MODELING OF A SPRAY ASSISTED NATURAL DRAFT COOLING TOWER

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ABSTRACT

Cooling towers are one of the largest heat and mass transfer devices that are in common use. A novel type of cooling tower has been proposed in which air flow rate into the tower is drawn by ejector action of sprays instead of fans as is done in conventional mechanical forced or induced draft cooling towers. This novel design offers the potential of saving the energy cost for driving the fan. The paper presents mathematical models for momentum transfer which is the driving force causing the entrainment of air. Also the heat transfer model for co-current flow of liquid and gas in the tower has been presented. The liquid to gas ratio tend to decrease as liquid rate increases. The ratio attained in the experimental laboratory tower was 3.3, correspondingly the Momentum transfer efficiency for the tower was 60% and was the highest. Experiments for cooling water initially at 45^{o}C to final water temperature 27^{o}C showed that the cooling tower efficiency was 54% and number of transfer unit 0.8.

Key words: Cooling tower, Spray assisted, momentum transfer

INTRODUCTION

In some chemical plants such as edible oil processing plants, refineries, and power generation plants, process water has to be cooled down, and one way of effecting this is by using cooling towers. The existing designs of cooling towers are Mechanical draft, Natural draft and Fan assisted natural draft cooling tower. A new concept of designing and operating cooling tower is proposed in this paper and is referred to as Spray Assisted Natural Draft Cooling Tower. An assembly of nozzles enclosed in a duct when used to spray water will cause the surrounding air to accelerate in the direction of sprays. This phenomenon has been employed to induce an upward flow of air in a cooling tower – hence the name Spray Assisted Natural Draft Cooling Tower. This novel type of a cooling tower has the advantage of avoiding the usage of fan and by so doing there is potential of saving the costs associated with driving the fan.

This paper therefore presents the findings of a study that has been conducted with an objective of establishing the performance of the Spray Assisted Natural Draft Cooling Tower in terms of: (i) its effectiveness in inducing flow of air into the tower; and (ii) cooling effectiveness. The study was done using a laboratory-size cooling tower. Upon successful development and scaling up, Spray Assisted Natural Cooling Tower has a potential of replacing the existing designs currently in use in chemical plants.

LITERATURE SURVEY

Categorization of Cooling Towers

Cooling towers are very important part of chemical plants. They represent a relatively inexpensive and dependable means of removing low grade heat from cooling water (Cheresources, 2004). They fall into three types (Wikipedia, 2007):

- Natural draft cooling tower, which utilizes buoyancy via a tall chimney. Warm, moist air naturally rises due to the density differential to the dry, cooler outside air. Warm moist air is less dense than drier air at the same temperature and pressure. This moist air buoyancy produces a current of air through the tower. Natural draft towers are very large in size and are used by utility power stations such as coal fired plants.
- Mechanical draft cooling towers are much more widely used. These towers utilize power driven fan motors to force or draw air through the tower. The water falls downward over packing surfaces which help increase the contact time between water and the air. This helps maximize heat transfer between the two.
- Fan assisted natural draft cooling tower which is a hybrid type that appears like a natural draft though airflow is assisted by a fan.
  With respect to categorization by air to water flow there are two types of cooling tower (McCabe et al., 1993; Wilipedia, 2007)
- Counterflow in which the air flow is directly opposite of the water flow. Air flow first enters an open area beneath the packing media and is then drawn up vertically. The water is sprayed

through pressurized nozzles and flows downward through the packing.

- Crossflow is a design in which the air flow is directed perpendicular to the water flow. Air flow enters one or more vertical faces of the cooling tower to meet the packing material. Water flows (perpendicular to the air) through the packing by gravity. The air continues through the packing and thus past the water flow into an open plenum area.

Mass and Heat Transfer

Counterflow

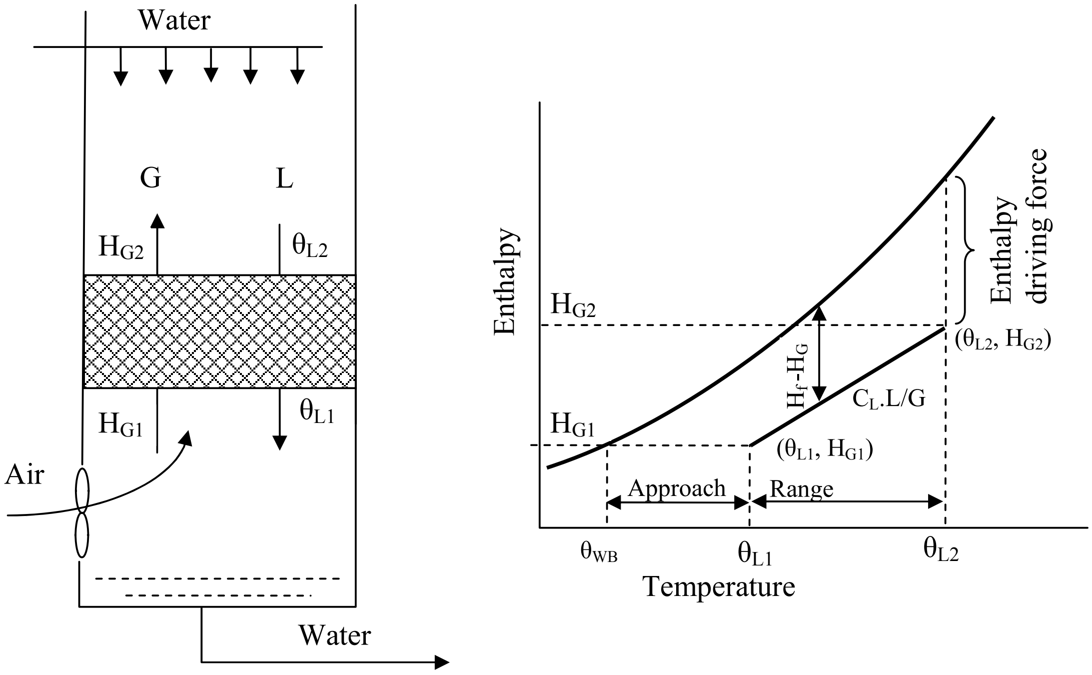
Consider a section of a Cooling Tower Figure 1(i) in which gas and liquid are flowing in opposite directions. Taking liquid and gas enthalpy balance:

$$L.C_L.(\theta_{L2}-\theta_{L1}) = G.(H_{G2}-H_{G1}) \qquad (1)$$

Equation 1 is the equation for the operating line which in Enthalpy-Temperature diagram passes through (θ_{L1}, H_{G1}) and (θ_{L2}, H_{G2}) and has slope $C_L.L/G$ as shown in Figure 1(ii). The ratio L/G is referred to as the Liquid-to-Gas ratio (Treybal 1980, Coulson and Richardson, 1983).

Further considerations of heat balance between bulk of fluids and the liquid-gas interface enables the estimation of the height of packing, Z:

$$Z = \frac{G}{h_D.\rho_G.a}\int \frac{dH_G}{H_f - H_G}. \qquad (2)$$



i) Conventional Mechanical (Forced) Draft Cooling Tower

ii) Enthalpy Temperature diagram

Figure 1. Cooling tower basics

The term $G/h_D.\rho_G.a$ is the Height of Transfer Units (HTU), the term under integral sign is a Number of Transfer Units (NTU) and H_f-H_G is the enthalpy driving force. Thus the NTU can be evaluated using graphical integration.(Brit. Stand. Inst.,,1962 and 1977, Ergun, 1952) as per the equation.

Cooling tower efficiency

Cooling towers use the principle of evaporative cooling in order to cool water. With reference to Figure 1(ii), the *Approach* is the difference in temperature between the cooled-water temperature and the entering-air wet bulb temperature, θ_{WB}. The

Range is the temperature difference between the water inlet and exit states (θ_{L2}-θ_{L1}). The maximum cooling tower efficiency depends on the wet bulb temperature of the air.

The cooling tower efficiency can be expressed as (The Engineering Toolbox, 2005):

$$\mu = \frac{(\theta_{L2} - \theta_{L1})*100\%}{(\theta_{L2} - \theta_{WB})} \qquad (3)$$

The temperature difference between inlet and outlet water ($\theta_{L2} - \theta_{L1}$) is normally in the range 10 - 15°C, and the cooling tower efficiency commonrange is between 70 -75%.

SPRAY ASSISTED NATURAL DRAFT COOLING TOWER

It is proposed to use an assembly of sprays – instead of a fan – so as to induce air flow in cooling towers. In this novel design of cooling tower, water will be sprayed upwards, consequently causing an upward flow of air. Water will then impact on the disentrainer packing above the spray nozzles and then flow downwards on the walls of the tower before being distributed over the main packing below the spray nozzles

Figure 2 shows a schematic diagram of the Spray Assisted Natural Draft Cooling Tower. The tower consisted of assembly of nozzles spraying warm water (to be cooled) upwards, which in turn induce an upward flow of air to flow inside the tower. On impinging on the disentrainer packing, the sprays loose their momentum and flows down the tower walls to the water distributor troughs below the assembly of nozzles. Water is then distributed over the main packing. Below the main packing there was a water collector trough to catch water dripping from the tower and discharge it into the water tank underneath. The tank was partitioned such that one part was supplied with heating elements for warming up the water.

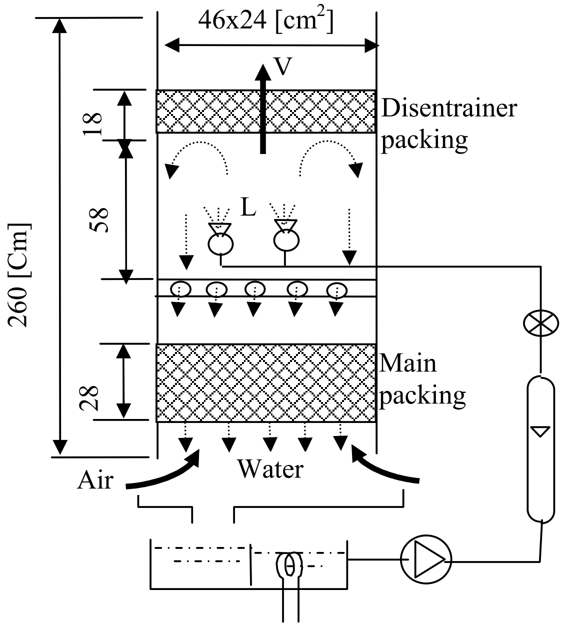


Fig 2. Spray assisted natural draft cooling tower

Specifications of the experimental Spray Assisted Natural Draft Cooling Tower

Duct dimensions	46 cm x 24 cm x 260 cm
Packing material	Munters cooling tower packing (plastic)
Main packing	46 cm x 24 cm x 280 cm
Disentrainer	3 layers, each of 46 cm x 24 cm x 6 cm
Nozzle assembly	8 flat nozzles, size 0.4, CD = …
Height of water spray	58 cm approximately
Water flow rate (Max)	1.45 kg/m^2.s
Water supply pressure (Max)	140 kN/m^{2}s

MODELING OF A SPRAY ASSISTED NATURAL DRAFT COOLING TOWER

Momentum transfer in Spray Assisted Natural Draft Cooling Tower

In the Spray Assisted Natural Draft Cooling Tower entrainment of air by water sprays is brought about by momentum transfer from sprays to the surrounding air. The overall momentum balance equation is:

$$\begin{pmatrix}\text{Rate of change}\\ \text{of momentum of}\\ \text{Sprays}\end{pmatrix} = \begin{pmatrix}\text{Rate of change}\\ \text{of momentum}\\ \text{of Air}\end{pmatrix} + \begin{pmatrix}\text{Rate of change}\\ \text{of momentum to}\\ \text{overcome Resistances}\end{pmatrix} \tag{4}$$

Rate of Change of Momentum of Water

An assumption is made that air initially at zero velocity is accelerated to a velocity, V, by sprays leaving the nozzles at velocity U_N. After interaction with the air the velocity of water would approach that of air thus the momentum of water would be estimated by

$$M_w = Q_W.\rho_L.(U_N - V) \tag{5}$$

The actual momentum transfer in a spray entrainment water heater will be reduced as some of the spray momentum will be consumed to overcome effect of gravity. In addition there will be other resistance to air flow which are not susceptible to a complete and exact mathematical analysis. These include pressure drop due to entry losses, exit losses and due to bends. It is convenient to express these inefficiencies as a fraction that would lower the momentum transferred from water sprays. Hence we introduce the Momentum Transfer Efficiency, η, as per the equation:

$$M_w = \eta.Q_W.\rho.(U_N - V) \tag{6}$$

Expressing U_N in terms of flow rate and substituting, we get:

$$M_w = \eta.Q_W.\rho_L.\left(\frac{Q_w}{N.C_D.A_N} - V\right) \tag{7}$$

where: $N.C_D.A_N$ is the effective cross sectional area of a nozzle assembly (Bolz et al., 1973).

Rate of Change of Momentum of Air

As air is accelerated from zero to a velocity V, its momentum will be increased according to:

$$M_G = G.A_T.V = \rho_G.A_T.V^2 \tag{8}$$

Rate of Change of Momentum to Overcome Resistances

Contribution to this category is mainly due to pressure drop across the packing $\Sigma\Delta P$. Its rate of change of momentum is given by:

$$M_R = \sum \Delta P.A_T \tag{9}$$

Combining the individual contributions listed above the overall momentum transfer equation becomes:

$$\eta.\rho_w.Q_w.\left(\frac{Q_w}{N.C_D.A_N} - V\right) = \rho_G.A_T.V^2 + \sum \Delta P.A_T \tag{10}$$

Heat Transfer in Spray Assisted Natural Draft Cooling Tower

With reference to Figure 3, a Spray Assisted Natural Draft Cooling Tower may be seen to consist of two distinct sections where heat transfer is taking place.

(i) Counter current flow region -This is a region covered by the main packing where water is flowing downwards and air is upwards.

(ii) Co-current flow region -This covers a region above spray nozzles but below disentrainer packing, where air and water sprays are both flowing upwards.

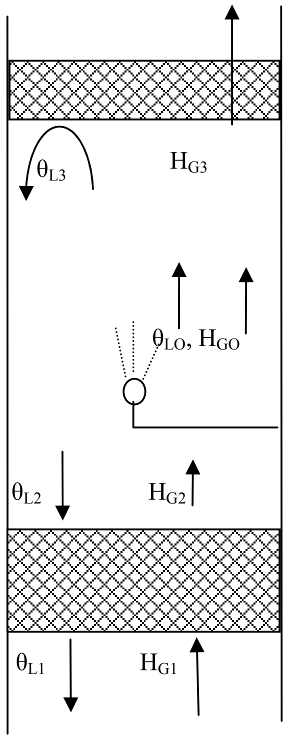


Fig. 3 Spray assisted natural draft cooling tower

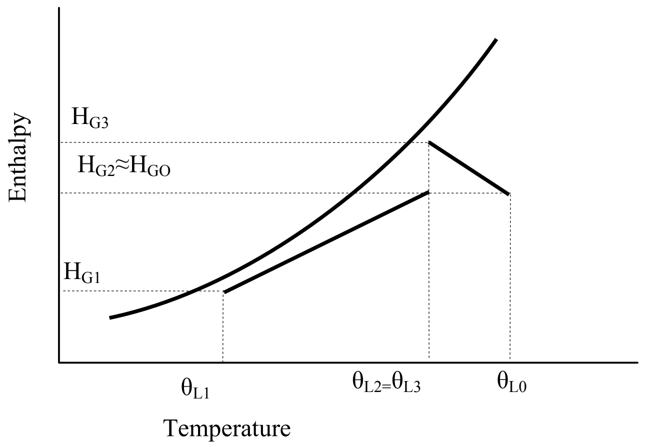


Fig. 4. Cooling water by air: Enthalpy-Temperature diagram

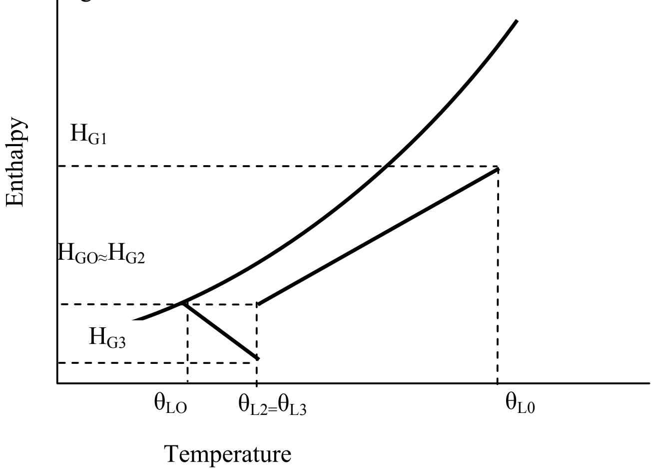


Fig 5: Cooling of air by water: Enthalpy-Temperature diagram

Co-Current Flow

Analysis of mass and heat balance due to co-current flow of liquid and air is carried out in the same way as it is done for counter flow. With reference to Figure 3 the enthalpy balance in co-current flow is given by:

$$-L.C_L.(\theta_{L3}-\theta_{L0}) = G.(H_{G3}-H_{G0}) \quad (11)$$

Equation (11) is similar to equation (1) with a negative sign introduced so as to make both LHS and RHS positive since in co-current flow ($\theta_{L3} < \theta_{L0}$) when ($H_{G3} > H_{G0}$) or vice versa. Consequently:

$$\frac{H_{G3}-H_{G0}}{\theta_{L3}-\theta_{L0}} = \frac{-C_L.L}{G} \quad (12)$$

The operating line for co-current flow therefore has a negative slope, i.e. $(-C_L.L/G)$.

In the co-current flow section of the tower, it can be assumed that:

(i) Enthalpy of air H_{G0} surrounding a jet of water at ext is approximately the same as the enthalpy of air just after leaving the main packing H_{G2}, thus we have $H_{Go} \approx H_{G2}$

(ii) Neglecting cooling due to downward flow of water within a spray chamber then $\theta_{L3} \approx \theta_{L2}$.

These assumptions are made from a view point of easiness of taking readings during the experimental run. Equation 12 therefore becomes:

$$\frac{H_{G3}-H_{G2}}{\theta_{L2}-\theta_{L0}}=\frac{-C_L.L}{G} \qquad (13)$$

Complete Enthalpy -Temperature Diagram Due to Counter and Co-Current Flows

In the foregoing analysis, the model for co-current flow is based on cooling of water by air. In other situations the cooling tower may be used to cool hot gases.

Therefore, depending on whether water or air/gas is being cooled the operating line for counter current and co-current flows when superimposed on the same Enthalpy –Temperature diagram shall result in either Figure 4 or Figure 5 respectively.

EXPERIMENTS AND ANALYSIS OF RESULTS

Methods of measurements

Water flow rate in the Spray Assisted Natural Draft Cooling Tower was varied by adjusting the opening of the valve. The Rotameter was used to set and eventually establish the flow rates, temperatures of air and water was measured by Thermocouples, while the wind speed was measured by Rotating Wind Vane Anemometer. Due to uneven air distribution across the tower an average value of air velocity, taken at nine points across the tower was used.

Momentum Transfer results and analysis

The air velocity in a Spray Entrainment Cooling Tower, V, pressure drop across its main packing, ΔP_{mp}, and pressure drop across disentrainer packing, ΔP_{dp} were measured for several liquid rates and the respective sum of the pressure drops, $\Sigma\ \Delta P$ due to packings was calculated as per the equation:

$$\sum \Delta P=\Delta P_{mp}+\Delta P_{dp} \quad [mm/H_2O] \qquad (14)$$

Based on measured values the liquid to gas ratio the Momentum Transfer Efficiency, η, was calculated at operating points of the spray cooling tower using equation 10.

The results showing the relationship between Liquid to Gas Ratio, L/G, and the liquid rate, L, are presented in Figure 7, while those for and that of momentum transfer due to sprays are presented in Figure 8.

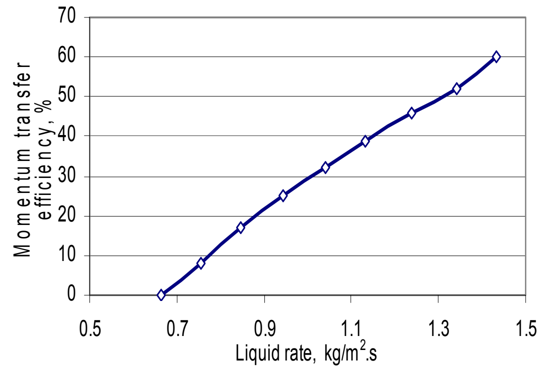


Fig. 8. Momentum transfer efficiency vs Liquid rate

Figure 7 illustrates the fact that for a given set of nozzles operating in a Spray Assisted Natural Draft Cooling Tower, there exists a relationship between the liquid rate and the amount of air being entrained. This relation however is dependent on other specifics mainly being the tower dimensions; and the specifications and layout of the nozzles.

Generally at higher liquid flow rate the liquid to gas ratio becomes smaller implying that the air flow rate tends to increase faster as liquid flow rate is increased. This may be explained by the fact that air is less dense that water.

Figure 8 suggests that the Spray Assisted Natural Draft Cooling Tower should be operated at higher liquid flow rate as under such conditions high momentum transfer of water sprays is achieved resulting into higher air flow rates.

Water Cooling Results and Analysis

Warm at pre determined temperature was pumped from a water tank into the tower in which cooling was affected due to a current of induced air. Cooled water returning from the tower was collected in cold water tank. Water temperature in both cold and hot tanks before and after water circulation, and the amount of water that has undergone cooling were determined. At each liquid rate air flow and its temperature as it leaves the tower were recorded. In addition, dry bulb temperature (DBT) and wet bulb temperature (WBT) of the surrounding air were also recorded. The experiment was repeated starting with different temperatures of feed water, and at different liquid rates.

Mass flow rate of dry air, G, was calculated using the equation:

$$G = (1.0 - 0.016).V\ .\rho_a\ kg/m^2s \qquad (15)$$

Temperature of Water Leaving the Tower, $\theta_{L1,}$ was calculated using heat balance equation

$$C_L.\Delta W.\theta_{L1} + C_L.W_C.\theta_{LC} = C_L(\Delta W + W_c).\theta_{Lmix} \qquad (16)$$

The State of air H_{G2},was calculated using enthalpy balance equation 1:

Hence operating lines were drawn on the enthalpy-temperature diagram by joining

$$(\theta_{L1}\ , H_{G1})\ and\ (\theta_{L2}\ , H_{G2})$$

The above analysis considered overall performance of a tower rather than performance of separate regions which would otherwise require drawing the operating line for counter current and co-current regions separately as illustrated in Figure 4. Practically it is not possible to measure separately the temperatures and enthalpy values of air and water in the concurrent region, as they are both occurring inside the tower. Figure 9 therefore shows the operating lines which were obtained in the spray entrainment cooling tower based on overall performance of the tower. These operating lines show anincrease in cooling range, $(\theta_{L2} - \theta_{L1})$, and therefore increase in heat load as temperature of the feed water, θ_{L2}, is increased. In this specific case feed water temperature was between 30° and 45°C and water outlet temperatures were between 24° and 30°C. Similar trend (though not plotted) was obtained for higher liquid flow rate. However, as an example, an increase in liquid rate from 0.944 kg/m^{2}s to 1.344 kg/m^{2}s (40% increase) causes a relatively small increase in cooling range (about 6% only)

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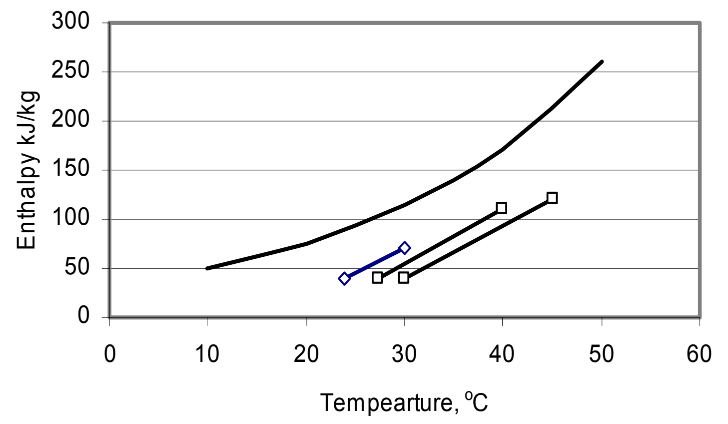

Fig 9. Operating lines for cooling water in SANDCT

The Number of Transfer Units attained in the experimental tower are shown in Figure 10. This figure shows that NTU is dependent on the cooling range. This also implies that the NTU depend also on the temperature of incoming water and air and the liquid rate. For the experimental tower the NTU attained was about 0.8.

Figure 11 is a plot of Efficiency of Spray Assisted Natural Draft Cooling Tower against temperature of feed water. The curves show that the efficiency is highest with high feed temperature of water. In this specific case a maximum efficiency of about 56% was attained at feed water temperature 45°C.

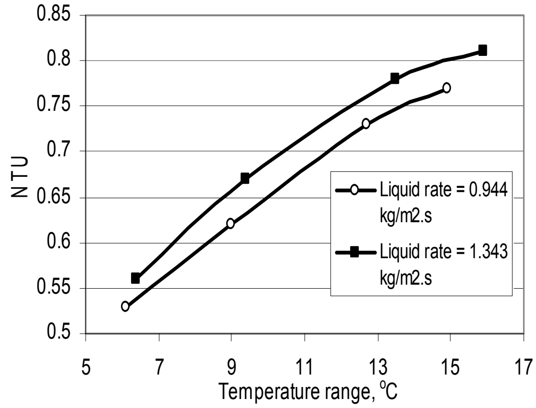

Fig 10. NTU versus Temperature range

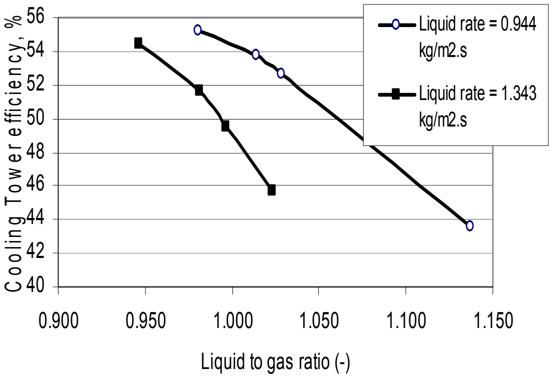

Fig 11. Tower cooling efficiency versus Liquid to gas ratio

CONCLUSIONS

In this study, laboratory experiments have demonstrated that the new concept of a Spray Assisted Natural Draft Cooling Tower being proposed is a feasible one. This would add to the available designs of cooling towers namely: Mechanical draft, Natural draft and Fan Assisted Natural Draft cooling Tower. The Spray Assisted Natural Draft Cooling Tower would offer an advantage of eliminating the usage of fan and therefore generating the potential of saving the costs associated with it. This work should therefore spark interest to researchers in the same field to put more thought in developing this novel design of the tower for commercial operations.

LIST OF SYMBOLS

a	Specific interfacial area, based on volume of packed height, m^2/m^3
A_N	Cross sectional area of nozzle, m^2
A_T	Cross sectional area of tower, m^2
C_D	Coefficient of discharge, (-)
C_L	Specific heat of water, J/kg.K
G	Mass flow rate of dry air per unit area, Kg/m^2.s
h_D	Convective heat transfer coefficient, Nm/m^2.K
H_G	Enthalpy per unit mass of air, J/kg
L	Mass flow rate of liquid per unit area, Kg/m^2.s
M_G	Rate of change of momentum of air, N
M_R	Rate of change of momentum of air to overcome resistance, N
M_w	Rate of change of momentum of water, N
N	Number of nozzles, (-)
Q_w	Volumetric flow rate of water, m^3/s
U_N	Velocity of spray at nozzle exit, m/s
V	Air velocity, m/s
W	Amount of water undergoing cooling, kg
W_C	Initial amount of cold water in tank, kg
Z	Height of packing, m
ΔP	Pressure drop across packing, N/m^2
μ	Cooling tower efficiency, %
η	Momentum transfer efficiency, %
ρ_a	Density of air, kg/m^3
ρ_w	Density of water, kg/m^3
θ_G	Temperature of air, °C
θ_L	Temperature of water, °C
θ_{LC}	Initial temperature of water in cold tank, °C
θ_{Lmix}	Temperature of water in cold tank after mixing with cooled water returning from tower, °C
θ_{WB}	Wet bulb temperature of water, °C

Subscripts

G	Gas (air)
L	Liquid (water)
1, 2, 3	Locations in a Cooling Tower

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