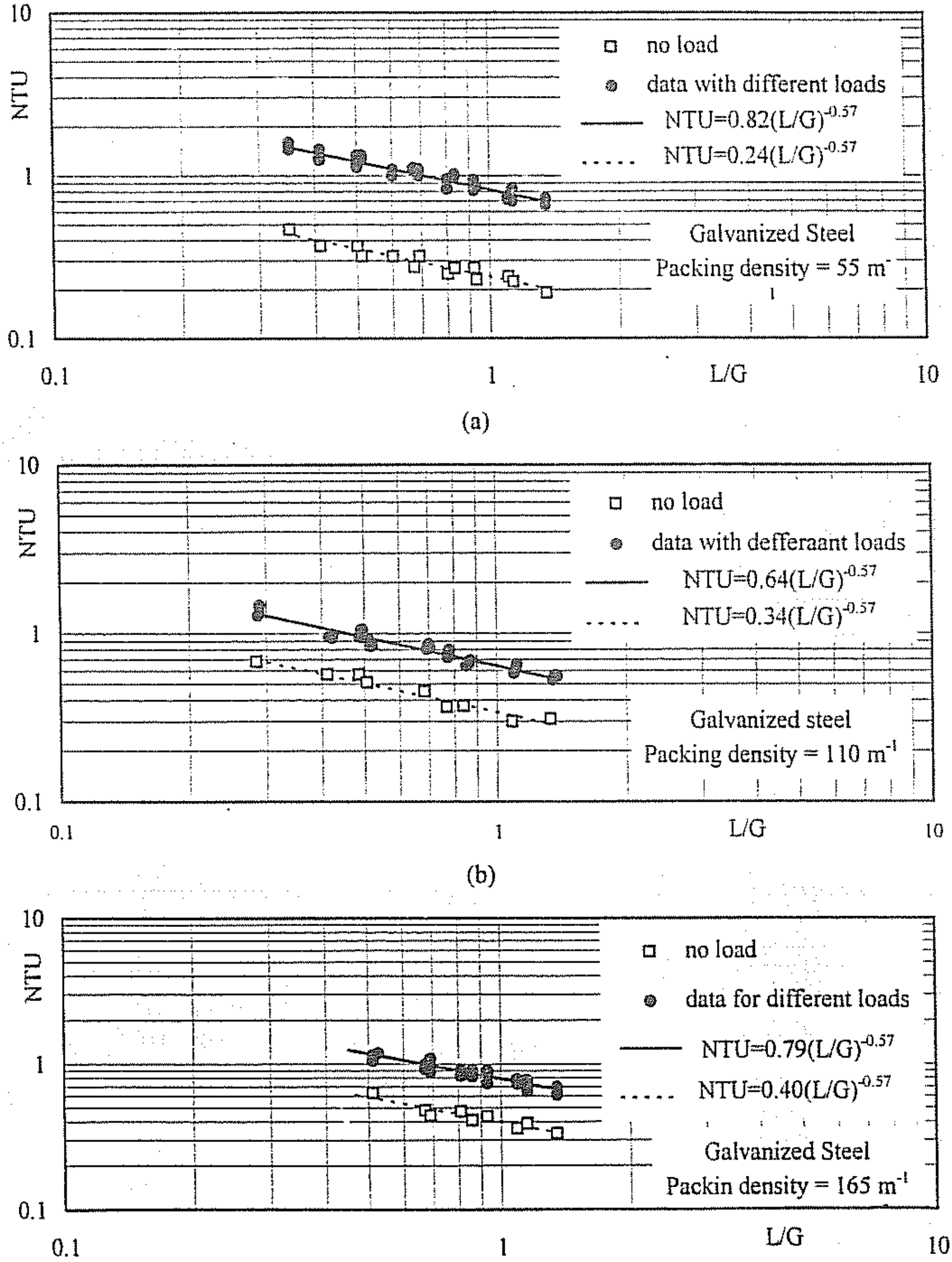
Fig. 5 Relationship between NTU (Number of Transfer Units) and mass flow ratio (L/G), for plastic with different packing densities

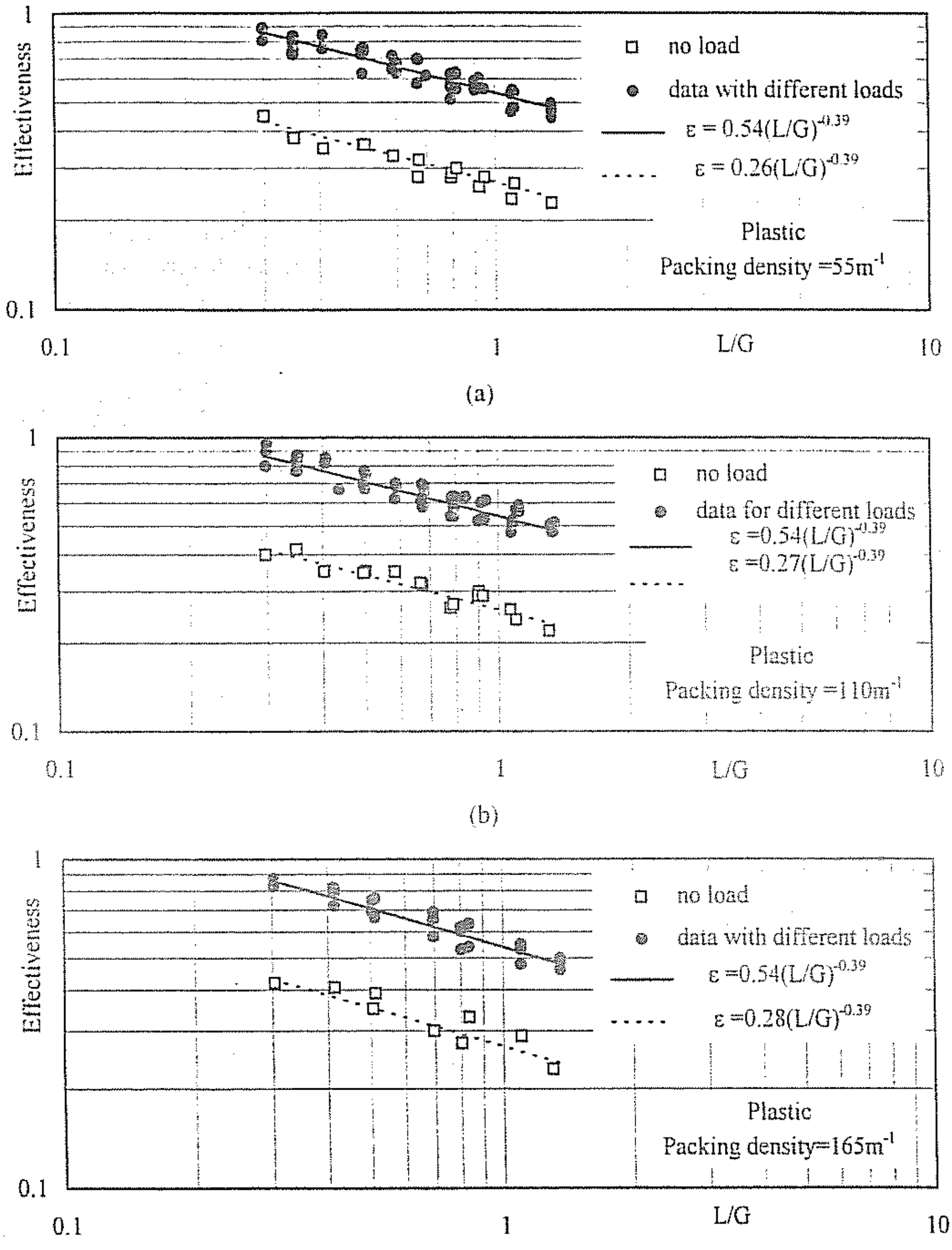


(a)

(b)

(c)

Fig. 6 Relationship between NTU (Number of Transfer Units) and mass flow ratio (L/G), for galvanized steel with different packing densities



(a)

(b)

(c)

Fig. 7 Relationship between cooling tower effectivness and mass flow ratio (L/G), for plastic with different packing densities

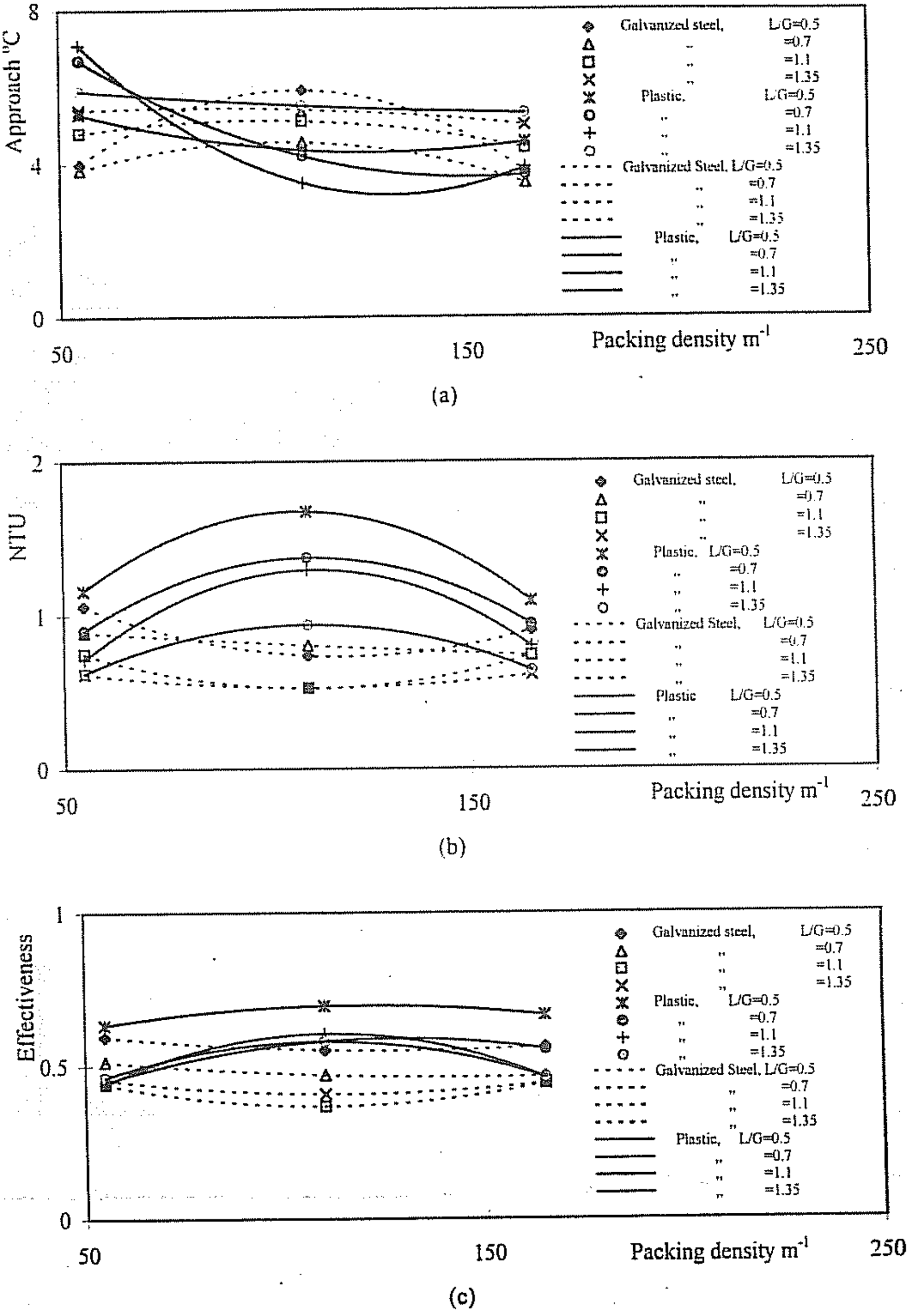
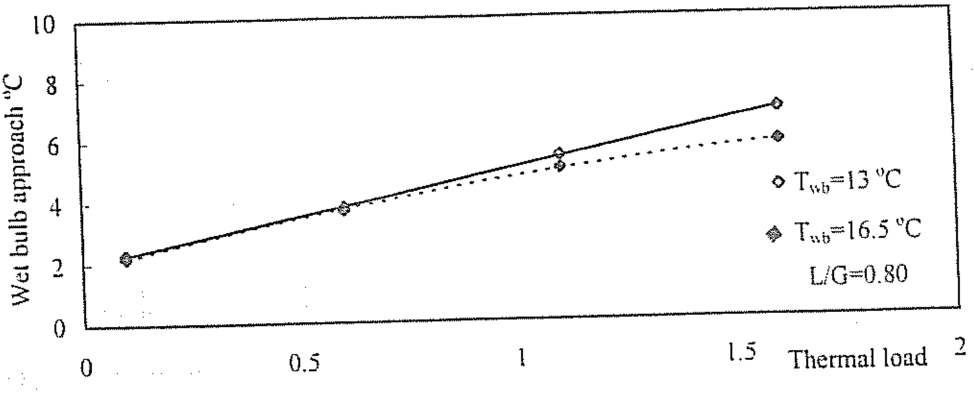
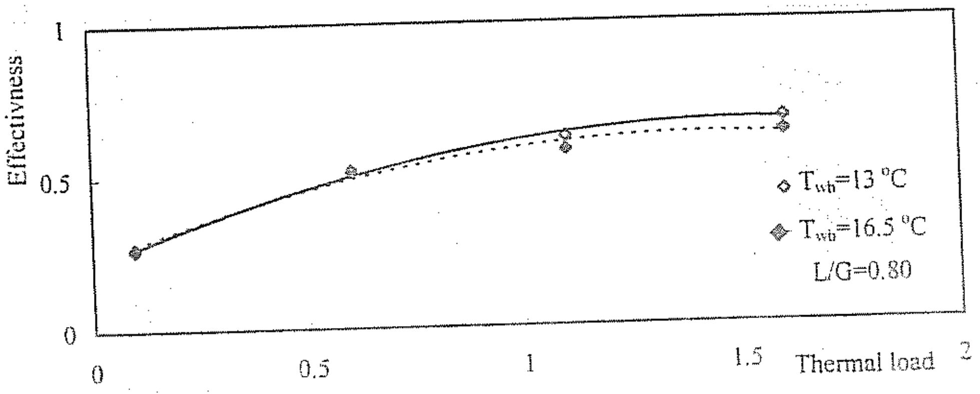


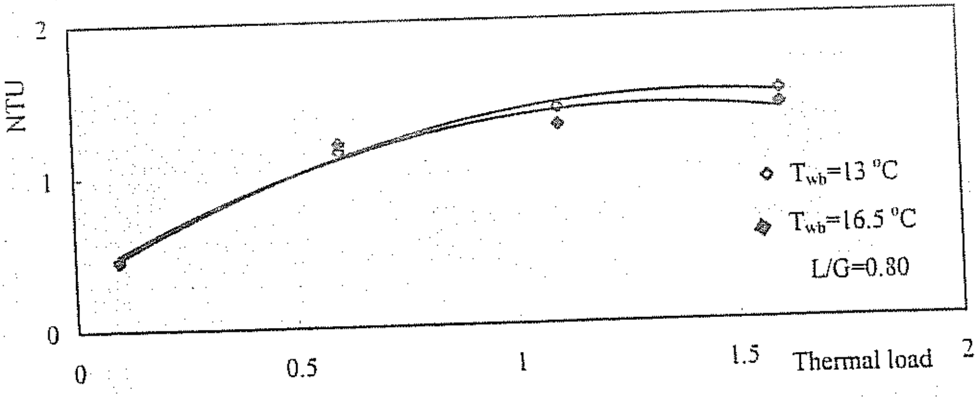
Fig. 9 Performance of cooling tower characteristics for different packing densities and mass ratios (L/G), for the same thermal load.



(a) Wet bulb temperature approach

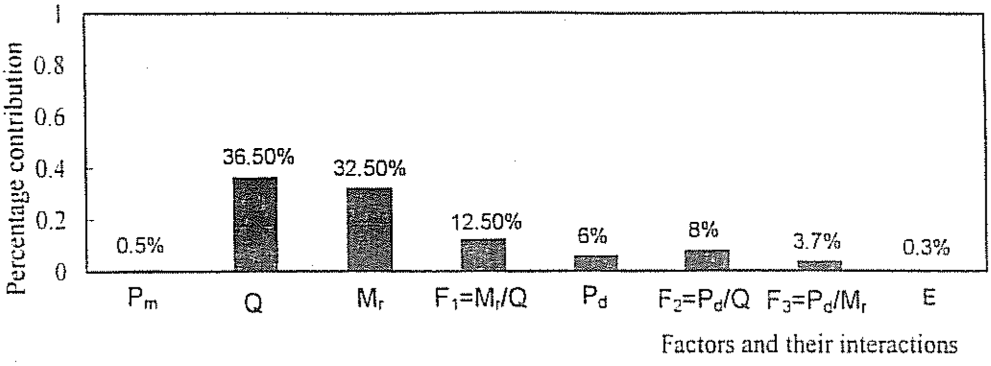


(b) Cooling tower effectiveness

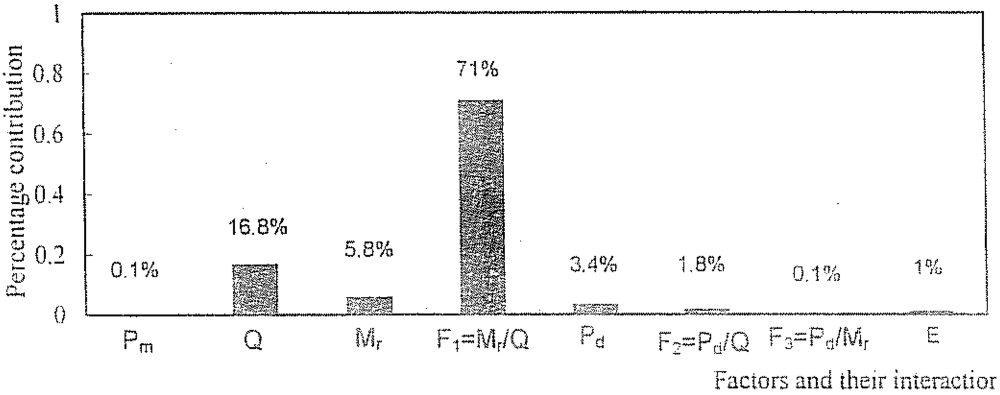


(c) Number of Transfer Units

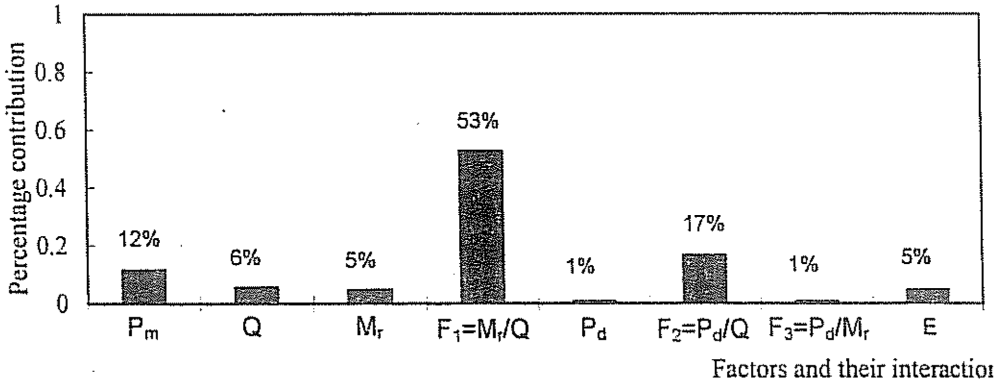
Fig 10 Effevt of weather (air ambient conditions) on cooling tower characteristics performance



(a) Wet bulb temperature approach percentage contributions



(b) Cooling tower effectiveness percentage contributions



(c) Number of Transfer Units percentage contributions

Fig 11 Taguchi analysis results based on smaller the better or larger the better for cooling tower characteristics factors