# Computational Model and Analysis of Hybrid (Wet/Dry) Cooling Tower Concept for Thailand

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***Abstract***

A computational model for predicting the behavior of wet, dry and hybrid cooling systems has been developed. Conceptual designs are presented and chosen to be representative of conditions in Thailand. A dry system, which is limited by the ambient dry bulb temperature, cannot achieve as low water outlet temperature as a wet system, which is limited by the ambient wet bulb. In a hybrid system, both wet and dry components are included in the system, and they can be used separately or simultaneously for either water conservation or plume abatement purpose. In this report, the primary emphasis is on proportional share of the heat load in hybrid (wet/dry) cooling system, since this system is the one that will be involved in the tradeoff between capacity limitation and the water consumption depending on the weather conditions in Thailand.

***Keywords:*** Wet cooling tower, Dry cooling tower, Hybrid cooling tower, Thermal performance, Cooling tower design condition.

## 1. Introduction

Wet cooling towers bring water and air into direct contact to form heat transfer mechanisms (convection and evaporation). The major portion of heat load is transferred by water phase change or evaporation. Therefore some water must be added to replace, or makeup, the amount of water that evaporates. Although water is a renewable resource, in some regions the available water is limited and high cost. Other drawbacks are visual plume, fog, mineral drift, and disposal issues associated with wet cooling. One of the advantages of wet cooling towers over the dry towers is evaporative cooling where the water temperature may approach the atmospheric wet bulb temperature rather than the dry bulb temperature.

Dry cooling towers using finned tube heat exchangers in which water flows in tubes and air passes through the exchangers. These towers have no water loss and are suitable to operate under cold and moderate climates. Except of their high investment cost, the main problem with dry towers is that their efficiency decreases with the increase of the ambient air temperature. Especially in hot summer days when the heat transfer driving force decreases [1].

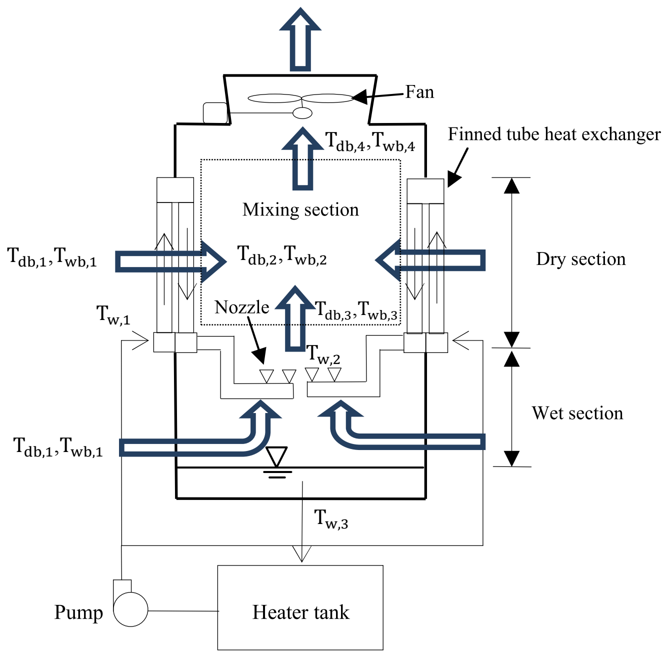


Fig. 1 The operation of hybrid cooling tower

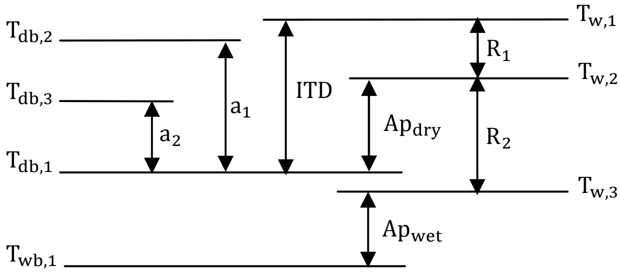


Fig.2 Relationship between the air temperatures and the water temperatures

**Nomenclature**

| | |
|---|---|
| A | area ($m^2$) |
| Ap | approach ($^oC$) |
| a | air range ($^oC$) |
| Bl | blow down (kg/s) |
| C | heat capacity rate (kW/K) |
| C.O.C | cycle of concentration |
| Cr | heat capacity ratio |
| cp | specific heat (kJ/kg.K) |
| D | drift (kg/s) |
| E | evaporation (kg/s) |
| G | air flow rate (kg/s) |
| h | specific enthalpy (kJ/kg dry air) |
| $h_{mass}$ | convection mass transfer coefficient ($kJ/m^2.s$) |
| $\frac{h_{mass}A}{L}$ | cooling tower characteristic |
| ITD | initial temperature different ($^oC$) |
| L | water flow rate (kg/s) |
| M | make up water (kg/s) |
| NTU | number of heat transfer unit |
| Q | heat load (kW) |
| R | water range ($^oC$) |
| RH | relative humidity (%) |
| T | temperature ($^oC$) |
| U | overall heat transfer coefficient ($kW/m^2.K$) |

*Greek symbol*

| | |
|---|---|
| ω | humidity ratio (kg water vapor/ kg dry air) |
| ε | effectiveness |

*Subscripts*

| | |
|---|---|
| a | air |
| db | dry bulb |
| design | design point |
| dry | dry section |
| tot | total |
| w | water |
| mix | mixing section |
| wb | wet bulb |
| wet | wet section |
| 1 | inlet dry section |
| 2 | outlet dry section or inlet wet section |
| 3 | outlet wet section |
| 4 | outlet mixing section |

This study defines and explains the potential benefits of a novel way to cool waste heat carried by water, the hybrid (wet/dry) cooling tower, which is conceived to overcome the drawbacks of the conventional wet and dry cooling towers. The hybrid (wet/dry) cooling tower is intended to counteract (1) the great water consumption of a wet tower and (2) the reduced performance of a dry tower in a very hot ambient temperature [2]. The design involved adding dry sections, using finned tube heat exchangers, above the wet sections. First the hot water passes though the dry section in order to cool some portion of the total cooling range. Then it passes though the wet sections where the air is drawn by an induced draft fan in parallel though the dry section and the wet section, mixed in a plenum, and discharged from the fan at a reduced relative humidity [3] (see Fig.1). The concept is not new-it has been used in many industrial countries for years. It apparently has not been applied, however, to large, bulk power plants in Thailand. The purpose of this study is to define and compare the performance in Thailand of dry and hybrid (wet/dry) cooling towers relative to wet cooling tower and to identify future research that can improve the performance of wet, dry and hybrid cooling towers.

## 2. Operation concept

The operation concept for the hybrid cooling tower, first, the hot water entering the dry section of temperature $T_{w,1}$ is cooled in finned tube heat exchanger at an ambient air $T_{db,1}$ (see Fig.1). The exit water temperature from the finned tube heat exchanger is decreased to $T_{w,2}$ while the outlet air temperature is increased to $T_{db,2}$. Then the water flows to the wet section where it rejects heat via a direct contract to the ambient air ($T_{db,1}, T_{wb,1}$). The water and air are left the wet section with $T_{w,3}$ and $T_{db,3}$ , respectively. The outlet air of both dry and wet sections are then mixed in a plenum before discharged though fan stack with $T_{db,4}$, $T_{wb,4}$.

The temperature difference between the hot water ($T_{w,1}$) entering dry section and the dry bulb temperature of the incoming ambient air ($T_{db,1}$) is initial temperature different (ITD). The range is the difference between the water inlet and outlet temperatures. Therefore range of dry section is $R_1$ and that of wet section is $R_2$. The air range is the difference between the air inlet and outlet temperatures. In this case air range of dry section is $a_1$ and that of wet section is $a_2$. The dry section approach ($Ap_{dry}$) is the difference between the outlet water temperature and the dry bulb temperature of the ambient air. In a similar manner, the wet section approach ($Ap_{wet}$) is the difference between the outlet water temperature and the wet bulb temperature of the ambient air. Relationship between water temperatures and air temperatures are shown in Fig.2.

## 3. Mathematical models

In this study, cooling tower of wet, dry and hybrid types were analyzed using mathematical models for the computation of towers characteristics.

### 3.1 Dry cooling type

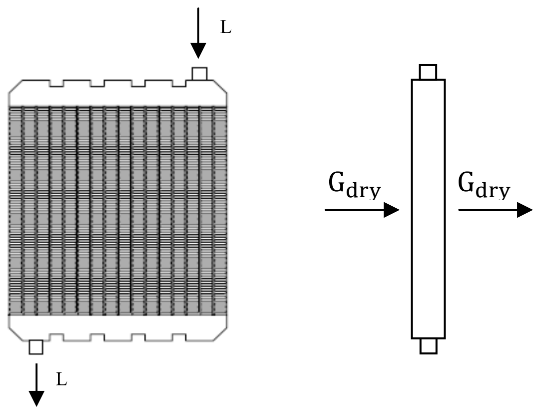


Fig.3 Heat transfer between water flow inside tube of finned tube heat exchanger and outside air (a) front view (b) side view

The analysis of a dry cooling type is based on the effectiveness-NTU method since it is best suited to predict the outlet temperatures of water and air in a specified heat exchanger. In dry cooling section, the hot water flows inside the finned tube heat exchanger while the outside air flows across it. Both fluids are unmixed type (see Fig.3). The water-side heat transfer and air-side heat transfer can be calculated as

$$Q_w = Lc_{pw}\left(T_{w,1} - T_{w,2}\right) = C_w R_1 \quad (1)$$

$$Q_a = G_{dry}c_{pa}\left(T_{db,2} - T_{db,1}\right) = C_a a_1 \quad (2)$$

where $Q_w$ and $Q_a$ are the heat transfer rates at the water and the air streams, respectively.

The effectiveness (ε) is defined as

$$\varepsilon = \frac{Lc_{pw}\left(T_{w,1}-T_{w,2}\right)}{Gc_{pa}\left(T_{w,1}-T_{db,1}\right)} = \frac{C_w R_1}{C_a ITD} \quad (3)$$

The relationship of the effectiveness to the number of transfer unit (NTU) based on minimum air side heat capacity rate for cross flow both fluid unmixed are as following [4]

$$\varepsilon = 1 - \exp\left[\left(\frac{1}{C_r}\right)(NTU^{0.22})\{\exp[-C_r(NTU^{0.78})] - 1\}\right] \quad (4)$$

$$NTU = \frac{UA}{C_a} \quad (5)$$

### 3.2 Wet cooling type

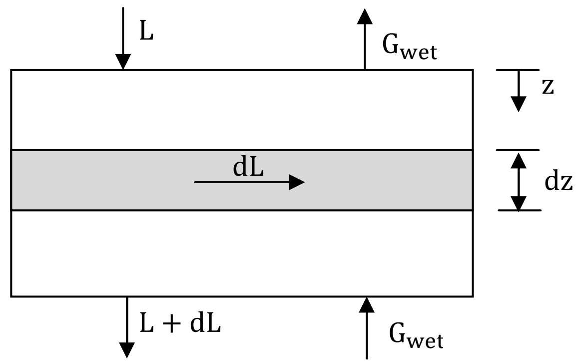


Fig. 4 Heat and mass transfer between water and air in wet cooling

The wet cooling section cools water by the combination of heat and mass transfers (see Fig.4). The operating conditions at design or off-design of a wet cooling tower may be determined directly from the slope of cooling tower characteristics curve as shown in Fig. 5. The techniques used in this study are based on the work of Asvapoositkul and Treeutok [5].

$$\frac{h_{mass}A}{L} = c\left(\frac{L}{G_{wet}}\right)^{-n} \quad (6)$$

$$\frac{L}{G_{wet}} = \frac{(h_{a,3}-h_{a,1})-h_{w,3}(\omega_{a,3}-\omega_{a,1})}{c_{p,w}(T_{w,2}-T_{w,3})} \quad (7)$$

Value of c and n are determined from performance data provided by manufacturers. Typical values of n are in the range of 0.4 – 0.6 [6]. If a typical value of n is assumed, the value of c can be determined from L and G at nominal design conditions.

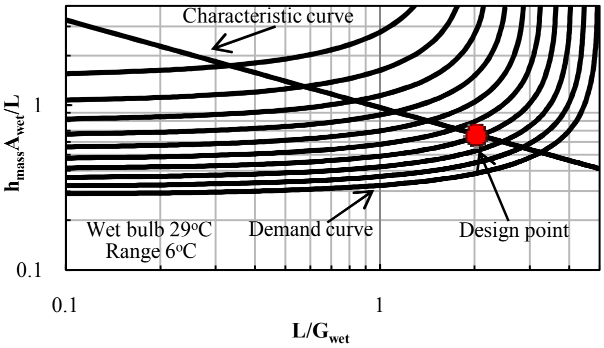


Fig.5 The cooling tower demand and characteristic curves

### 3.3 Mixing process

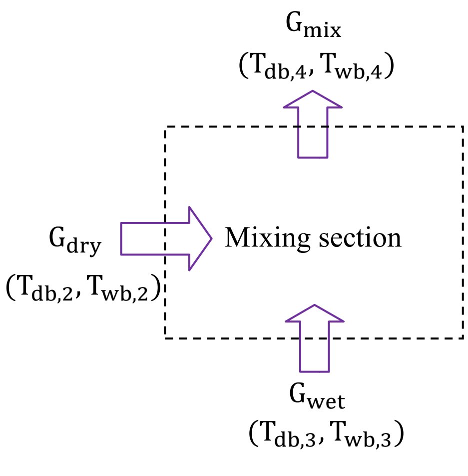


Fig.6 Adiabatic mixing of moist air streams

The outlet moist air of both dry and wet sections are mixed in the mixing section (see Fig.6). The heat transfer with the surrounding is ignored, and the mixing process is assumed to be adiabatic. Mixing processes normally involve no work interactions, and the changes in kinematic and potential energies are negligible. The mass and energy balance for the adiabatic mixing of air streams reduce to

Mass of dry air:

$$G_{dry} + G_{wet} = G_{mix} \quad (8)$$

Mass of water vapor:

$$G_{dry}\omega_{a,2} + G_{wet}\omega_{a,3} = G_{mix}\omega_{a,4} \quad (9)$$

Energy:

$$G_{dry}h_{a,2} + G_{wet}h_{a,3} = G_{mix}h_{a,4} \quad (10)$$

Eliminating $G_{mix}$ from the relation above, we obtain

$$\omega_{a,4} = \frac{G_{dry}\omega_{a,2}+G_{wet}\omega_{a,3}}{G_{dry}+G_{wet}} \quad (11)$$

$$h_{a,4} = \frac{G_{dry}h_{a,2}+G_{wet}h_{a,3}}{G_{dry}+G_{wet}} \quad (12)$$

Equation (11) and (12) are used to calculate mixing air conditions.

### 3.4 Water consumption

Water consumption of wet cooling tower is caused by three major ways: Evaporation (E), Drift (D) and Blow down (Bl). Makeup water (M) is required to replace the consumed water can be calculated as [7]

$$M = E + D + Bl \quad (8)$$

when

Evaporation (E):

$$E = (\omega_{a,3} - \omega_{a,2})G_{wet}$$

Drift (D):

$$D = 0.002L$$

based on drift rate 0.2%.

Blow down (Bl):

$$Bl = \frac{E}{C.O.C-1}$$

C.O.C = 4 is used in this studied.

## 4. Design conditions

The hybrid (wet/dry) tower would operate as a combined of wet and dry tower. In evaluating cooling tower thermal capacity, the design conditions of the tower are selected. When design or sizing a cooling tower, the highest anticipated ambient conditions should be used. Generally, the design conditions are typically determined by reviewing a chart that has been prepared by taking numerous readings in a particular area our several years and determining the maximum readings. At the Don Mueang air port, the maximum reading in each month of 2010 is shown in Fig.7.

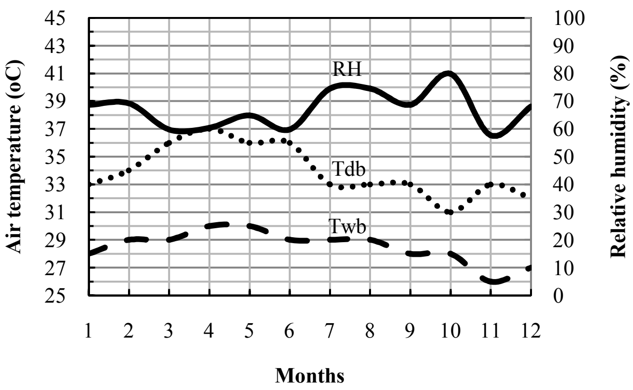


Fig.7 Thailand weather condition in 2010
Resource: Thai Meteorological Department at Don Mueang airport station

It was found that 47% of occurrence in dry bulb temperature is exceeded 33°C while at 19% of occurrence in wet bulb temperature is exceeded 29°C. Therefore, these temperatures are selected in this study. The design point of wet, dry and hybrid cooling tower at various percentage heat load operation of wet and dry sections are showed in Table 1. Each of these designs is based on the same heat transfer load (25kW) for a set of fixed design inlet conditions.

Table 1 The design point of wet, dry and hybrid cooling tower of total heat load 25 kW

| Description | Wet 100% | Hybrid (80/20) | Hybrid (60/40) | Hybrid (40/60) | Hybrid (20/80) | Dry 100% |
|---|---|---|---|---|---|---|
| $T_{w,1}$ (°C) | 49 | 49 | 49 | 49 | 49 | 49 |
| $T_{w,2}$ (°C) | - | 47.8 | 46.6 | 45.4 | 44.2 | 43 |
| $T_{w,3}$ (°C) | 43 | 43 | 43 | 43 | 43 | - |
| $T_{db,1}$ (°C) | 33 | 33 | 33 | 33 | 33 | 33 |
| $T_{wb,1}$ (°C) | 29 | 29 | 29 | 29 | 29 | 29 |
| L (kg/s) | 1 | 1 | 1 | 1 | 1 | 1 |
| $G_{dry}$ (kg/s) | - | 0.44 | 0.84 | 1.19 | 1.51 | 1.8 |
| $G_{wet}$ (kg/s) | 0.21 | 0.17 | 0.14 | 0.1 | 0.05 | - |
| $G_{tot}$ (kg/s) | 0.21 | 0.61 | 0.98 | 1.29 | 1.56 | 1.8 |
| $A_{dry}$ (m$^2$) | - | 11.6 | 26.2 | 46.2 | 74.4 | 97.8 |
| $A_{wet}$ (m$^2$) | 12.9 | 11.3 | 9.4 | 7.1 | 4.3 | - |
| $A_{tot}$ (m$^2$) | 12.9 | 22.9 | 35.6 | 53.3 | 78.7 | 97.8 |

## 5. Result and discussion

Fig.8 shows the moist air properties at the inlet, exit of the wet and the dry sections as well as at the plenum. With the relative humidity (RH) of 98% at the exit of wet cooling tower, it is possibility that the plume will be formed if this moist air is discharged to the atmospheric air. On the other hand, no plume is formed in the dry cooling tower. The visual plume or fog in the wet cooling tower can be remedied by using hybrid cooling towers as shown in Fig.8 where the discharged moist air properties are much lower than the saturated line.

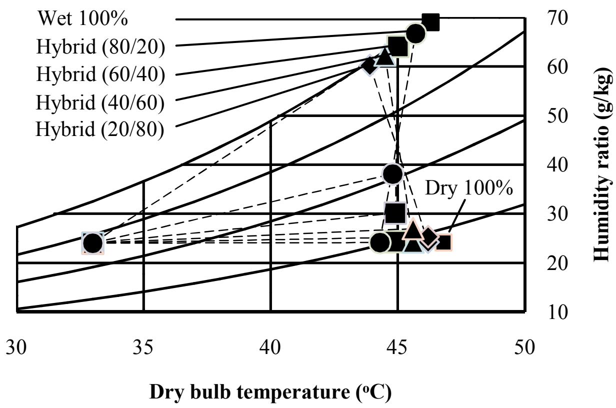


Fig.8 Psychometric chart at design condition of wet, dry and hybrid cooling towers

## 6. Off-design condition

At the off-design conditions, the performance of wet, dry and hybrid cooling towers were compared in terms of thermal capacity, air flow rate and water consumption.

### 6.1 Heat transfer rate

Fig.9 shows how the cooling towers works with variation ambient conditions monthly in Thailand with water and air flow rate were constants for each design. We found that wet cooling tower has the highest thermal performance for all cooling type throughout the year. Except at low ambient air temperature and high relative humidity, dry cooling tower thermal capacity is better than that of wet cooling tower.

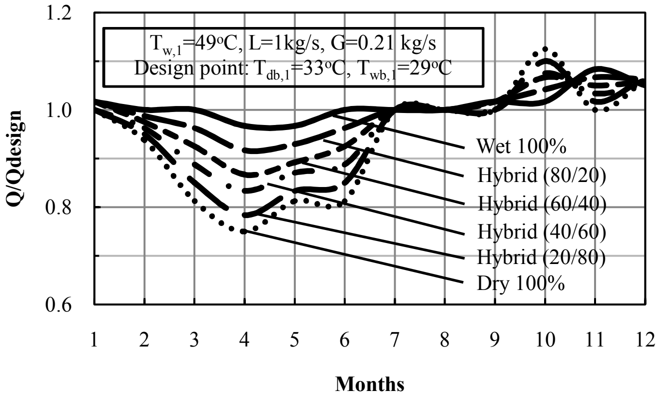


Fig.9 Comparison of heat rejection ratio of wet, dry and hybrid tower in monthly operation with constant water and air flow rate for each designs

### 6.2 Air flow rate

With the same heat load, the amount of air required relative to wet cooling tower at design point to cool water depends on monthly ambient conditions (see.Fig.10). The required air varies directly with increasing the ratio of heat transfer of dry section. In the summer, when ambient air temperatures is higher than the design point, the required air of the dry cooling tower is about 10-12 times of that of the wet cooling tower at design point. The required air of the wet cooling tower is nearly constant throughout the year.

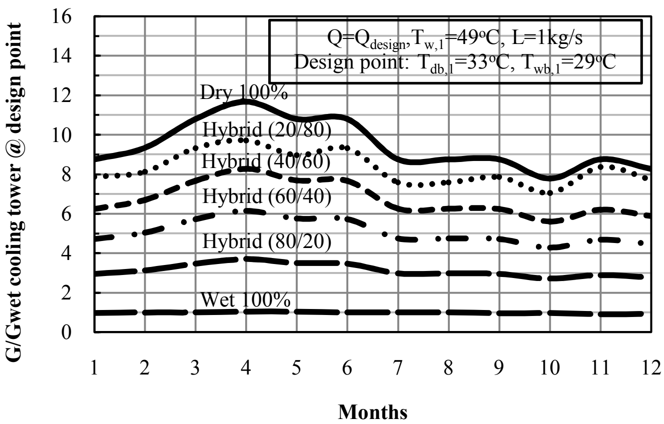


Fig.10 Comparison of required air cooling flow rate ratio of wet, dry and hybrid tower in monthly operation with the same heat load (25kW)

### 6.3 Water consumption

With the same heat load, the amount of water consumption relative to wet cooling tower at design point depends on monthly ambient conditions (see.Fig.11). The water consumption varies directly with increasing the ratio of heat transfer of wet section. The requirements are related to the ambient air conditions especially wet bulb temperature ($T_{wb}$) and Relative humidity (RH). The variations of water consumption for each type are within $\pm 0.05$ of that of wet cooling tower at design point.

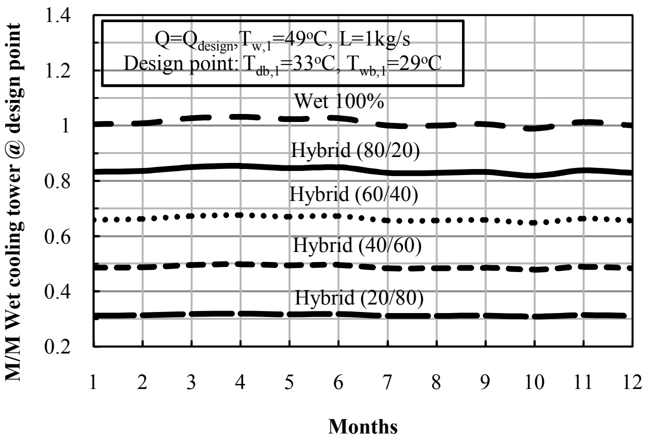


Fig.11 Comparison of water consumption ratio of wet, hybrid tower in monthly operation with the same heat load (25kW)

## 7. Conclusion

The monthly temperature distribution, particularly the high or "worst-case" ambient temperature, is important in determining the towers capacity. For dry cooling tower; that is the high dry-bulb temperature, and for wet towers it is the high wet-bulb temperature. These high ambient conditions are involved in the tradeoff between capacity limitation and the water consumption.

Currently work is underway to validate the prediction from the mathematical model. The experiment will be conducted in the cooling tower test rig at King Mongkut's University of Technology Thonburi (KMUTT), Mechanical Engineering Department. Furthermore, work is in progress to analyses the hybrid (wet/dry) cooling tower based on Exergy (The second law of thermodynamics).


## 8. Acknowledgement

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## 9. References


[1] Razaei, E., Shafiel, S., and Abdollahnezhad, A. (2009). Reducing water consumption of an industrial plant cooling unit using hybrid cooling tower, *Energy Conversion and Management*, vol.51, pp.311-319.

[2] Salter, R.G. (1973). The dry/spray tower: a power plant cooling tower concept for semi-arid locations, R-1086-RF/CSA, January 1973, pp.1-18.

[3] Lindahl, P. and Mortensen, K. (2010). Plume Abatement-The Next Generation, *Cooling Technology Institute*, vol.31, pp. 2-23.

[4] Wang, C.C. and Webb, R.L. (2000). Data reduction for air-side performance of fin and-tube heat exchanger*, Experimental Thermal and Fluid Science*, vol. 21, pp.18–26.

[5] Asvapoositkul, W. and Treeutok, S. (2012). A simplified method on thermal performance capacity evaluation of counter flow cooling tower, *Applied Thermal Engineering*, vol.38, pp.160-167.

[6] Baker, D. (1984). Cooling tower performance, Chemical Publishing Co. Inc., New York.

[7] Leeper, S.A. (1981). Wet cooling towers: rule of thumb design and simulation, U.S. Department of Energy, July 1981, pp.1-7.