THESIS APPROVAL

GRADUATE SCHOOL, KASETSART UNIVERSITY

Doctor of Engineering (Mechanical Engineering)

DEGREE

Mechanical Engineering	Mechanical Engineering
FIELD	**DEPARTMENT**

TITLE: The Simulation of Heat and Mass Transfer in Corrugated Packing for Counter - Flow Cooling Towers

NAME: Mr. Montri Pirunkaset

THIS THESIS HAS BEEN ACCEPTED BY

.... **THESIS ADVISOR**

(Associate Professor Santi Laksitanonta, D.Eng.)

.... **THESIS CO-ADVISOR**

(Assistant Professor Pipon Boonchanta, Ph.D.)

.... **THESIS CO-ADVISOR**

(Associate Professor Thanya Kiatiwat, Ph.D.)

.... **THESIS CO-ADVISOR**

(Associate Professor Apichart Chirattiyangkur, Dr.Ing.)

.... **THESIS CO-ADVISOR**

(Assistant Professor Saroj Saimek, Ph.D.)

.... **DEPARTMENT HEAD**

(Associate Professor Chawalit Kittichaikarn, Ph.D.)

APPROVED BY THE GRADUATE SCHOOL ON ....

.... **DEAN**

(Associate Professor Gunjana Theeragool, D.Agr.)

THESIS

THE SIMULATION OF HEAT AND MASS TRANSFER IN CORRUGATED PACKING FOR COUNTER-FLOW COOLING TOWERS

MONTRI PIRUNKASET

A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
Doctor of Engineering (Mechanical Engineering)
Graduate School, Kasetsart University
2009

Montri Pirunkaset 2009: The Simulation of Heat and Mass Transfer in Corrugated Packing for Counter-Flow Cooling Towers. Doctor of Engineering (Mechanical Engineering), Major Field: Mechanical Engineering, Department of Mechanical Engineering. Thesis Advisor: Associate Professor Santi Laksitanonta, D.Eng. 179 pages.

This study presents the simulated results of the simulation of heat and mass transfer in the corrugated packing of counter-flow cooling towers. This numerical analysis has been partially validated by comparing it with the experimental data. Due to the complicated configuration of the packing surface, it was not able to measure temperatures of air at the intermediate horizontal sections, but was able to measure only the water temperatures and the outlet temperatures of water and air. Under the same conditions at inlet dry bulb temperature of 35.5 ^{o}C, inlet wet bulb temperature of 27.4 ^{o}C, inlet water temperature of 40 ^{o}C, and three values of L/G ratios, the water temperatures were predicted at the vertical positions of 0, 0.09, 0.18, 0.27, 0.36 and 0.45m from the bottom of packing by using the simulation method and the Merkel's method. A comparison of the water temperatures at the vertical positions in the packing, it was found that all temperature differences of the water by using the simulation method and the measured data were approximately less than 3.19%, 3.06% and 2.77% and all temperature differences of the water by using the Merkel's method and the measured data were approximately less than 3.84%, 3.4% and 2.84% for the given L/G ratios of 0.553, 0.719 and 0.933, respectively. Within the 95% confidence interval, it was found that the simulation model and the Merkel's method could predict the water temperatures at the vertical positions within the deviation of $0.5450 \pm 0.1443^{o}C$ and $0.5639 \pm 0.1790^{o}C$, respectively by using the K-type of thermocouples within the deviation of calibrated temperatures of $0.5333 \pm 0.2054^{o}C$. In the experiments, the orifice flow meter could measure the flow rates of water with the uncertainty of $\pm$6.5% within the 95% confidence interval.

Finally, this simulation model has been used as a tool for studying the phenomenon of heat and mass transfer in the corrugated packing and for predicting the water temperatures at the vertical positions and the outlet temperatures of water and air of packing.

____________________ ____________________ ___ / ___ / ___

Student's signature Thesis Advisor's signature

ACKNOWLEDGEMENT

The author would like to express his deepest gratitude and grateful thank to Associate Professor Santi Laksitanonta, D.Eng., his thesis advisor, Assistant Professor Pipon Boonchanta, Ph.D., his major consultant committee, Associate Professor Thanya Kiatiwat, Ph.D., his minor consultant committee, Associate Professor Apichart Chirattiyangkur, Dr.Ing., and Assistant Professor Saroj Saimek, Ph.D., his external committee for their continued encouragement, guidance and valuable suggestions toward achieving his graduate study and for providing their useful comments on writing thesis completely.

The author is indebted to the Department of Mechanical Engineering, Faculty of Engineering and Kasetsart University (Bangkhen Campus) for giving a chance of his studying in this Ph.D. program and facilities over the period of working and study. The author has been proud of graduating the bachelor's degree and studying in this Ph.D. program from Kasetsart University. This university gave him the effectiveness of teaching, the improved knowledge transfers, the innovation, and the education development.

Finally, the author really appreciates his family for their supports, continued encouragement, and giving their heart-felt gratitude during the graduate study. All of your help is greatly appreciated.

Montri Pirunkaset

December 2009

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

Page

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

Appendix Table | Page

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

Appendix Figure | Page

LIST OF ABBREVIATIONS

a_m	=	Surface area per unit of the packing volume (m^2/m^3)
A_{fr}	=	Frontal cross-sectional area of the packing (m^2)
A_c	=	Flow cross-sectional area of the packing (m^2)
A_{or}	=	Cross sectional area of the orifice (m^2)
$C_{p,da}$	=	Specific heat of the dry air (kJ/kg-dry air.K)
$C_{p,v}$	=	Specific heat of the water vapor (kJ/kg.K)
$C_{p,a}$	=	Specific heat of the moist air (kJ/kg-dry air.K)
$C'_{p,a}$	=	Specific heat of the moist air (kJ/kg-moist air.K)
C_w	=	Specific heat of the water (kJ/kg.K)
CTI	=	Cooling Tower Institute
CWT	=	Cold water temperature (^{o}C)
D_{or}	=	Diameter of the orifice (m)
D_{pipe}	=	Diameter of the water pipe (m)
DBT	=	Dry bulb temperature (^{o}C)
G_m	=	Mass transfer conductance (kg/m^2.s)
G_h	=	Heat transfer conductance (kg /m^2.s) and $G_h = \alpha / C'_{p,a}$
H	=	Packing height (m)
HWT	=	Hot water temperature (^{o}C)
h_a	=	Enthalpy of the moist air (kJ/kg-dry air)
h_{flm}	=	Enthalpy of the water film (kJ /kg)
h_{fg}	=	Latent heat of the water vaporization (kJ/kg)
$h_{fg,ref}$	=	Latent heat of the water vaporization at reference temperature 0 ^{o}C and $h_{fg,ref}$ = 2501 kJ/kg
h_f	=	Enthalpy of the saturated liquid water (kJ/kg)
h_s	=	Enthalpy of the saturated air at water temperature (kJ/kg-dry air)
$h_{sat,in}$	=	Enthalpy of the saturated air at inlet WBT (kJ/kg-dry air)
$h_{sat,out}$	=	Enthalpy of the saturated outlet air (kJ/kg-dry air)
h_w	=	Enthalpy of the water stream (kJ /kg)

LIST OF ABBREVIATIONS (Continued)

$h_{w,in}$	=	Inlet enthalpy of the water stream (kJ /kg)
$h_{w,out}$	=	Outlet enthalpy of the water stream (kJ /kg)
$(h_s - h_a)_m$	=	Arithmetic-mean enthalpy difference for the increment of volume (kJ/kg-dry air)
G_m	=	Mass transfer conductance (kg /m^2.s)
$G_m a_m$	=	Mass transfer per unit of the packing volume (kg /m^3.s)
g	=	Gravitational acceleration (g = 9.81 m/s^2)
Ka	=	Volumetric heat transfer coefficient of packing (kW /m^3 per a unit of enthalpy difference)
KaV / L	=	Volumetric heat transfer coefficient of the packing (dimensionless term)
K_{or}	=	Flow coefficient of the orifice flow meter (dimensionless term)
L / G	=	Water to air flow ratio (kg-water /kg-dry air)
L'	=	Water loading (kg/m^2.s)
$\dot{m}_{da}$	=	Mass flow rate of the dry air (kg/s)
$\dot{m}_a$	=	Mass flow rate of the moist air (kg/s)
m''_{diff}	=	Diffusivity of mass transfer (kg/s.m^2)
$\dot{m}_w$	=	Water mass flow rate (kg/s)
m_w	=	Water mass in the weighing tank (kg)
N	=	Number of the divided horizontal sections of packing
P_s	=	Saturated pressure of the water vapor in air (kPa)
P_{sf}	=	Saturated pressure of the vapor at water film temperature (kPa)
P	=	Perimeter of the cross-sectional area of packing (m)
q''_{conv}	=	Convective heat transfer rate (kW/m^2)
q''_{evap}	=	Latent heat of the evaporation of water (kW/m^2)
r^2	=	Correlation coefficient of the fitted line
SG_{Hg}	=	Specific gravity of the mercury (dimensionless)

LIST OF ABBREVIATIONS (Continued)

s_{yy}	=	Mean total variation
$s_{y/x}$	=	Standard error of the y-data
S_{yy}^2	=	Total squared variation of data set of the y-data
S_{xx}^2	=	Total squared variation of data set of the x-data
T_a	=	Dry bulb temperature (°C)
T_{wb}	=	Wet bulb temperature (°C)
T_f	=	Water film temperature (°C)
T_{ref}	=	Reference temperature at 0 °C
T_1	=	Hot water temperature (°C)
T_2	=	Cold water temperature (°C)
$T_{measured}$	=	Measured value of temperature (°C)
T_{true}	=	True value of temperature (°C)
T_{offset}	=	Zero offset error of the temperature (°C)
$t_{\infty/2,\nu}$	=	Student's t-distribution
u_K	=	Uncertainty for the flow coefficient K_{or} (%)
$\dot{V}_a$	=	Volume flow rate of the air (m^3/min)
$\dot{V}_{or}$	=	Volume flow rate of water passing through the orifice meter (m^3/s)
$\dot{V}_w$	=	Volume flow rate of the water (L/min)
v_a	=	Specific volume of the moist air (m^3/kg)
V_a	=	Velocity of the moist air (m/s)
x_i	=	Measured value of the independent variables
x_m	=	Mean value of the independent variables
y_i	=	Measured value of the dependent variables
y_m	=	Mean value of the dependent variables
WBT	=	Inlet wet bulb temperature of the air (°C)
ρ	=	Density of water passing through the orifice meter (kg/ m^3)
ρ_a	=	Density of the moist air (kg / m^3)

LIST OF ABBREVIATIONS (Continued)

ρ_f	=	Density of water passing through the packing (kg/ m^3)
ρ_{mano}	=	Density of mercury in manometer of the orifice meter (ρ_{mano} = 13600 kg/ m^3)
ω	=	Humidity ratio of the moist air (kg/kg-dry air)
ω_s	=	Humidity ratio of the saturated air (kg/kg-dry air)
α	=	Convective heat transfer on the film surface (W/m^2.K)
β	=	Scale error for the temperature calibration
ΔA	=	Mass or heat transfer surface of the increment of volume (m ^{2})
Δh	=	Difference of water level in the manometer (m-H_2O)
Δh_{mano}	=	Difference of mercury level in the manometer (m-Hg)
ΔZ	=	Increment of the packing height (m)
$\Delta T_{increment}$	=	Temperature difference of the increment of volume (^{o}C)

THE SIMULATION OF HEAT AND MASS TRANSFER IN CORRUGATED PACKING FOR COUNTER-FLOW COOLING TOWERS

INTRODUCTION

Cooling tower performance depends on wet bulb temperature, contact surface area between water and air, contact time, and water droplet distribution. This includes the droplet size and a number of droplets, which determines the proper sizes for the packing and cooling tower. So, the packing is a necessary component of the cooling tower. The heat and mass can be exchanged between water and air in the packing by increasing contact surface area and contact time between water and air. Therefore, the fundamental principles of heat and mass transfer can be determined and analyzed for setting up the mathematical models of the heat and mass transfer within the packing, which can predict the packing performance for its design and development.

Currently, the combined simulation and experimental study has been carried out on the engineering applications and the physical models. It is an important application for the engineering work, because it is a tool for studying of the operating variables of involved systems and their performance over a wide range of conditions. We are particularly interested in the models of heat and mass transfer between air and water on the packing film in the counter-flow cooling tower and set the equations for these models in the differential form. Consequently, we proceed to simulate sets of these equations by using of the fourth-order Runge-Kutta method for solving the operating variables (dry bulb temperature, wet bulb temperature, water temperature, humidity ratio, and water flow rate) at each level of the packing height for the given initial conditions. The simulation results always are sets of the previous operating variables. Finally, we prepare the apparatus for a test model by using experimental analysis and we compare the mathematical packing model with the experimental results at the same initial conditions and setting values of L/G ratios.

OBJECTIVES

The following procedures are my study's objectives:

1. To study the behavior of heat and mass transfer between air and water film on the packing surface in the counter-flow cooling tower.

2. To set up mathematical models for the heat and mass transfer.

3. To proceed to simulate sets of equations by the fourth-order Runge-Kutta method for solving the operating variables at the vertical position of packing under the given initial conditions.

4. To prepare the apparatus for testing using mathematical models in accordance with CTI standards.

5. To conclude and report on a numerical analysis from mathematical models and the on-site experimental data.

LITERATURE REVIEW

Concerned Research

1. National Research

In 1997, Suradej studied the efficiency of plastic film packing in the induced-draft water cooling tower. Two types of PVC plastic film packing had film spacing of 3.2 cm and 2.0 cm. Film spacing could be selected in order to compare its efficiency with the design conditions. The efficiency comparison method was based on “number of transfer unit on the gas-side” and efficiency in terms of water cooling capacity was determined by using “tower characteristic curve”. The results were found that 2.0 cm film spacing of packing had efficiency and pressure drop more than that of 3.2 cm film spacing. Compared to the effects of shape and spacing on the film performance, properly designed packing was more efficient.

In 2002, Danucha studied the air pressure drop and volumetric heat transfer coefficient of corrugated PVC packing in induced-draft counter-flow cooling towers and the representative equations of relationships between air pressure drop across packing, circulating water mass flow rate, air mass flow rate, air average density, volumetric heat transfer coefficient, height and diameter of packing. The test conditions were based on the given circulating water flows ranging from 29.63 liter per min to 50.14 liter per min with a packing height of 235 mm and 470 mm by maintaining the water inlet temperature at 40 ^{o}C and cooling tower capacity of 3 tons. During testing, data was analyzed by using the dimensions of the Buckingham π theorem and correlating, and then the results of this analysis were obtained for functional relationships between involved parameters. These function relationships would be valuable for engineer applications involving cooling tower design and optimum selection of fans.

Also in 2002, Phansak studied the performance of the induced-draft counter-flow cooling tower with a 3 tons of capacity and tower were tested in accordance with the standard of the Cooling Tower Institute (CTI) using representative equations of relationships between circulating water flow rate, air flow rate, cooling range, wet bulb temperature, inlet and outlet water temperature, and volumetric heat transfer coefficient. The testing conditions were adjusted circulating water flow rates went from 29.676 l/min to 49.818 l/min. At each value of these circulating water flow rates, the water inlet temperatures were varied from 30 ^{o}C to 41 ^{o}C. The tested results of the designed L/G ratio were about 0.749 to 1.228 and cooling tower capability varied from 63.570 to 92.095 percent of the design inlet flow rate under the same design approach, range, and inlet air conditions.

In 2003, Khanchai studied the heat and mass transfer between water droplets and surrounding air in counter-flow cooling towers using mathematical models. This simulation was able to predict the mass and heat transfer behaviors. The mathematical models were developed to study the effect of inlet water temperature at the position of nozzle installation on water droplets size, water temperature, air temperature, and humidity ratio at the given height of the water distribution section. The results were found that the water droplet size effected the changing rate of droplet size, temperature, and velocity of water droplets whilst passing through the air at each section. The smaller the water droplets were in size would effect the faster in size reduction, the lower temperature, and the more easily balance in the force equilibrium between its molecular weight and drag force. The inlet water temperature at the site of the nozzle installation also effected the changing rate of water droplet size, water temperature, air temperature, and humidity ratio. Consequently, the higher inlet water temperature at the site of nozzle installation would effect the higher in the changing rate of water droplet size, water temperature, air temperature, and humidity ratio more than that for the lower inlet water temperature.

2. International Research

In 1996, Mohiuddin and Kant studied the detailed methodology for the thermal design of wet, counter-flow and cross-flow types of mechanical and natural draught cooling towers. They presented different steps of cooling tower design. There were 2 steps, the first step included selection of a cooling tower, determination of tower characteristic ratio and ratio of the water-to-air loading, computation of moist air properties and integration procedures for the tower characteristic ratio and the second step described the packing, total packed height and number of decks, water-to-air loading, pressure drop across the packing, and fan design for a mechanical draught cooling tower.

In 2001, Milosavljevic and Heikkilä studied the mathematical models for a counter-flow wet cooling tower, which was based on one-dimensional heat and mass balance equations by using the measured heat transfer coefficient. The balance equations were solved numerically to predict the temperature change of air and water, as well as the humidity as a function of the cooling tower high. Experimental measurements on two pilot-scale cooling towers were carried out in order to analyze the performance of different cooling tower packing materials. Also, the performance of other cooling tower elements, such as droplet separators and water spray nozzles, was investigated in the pilot experiments. The flow distribution i.e. the velocity field, upstream to the packing materials was predicted using the three-dimensional version of the computational fluid dynamics (CFD). The calculated flow fields were presented for different distances between the inlet of the air and the packing material. In addition, the two-dimensional version of CFD was applied to predict the external airflow around the cooling tower and the backflow in different weather conditions in summer and winter. The research project was carried out in connecting to an industrial cooling tower installation.

In 2002, Tan and Deng studied methods for evaluating the heat and mass transfer characteristics in a reversibly used water of cooling tower (RUWCT) for heat recovery. The method was developed by introducing the Merkel's equation for standard cooling towers the revisions that account for the differences in heat and mass transfer characteristics between the water in cooling tower and a RUWCT. Field experimental results from a RUWCT installed in a sub-tropical region in China indicated that the method developed could be used to evaluate the thermal performance of a RUWCT with an acceptable accuracy.

Introduction and Fundamental Theory of Heat and Mass Transfer

1. Mass and Heat Transfer for an Induced-Draft Counter-Flow Cooling Tower

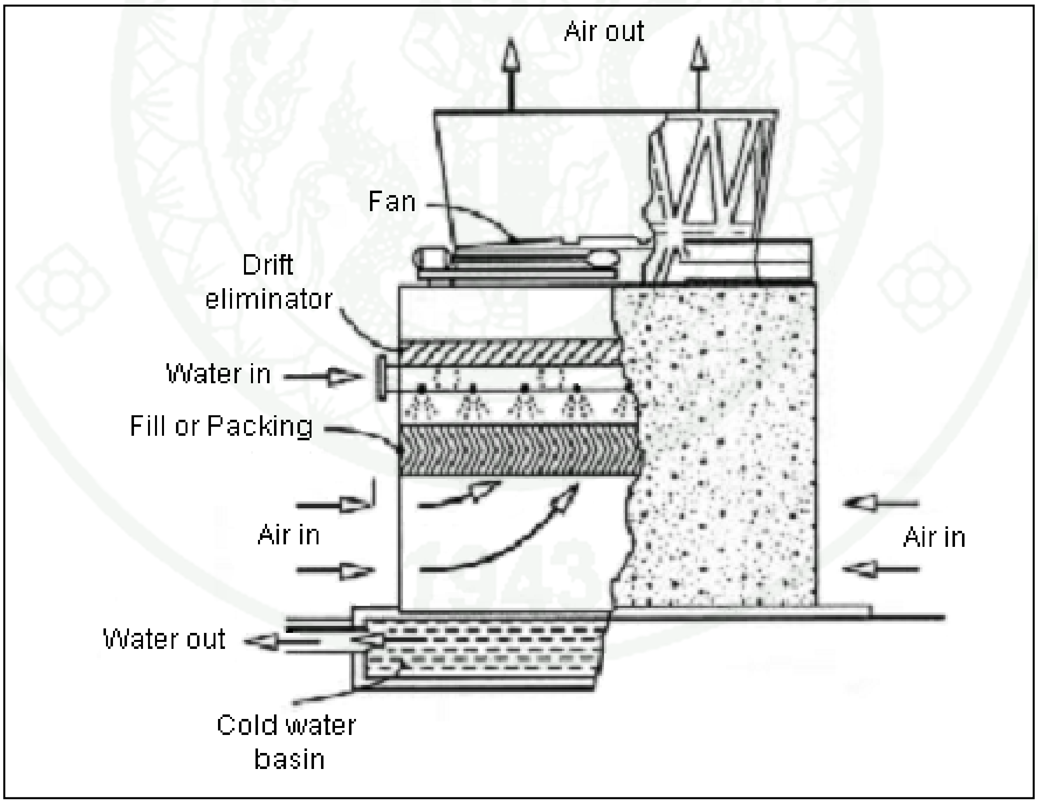


Figure 1 Induced-draft counter-flow cooling tower.

Source: Mills (1995)

In the induced-draft counter-flow cooling tower (Cheremisinoff, 1983), the heat and mass are transferred simultaneously which causes the warm inlet water to be cooled. From Figure1, the warm water enters at top of the cooling tower and is distributed by water distribution within the cooling tower. After that, the distributed water covers the packing as downward thin films. This situation increases the contact surface area of water and air. The cooling air is either induced or forced through the cooling tower from the bottom to the top. The warm water flows counter the air, where this takes to transfer sensible heat between the high temperature water and the low temperature air and takes to transfer partly evaporative heat. By obtaining latent heat from the downward thin water films, the evaporative vapor is extracted from those water films. After that, the cooled water leaves from the bottom and warm air with high moistures leaves from the top of cooling tower. Evaporation occurs due to the differing pressure of water vapor at the water surface and the surrounding air. The vapor pressure depends on the water temperature and the degree of saturation of the air, respectively.

The sensible heat is transferred from higher water temperature to lower air temperature. The latent heat is transferred from water film to moist air, due to vapor pressure difference between air at the interface and surrounding air. Because the simultaneous heat and mass exchangers are presented in the packing of the cooling tower, the coupled differential equations governing the conservation of mass and energy must be solved simultaneously.

In a cooling tower (Hill *et al*., 1990), the water and air streams are generally opposed so that the cooled water leaving the bottom of packing is in contact with the entering air. Similarly, the hot water entering packing will be in contact with air leaving the packing. At the top of cooling tower the water temperature will be above the dry bulb temperature of the air, but as the water descends and its temperature continuously decreases and falls to a point below the dry bulb temperature, but remains above the wet bulb temperature and doesn’t approach it. Therefore, it only causes the latent heat on the water film of packing whilst descending downward of water.

2. Packing

In general, the packing is classified into two fundamental approaches for packing design (Hill *et al*., 1990), the first is splash packing in which the hot water falling through the tower is encouraged to form droplets. The second approach is the thin film forming on packing in which the hot water is encouraged to spread out on a surface and form a thin film. Therefore, the packing can provide the maximum surface area for evaporation and allow cooling of water to take place.

PVC is the most widely used material as shown in Figure 2 but other plastics have been used, including polystyrene, polypropylene (for high temperature applications), and polyethylene. Other plastics can be used up to 60 $^{\circ}$C. Plastic packing has many advantages, such as lightness and consequent ease of removal and replacement, inert in any water whether acid or alkaline, inhibition of growth of scale, and is non-flammable.

Figure 2 PVC-corrugated film packing.

3. Psychrometric Properties

The air is a mixture of several constituent gases. Moist air is an ideal mixtures gas including dry air and low partial-pressure water vapor. In general, the moist air always exists at any state which is usually lower than the critical temperature of water vapor, and the process of moist air may be evaporation or condensation. It causes the appearance of two-phase mixtures between vapor and liquid of water.

3.1 Humidity Ratio

The humidity ratio is defined as the mass of water vapor per unit mass of dry air. At given dry bulb and wet bulb temperature, the humidity ratio of moist air can be calculated:

$$\omega = \frac{\left[1.005(T_{wb} - T_a) + (\frac{0.622P_s}{101.325 - P_s})h_{fg}\right]}{2501.5 + 1.806T_a - h_f} \quad (1)$$

where P_s , h_{fg}, and h_f are considered at the wet bulb temperature of that moist air. The humidity ratio of saturated air can be determined as:

$$\omega_s = \frac{0.622P_{sf}}{101.325 - P_{sf}} \quad (2)$$

where P_{sf} is saturated pressure at the same water temperature of any vertical position of packing.

3.2 Density or Specific Volume of Moist Air

The moist air mainly consists of dry air and water vapor, mole fraction of water vapor and dry air in this moist air can be determined as:

$$y_{vap} = \frac{(\omega/18)}{(\frac{1}{28.9}+\frac{\omega}{18})} \quad , y_{da} = \frac{(1/28.9)}{(\frac{1}{28.9}+\frac{\omega}{18})} \qquad (3)$$

The mass molecule of moist air can be written as:

$$M_a = \frac{(1+\omega)}{(\frac{1}{28.9}+\frac{\omega}{18})} \qquad (4)$$

By assuming air-vapor mixture to be ideal gas behavior, the density of moist air can be written as:

$$\rho_a = \frac{P_{atm}M_a}{\bar{R}T_a} = \frac{101.325}{8.3143T_a}\left(\frac{1+\omega}{\frac{1}{28.9}+\frac{\omega}{18}}\right) \qquad (5)$$

The specific volume of moist air can be determined from Eq.(5), we obtain

$$v_a = \frac{(0.082T_a + 22.4135)(\frac{1}{28.9}+\frac{\omega}{18})}{(1+\omega)} \quad (\text{ m}^3\text{/kg-moist air }) \qquad (6)$$

$$v_a = (0.082T_a + 22.4135)(\frac{1}{28.9}+\frac{\omega}{18}) \quad (\text{ m}^3\text{/kg-dry air }) \qquad (7)$$

3.3 Specific Heat of Moist Air

By assuming air-vapor mixture to be ideal gas behavior, the specific heat of moist air can be determined as:

$$C_{p,a} = C_{p,da} + \omega C_{p,v} \quad \text{,a unit of kJ / kg-dry air. K} \qquad (8)$$

For the normal ambient temperatures, the specific heat of dry air $C_{p,da}$=1.005 kJ / kg-dry air. K and water vapor $C_{p,v}$= 1.88 kJ / kg-vap.K are substituted into Eq.(8) and divided by $(1+\omega)$.Therefore, we obtain the specific heat of moist air in unit of kJ / kg-moist air. K as:

$$C'_{p,a} = \frac{1.005 + 1.88\omega}{1+\omega} \quad \text{a unit of kJ / kg-moist air. K} \qquad (9)$$

3.4 Enthalpy of Moist Air

The enthalpy of water vapor and air mixture is based on the datum temperature of 0 °C at which the enthalpy of dry air and saturated liquid water are equal to zero. Thus the enthalpy of moist air can be written in terms of dry air and water vapor as:

$$h_a = 1.005T_a + \omega(2501 + 1.88T_a) \qquad (10)$$

where the unit of T_a is °C and h_a is kJ/kg-dry air.

4. Heat and Mass Transfer on the Packing.

To study the behavior of the heat and mass transfer between air and water film on the surface of the packing, we should set up the representative equations of models that are based on the conservation of mass and energy for control volume. The heat and mass transfer on the packing can be exchanged simultaneously at air-water interface (Mills, 1995). The water flows as thin film down over the packing in which the water evaporates into the upward moving air stream and exchanges heat and mass together. For usual operating conditions, the latent heat of evaporation q''_{evap} is considerably larger than the convective heat transfer rate q''_{conv} on the packing surface.

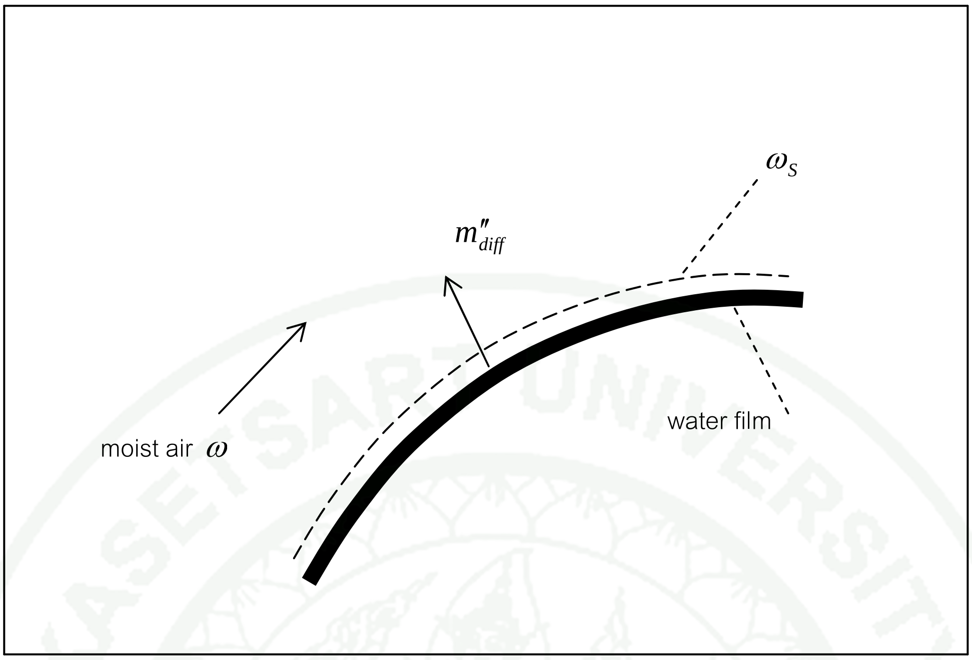


Figure 3 Convective mass transfer from the water film into the air flow.

The convective heat transfer from water film into air stream can be obtained

$$q''_{conv} = \alpha(T_s - T_\infty) \tag{11}$$

Based on the low mass transfer rate theory, the rate of evaporation of water film on the packing can be approximated as

$$m''_{diff} = \frac{G_m(\omega_s - \omega)}{(1+\omega_s)(1+\omega)} \tag{12}$$

Assuming a Lewis number of unity for the dilute water vapor and air mixture, thus we will let $G_m = G_h$ and the convective heat transfer can be written as

$$q''_{conv} = \alpha(T_f - T_a) = G_m C'_{pa}(T_f - T_a) \tag{13}$$

and the latent heat of vaporization of water film is

$$q''_{evap} = m''_{diff} h_{flm} \tag{14}$$

where h_{flm} can be written as:

$$h_{flm} = h_{fg,ref} + \int_{T_{ref}}^{T_f} C_{pv} dT \tag{15}$$

5. Volumetric Heat Transfer Coefficient

The method of calculating the volumetric heat transfer coefficient of cooling tower (KaV/L) was originally developed by Merkel, this has been called that “Merkel’s Method”. In general, the heat transfer from water to air can be determined on the water side and the packing side, where the water descends downward with a flow rate of L and volumetric heat transfer coefficient of packing Ka and we can use the energy balance. So, it can be written as:

$$LC_w dT_w = Ldh_w = KadV(h_s - h_a)$$

$$\frac{Ka.dV}{L} = \frac{dh_W}{(h_S - h_a)} \tag{16}$$

which can be integrated by using a lower limit at $V = 0$, then $h_w = h_{w,out}$ and an upper limit at $V = V$, then $h_w = h_{w,in}$. So, it can be written as:

$$\frac{KaV}{L} = \int_{h_{w,out}}^{h_{w,in}} \frac{dh_w}{(h_s - h_a)} \tag{17}$$

Energy balance between air and water stream for differential control volume of packing can be written as:

$$Gdh_a = Ldh_w \quad , \quad dh_a = \left(\frac{L}{G}\right)dh_w \tag{18}$$

The ratio L/G can be assumed constant, Eq.(18) can be integrated from the bottom of tower where $h_a = h_{a,in}$ and $h_w = h_{w,out}$. At any divided cross section of packing, the enthalpy of moist air can be written as:

$$h_a = h_{a,in} + \left(\frac{L}{G}\right)(h_w - h_{w,out}) \tag{19}$$

The Eq.(18) can be integrated numerically by using the trapezoidal rule.

6. Characteristics and Performance of Cooling Towers

Cooling tower characteristics are generally presented in the form of an empirical correlation. This correlation defines the relationship between the available coefficient KaV/L and water-air flow ratio L/G under the operating conditions. Cooling tower data are most often plotted in the form of KaV/L versus L/G for various wet bulb temperature (approach) and cooling range. These graphs have been published by the Cooling Tower Institute (CTI).

Common practice is to neglect the effect of air velocity and develop the tower correlation in the form of a power law relation:

$$\frac{KaV}{L} = C\left(\frac{L}{G}\right)^{-n} \tag{20}$$

The value of $a_m G_m$ can be determined from this characteristic equation of packing which is considered in the dimensionless term of $Ha_m G_m / L' = KaV / L$ and $a_m G_m$ can be expressed as:

$$a_m G_m = \frac{CL'}{H}\left(\frac{L}{G}\right)^{-n} \tag{21}$$

A commercial cooling tower is to be used to perform the structural equipment of model, which can be operated and tested in accordance with the CTI standard.

Cooling tower performance is specified in terms of the cooling range, approach, wet bulb temperature, and water flow rate. The rating of a tower is established by developing series of charts that relate these variables.

7. Calculation of Kav/L using the Tchebycheff's Method

The Tchebycheff method for numerically evaluating the integral $\int_a^b ydx$ uses values of y at predetermined values of x within interval a to b, so 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 selected four-point form the values of y are taken at values of x of 0.102673 ….0.406204….0.593796…and 0.897327…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 as:

$$\int_a^b ydx = \frac{(b-a)}{4}(y_1 + y_2 + y_3 + y_4) \tag{22}$$

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 $x = b - 0.4(b-a)$

y_5= value of y at $x = b - 0.1(b-a)$

For the evaluation of KaV/L, it can be determined by substituting $dh_w = C_w dT$ into Eq.(17) and Eq.(22) :

$$\frac{KaV}{L} = \frac{C_w(T_1 - T_2)}{4}\left[\frac{1}{\Delta h_1} + \frac{1}{\Delta h_2} + \frac{1}{\Delta h_3} + \frac{1}{\Delta h_4}\right] \tag{23}$$

where

Δh_1 = value of $(h_s - h_a)$ at $T_2 + 0.1(T_1 - T_2)$

Δh_2 = value of $(h_s - h_a)$ at $T_2 + 0.4(T_1 - T_2)$

Δh_3 = value of $(h_s - h_a)$ at $T_1 - 0.4(T_1 - T_2)$

Δh_4 = value of $(h_s - h_a)$ at $T_1 - 0.1(T_1 - T_2)$

8. Stepwise Integration

The volumetric heat transfer coefficient can also be found using the stepwise integration method. From Eq.(17), it can be determined as:

$$\frac{KaV}{L} = \int \left(\frac{1}{h_s - h_a}\right) dh_w \approx C_w \Delta T_{increment} \sum \frac{1}{(h_s - h_a)_m} \tag{24}$$

where $\Delta T_{increment} = \frac{\Delta T}{N} = \frac{T_1 - T_2}{N}$ (25)

9. Uncertainty Analysis for Calibrating the Orifice Flow Meter

Calibration

The calibration of all instruments is important to reduce errors in accuracy. For example an orifice flow meter can be calibrated by a comparison of particular instrument as follows:

1. Comparing it with a standard flow measurement facility of the National Bureau of Standards, or

2. Comparing it with another flow meter of known accuracy, or

3. Direct calibration with a primary measurement such as weighing a certain amount of water in a tank and recording the time elapsed for this quantity to flow through the meter.

For this study, item 3 has been selected for calibration of an orifice flow meter. This technique provides a means for measuring flow rates of water passing through the orifice in the difference of mercury levels in the manometer as shown in Appendix Figure A4. The flow rate can be determined by collecting the flowing water in a weighing tank on the platform scale for some convenient time interval. During the calibration period, the flow is held as constant as possible and the height difference in the manometer can be recorded.

In the experiments, the orifice flow meter is used to measure the steady state fluid flow as shown in Figure 4. The actual flow rate of water passing through this flow meter can be expressed as

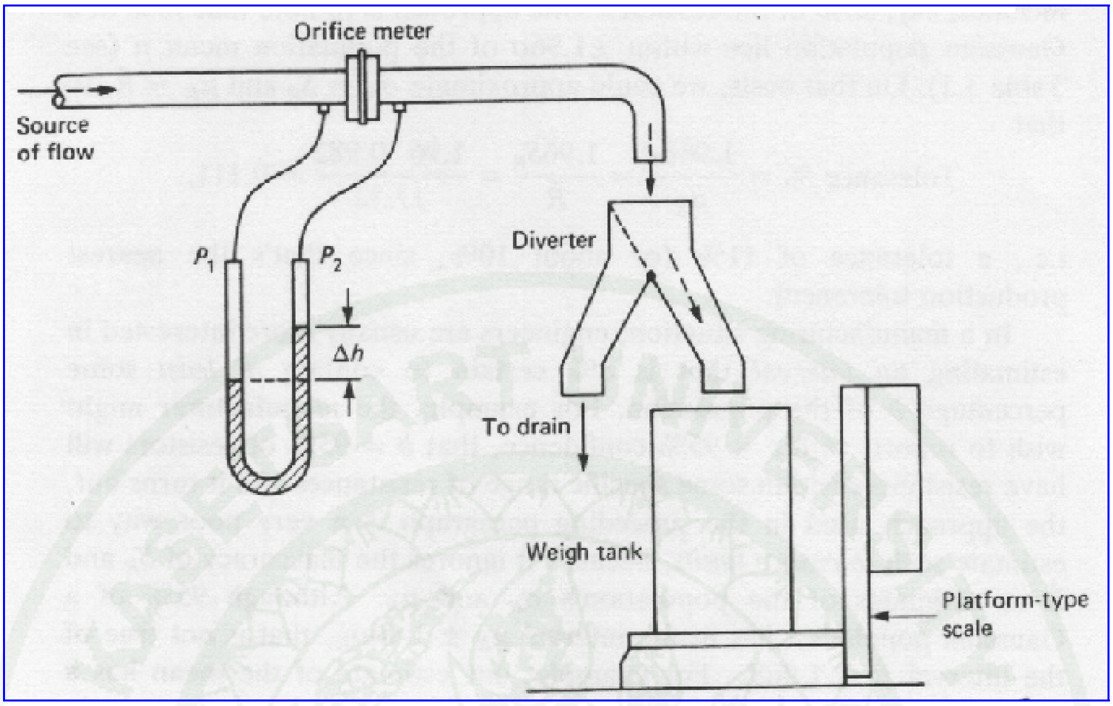


Figure 4 Setup for calibrating the orifice flow meter.

Source: Bechwith *et al*. (1993)

$$\dot{V}_{or} = K_{or} A_{or} \sqrt{\frac{2g(SG_{Hg} - 1)\Delta h_{mano}}{1 - \frac{D_{or}^4}{D_{pipe}^4}}} \tag{26}$$

This technique provides a means for measuring flow rates of water passing through the orifice in terms of difference of mercury levels in the manometer. Figure 4 shows an arrangement for steady state calibration of a thin plate orifice. The calibration consists of experimentally determining the coefficient K_{or} in Eq.(26) by collecting the flowing water in a weighing tank on platform scales for some convenient time interval, $\dot{V}_{or} = W / \rho t$. During the calibration period the flow has to remain as constant as possible and the height difference of mercury in the manometer, Δh_{mano} can be recorded.

Eq.(26) can be written in the form of a straight line as:

$$\dot{V}_{or} = \left(\frac{\pi D_{or}^2}{4} \sqrt{\frac{2g(SG_{Hg}-1)}{1-\frac{D_{or}^4}{D_{pipe}^4}}} \right) K_{or} \sqrt{\Delta h_{mano}} \tag{27}$$

Analysis of the uncertainty

The uncertainty of the experimentally determined value of the flow coefficient, u_K can be estimated in terms of the uncertainty in line fits of data ($\Delta h_{mano}, \dot{V}_{or}$) which can be obtained from calibration of the orifice flow meter. When the precision error in y is substantially greater than that in x, the method of least squares can yield good line fits through the data in the form of y = a + b x (where x = $\sqrt{\Delta h_{mano}}$ and y = $\dot{V}_{or}$).

From line fitting can be obtained by the method of least square, the result of least square is

$$\dot{V}_{or} = a + b\sqrt{\Delta h_{mano}} \tag{28}$$

As you know the slope of a fitted line, the flow coefficient can be calculated as:

$$K_{or} = \frac{b}{\frac{\pi D_{or}^2}{4} \sqrt{\frac{2g(SG_{Hg}-1)}{1-\frac{D_{or}^4}{D_{pipe}^4}}}} \tag{29}$$

The fitted line can be obtained by the method of least squares, the uncertainty of the flow coefficient can be determined by the statistical tests of least squares results within some confidence interval.

The total squared variation of the data set (both the precision error and straight – line variation of y with x) is defined as:

$$S_{yy}^2 = \sum_{i=1}^{n} (y_i - y_m)^2 \tag{30}$$

where n is the number of experimental observations and y_m is the mean measured y_i with $y_m = \frac{1}{n}\sum_{i=1}^{n} y_i$.

The mean total variation is defined as:

$$s_{yy}^2 = \frac{S_{yy}^2}{n-1} = \frac{\sum_{i=1}^{n} y_i^2 - \frac{1}{n}(\sum_{i=1}^{n} y_i)^2}{n-1} \tag{31}$$

The standard error of the y- data about the fitted line, $s_{y/x}$ can be determined as:

$$\frac{s_{y/x}}{s_{yy}} = \left(\frac{n-1}{n-2}\right)^{1/2} \left(1 - r^2\right)^{1/2} \tag{32}$$

where r^2 is the correlation coefficient of the fitted line.

As the least squares is justifiable, the confidence interval for the slope can be calculated under the assumption that the precision error in y_i satisfies the normal distribution. In this case, the true slope lies within the c% confidence interval and it can be written as:

$$(Slope_{fit\ line} - t_{\alpha/2,\upsilon} \frac{s_{y/x}}{S_{xx}}) < True\ \ slope < (Slope_{fit\ line} + t_{\alpha/2,\upsilon} \frac{s_{y/x}}{S_{xx}}) \tag{33}$$

where $t_{\alpha/2,\upsilon}$ is the t-statistics with ν degrees of freedom at a α level of significance (where $\upsilon = n-2$ and $\alpha = (1-c)$) , and S_{xx}^2 can be determined as:

$$S_{xx}^2 = \sum_{i=1}^{n} x_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right)^2 \tag{34}$$

So, the interval for flow coefficient can be calculated as:

$$(Slope_{fit\ line} - t_{\alpha/2,\upsilon}\frac{s_{y/x}}{S_{xx}}) / \left(t_{\alpha/2,\upsilon}\frac{s_{y/x}}{S_{xx}} / \frac{\pi D_{or}^2}{4}\sqrt{\frac{2g(SG_{Hg}-1)}{1-\frac{D_{or}^4}{D_{pipe}^4}}} \right) < True\ K_{or} <$$

$$(Slope_{fit\ line} + t_{\alpha/2,\upsilon}\frac{s_{y/x}}{S_{xx}}) / \left(t_{\alpha/2,\upsilon}\frac{s_{y/x}}{S_{xx}} / \frac{\pi D_{or}^2}{4}\sqrt{\frac{2g(SG_{Hg}-1)}{1-\frac{D_{or}^4}{D_{pipe}^4}}} \right) \tag{35}$$

Using Eq.(29) and (35), the error of flow coefficient can also be determined.

10. Calibration of the K-type of Thermocouple

The calibration of temperature sensors are usually accomplished by the freezing point method (boiling-point method), the melting-wire method, and the comparison method. In this thesis, we used the K-type of thermocouples to measure the water and air temperature. Accordingly, we had to calibrate the thermocouple before measuring for the experiments, and we selected the comparison method for calibration.

The scale may have a fixed offset error, so that the indicated value for every reading of temperature from the K-type of thermocouple is higher than the true value by an amount the offset value.

For the ideal response, it can be found that the measured value equals the true value of temperature, $T_{measured} = T_{true}$. The actual response can include the zero-offset error (T_{offset}) and scale error (β) so that we can obtain in the form of

$$T_{measured} = \beta \cdot T_{true} + T_{offset} \tag{36}$$

On plotting temperatures of the thermocouple reading versus on temperatures of the thermometer reading. This fitted line of actual response can be obtained by the least square method. So, we can obtain the scale error, β and the zero-offset errors, T_{offset}.

MATERIALS AND METHODS

Materials

This research could be classified into two parts as follows:

1. Instrument for Simulating and Computing Mathematical Packing Models

1.1 A computer with a CPU speed of 677 MHz.

1.2 The program “Visual Basic” version 6.

2. Experiments Lab

2.1 The Counter-flow Cooling Tower Testing Laboratory

The counter-flow cooling tower testing laboratory included a circulating system of cooled water (the outlet water of the cooling tower) and hot water (the inlet water of the cooling tower) as shown in Figure 5. The components of counter-flow cooling tower system could be classified as follows:

Figure 5 Setup of the counter-flow cooling tower for experiments.

2.1.1 The counter-flow cooling tower for experiment.

In this study, a commercial cooling tower with a refrigeration capacity of 5 tons was used as the structural equipment of the model, which could be operated and tested in accordance with the CTI standard.

In Figure 6, the counter-flow cooling tower was the heat exchanger between the hot water and the air. The given specifications were as follows:

- The refrigeration capacity of the cooling tower	5	tons
- Water volume flow rate	65	L/min
- Air volume flow rate	55	m^3/min
- Hot water temperature	37	^{o}C

- Cold water temperature	32	^{o}C
- Inlet wet bulb temperature	27	^{o}C
- Fan horsepower	0.20	hps

Figure 6 Counter-flow cooling tower for the experiments.

2.1.2 The water pumps

The experimental lab had three units of water pumps and their details were as follows:

Cold water pump

A cold water pump was used to pump the water from the cold water tank to the heater tank and it had a discharge pressure of 22 m, a pumping flow rate of 10-80 L/min, a motor horsepower of 0.37 kW, a motor speed of 2900 rpm, and a water connection pipe with a diameter of 25 mm.

Hot water pump

A hot water pump was used to pump the water from the heater tank to the cooling tower and it had the same specifications as the cold water pump.

Balancing pump

A balancing pump was used to control the level of water in the heater tank, the cold water tank, and the water basin of the cooling tower. It operated at a discharge pressure of 35 m, a pumping flow rate of 30 L/min, a motor horsepower of 0.33 kW, a motor speed of 2900 rpm, and a water connection pipe with a diameter of 25 mm.

2.1.3 Water tank

The experiment lab used the water tank with three units of tanks and their details were as follows:

Heating tank

A heating tank was used to supply the hot water for testing the cooling tower and it had seven units of heater. Each unit had a capacity of 2 kW and used a current of 9.09 A and a voltage of 220 V.

Cold water tank

A cold water tank and a pump were used to supply cold water to fill the heating tank and it had a volume of 240 liters.

Balancing tank

A balancing tank was used to supply water for controlling the water level in the heating tank, the cold water tank, and the water basin of cooling tower during testing and experiments. It had a volume of 200 liters, a height of 85 cm, and a diameter of 55 cm.

2.2 Devices for measuring the water flow rate.

The water flow rate was measured by an orifice meter and a differential manometer.

- An orifice plate with 1D and $\frac{1}{2}$D taps was designed from the standard ASME PCT19.5: 4 – 1959, as shown in Figure 7 and the details of the orifice plate was illustrated in Appendix G.

Figure 7 Orifice plate for measuring the water flow rate.

- A manometer was used to measure the pressure drop across the orifice plate by showing a different height of mercury with a range from 0 to 300 mm of Hg and its dimension was of 60 mm x 440 mm x 28 mm as shown in Figure 8.

Figure 8 Manometer for measuring the pressure drop across an orifice plate in the different height of mercury.

2.3 Instrument for Measuring and Recording the Air Velocity (Anemometer).

An anemometer was used to measure and record the air velocity by measuring the outlet air velocity (at the top of packing) as shown in Figure 9.

Specifications of the anemometer were as follows:

- Anemometer with a fan diameter of 10 mm.
- Range of measuring the air velocity was from 0.2 to 20 m/s.
- Resolution was 0.1 m/s.
- Accuracy was $\pm$ 3 % of the reading.
- Internal battery was 3 volts.

Figure 9 Anemometer for measuring and recording the air velocity.

2.4 Digital Instrument for Measuring and Recording Temperatures.

The digital instrument and temperature recorder was used to measure the water and air temperatures namely, the wet bulb and dry bulb temperature, the inlet and outlet temperatures of water, and the water film temperature. This instrument was shown in Figure 10.

Specifications of this instrument were as follows:

- Sensor for measuring temperatures used the K-type of thermocouples.
- Range of measuring temperatures was from -70 to +1100 ^{o}C.
- Resolution was 0.1 ^{o}C.
- Accuracy was $\pm$ 0.2 % of the reading $\pm$ 0.2 ^{o}C.
- Measuring and recording temperatures on a maximum of 10-channels.

- External power supply used a voltage of 230 volts (a.c. current) and a frequency of 50 Hz.

Figure 10 Digital instrument for measuring and recording temperatures.

2.5 Dry Bulb and Wet Bulb Thermometer in Glass -Tube Type.

This instrument was used to measure the dry bulb and wet bulb temperatures of the air by measuring the inlet air temperature (at the bottom of packing) as shown in Figure 11.

Specifications of the thermometer were as follows:

- Glass tube contained a liquid substance as alcohol.
- Range of temperature measurement was from -10 to +50 ^{o}C.
- Resolution was 0.1 ^{o}C.

Figure 11 Dry bulb and wet bulb thermometer of the glass tube type.

2.6 Platform Scale and Weighing Tank

The calibration consisted of experimentally determining the coefficient K_{or} in Eq.(26) by collecting the flowing water in the weighing tank on the platform scale as shown in Figure 12 and 13. This calibration used the weighing tank with a volume of 100 liters and the platform scale with a range from 0 to 150 kg.

Figure 12 Weighing tank with a volume of 100 liters.

Figure 13 Platform scale with a range of 0 – 150 kg.

2.7 Temperature Measurement Bench

In this thesis, we used the K-type of thermocouples to measure the water and air temperature. Accordingly, we had to calibrate the thermocouple before measuring in the experiments, and we chose the comparison method for the calibration. In laboratory, we used the temperature measurement bench for the calibration of thermocouples as shown in Figure 14.

Figure 14 Temperature Measurement Bench.

The procedure of calibration could be discussed as:

1) Fill the water heater with clean water, locate the heater on the bench, and connect the power cord.

2) Locate the platen above the water heater.

3) Remove two chromel/alumel thermocouples (red and black sleeves) from the storage case and connect these thermocouples together as indicated overleaf.

4) Locate both thermocouples in the vacuum flask and observe that the milli-voltmeter reads mV.

5) Transfer one thermocouple to the water heater and locate the sheath in the appropriate hole in the platen.

6) Record the reading on the milli-voltmeter together with the temperature indicated on the thermometer.

7) Operate the rocker switch adjacent to the water heater power regulator and turn the regulator to approximately 50 %.

8) As the water temperature rises, record the readings on the milli-voltmeter and the thermometer.

9) Continue recording the voltage and temperature up to the boiling point.

10) When the experiment is completed, turn the water heater power regulator fully counter-clockwise and turn the rocker switch (on / off) to isolate the mains supply from the water heater.

Methods

1. To Set Up the Mathematical Model of Packing for Predicting Heat and Mass Transfer between Water Film and Air on the Packing.

The conservation of mass and energy was used to consider the mathematical model, which these equations of conservation are related. The detail of the consideration in the mathematical model for predicting the heat and mass transfer between water film and air in the counter-flow cooling tower was as follows:

1.1 Assumptions for the Mathematical Model of Packing

To study the behavior of heat and mass transfer between air and water film on the surface of the packing, we should set up the representative equations of models were based on the concept of heat and mass balance. It was important to understand the mechanism of this transport phenomenon first. Therefore, the energy and mass balance were the concepts for determining of the governing differential equations in this model.

Before deriving the governing equations, the following assumptions were made:

1) Heat and mass transfer were the stead-state and steady flow process.

2) The water film temperature was equal to the water temperature at a vertical position of the packing.

3) The effect of water drift loss on this simulation model was negligible.

4) The contact areas of heat and mass transfer were the same.

5) The specific heat of dry air, water vapor and water were constant. For the moist air, its specific heat was the sum of the specific heat of dry air and the product of the humidity ratio and the specific heat of water vapor.

6) At an intermediate horizontal cross section of the packing, temperatures of water and air were uniformly throughout the cross sectional area of packing.

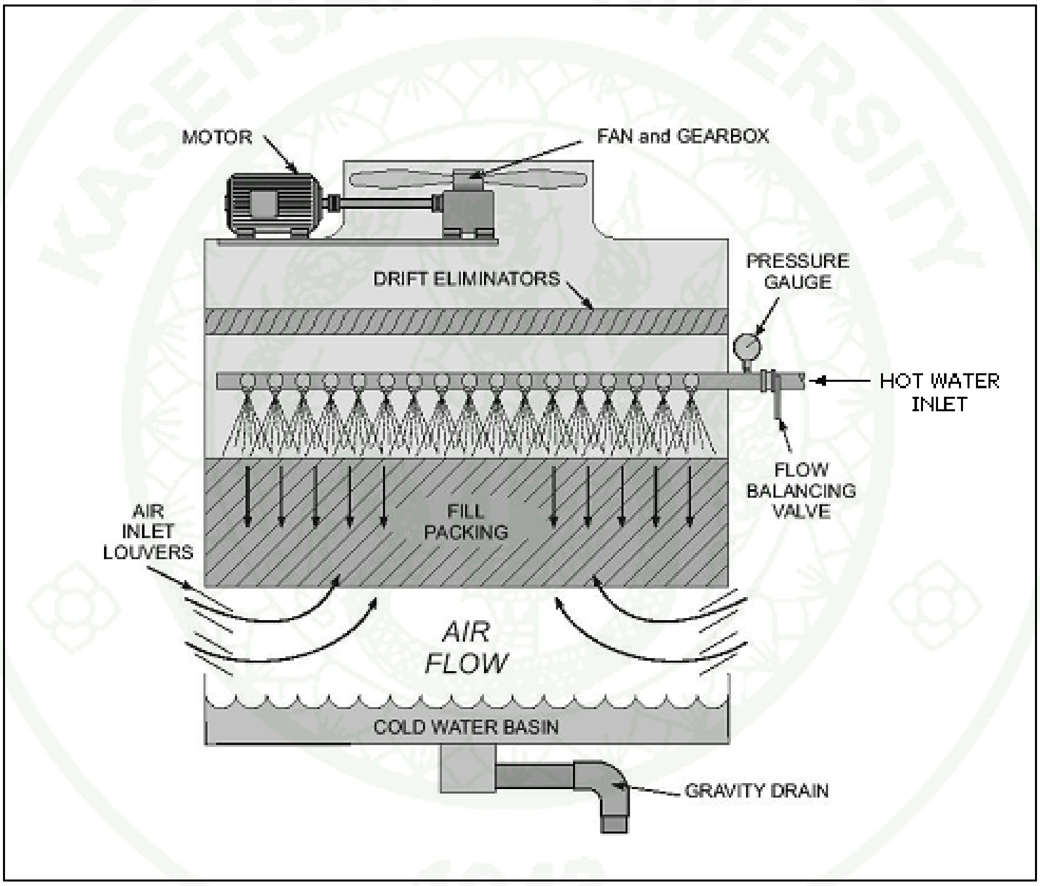


Figure 15 Configuration of the counter-flow cooling tower for the mathematical models of packing.

7) Lewis number equaled 1.

8) The cooling tower operated at an atmospheric pressure of 1 atm.

1.2 The Mathematical Model of Heat and Mass Transfer on the Packing.

1.2.1 Mass Conservation of the Water Vapor in Air.

In Figure 16, the mass balance of water vapor in the air stream on the differential control volume contains a transfer area ΔA and height Δz. Consider the differential control volume with the constant cross sectional area of packing and a transfer area, $\Delta A = a_m A_{fr} \Delta z$, the mass conservation of water vapor in the upward

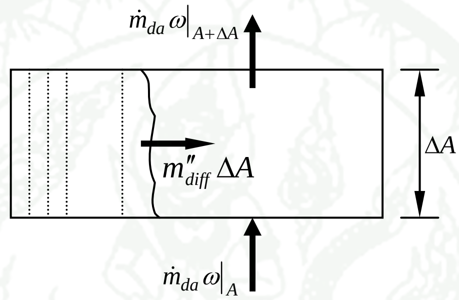


Figure 16 Mass diffusion of the water vapor into the air stream on the control volume with an area, ΔA.

moving air stream can be written as :

$$\dot{m}_{da}\,\omega\big|_{A+\Delta A} - \dot{m}_{da}\,\omega\big|_{A} = m''_{diff}\,\Delta A \tag{37}$$

Based on the low mass transfer rate theory, the rate of evaporation of water film on the packing can be approximated as:

$$m''_{diff} = G_m\,(\omega_s - \omega)\,/(1 + \omega_s)(1 + \omega) \tag{38}$$

Substituting Eq.(38) into Eq.(37) and dividing by Δz and letting Δz approach zero, it can be written as:

$$\frac{d\omega}{dz} = \frac{A_{fr} a_m G_m (\omega_s - \omega)}{\dot{m}_{da} (1+\omega_s)(1+\omega)} \tag{39}$$

1.2.2 Mass Conservation between Water Film and Water Vapor in the Air.

In Figure 17, the mass balance of water vapor in the upward moving air stream and the downward moving water for the differential control volume that contains a transfer area, ΔA. The mass conservation for water film and vapor in the air

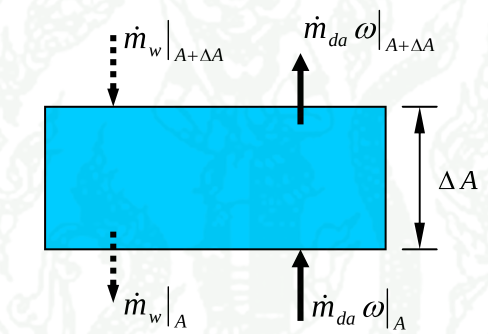


Figure 17 Mass balance of the water vapor in the upward moving air stream and the downward moving water.

stream can be written as:

$$\dot{m}_{da}\,\omega|_{A+\Delta A} - \dot{m}_{da}\,\omega|_A + \dot{m}_w|_A - \dot{m}_w|_{A+\Delta A} = 0 \tag{40}$$

Rearranging and Dividing Eq.(40) by Δz and letting Δz approach zero. By using Eq.(39), the differential change of water mass flow rate can be written as:

$$\frac{d\dot{m}_w}{dz} = \dot{m}_{da}\frac{d\omega}{dz} = \frac{A_{fr}a_m G_m(\omega_s - \omega)}{(1+\omega_s)(1+\omega)} \tag{41}$$

1.2.3 Energy Conservation of Water on the Packing Surface Area.

In Figure 18, the energy balance of heat transfer from the water film and enthalpy of the moist air stream in the differential control volume of packing can be considered as the transfer mechanism for the sensible heat transfer, $q''_{conv}\Delta A$ and the latent heat due to mass transfer, $m''_{diff}\Delta A h_{flm}$. The energy conservation of the control volume can be written as:

$$\dot{m}_{da}h_a\big|_{A+\Delta A} - \dot{m}_{da}h_a\big|_{A} = q''_{conv}\,\Delta A + (m''_{diff}\,\Delta A)h_{flm} \tag{42}$$

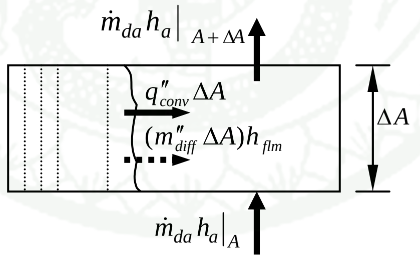


Figure 18 Heat and mass transfer from the water film to the upward moving air stream.

Dividing Eq.(42) by Δz and letting Δz approach zero, the differential change of water mass flow rate can be written as:

$$\dot{m}_{da}\frac{dh_a}{dz} = A_{fr}a_m G_m(q''_{conv} + m''_{diff}\,h_{flm}) \tag{43}$$

Substituting $G_m = G_h$, the convective heat transfer can be written as $q''_{conv} = \alpha(T_f - T_a) = G_m C'_{pa}(T_f - T_a)$ and the specific heat of moist air is used in the form of $C'_{pa} = (1.005 + 1.88\omega)/(1+\omega)$. Hence, the air enthalpy can be determined in the form of $h_a = 1.005T_a + \omega(2501 + 1.88T_a)$ and the differential equation of T_a can be expressed as:

$$\frac{dT_a}{dz} = \frac{A_{fr} a_m G_m}{\dot{m}_{da}(1.005 + 1.88\omega)} \left[\begin{array}{l} \dfrac{(1.005+1.88\omega)}{1+\omega}(T_f - T_a) \\ + \dfrac{(\omega_s - \omega)h_{flm}}{(1+\omega_s)(1+\omega)} - \dfrac{(2501 + 1.88T_a)(\omega_s - \omega)}{(1+\omega_s)(1+\omega)} \end{array} \right] \tag{44}$$

1.2.4 Energy Conservation between the Water Film and the Air.

In Figure19, the differential control volume contains a transfer area ΔA, the energy conservation for the downward moving water and the upward moving air passing through the control volume can be written as:

$$(\dot{m}_w h_w)\big|_{A+\Delta A} - (\dot{m}_w h_w)\big|_{A} = \dot{m}_{da}(h_a\big|_{A+\Delta A} - h_a\big|_{A}) \tag{45}$$

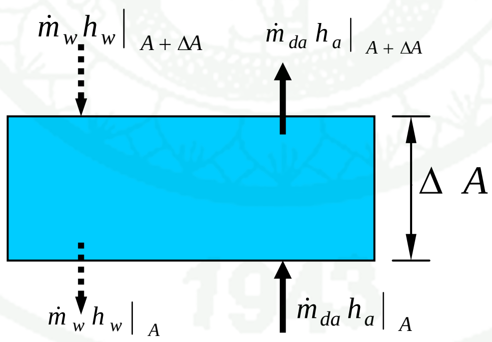


Figure 19 Energy balance of the downward moving water and the upward moving air.

Dividing Eq.(45) by Δz and letting Δz approach zero, the differential change of water enthalpy can be expressed as:

$$\frac{d(\dot{m}_w h_w)}{dz} = \dot{m}_w \frac{dh_w}{dz} + h_w \frac{d\dot{m}_w}{dz} = \dot{m}_{da} \frac{dh_a}{dz} \tag{46}$$

Substituting Eq.(43) and (44) into Eq.(45), we obtain the change of water enthalpy as:

$$\frac{dh_w}{dz} = \frac{A_{fr} a_m G_m}{\dot{m}_w}\left[\frac{(1.005+1.88\omega)}{1+\omega}(T_f - T_a) + \frac{(\omega_s - \omega)h_{flm}}{(1+\omega_s)(1+\omega)} - \frac{(\omega_s - \omega)h_w}{(1+\omega_s)(1+\omega)}\right] \tag{47}$$

To fit the representative equations for the water enthalpy by using the steam tables in a range of water temperature from 25 to 49°C, the relationship of h_w and T_f can be expressed as $h_w = 4.179T_f + 0.4164$. The differential equation of T_f can be obtained in the form of

$$\frac{dT_f}{dz} = \frac{A_{fr} a_m G_m}{4.179\dot{m}_w}\left[\frac{(1.005+1.88\omega)}{1+\omega}(T_f - T_a) + \frac{(\omega_s - \omega)h_{flm}}{(1+\omega_s)(1+\omega)} - \frac{(\omega_s - \omega)(4.179T_f + 0.4164)}{(1+\omega_s)(1+\omega)}\right] \tag{48}$$

Finally, the four governing differential equations for this model are completed, which are Eq. (39), (41), (44), and (48), respectively.

1.3 The Necessarily Required Relations.

Before proceeding with the simulation of these four governing equations, we must define the various terms in these equations. The required relations are used to solve any parameters in the four governing equations as follows:

Enthalpy of the water film;

$$h_{flm} = 2501 + 1.789T_f + 5.337x10^{-5}[(T_f + 273.15)^2 - 273.16^2]$$
$$+1.952x10^{-7}[(T_f + 273.15)^3 - 273.16^3] - 5x10^{-11}[(T_f + 273.15)^4 - 273.16^4] \quad (49)$$

Saturated pressure of the water vapor in the atmospheric air;

For $6^o C \le T_{wb} \le 28^o C$;

$$P_s = 0.0034T_{wb}^2 + 0.0108T_{wb} + 0.7645 \quad (50)$$

For $28^o C \le T_{wb} \le 60^o C$;

$$P_s = 0.0109T_{wb}^2 - 0.4754T_{wb} + 8.7967 \quad (51)$$

Saturated pressure of vapor at the temperature of water film, P_{sf} can be determined from Eq. (50) and (51).

Latent heat of the water vaporization and enthalpy of the saturated liquid water;

For $5^o C \le T_{wb} \le 60^o C$;

$$h_{fg} = 2501.8 - 2.387T_{wb} \quad (52)$$

$$h_f = 4.182T_{wb} + 0.2293 \quad (53)$$

Also, the humidity ratio and the specific heat of air can be determined from Eq.(1), (2), (8) and (9), respectively.

Density of water

$$\rho_f = 2.116235x10^{-10}(T_f + 273.15)^6 - 4.0524x10^{-7}(T_f + 273.15)^5 + 3.221635x10^{-4}(T_f + 273.15)^4$$
$$-1.36077x10^{-1}(T_f + 273.15)^3 + 32.1989(T_f + 273.15)^2 - 4045.674(T_f + 273.15) + 211816.2$$

(54)

Water mass flow rate;

$$\dot{m}_w = \frac{\rho_f \left(\dot{V}_w x 10^{-3}\right)}{60} \tag{55}$$

Mass flow rate of the moist air and the mass flow rate of dry air;

$$\dot{m}_a = \frac{\dot{V}_a}{v_a} \tag{56}$$

$$\dot{m}_{da} = \frac{\dot{m}_a}{(1+\omega)} \tag{57}$$

where

$$v_a = \frac{(0.082T_a + 22.4135)(\frac{1}{29} + \frac{\omega}{18})}{1+\omega} \tag{58}$$

The calculation of wet bulb temperature at a vertical position of the packing can be proceeded by using equation (1) with the known dry bulb temperature and humidity ratio at that position by using the technique of trial and error.

1.4 Solving of the Governing differential Equations for this Model.

These four governing equations and four operating variables namely, ω, $\dot{m}_w$, T_f, and T_a of this model can be given by $f_1 = dT_a / dz$, $f_2 = dT_f / dz$, $f_3 = d\omega / dz$, and $f_4 = d\dot{m}_w / dz$. The recursion equations can be given by relationships as:

$$T_{a,i+1} = T_{a,i} + \frac{a_1 + 2a_2 + 2a_3 + a_4}{6} \tag{59}$$

$$T_{f,i+1} = T_{f,i} + \frac{b_1 + 2b_2 + 2b_3 + b_4}{6} \tag{60}$$

$$\omega_{i+1} = \omega_i + \frac{c_1 + 2c_2 + 2c_3 + c_4}{6} \tag{61}$$

$$\dot{m}_{w,i+1} = \dot{m}_{w,i} + \frac{d_1 + 2d_2 + 2d_3 + d_4}{6} \tag{62}$$

where

$$a_1 = (\Delta z)\, f_1(T_{a,i}, T_{f,i}, \omega_i) \tag{63a}$$

$$b_1 = (\Delta z)\, f_2(T_{a,i}, T_{f,i}, \omega_i, \dot{m}_{w,i}) \tag{63b}$$

$$c_1 = (\Delta z)\, f_3(\omega_i) \tag{63c}$$

$$d_1 = (\Delta z)\, f_4(\omega_i) \tag{63d}$$

$$a_2 = (\Delta z)\, f_1(T_{a,i} + \frac{a_1}{2}, T_{f,i} + \frac{b_1}{2}, \omega_i + \frac{c_1}{2}) \tag{64a}$$

$$b_2 = (\Delta z)\, f_2(T_{a,i} + \frac{a_1}{2}, T_{f,i} + \frac{b_1}{2}, \omega_i + \frac{c_1}{2}, \dot{m}_{w,i} + \frac{d_1}{2}) \tag{64b}$$

$$c_2 = (\Delta z)\, f_3(\omega_i + \frac{c_1}{2}) \tag{64c}$$

$$d_2 = (\Delta z)\, f_4(\omega_i + \frac{c_1}{2}) \tag{64d}$$

$$a_3 = (\Delta z)\, f_1(T_{a,i} + \frac{a_2}{2}, T_{f,i} + \frac{b_2}{2}, \omega_i + \frac{c_2}{2}) \tag{65a}$$

$$b_3 = (\Delta z)\, f_2(T_{a,i} + \frac{a_2}{2}, T_{f,i} + \frac{b_2}{2}, \omega_i + \frac{c_2}{2}, \dot{m}_{w,i} + \frac{d_2}{2}) \tag{65b}$$

$$c_3 = (\Delta z)\, f_3(\omega_i + \frac{c_2}{2}) \tag{65c}$$

$$d_3 = (\Delta z)\, f_4(\omega_i + \frac{c_2}{2}) \tag{65d}$$

$$a_4 = (\Delta z)\, f_1(T_{a,i} + a_3, T_{f,i} + b_3, \omega_i + c_3) \tag{66a}$$

$$b_4 = (\Delta z)\, f_2(T_{a,i} + a_3, T_{f,i} + b_3, \omega_i + c_3, \dot{m}_{w,i} + d_3) \tag{66b}$$

$$c_4 = (\Delta z)\, f_3(\omega_i + c_3) \tag{66c}$$

$$d_4 = (\Delta z)\, f_4(\omega_i + c_3) \tag{66d}$$

2. To Simulate Programs for Predicting Heat and Mass Transfer between Water Film and Air on the Packing.

We are particularly interested in the models of heat and mass transfer between air and water on the surface area of packing in the counter-flow cooling tower and set the equations of the mathematical models in the differential form. Consequently, we can proceed with the simulation of the set of these equations by using of the fourth-order Runge-Kutta method for solving the operating variables (dry bulb temperature, wet bulb temperature, water temperature, humidity ratio, and water flow rate) at any vertical positions of the packing. The simulation can be dictated by developing computer programs under the given initial operating variables and the increment of the packing height.

3. To Test Validation of the Packing Model.

The objective of this study is to determine the simulation model of the heat and mass transfer between the water film and air at the interface of the packing. The operating variables are the humidity ratio (ω), the water mass flow rate ($\dot{m}_w$), the water film temperature (T_f), and the air temperature (T_a), which can be determined at each vertical position of the packing. The variables of the mathematical models can be calculated by the fourth-order Runge-Kutta method.

The validation of the mathematical models can be considered as follows:

- Testing validation of operating variables (ω, $\dot{m}_w$, T_f, and T_a) by comparison of the mathematical model and the experimental data at each vertical position of the packing.

- Comparison of the volumetric heat transfer coefficient of the cooling tower (KaV/L) by the mathematical models and the Tchebycheff method for the same flow ratio (L/G).

3.1 Testing Validation of Operating Variables by Experimental Data.

Testing validation of the simulation model and the experimental data must be proceeded on the same operating conditions. Practically, the values of ω and $\dot{m}_w$ are difficult to measure, the validation of the mathematical models is specifically to test the water film temperatures at the intermediated sections (T_f) and the outlet temperatures of air and water.

3.1.1 Experimentation for measuring and recording the water film temperature (T_f) and the dry bulb temperature (T_a) using instruments.

The steps of experiments are as follows:

3.1.1.1 To prepare and set up equipment for the experiments:

(a) To divide the packing into 5 cross sectional areas (from the top to the bottom of the packing at positions of 0, 9, 18, 27, 36, and 45 cm, respectively) to install temperature sensors and marking positions for measuring the air velocity using an anemometer.

(b) To check the normal operation of the cooling tower system namely, packing, water distribution system, fan motor, pumps, heaters, pipe systems, orifice plate, manometer, and water tank before commencing operation of the cooling tower system.

(c) To calibrate the orifice plate and the manometer, which is used to measure the water flow rate (see Appendix B).

(d) To install sensors for measuring the dry bulb and wet bulb temperatures at the top and bottom level of packing and to install sensors for measuring the temperature of the water film and air at each vertical position of the packing.

(e) To set up instruments for measuring the temperature and the air velocity.

(f) To connect the measuring sensors to the instrument.

(g) To operate the cooling tower in accordance with the equivalent CTI standard.

3.1.1.2 These are the steps for operating the cooling tower and recording the data:

(a) To fill the heater tank, the cold water tank, and the balancing tank with water equal $^{3}/_{4}$ of tank's height in each tank.

(b) To set up the instruments by controlling the inlet water temperature of the cooling tower at 40 $^{\circ}$C.

(c) To push button on the control panel for starting the circulating water pumps, while the fan motor is stationary. The control panel is illustrated in Figure17 and the initiation system is as follows:

- Push button M1 to start the hot water pump.
- Push button M2 to start the cold water pump.
- Do not push button M4 (don't start the fan motor).

(d) To set the water flow rate of the system by adjusting the position of discharge valve of the cold water pump for the cooling tower operation.

(e) To balance the water flow rate during system testing in step (d) by mutually adjusting the discharge valve of the cold water pump, the discharge valve of the hot water pump, and the balancing valve until the water level in each tank (cold water tank, heater tank, and balancing tank) is constant. In this experiment, the water flow rate should remain constant by mutually controlling the water level at each water tank. Accordingly, the water flow rate can be found by measuring the differential height level of mercury in the manometer.

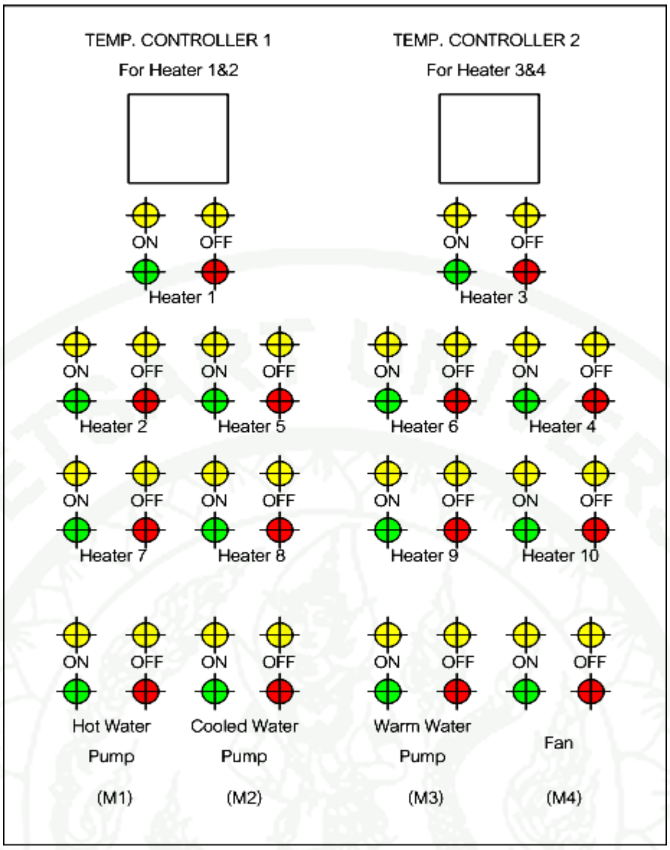


Figure 20 Control panel for operating the cooling tower.

(f) After the hot water temperature of the cooling tower reaches about 1 to 2 °C over 40°C, the fan can be started by pushing button M4 of the control panel.

(g) To adjust the water temperature again (by setting TEMP. CONTROLLER 1 in Figure 20) until the water temperature reaches 40°C.

(h) To wait until the system approaches a steady state of the water temperature and the water flow rate which should remain constant for 15 minutes.

(i) As the inlet water temperature and the dry bulb and wet bulb temperature remain constant, the following data must be measured and recorded every 5 minutes for each setting value of water flow rate:

- Outlet water temperature (at the bottom of the packing).
- Outlet dry bulb and wet bulb temperature (at the top of the packing).
- Water film and air temperature at each vertical position of the packing. The height level of the packing is divided into 6 levels namely 0, 9, 18, 27, 36, and 45 cm from the bottom of the packing.

(j) To measure and record the air velocity passing the cooling tower at the position above the water distribution zone. The air velocity is measured in a total of 20 mark positions by the anemometer (see Appendix C).

(k) After measuring and recording these data in step (i) are complete. Other values of water flow rate can be set by adjusting the cold water valve and mutually balancing water flow by following step (e) to (j) again.

3.1.2 Calculating the operating variables in the packing models for testing validation with the experimental data.

The steps can be classified as follows:

3.1.2.1 To input the initial values of operating variables(inlet dry bulb and wet bulb temperature, inlet water temperature, water volume flow rate, and air volume flow rate) into the computer programs by determining the same values of experimental data.

3.1.2.2 The operating variables in this simulation model are the humidity ratio (ω), the water mass flow rate on the packing model ($\dot{m}_w$), the water film temperature (T_f), the dry bulb temperature (T_a), and the wet bulb temperature (T_{wb}) which should be calculated at the vertical position of the packing.

3.1.2.3 The calculated variables can be solved by running the computer program.

3.1.2.4 To input other initial operating variables and proceed following steps 3.1.2.1 to 3.1.2.3.

4. Testing the Packing Model by the Merkel's Method

As we know the operating conditions of cooling tower (inlet water temperature, inlet wet bulb temperature, inlet dry bulb temperature, circulating water flow, and air flow rate) and select the type of packing with the known characteristic equation, the outlet water temperature (cold water temperature) can be calculated by the Merkel's method.

The procedure of the Merkel's method can be determined as follows:

Given operating conditions;

1) Hot water temperature (HWT)
2) Inlet wet bulb temperature (inlet WBT)
3) Inlet dry bulb temperature (inlet DBT)
4) Circulating water flow
5) Air flow rate

Characteristic equation of the packing; The characteristic equation of packing can be written in the form of

$$\left(\frac{KaV}{L}\right)_{char} = C\left(\frac{L}{G}\right)^{-n} \tag{67}$$

The steps of calculation; The outlet water temperature can be calculated by the Merkel's method, which has a procedure of calculation as follows:

Step 1 Assume the outlet water temperature (CWT) and calculate the mean water temperature like this:

$$T_m = \frac{HWT + CWT}{2} \tag{68}$$

Step 2 The calculated mean water temperature, we can find the water density from table of water properties. On the required conditions, the circulating water flow can be found. The water mass flow rate can be calculated as:

$$L = \rho_w \dot{V}_w \tag{69}$$

Step 3 We can calculate the specific volume of the moist air from

$$v_a = (0.082DBT + 22.4135)\left(\frac{1}{28.9} + \frac{\omega}{18}\right) \tag{70}$$

From the given conditions, the air flow rate ($\dot{V}_a$) can be known. The air mass flow rate can be calculated as:

$$G = \frac{\dot{V}_a}{v_a} \tag{71}$$

Step 4 To calculate the volumetric heat transfer coefficient by substituting the water to air flow ratio (L/G) into the characteristic equation, Eq.(67).

Step 5 To calculate the mean driving force by using the energy balance of air and water as shown in Figure 21,

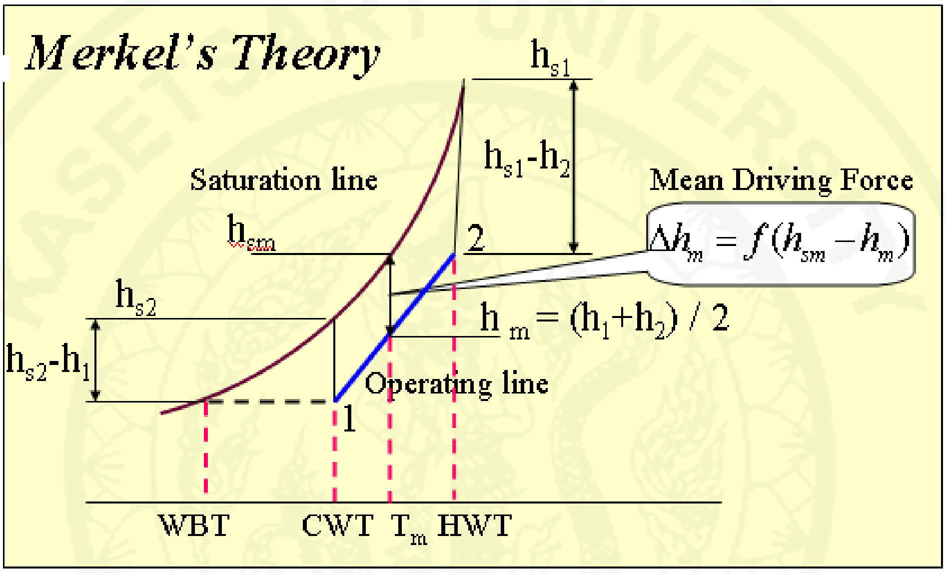


Figure 21 Mean driving force of the Merkel's theory.

The outlet air enthalpy of packing can be calculated as:

$$h_{a2} = h_{a1} + C_w \left(\frac{L}{G}\right)(HWT - CWT) \tag{72}$$

where h_1 is the enthalpy of saturated air at the inlet wet bulb temperature.

Therefore, the mean driving force can be calculated as:

$$\Delta h_m = f(h_{sm} - h_m) \tag{73}$$

where

$h_{sm} = (h_{s1} + h_{s2})/2$ $\qquad$ $h_m = (h_{a1} + h_{a2})/2$

h_{s1} enthalpy of the saturated air at the same inlet water temperature (HWT).

h_{s2} enthalpy of the saturated air at the same outlet water temperature (CWT).

f Steven's factor as shown in Appendix Figure F1.

Step 6 To calculate the volumetric heat transfer coefficient from the energy balance of air and water.

$$\left(\frac{KaV}{L}\right)_{cal} = \frac{C_w(HWT - CWT)}{\Delta h_m} \tag{74}$$

Step 7 To compare $(KaV/L)_{cal}$ with $(KaV/L)_{char}$. If $(KaV/L)_{cal}$ is not equal to $(KaV/L)_{char}$, we should repeat from step1 to step 6 until $(KaV/L)_{cal}$ approaches $(KaV/L)_{char}$.

Step 8 To calculate the outlet wet bulb temperature from enthalpy of saturated outlet air $(h_{sat,out})$ and $h_{sat,out}$ can be calculated from

$$h_{sat,out} = h_{sat,in} + \left(\frac{L}{G}\right)C_w(HWT - CWT) \tag{75}$$

where $h_{sat,in}$ is the enthalpy of saturated air at the inlet wet bulb temperature.

Step 9 To calculate the outlet dry bulb temperature from the energy balance of air and water whilst passing through the packing. So, the enthalpy of outlet air can be calculated from

$$h_2 = h_1 + \left(\frac{C_w \rho_w \dot{V}_w (HWT - CWT)}{\dot{V}_a / v_2}\right) \tag{76}$$

In the psychrometric chart, the specific volume and the enthalpy of moist air can be determined from

$$v_2 = (0.082T_{a2} + 22.436)\left(\frac{1}{29} + \frac{\omega_2}{18}\right)$$

$$h_{a2} = 1.005T_{a2} + \omega_2(2501.6 + 1.868T_{a2})$$

From the aforementioned equations, the iteration technique can be used for solving the outlet dry bulb temperature (T_{a2}) and the flow chart for determining the outlet dry bulb temperature is shown in Figure 22.

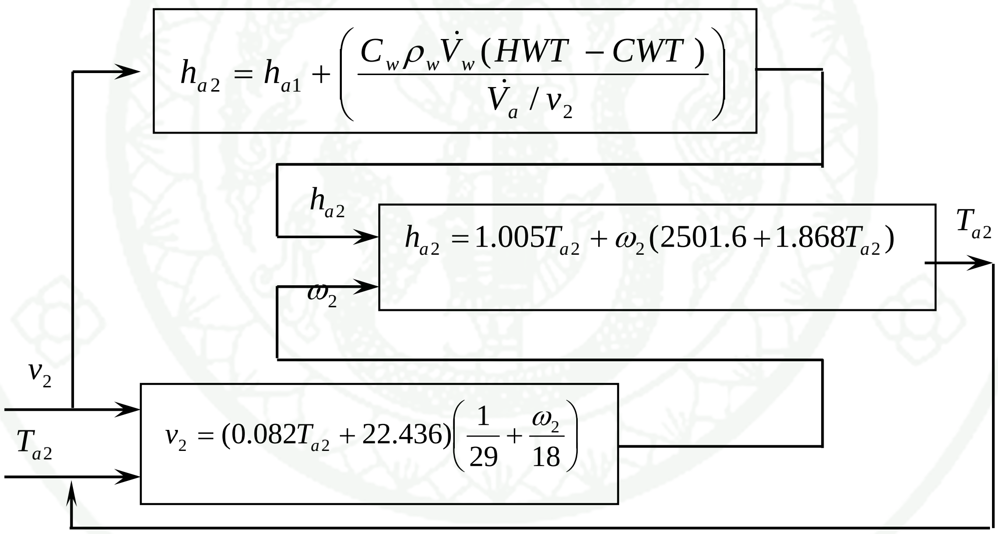


Figure 22 Flow chart for determining the outlet dry bulb temperature.

The outlet water temperature can be calculated in accordance with the Merkel's method, which can be solved by the computer program.

5. Conclusion and Reports

Location and Term of Study

1. Location of Study

The rooftop of the sixth building of the Mechanical Engineering Department was the location for the testing apparatus of the simulation model which is located in the Faculty of Engineering and Kasetsart University (Bangken).

2. Term of Study

The term of study was from November 2006 to November 2007.

RESULTS AND DISCUSSION

The simulation model of heat and mass transfer between water film and air at the interface of corrugated packing in the counter-flow cooling tower can be set up by the conservation of mass and energy, which depends on the given assumptions. It can be set up the four governing equations for this model in the differential form that includes with Eq. (39), (41), (44), and (48), respectively. By running the computer program, the dry bulb temperatures(T_a, °C), the wet bulb temperatures(T_{wb},°C), the water temperatures (T_f,°C), the humidity ratio (ω, kg/kg-da), and the mass flow rate of water ($\dot{m}_w$,kg/s) could be calculated at any vertical positions of the divided section of packing. Accordingly, the volumetric heat transfer coefficient of the cooling tower (KaV/L) was calculated by using the trapezoidal rule.

The operating variables in this simulation model could be solved by the fourth-order Runge-Kutta method. The computer programs were used to apply and run the results of model by giving the same initial conditions of the experimental data.

The testing of validation was to be considered between the simulation model and the experimental data under the same operating and initial conditions. In this thesis, the operating conditions could be set up under the same conditions at inlet dry bulb temperature of 32.3°C, inlet wet bulb temperature of 25.2°C, inlet water temperature of 40°C, and the given three values of L/G ratio. In the simulation of heat and mass transfer, these mathematical models could be determined by the given L/G ratios of 1.800, 2.171, and 2.820 (correspondingly water flow of 31.03, 36.8, and 46.41 L/min).

The details of the experimental data can be seen in Appendix A.

1. **The Calculated Water Film and Air Temperatures by the Simulation Model.**

The air and water temperatures, water flow rates, and humidity ratios at the vertical positions of packing in the cooling tower could be calculated by the given L/G ratio of 1.800, 2.171, and 2.820 as shown in Tables 1, 2, and 3, respectively. However, all operating variables could be solved by the computer program under the same conditions at inlet dry bulb temperature of 32.3^{o}C, inlet wet bulb temperature of 25.2^{o}C, and inlet water temperature of 40^{o}C.

Table 1 Calculated air and water temperatures, water flow rates, and humidity ratios at the vertical positions of packing in the cooling tower under the given L/G ratio of 1.801.

vertical position (m)	dry bulb temperature T_a (^{o}C)	wet bulb temperature T_{wb} (^{o}C)	water film temperature T_f (^{o}C)	water mass flow rate $\dot{m}_w$ (kg/s)	humidity ratio ω
0	32.30	25.20	34.96	0.5159	0.0176
0.012	32.44	25.73	35.24	0.5161	0.0184
0.024	32.58	26.23	35.51	0.5164	0.0192
0.035	32.73	26.72	35.78	0.5166	0.0200
0.047	32.89	27.20	36.04	0.5168	0.0208
0.059	33.05	27.66	36.31	0.517	0.0216
0.070	33.21	28.11	36.57	0.5172	0.0224
0.082	33.38	28.54	36.82	0.5175	0.0232
0.094	33.56	28.96	37.08	0.5177	0.0239
0.106	33.74	29.36	37.33	0.5179	0.0247
0.117	33.92	29.77	37.58	0.5181	0.0254
0.129	34.10	30.15	37.83	0.5183	0.0261
0.141	34.29	30.53	38.07	0.5185	0.0269
0.153	34.48	30.90	38.32	0.5187	0.0276

Table 1 (Continued)

vertical position (m)	dry bulb temperature T_a (°C)	wet bulb temperature T_{wb} (°C)	water film temperature T_f (°C)	water mass flow rate $\dot{m}_w$ (kg/s)	humidity ratio ω
0.164	34.67	31.26	38.56	0.5189	0.0283
0.176	34.87	31.62	38.80	0.5191	0.0290
0.188	35.06	31.96	39.04	0.5193	0.0297
0.200	35.26	32.30	39.28	0.5194	0.0304
0.212	35.46	32.64	39.52	0.5196	0.0311
0.223	35.67	32.97	39.76	0.5198	0.0318
0.235	35.87	33.29	40.00	0.5200	0.0325

Table 2 Calculated air and water temperatures, water flow rates, and humidity ratios at the vertical positions of packing in the cooling tower under the given L/G ratio of 2.171.

vertical position (m)	dry bulb temperature T_a (°C)	wet bulb temperature T_{wb} (°C)	water film temperature T_f (°C)	water mass flow rate $\dot{m}_w$ (kg/s)	humidity ratio ω
0	32.30	25.20	35.54	0.6117	0.0176
0.012	32.47	25.78	35.80	0.6120	0.0185
0.024	32.65	26.33	36.05	0.6122	0.0194
0.035	32.82	26.87	36.30	0.6125	0.0203
0.047	33.00	27.38	36.54	0.6127	0.0211
0.059	33.19	27.87	36.78	0.6129	0.0220
0.070	33.37	28.34	37.01	0.6132	0.0228
0.082	33.56	28.80	37.24	0.6134	0.0236
0.094	33.75	29.24	37.47	0.6136	0.0244

Table 2 (Continued)

vertical position (m)	dry bulb temperature T_a (°C)	wet bulb temperature T_{wb} (°C)	water film temperature T_f (°C)	water mass flow rate $\dot{m}_w$ (kg/s)	humidity ratio ω
0.106	33.95	29.67	37.70	0.6138	0.0252
0.117	34.14	30.08	37.92	0.6140	0.0260
0.129	34.33	30.48	38.14	0.6142	0.0267
0.141	34.53	30.87	38.35	0.6145	0.0275
0.153	34.73	31.24	38.57	0.6147	0.0282
0.164	34.92	31.61	38.78	0.6149	0.0290
0.176	35.12	31.96	38.98	0.6151	0.0297
0.188	35.32	32.31	39.19	0.6153	0.0304
0.200	35.51	32.64	39.39	0.6154	0.0311
0.212	35.71	32.97	39.59	0.6156	0.0318
0.223	35.91	33.29	39.79	0.6158	0.0325
0.235	36.11	33.60	39.99	0.6160	0.0332

Table 3 Calculated air and water temperatures, water flow rates, and humidity ratios at the vertical positions of packing in the cooling tower under the given L/G ratio of 2.822.

vertical position (m)	dry bulb temperature T_a (°C)	wet bulb temperature T_{wb} (°C)	water film temperature T_f (°C)	water mass flow rate $\dot{m}_w$ (kg/s)	humidity ratio ω
0	32.30	25.20	36.26	0.7713	0.0176
0.012	32.51	25.85	36.49	0.7716	0.0186
0.024	32.73	26.47	36.71	0.7718	0.0196
0.035	32.94	27.05	36.93	0.7721	0.0206

Table 3 (Continued)

vertical position (m)	dry bulb temperature T_a ($^{\circ}$C)	wet bulb temperature T_{wb} ($^{\circ}$C)	water film temperature T_f ($^{\circ}$C)	water mass flow rate $\dot{m}_w$ (kg/s)	humidity ratio ω
0.047	33.15	27.61	37.14	0.7724	0.0215
0.059	33.37	28.14	37.35	0.7726	0.0224
0.070	33.58	28.65	37.55	0.7729	0.0233
0.082	33.79	29.14	37.75	0.7731	0.0242
0.094	34.00	29.60	37.94	0.7733	0.0250
0.106	34.21	30.05	38.13	0.7736	0.0259
0.117	34.42	30.48	38.32	0.7738	0.0267
0.129	34.62	30.89	38.50	0.7740	0.0275
0.141	34.83	31.28	38.68	0.7742	0.0283
0.153	35.03	31.66	38.85	0.7744	0.0290
0.164	35.23	32.03	39.02	0.7746	0.0298
0.176	35.43	32.39	39.19	0.7748	0.0305
0.188	35.63	32.73	39.36	0.7750	0.0312
0.200	35.82	33.06	39.52	0.7752	0.0320
0.212	36.02	33.38	39.68	0.7754	0.0326
0.223	36.21	33.69	39.83	0.7756	0.0333
0.235	36.40	33.99	40.00	0.7758	0.0340

From Tables 1 to 3, the given operating variables were the inlet dry bulb and wet bulb temperatures T_a and T_{wb} as shown in the first row and the inlet water temperature as shown in the last row. The results in other rows were dry bulb temperatures, wet bulb temperatures, water film temperatures, water mass flow rates, and humidity ratios at the vertical positions of packing. The outlet dry bulb temperature, the outlet wet bulb temperature, the inlet water temperature, the outlet water flow rate, and the outlet humidity ratio were shown in the last row.

In Figures 23 and 24, it was found that the water descended from the top to the bottom of packing, its temperature decreased whilst maintaining the inlet water temperature at 40°C. For a large air flow (correspondingly low L/G ratio), the effect of air on the water temperature and humidity was large. Therefore, the change of air temperature (the change of humidity ratio) for a low L/G ratio was less than that for a large L/G ratio under a given inlet dry bulb temperature of 32.3°C. On the other hand, the change of water temperature (change of saturated humidity ratio) for a low L/G ratio was larger than that for a large L/G ratio under a given inlet water temperature of 40°C. For a low L/G ratio, it was found that the temperature gradient ($T_f - T_a$) increased with the vertical position of packing. Therefore, the sensible heat transfer in the upper zone was larger than that in the lower zone of packing. On the other hand, it was found that the temperature gradient decreased with the vertical position of packing for a large L/G

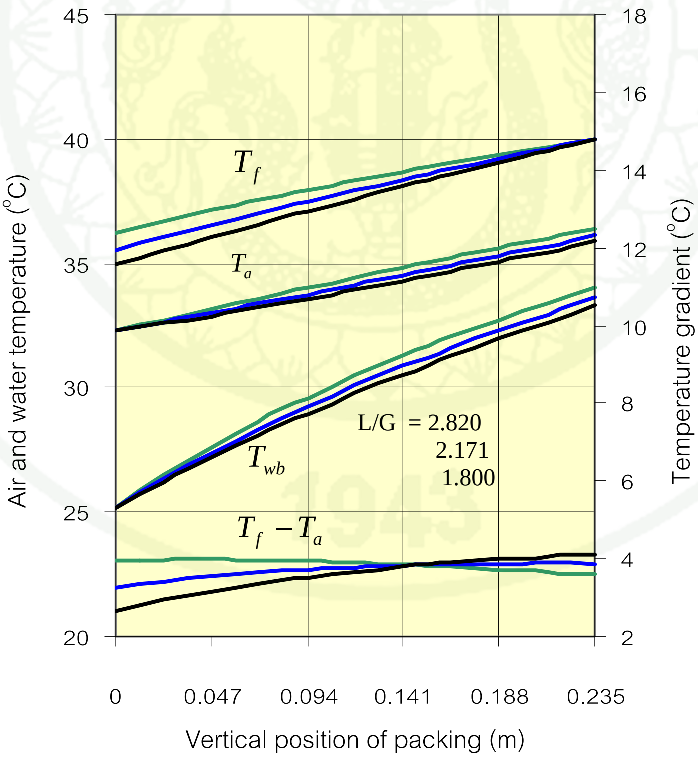


Figure 23 Calculated air and water temperatures and the air-water temperature gradient at the vertical positions of packing in the counter-flow cooling tower.

ratio. Therefore, the sensible heat transfer in the upper zone was less than that in the lower zone of packing.

For a large L/G ratio (correspondingly large water flow), the vapor absorption of air at any vertical position was more than that for a low L/G ratio. The change of humidity ratio for a large L/G ratio was larger than that for a low L/G ratio. On the other hand, the change of saturated air humidity ratio for a large L/G ratio was less than that for a low L/G ratio because of the small change of water temperature for a large L/G ratio. Therefore, it was found that the humidity gradient ($\omega_S - \omega$) decreased with the vertical position of packing for all L/G ratios. Accordingly, the latent heat transfer in the lower zone was larger than that in the upper zone of packing.

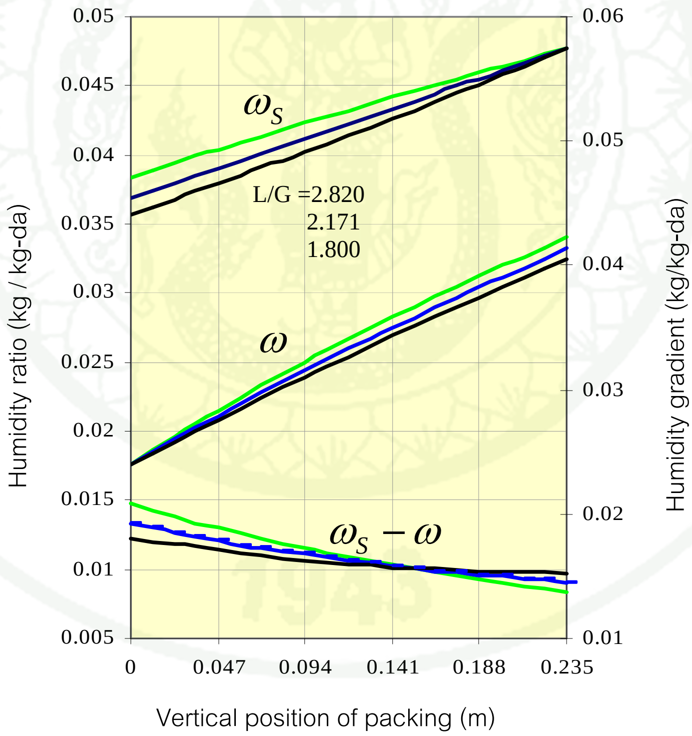


Figure 24 Calculated air humidity ratio, saturated air humidity ratio and the humidity gradient at the vertical positions of packing in the counter-flow cooling tower.

2. The Variation of Water Film Temperatures with Wet Bulb Temperatures.

Figure 25 showed that the water temperatures at the vertical positions of packing depended on the wet bulb temperatures of air whilst passing that position for the given L/G ratio of 1.800, 2.171, and 2.820, respectively under the same conditions at inlet dry bulb temperature of 32.3 °C, inlet wet bulb temperature of 25.2°C, and inlet water temperature of 40 °C. For a large L/G ratio (a large water flow), the effect of water on the air was larger than that for a low L/G ratio. Accordingly, the outlet wet bulb temperature for a large L/G ratio was higher than that for a low L/G ratio. On the other hand, the outlet water temperature for a large L/G ratio was less than that for a low L/G ratio.

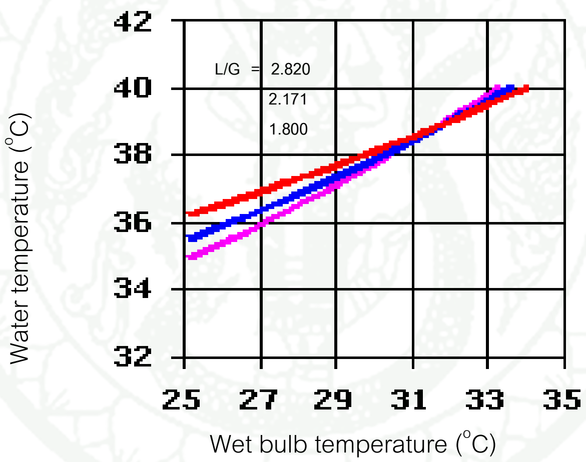


Figure 25 Variation of water temperatures with the wet bulb temperatures at the vertical positions under the same conditions at inlet water temperature of 40°C and inlet wet bulb temperature of 25.2°C.

Figure 26 indicated the principles of the heating and humidifying processes for air moving upward in the packing, it could be noted that the humidity ratio at the vertical position of packing increased with the dry bulb temperature and did not depend on the

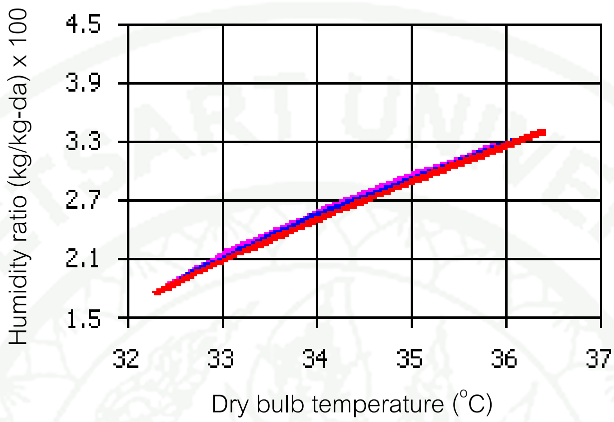


Figure 26 Humidity ratios at the vertical positions of packing depended on the dry bulb temperatures but did not depend on the L/G ratios.

L/G ratio. At any vertical position, the process performed the air and the process line could appear as the theoretical curved line on the psychrometric chart. It was obvious that this simulation model could also predict the behavior of the moist air at the atmospheric pressure.

3. The Volumetric Heat Transfer Coefficient of Cooling Tower by the Mathematical Models and the Tchebycheff Method.

.

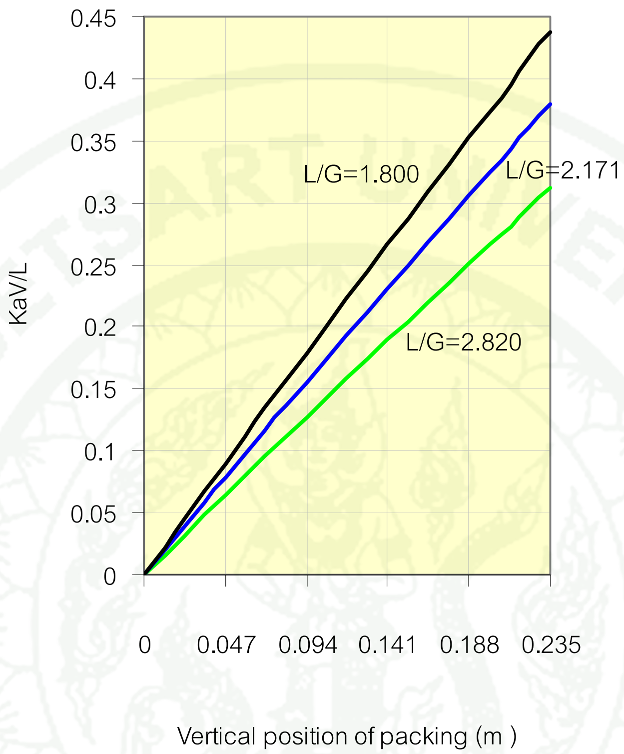


Figure 27 Calculated volumetric heat transfer coefficient of the packing in the counter-flow cooling tower.

Figure 27 showed the relationship between the volumetric heat transfer coefficient, KaV/L and the vertical positions for given three L/G ratios of 1.800 , 2.171 and 2.820, respectively. Running the model under the same inlet conditions indicated that the operating at a low L/G ratio would enhance the heat and mass transfer from water film to the air stream more than that for a large L/G ratio. It was found that the calculated KaV/L by in this simulation model was close to those using the Tchebycheff method as shown in Table 4. The differences of KaV/L between this simulation model and the Tchebycheff method were approximately less than 4.82 % which were considered acceptable.

Table 4 Comparison of the volumetric heat transfer coefficient of packing under the same conditions at inlet dry bulb temperature of 32.3 °C, inlet wet bulb temperature of 25.2 °C, and inlet water temperature of 40 °C.

Outlet Water temperature and flow rate		Simulation Method	Tchebycheff Method	Difference (%)
CWT=34.96°C, V_a=15.4m^3/min,				
V_w=31.03L/min ;	L/G	1.800	1.800	
	KaV/L	0.4378	0.4172	4.82
CWT=35.54 °C,V_a =15.12 m^3/min,				
V_w=36.8L/min ;	L/G	2.171	2.171	
	KaV/L	0.3797	0.3632	4.44
CWT=36.26°C, V_a =14.66 m^3/min,				
V_w=46.41L/min ;	L/G	2.820	2.820	
	KaV/L	0.3113	0.3018	3.10

4. The Effect of Inlet Wet Bulb Temperature on Water Temperature by using the Mathematical Models.

Furthermore, this simulation model could be used to study the effect of inlet wet bulb temperature on the humidity ratio and the water temperature under the same conditions at inlet dry bulb temperature of 32.2 °C, inlet water temperature of 40 °C, and the water flow rate of 46.41 L/min as shown in Figure 28 and Figure 29.

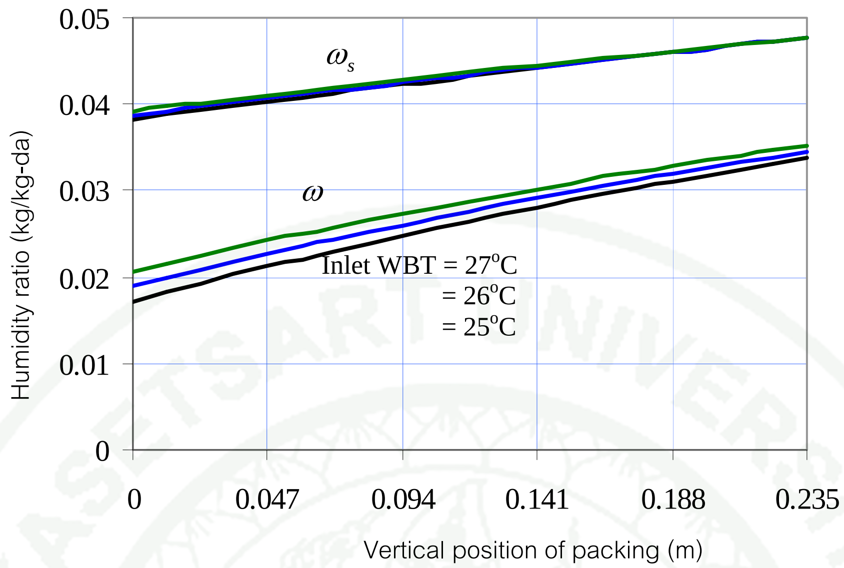


Figure 28 Effect of the inlet wet bulb temperatures on the humidity ratios under the same conditions at inlet dry bulb temperature of 32.2 °C, inlet water temperature of 40 °C, and the water flow rate of 46.41 L/min.

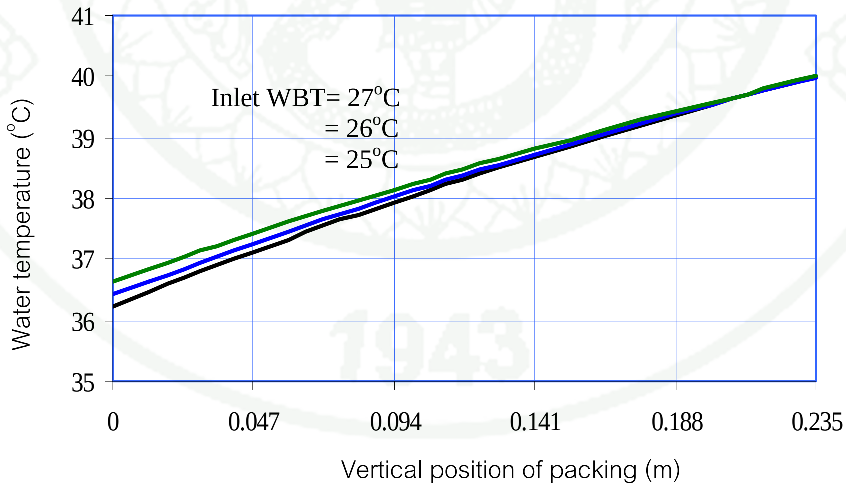


Figure 29 Effect of the inlet wet bulb temperatures on the water temperatures under the same conditions at inlet dry bulb temperature of 32.2 °C, inlet water temperature of 40 °C, and the water flow rate of 46.41 L/min.

At the same inlet dry bulb temperature, the air with a low inlet wet bulb temperature has a low humidity ratio. The humidity gradient for a low inlet wet bulb temperature was larger than that for a high inlet wet bulb temperature as shown in Figure 28. Accordingly, the air was able to absorb the latent heat from water for a low inlet wet bulb temperature more than that for a high inlet wet bulb temperature. Therefore, the required outlet temperature of water for a low inlet wet bulb temperature was lower than that for a high inlet wet bulb temperature as shown in Figure 29.

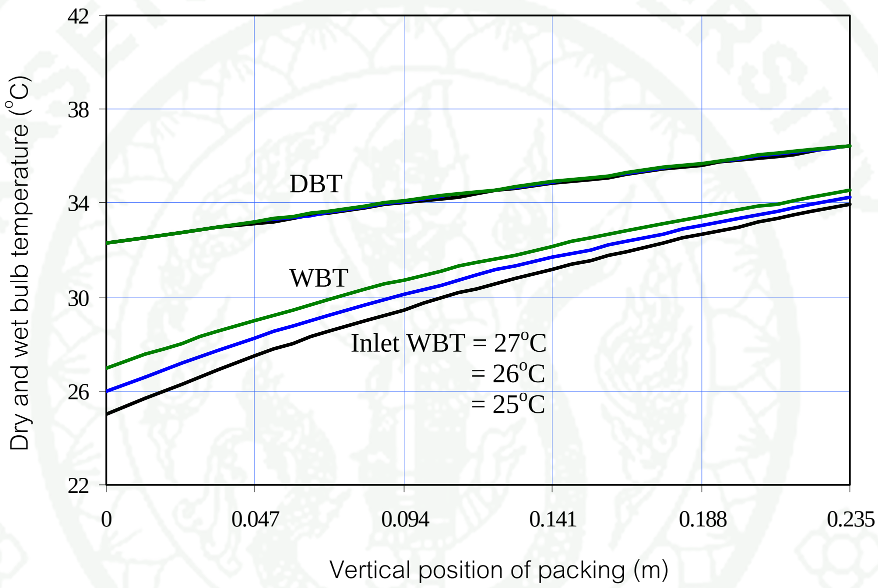


Figure 30 Effect of the inlet wet bulb temperatures on the wet bulb temperatures under the same conditions at inlet dry bulb temperature of 32.2 °C, inlet water temperature of 40 °C, and the water flow rate of 46.41 L/min.

For a high inlet wet bulb temperature, it could approach the saturated air more than that for a low inlet wet bulb temperature. It was obvious that the performance of a cooling tower under the given inlet conditions depended on the inlet wet bulb temperature of air but did not depend on inlet dry bulb temperature. The aforementioned behavior could be treated by remaining the same conditions at inlet dry bulb temperature of 32.2 °C, inlet water temperature of 40 °C, and the water flow rate of 46.41 L/min. In Figure 30, it was found that the air would nearly reach a saturated condition as it was moving upward to the top of packing.

4. A Comparison of the Calculated and Measured Outlet Temperatures of Air and Water.

A comparison of the outlet temperatures of air and water by the simulation model and the measured data and a comparison of the outlet wet bulb temperatures by the simulation model and the measured data under the same conditions at inlet dry bulb temperature of 32.3 ^{o}C, inlet wet bulb temperature of 25.2 ^{o}C, and inlet water temperature of 40 ^{o}C could be operated on three different values of L/G ratio of 1.800, 2.171 and 2.820, respectively as shown in Table 5. It was found that the temperatures of air and water for the simulation model were close to the measured data. All differences of the outlet temperatures were approximately less than 2.46 % for the dry bulb temperatures, approximately less than 2.21% for the wet bulb temperatures, and approximately less than 1.29 % for the water which were considered acceptable.

Table 5 Comparison of the outlet temperatures of air and water during passing through packing under the same conditions at inlet dry bulb temperature of 32.3 ^{o}C, inlet wet bulb temperature of 25.2 ^{o}C, and inlet water temperature of 40 ^{o}C.

Flow ratio	Parameters	Simulation model	Measured data	difference (%)
L/G=1.800	$T_a(^oC)$	35.87	35.00	2.46
	$T_{wb}(^oC)$	33.29	33.40	0.33
	$T_f(^oC)$	34.96	35.20	0.68
L/G=2.171	$T_a(^oC)$	36.11	35.80	0.86
	$T_{wb}(^oC)$	33.60	34.35	2.21
	$T_f(^oC)$	35.54	36.00	1.29
L/G=2.820	$T_a(^oC)$	36.40	36.80	1.09
	$T_{wb}(^oC)$	33.99	34.08	0.26
	$T_f(^oC)$	36.26	36.58	0.88

A Comparison of Water Temperatures using the Simulation Model, the Merkel's method and the Measured Data.

Under the same conditions at inlet water temperature of 40 °C, inlet wet bulb temperature of 27.4 °C, inlet dry bulb temperature of 35.5 °C, and the L/G ratio of 0.553, the water temperatures could be predicted at the vertical positions (0, 0.09, 0.18, 0.27, 0.36 and 0.45m from the bottom of packing) by the simulation model and the Merkel's method as shown in Table 6 and Figure 31.

Table 6 Comparison of the water temperatures at the vertical positions of packing under the same conditions at inlet dry bulb temperature of 35.5 °C, inlet wet bulb temperature of 27.4 °C, inlet water temperature of 40 °C, and the L/G ratio of 0.553.

Vertical position (m)	Simulation Model(1)	Merkel's Method(2)	Measured Data(3)	%Difference of(1) and (3)	%Difference of(2) and (3)
0	31.9	30.8	30.7	3.84	0.33
0.09	33.07	32.64	32.57	1.53	0.21
0.18	34.39	34.48	34.2	0.56	0.82
0.27	35.93	36.32	35.18	2.11	3.19
0.36	37.76	38.16	37.13	1.69	2.74
0.45	40	40	39.73	0.68	0.68

A comparison of water temperatures at the vertical positions of packing using the simulation model and the measured data, it was found that the simulation model were used to predict water temperatures above the measured data and all differences were approximately less than 3.84%.

A comparison of water temperatures at the vertical positions of packing using the Merkel's method and the measured data, it was found that the Merkel's method were used to predict water temperatures above the measured data and all differences were approximately less than 3.19%.

.

Under the same conditions at inlet water temperature of 40 °C, inlet wet bulb temperature of 27.4 °C, inlet dry bulb temperature of 35.5 °C, and the L/G ratio of 0.719, the water temperatures could be predicted at the vertical positions (0, 0.09, 0.18, 0.27, 0.36 and 0.45m from the bottom of packing) by the simulation model and the Merkel's method as shown in Table 7 and Figure 32.

Table 7 Comparison of the water temperatures at the vertical positions of packing under the same conditions at inlet dry bulb temperature of 35.5 °C, inlet wet bulb temperature of 27.4 °C, inlet water temperature of 40 °C, and the L/G ratio of 0.719.

Vertical position (m)	Simulation Model(1)	Merkel's Method(2)	Measured Data(3)	%Difference of (1) and(3)	%Difference of (2) and(3)
0	32.35	31.5	31.27	3.4	0.74
0.09	33.45	33.2	32.9	1.66	0.91
0.18	34.71	34.9	34.2	1.48	2.03
0.27	36.17	36.6	35.5	1.87	3.06
0.36	37.9	38.3	37.45	1.2	2.25
0.45	40	40	39.73	0.68	0.68

A comparison of water temperatures at the vertical positions of packing using the simulation model and the measured data, it was found that the simulation model were used to predict water temperatures above the measured data and all differences were approximately less than 3.4%.

A comparison of water temperatures at the vertical positions of packing using the Merkel's method and the measured data, it was found that the Merkel's method were used to predict water temperatures above the measured data and all differences were approximately less than 3.06%.

Under the same conditions at inlet water temperature of 40 ^{o}C, inlet wet bulb temperature of 27.4 ^{o}C, inlet dry bulb temperature of 35.5 ^{o}C, and the L/G ratio of 0.933, the water temperatures could be predicted at the vertical positions (0, 0.09, 0.18, 0.27, 0.36 and 0.45m from the bottom of packing) by the simulation model and the Merkel's method as shown in Table 8.

Table 8 Comparison of the water temperatures at the vertical positions of packing under the same conditions at inlet dry bulb temperature of 35.5 ^{o}C, inlet wet bulb temperature of 27.4 ^{o}C, inlet water temperature of 40 ^{o}C, and the L/G ratio of 0.933.

Vertical position (m)	Simulation Model(1)	Merkel's Method(2)	Measured Data(3)	%Difference of(1) and (3)	%Difference of(2) and (3)
0	32.87	32.5	31.95	2.84	1.71
0.09	33.91	34	33.55	1.07	1.33
0.18	35.1	35.5	34.53	1.64	2.77
0.27	36.47	37	36.15	0.89	2.33
0.36	38.08	38.5	37.78	0.79	1.89
0.45	40	40	39.73	0.68	0.68

A comparison of water temperatures at the vertical positions of packing by the simulation model and the measured data, it was found that the simulation model were used to predict water temperatures above the measured data and all differences were approximately less than 2.84%.

A comparison of water temperatures at the vertical positions of packing by the Merkel's method and the measured data, it was found that the Merkel's method were used to predict water temperatures above the measured data and all differences were approximately less than 2.77%.

Figure 31, 32 and 33 could be plotted from data in Table 6, 7 and 8, respectively. It was found that the water temperature profile along the vertical positions of packing was linear for the Merkel's method and nonlinear for both simulation model and measured data. As the water flowed downward along packing, the water temperature decreased below the inlet dry bulb temperature but remained above the inlet wet bulb temperature.

In Tables 6, 7, and 8, it was found that the outlet water temperature of the simulation model and the Merkel's method were larger than that of the measured data for all of L/G ratio. All differences were approximately less than 3.84% for a comparison of the simulation model and the measured data and approximately less than 3.19% for a comparison of the Merkel's method and the measured data as shown in Figure 34.

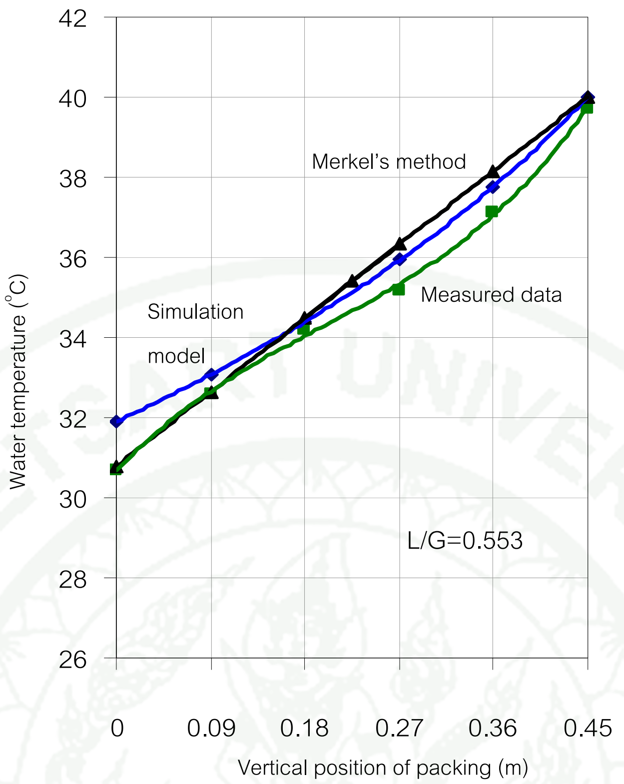


Figure 31 Comparison of water temperatures using the simulation model, the Merkel's method, and the measured data at the vertical positions of packing under the same conditions at inlet dry bulb temperature of 35.5 °C, inlet wet bulb temperature of 27.4 °C, inlet water temperature of 40 °C, and the given L/G ratio of 0.553.

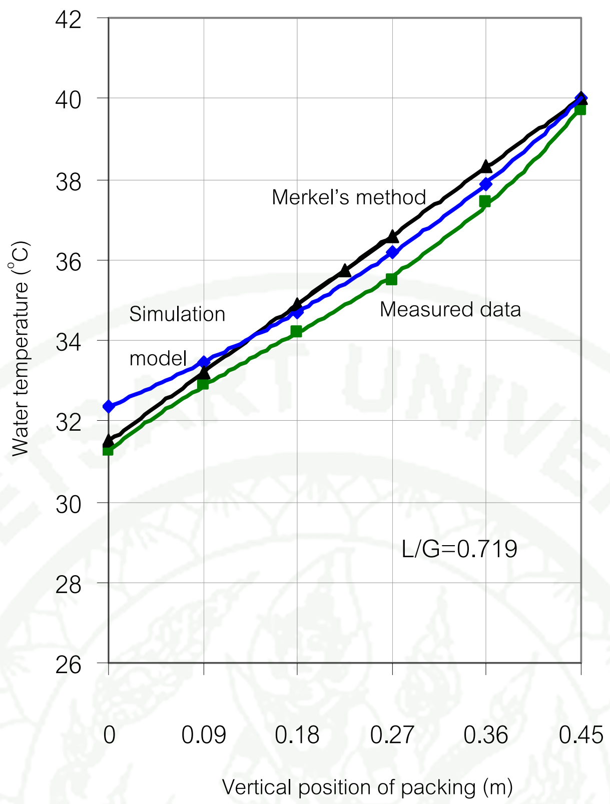


Figure 32 Comparison of water temperatures using the simulation model, the Merkel's method, and the measured data at the vertical positions of packing under the same conditions at inlet dry bulb temperature of 35.5 °C, inlet wet bulb temperature of 27.4 °C, inlet water temperature of 40 °C, and the given L/G ratio of 0.719.

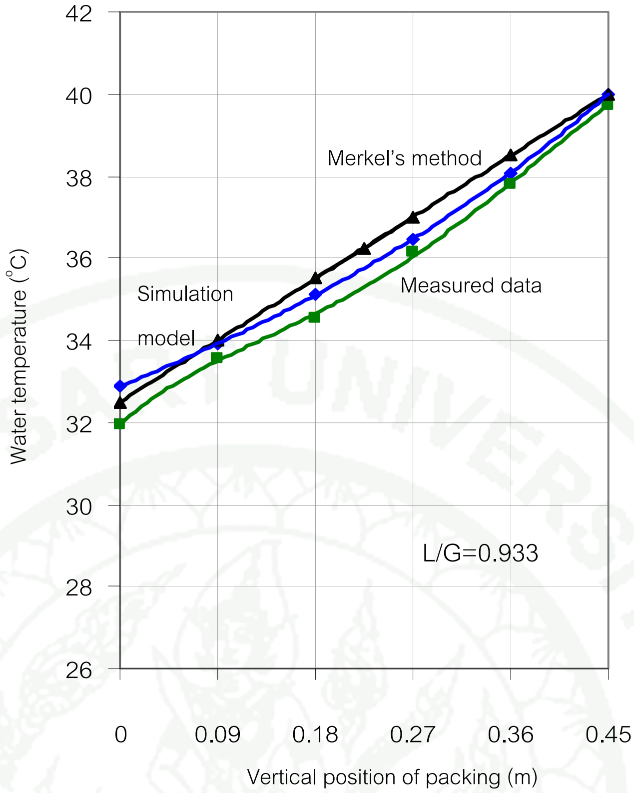


Figure 33 Comparison of water temperatures using the simulation model, the Merkel's method, and the measured data at the vertical positions of packing under the same conditions at inlet dry bulb temperature of 35.5 °C, inlet wet bulb temperature at 27.4 °C, inlet water temperature of 40 °C, and the given L/G ratio of 0.933.

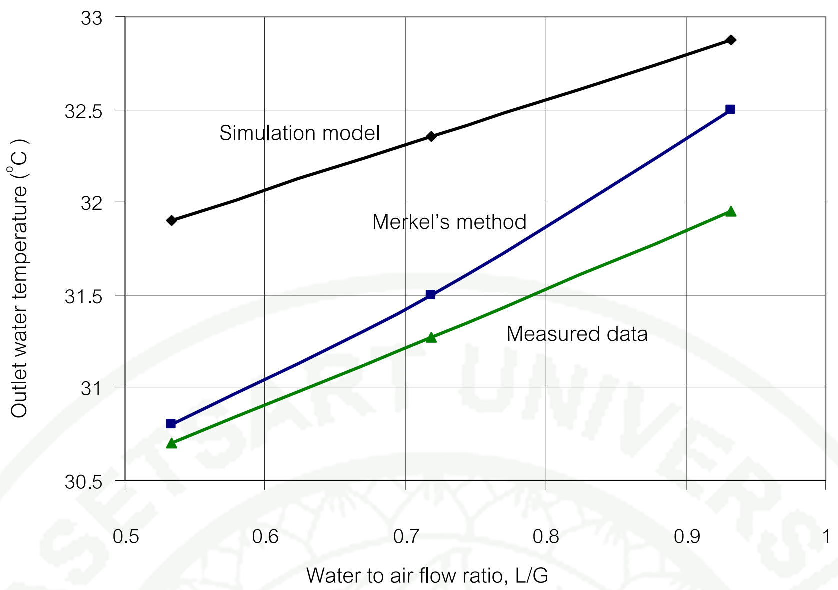


Figure 34 Comparison of the outlet water temperatures using the simulation model, the Merkel's method, and the measured data under the same conditions at inlet dry bulb temperature of 35.5 °C, inlet wet bulb temperature of 27.4 °C, inlet water temperature of 40 °C, and the given L/G ratios of 0.553, 0.719, and 0.933.

5. Confidence interval for prediction of water temperatures.

In Tables 6, 7, and 8, the mean temperature differences between the simulation model and the measured data and the mean temperature differences between the Merkel's method and the measured data could be used to estimate the uncertainty of these temperature differences by assuming a normal Student's t distribution. The 95% confidence interval of all temperature differences was used to estimate the width of the confidence interval.

Accordingly, the width of the 95% confidence interval was estimated as:

$0.5450 \pm 0.1443^{o}C$ ($0.4007^{o}C < Mean\ difference < 0.6893^{o}C$) for the mean temperature differences between the simulation model and the measured data.

$0.5639 \pm 0.1790^{o}C$ ($0.3851^{o}C < Mean\ difference < 0.7429^{o}C$) for the mean temperature differences between the Merkel's method and the measured data.

$0.5333 \pm 0.2054^{o}C$ ($0.3279^{o}C < Mean\ difference < 0.7387^{o}C$) for the mean calibrated temperature differences between the K type of thermocouple reading and the standard thermometer reading.

Within the 95% confidence interval, it was confidential that the simulation model could predict the water temperatures at the vertical positions with the deviation of $0.5450 \pm 0.1443^{o}C$ and the Merkel's method could predict the water temperatures at the vertical positions with the deviation of $0.5639 \pm 0.1790^{o}C$ under the calibrated temperature deviation of $0.5333 \pm 0.2054^{o}C$.

CONCLUSION

Conclusion

This paper would present a comparison of the simulation model, the Merkel's method, and the measured data of the air and water temperatures at the vertical positions of the packing in a small counter-flow cooling tower. Due to the complicated configuration of the packing and without the ability to measure the air temperatures in the intermediate sections, this numerical analysis has been partially validated.

For a range of differential height from 14 to 50 mm of the mercury manometer, it was found that the fitted line was obtained by the least square method in the form of $\dot{V}_{or} = 0.0047\sqrt{\Delta h_{mano}} - 9\times10^{-5}$ with the correlation, $r^2 = 0.9956$ and the flow coefficient, $K_{or} = 0.8471$. The flow coefficients laid within 95% confidence interval of the normal distribution were $0.7922 < K_{or} < 0.9020$. So, the orifice flow meter could predict the flow rate of water in the uncertainty of $\pm$6.5%, approximately.

Under the same conditions at inlet air temperature at 32.3 ^{o}C, inlet wet bulb temperature at 25.2 ^{o}C, and inlet water temperature at 40 ^{o}C, it was found that the temperatures of air and water for the simulation model were close to the measured data. All differences of outlet temperatures between the simulation model and the measured data were approximately less than 2.46 % for the dry bulb temperatures, approximately less than 2.21% for the wet bulb temperatures, and approximately less than 1.29 % for the water temperatures which were considered acceptable. A comparison of volumetric heat transfer coefficients between the simulation model and the Tchebycheff method was found that all differences were approximately less than 4.82 %.

Due to the complicated configuration of the packing surface with regard to installing the measuring probes, it was not possible to measure the air temperatures and the humidity ratios in the intermediate sections, only the water temperatures could be measured. Under the same conditions at inlet dry bulb temperature of 35.5 ^{o}C, inlet wet bulb temperature of 27.4 ^{o}C, inlet water temperature of 40 ^{o}C, and the given values of L/G ratio of 0.553, 0.719, and 0.933, the water temperatures were predicted at the vertical positions of 0, 0.09, 0.18, 0.27, 0.36 and 0.45m from the bottom of packing by the simulation method and the Merkel's method. A comparison of the water temperatures at the vertical positions of packing, it was found that all water temperature differences were approximately less than 3.19%, 3.06% and 2.77% between the simulation method and the measured data and approximately less than 3.84%, 3.4% and 2.84% between the Merkel's method and the measured data for the given L/G ratios of 0.553, 0.719 and 0.933, respectively.

Within the 95% confidence interval, it was confidential that the simulation model could predict the water temperatures at the vertical positions with the deviation of $0.5450 \pm 0.1443^{o}C$ and the Merkel's method could predict the water temperatures at the vertical positions with the deviation of $0.5639 \pm 0.1790^{o}C$ under the calibrated temperature deviation of $0.5333 \pm 0.2054^{o}C$. Consequently, this simulation model can be used as a tool for studying the phenomenon of heat and mass transfer on the corrugated packing for a small counter - flow cooling tower.

Recommendation

1. In the future, there should be a study about the heat and mass transfer in the rain zone.

2. Further the development of measuring in the controlled laboratory to have a full validation of the numerical analysis by measuring the dry bulb and wet bulb temperature at intermediate sections in the corrugated packing should be carried out.

3. Further the development of air duct for measuring the steady-flow velocities of air whilst passing through the packing sections.

LITERATURE CITED

Beckwith, T.J., R.D. Maragoni and J.H. Lienhard. 1993. **Mechanical Measurement** 5th ed. Addison Wesley Publishing Company, New York.

Boyce, W.E. and R.C. DiPrima. 1997. **Elementary Differential Equations and Boundary Value Problems.** 6th ed. John Wiley & Sons, Inc., New York.

Chokpraisin, K. 2003. **Study on Mathematical Modeling and Simulation of Water Distribution in Counter Flow Cooling Tower.** M.E. thesis, Kasetsart University.

Chuasuwan, S. 1997. **Study on Efficiency of Plastic Film Packing of Induced - draft Water Cooling Tower.** M.E. thesis, Kasetsart University.

Edwards, A.L. 1976. **An Introduction to Linear Regression and Correlation.** W.H. Freeman and Company Ltd., San Francisco.

Hewitt, G.F., G.L. Shires and T.R. Bott. 1993. **Process Heat Transfer.** CRC Press, Inc., Boca Raton, Florida.

Hill, G.B., E.J. Pring and P.D. Osborn. 1990. **Cooling Tower Principles and Practice.** 3rd ed. Butterworth-Heinemann Ltd., London.

Holman J.P. and W.J. Gajda. 1989. **Experimental Methods for Engineers.** 5th ed. Mc Graw-Hill Book Company, Singapore.

Incropera, F.P. and D.P. DeWitt. 1996. **Fundamentals of Heat and Mass Transfer.** 4th ed. John Wiley & Sons, Inc., New York.

Kells, L.M. 1964. **Analytic Geometry and Calculus.** 2nd ed. Prentice-Hall, Inc., United States of America.

Mills, A.F. 1995. **Heat and Mass Transfer.** Richard D. Irwin, Inc., Chicago.

Milosavljevic, N. and P. Heikkilä. 2001. A comprehensive approach to cooling tower design. **Applied Thermal Engineering** 21: 899-915.

Mohiuddin, A.K.M. and K. Kant. 1996. Knowledge base for the systematic design of wet cooling towers. **Int J. Refrig.** 19 (1): 43-60.

Cheremisinoff, N.P. and P.N. Cheremisinoff. 1983. **Cooling Towers Selection Design and Practice.** 2nd ed. Ann Arbor Science Publishers Ltd., Michigan.

Tan, K. and S. Deng. 2002. A method for evaluating the heat and mass transfer characteristics in a reversibly used water cooling tower (RUWCT) for heat recovery. **International Journal of Refrigeration** 25: 552-561.

APPENDICES

Appendix A

Experimental Data

Data for the Simulation of Mass and Heat Transfer and the Merkel's Method

Experimental Data

Data for the Simulation of Mass and Heat Transfer and the Merkel's Method

1. Operating Conditions for the Simulation Model and the Merkel's Method

1.1 Packing size with a height of 235 mm and a diameter of 550 mm

The operating conditions could be set up three conditions by maintaining inlet dry bulb temperature at 32.3°C, inlet wet bulb temperature at 25.2°C, and inlet water temperature at 40°C. In the simulation model, these mathematical models could be determined on three setting water flow rates of 31.03, 36.8, and 46.41 L/min and the air flow rates of 15.4, 15.12, and 14.66 m^3/min, respectively. These given values of water flow rates and air flow rates as the corresponding L/G ratios of 2.820, 2.171, and 1.800, respectively.

For the Merkel's Method, the computer program could be run by giving the following data as:

1.2 Packing size with a height of 450 mm and a diameter of 640 mm

The operating conditions could be set up three conditions by maintaining inlet dry bulb temperature at 35.5°C, inlet wet bulb temperature at 27.4°C, and inlet water temperature at 40°C. In the simulation model, these mathematical models could be determined by three setting water flow rates of 37.03, 42.76, and 50.9 L/min and the air flow rates of 36.04, 54.05, and 83.71 m^3/min, respectively. These given values of water flow rates and air flow rates as the corresponding L/G ratios of 0.935, 0.721, and 0.554, respectively.

For the Merkel's Method, the computer program could be run by giving the following data for the L/G ratios of 0.935, 0.721, and 0.554, respectively.

For L/G = 0.935

- inlet water temperature	=	40	°C
- water flow rate	=	37.03	L/min
- air flow rate	=	36.04	m^3/min
- inlet dry bulb temperature	=	35.5	°C
- inlet wet bulb temperature	=	27.4	°C
- packing constant C = 0.8556 and n = - 0.635			
- packing height	=	450	mm
Assume: outlet water temperature	=	30.8	°C

For L/G = 0.721

- inlet water temperature	=	40	°C
- water flow rate	=	42.76	L/min
- air flow rate	=	54.05	m^3/min
- inlet dry bulb temperature	=	35.5	°C
- inlet wet bulb temperature	=	27.4	°C
- packing constant C = 0.8556 and n = - 0.635			
- packing height	=	450	mm
Assume: outlet water temperature	=	31.5	°C

For L/G = 0.554

- inlet water temperature	=	40	°C
- water flow rate	=	50.9	L/min
- air flow rate	=	83.71	m^3/min
- inlet dry bulb temperature	=	35.5	°C
- inlet wet bulb temperature	=	27.4	°C
- packing constant C = 0.8556 and n = - 0.635			
- packing height	=	450	mm
Assume: outlet water temperature	=	32.5	°C

2. Measured Values of the Air Flow Rate and the Water Flow Rate

2.1 Measured air flow rates by the anemometer

On the experimental data, we used the anemometer to measure air velocities. Because of a large diameter of the anemometer, the air velocities were not measured on 20 marked positions in accordance with CTI-standard. So, the air velocities should be measured only 12 marked positions by setting the water flow rates of 37.03, 42.76, and 50.9 L/min as shown in Appendix Table A1- A3.

Appendix Table A1 Measured air velocities (m/s) on the cross sectional area of packing at the water flow rate of 37.03 L/min.

Position	R_1=10.51cm	R_2=17.703cm	R_3=22.73cm	R_4=26.8cm	R_5=30.37cm
0^o	1.8	2	1.6	-	-
90^o	2	1.9	1.8	-	-
180^o	1.2	2.2	1.7	-	-
270^o	2.1	2.3	2	-	-

(Positions at R_4=26.8cm and R_5=30.37cm could not be measured.)

Appendix Table A2 Measured air velocities (m/s) on the cross sectional area of packing at the water flow rate of 42.76 L/min.

Position	R_1=10.51cm	R_2=17.703cm	R_3=22.73cm	R_4=26.8cm	R_5=30.37cm
0^o	2.4	3.5	2.8	-	-
90^o	2.5	3.3	3	-	-
180^o	2.8	3	2.3	-	-
270^o	2.5	2.8	3	-	-

(Positions at R_4=26.8cm and R_5=30.37cm could not be measured.)

Appendix Table A3 Measured air velocities (m/s) on the cross sectional area of packing at the water flow rate of 50.9 L/min.

Position	R_1=10.51cm	R_2=17.703cm	R_3=22.73cm	R_4=26.8cm	R_5=30.37cm
0^o	4.4	5.2	3.6	-	-
90^o	3.8	5.3	3.8	-	-
180^o	4	4.8	4.2	-	-
270^o	4.1	5	4.3	-	-

(Positions at R_4=26.8cm and R_5=30.37cm could not be measured.)

2.2 Measured water flow rates by the orifice flow meter

On the experimental data, we used the orifice flow meter to measure water flow rates. The water flow rates could be recorded by setting the different height of mercury in manometer. The measured weight of the water in the weighing tank and time elapsed were recorded in the experiments as shown in Appendix Table A4.

Appendix Table A4 Measured water weights in the weighing tank and time elapsed for experiments.

Δh_{mano} (mm-Hg)	Experiment No.1		Experiment No.2		Experiment No.3	
	Weight (kg)	Time (s)	Weight (kg)	Time (s)	Weight (kg)	Time (s)
14	7.70	15	6.90	15	7.05	15
18	8.38	15	8.00	15	7.50	15
22	9.75	15	9.55	15	8.70	15
26	10.60	15	10.00	15	9.15	15
30	11.35	15	11.03	15	10.10	15
34	15.63	20	14.95	20	13.70	20
38	16.18	20	16.10	20	15.40	20

Appendix Table A4 (Continued)

Δh_{mano} (mm-Hg)	Experiment No.1		Experiment No.2		Experiment No.3	
	Weight (kg)	Time (s)	Weight (kg)	Time (s)	Weight (kg)	Time (s)
42	17.03	20	18.12	20	16.60	20
46	18.80	20	18.43	20	18.50	20
50	19.85	20	18.95	20	19.96	20

3. Measured water temperatures at the vertical positions of packing

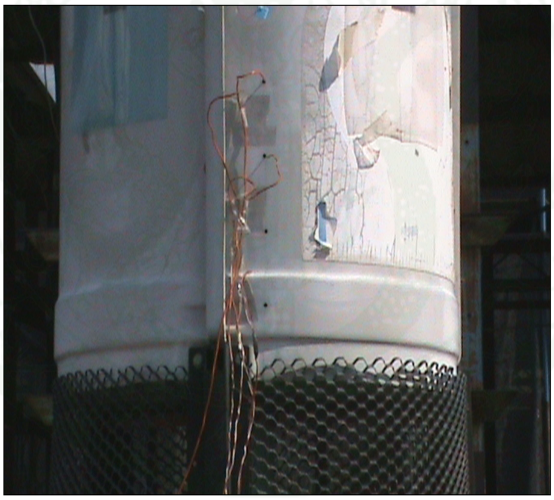
On the circumference of packing, we could specify the three positions at 0°, 120°, and 240°. Each angle, we marked the 6 measured points along the vertical distance as 0, 90, 180, 270, 360, and 450 mm from the lower edge of packing. So, the water temperatures could be measured on the 18 marked positions for the given water flow rates of 37.03, 42.76, and 50.9 L/min as shown in Appendix Table A5- A7.

Appendix Table A5 Measured water temperatures (°C) on the cross sectional area of packing at the water flow rate of 37.03 L/min.

Z(m)	Position at 0°	Position at 120°	Position at 240°
0	29	29	30
0.090	31	31	32
0.180	32	32	33
0.270	34	35	34
0.360	36	36	35
0.450	38	37	38

Appendix Table A6 Measured water temperatures (^{o}C) on the cross sectional area of packing at the water flow rate of 42.76 L/min.

Z(m)	Position at 0^{o}	Position at 120^{o}	Position at 240^{o}
0	30	29	30
0.090	31	31	32
0.180	32	32	33
0.270	33	35	34
0.360	35	36	35
0.450	38	37	37



Appendix Figure A1 Vertical positions for measuring the water temperatures.

Appendix Table A7 Measured water temperatures (^{o}C) on the cross sectional area of packing at the water flow rate of 50.9 L/min.

Z(m)	Position at 0^{o}	Position at 120^{o}	Position at 240^{o}
0	30	30	29
0.090	31	31	32
0.180	32	32	32
0.270	34	32	34
0.360	35	36	35
0.450	37	37	37

4. Measured values for the thermocouple calibration

In this thesis, we used the K-type of thermocouples to measure the water and air temperatures. Accordingly, we had to calibrate the thermocouple before measuring in the experiments, and we selected the comparison of thermometer calibration. The calibration data could be shown as

Appendix Table A8 Measured temperatures of the reading on the K-type of thermocouple and the thermometer.

K-type reading(^{o}C)	Thermometer reading(^{o}C)
27.2	27
29.5	29
31.5	31
35.5	34
38.5	38
43.5	43
51.6	52
54	53

Appendix Table A8 (Continued)

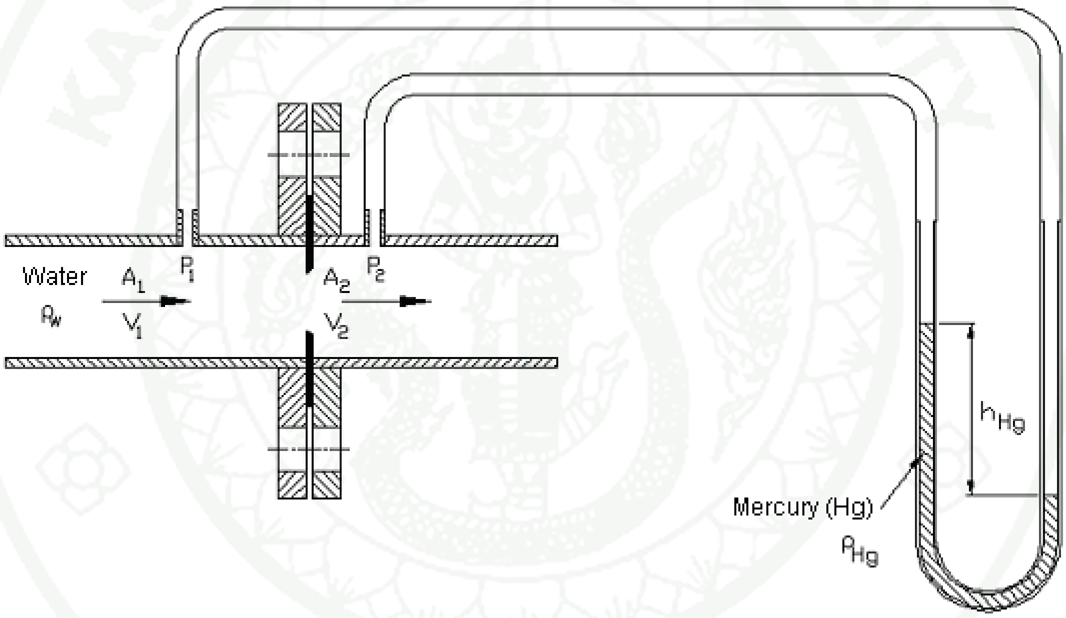
K-type reading(°C)	Thermometer reading(°C)
57.7	57
60.1	60
64.7	64
66.8	66
69.3	69
74.2	74
78.6	78
80.6	80
84	83
85.5	85

Appendix B

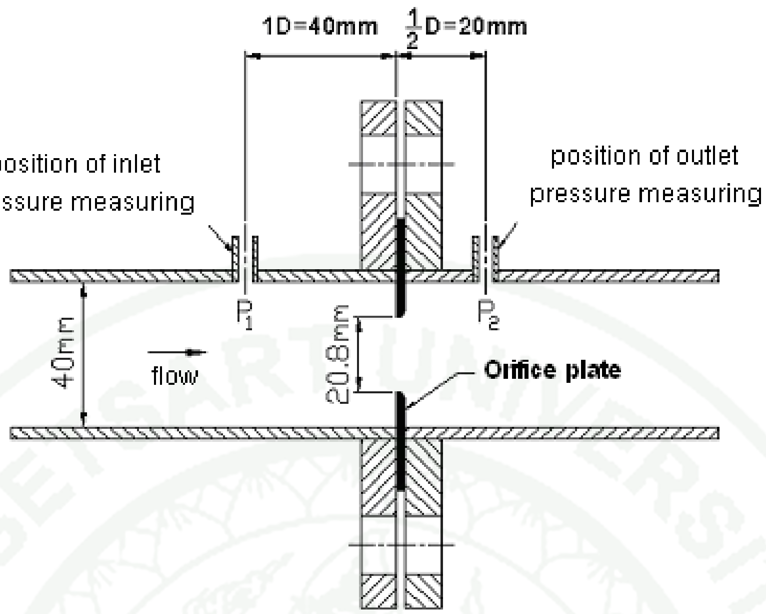
Measurement of Water Flow Rate for the Cooling Tower and the Uncertainty of Flow Coefficient, K_{or}

Measurement of Water Flow Rate for the Cooling Tower and the Uncertainty of Flow Coefficient, K_{or}

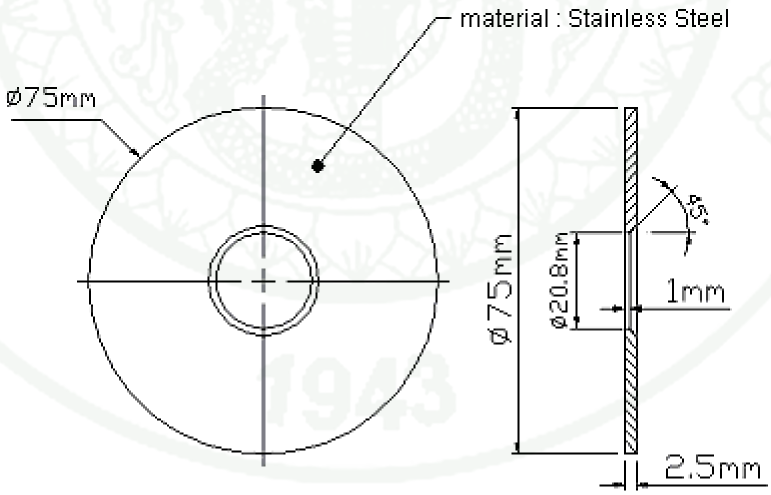
In this experiment, the water flow rates were measured by the orifice flow meter and the differential manometer with mercury liquid. The manometer was used to measure the pressure difference of water between the inlet (P_1) and outlet (P_2) of the orifice plate and the details should be illustrated in Appendix Figure B1, B2, and B3, respectively.



Appendix Figure B1 Measurement of the water flow rates by the orifice flow meter.



Appendix Figure B2 Positions for measuring pressures on the orifice plate with taps of D and $\frac{1}{2}$D.



Appendix Figure B3 Details and dimensions of the orifice plate.

The details of flow measurement for the orifice flow meter in the experiment as:

1. To design from ASME PCT19.5:4 - 1959 standard in topic “Flow Measurement by Means of Thin Plate Orifice, Flow Nozzles and Venturi Tubes.”

2. To measure the water flow rate passing through the pipe with a diameter of 40 mm as shown in Appendix Figure B3.

3. The positions for measuring pressures at the inlet and outlet of orifice plate were the distance D and $\frac{1}{2}$D from the flange.

4. The scale of manometer was the unit of mm-Hg.

Determination of the Flow Coefficient

For the experimentally determined the flow coefficient, the flow rates of water passing through orifice could be determined in terms of the differences of mercury level in manometer.

The details of parameters in the setup orifice flow meter were given and illustrated in Appendix Table B1.

By collecting the flowing water in a weight tank on platform scale for some convenient time interval, it can be known in term of $\dot{V}_{or} = W / \rho t$ and Δh_{mano} from the experiments as shown in Appendix Table A4.

Appendix Table B1 Parameters of the orifice flow meter.

Parameters	Details
Diameter of water pipe (D_{pipe})	40 mm
Diameter of orifice (D_{or})	20.8 mm
Density of water @ 25°C (ρ)	997.1 kg/m^3
Density of mercury (ρ_{mano})	13600 kg/m^3
Acceleration of gravity (g)	9.81 m/s^2

Appendix Table B2 Calculated volume flow rates of water passing through the orifice meter for experiments. (Use the data from Appendix Table A4)

Δh_{mano} (mm-Hg)	Volume flow rate (m^3/s)			
	Experiment No.1	Experiment No.2	Experiment No.3	Average
14	30.89	27.68	28.28	28.95
18	33.62	32.09	30.09	31.93
22	39.11	38.31	34.90	37.44
26	42.52	40.12	36.71	39.78
30	45.53	44.25	40.50	43.43
34	47.03	44.98	41.22	44.41
38	48.68	48.44	46.33	47.82
42	51.24	54.52	49.94	51.90
46	56.56	55.45	55.66	55.89
50	59.72	57.02	60.05	58.93

The procedure can be discussed as:

1) To fill the water into a system, namely the cold water tank, the hot water tank, and the balancing tank.

2) To set up the blade angle at a constant value.

3) To set up a constant volume flow rate of water by adjusting the discharge valve of the cold water pump, the discharge valve of the hot water pump, and the balancing valve until the water level in each tank reaches to be constant.

4) To set up a height difference of 14mm- mercury in the manometer by adjusting the discharge valve of hot water pump and keeping the constant water level in each tank.

5) To record the weight of water on platform scale for a time interval of 20 seconds.

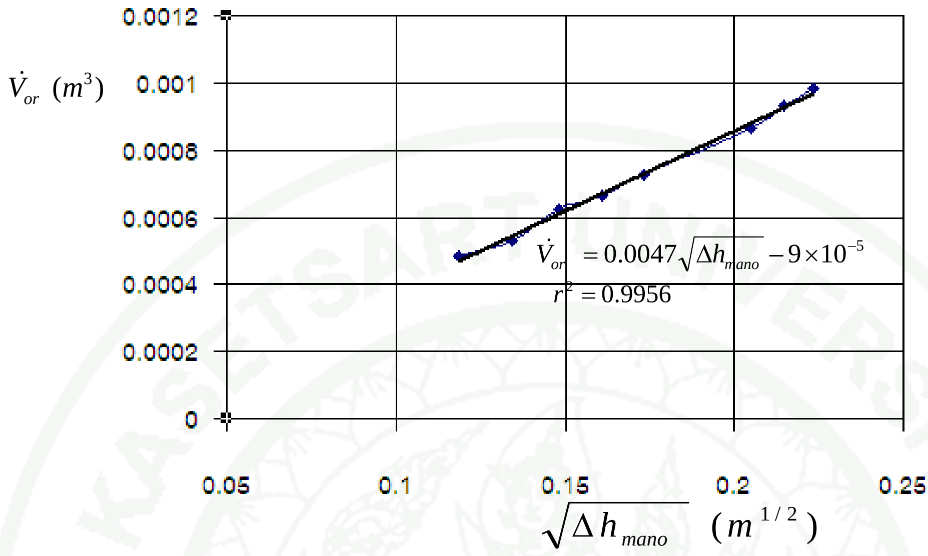
6) To set up the new values of water flow rate by the differential height of 18, 22, ……., 50 mm and repeat as the step (3) to (5) for each setting value of the differential height.

From relation of $\dot{V}_{or} = \dfrac{m\ (kg)}{\rho\ (kg/m^3)\cdot t\ (s)} \cdot \dfrac{60s}{1\min} \cdot \dfrac{L}{10^{-3}m^3}$ and $\rho = 997.1\ kg/m^3$,

we obtain as:

$$\dot{V}_{or} = 60.1745\frac{m}{t} \tag{77}$$

where unit of m is kg and unit of t is second, unit of $\dot{V}_{or}$ is L/min in Eq(77).



Appendix Figure B4 Fitted line of the relationship between $\dot{V}_{or}$ (m^3) and $\sqrt{\Delta h_{mano}}$ (m$^{0.5}$) by the least square method.

Substituting $D_{or} = 0.0208\ m$, $D_{pipe} = 0.040\ m$, $SG = 13.6$, $\rho = 997.1\ kg/m^3$ (the water at 25^oC) and $g = 9.807 m/s^2$ into Eq.(26) yields

$$\dot{V}_{or} = 5.54846x10^{-3} K_{or}\sqrt{\Delta h_{mano}} \tag{78}$$

Line fitting could be obtained by the method of least squares, the least squares results were:

$$\dot{V}_{or} = 0.0047\sqrt{\Delta h_{mano}} - 9\times10^{-5} \text{ and } r^2 = 0.9956 \tag{79}$$

From Eq.(78) and (79), the flow coefficient could be calculated as:

$5.54846x10^{-3}K_{or} = 0.0047$ and $K_{or} = 0.8471$

Substituting $K_{or} = 0.8471$ into Eq.(78), the flow could be calculated as:

$$\dot{V}_{or} = 0.0047\sqrt{\Delta h_{mano}} \tag{80}$$

where the unit of Δh_{mano} is meter and the unit of $\dot{V}_{or}$ is m^3/s.

Substituting $n = 8$ and $r^2 = 0.9956$ into Eq.(32) , it could obtain as:

$$\frac{s_{y/x}}{s_{yy}} = \left(\frac{8-1}{8-2}\right)^{1/2}(1-0.9956)^{1/2} = 0.07165$$

Substituting $\sum y_i^2 = 4.44946\times10^{-6}$ and $(\sum y_i)^2 = 0.005804$ into Eq.(31) yields

$$s_{yy} = \sqrt{\frac{4.44946\times10^{-6} - \frac{1}{8}(0.005804)^2}{8-1}} = 1.84646\times10^{-4}$$

and

$$s_{y/x} = 0.07165(1.84646\times10^{-4}) = 1.322986\times10^{-5}$$

Substituting into Eq.(34), it could be calculated as:

$$S_{xx} = \sqrt{0.248 - \frac{1}{8}(1.378282)^2} = 0.102675$$

and

$$\frac{s_{y/x}}{S_{xx}} = \frac{1.322986\times10^{-5}}{0.102675} = 1.28852\times10^{-4}$$

Within 95% confidence; $c = 0.95$, $\alpha = 1 - 0.95 = 0.05$, and $\upsilon = 8 - 1 = 7$

From Appendix Table H1, it could get $t_{\alpha/2,\upsilon} = 2.365$

So, the uncertainty in slope was

$$\pm t_{\alpha/2,\upsilon}\left(\frac{s_{y/x}}{S_{xx}}\right) = \pm 2.365(1.28852 \times 10^{-4}) = \pm 3.04735 \times 10^{-4}$$

Interval for the slope of $0.0047 \pm 3.04735 \times 10^{-4}$ and the flow coefficient $K_{or} = slope / 5.54846x10^{-3}$ could be calculated as:

$$0.0043953 < true\_slope < 0.0050047 \quad \text{(for 95\% confidence)}$$

$$0.7922 < true\_K_{or} < 0.9020 \quad \text{(for 95\% confidence)}$$

The foregoing calculation, it was found that $K_{or} = 0.8471$ and the error should also be determined and we obtained the uncertainty of K_{or} as:

$$u_K = \pm\left(\frac{(0.8471 - 0.7922) + (0.9020 - 0.8471)}{2}\right) \times \frac{100}{0.8471} = \pm 6.48\%$$

So, we could predict the flow rate from this orifice flow meter in the form of relation as:

$$\dot{V}_{or} = (5.5485 \times 10^{-3})(0.8471)\sqrt{\Delta h_{mano}} = 0.0047\sqrt{\Delta h_{mano}} \quad (81)$$

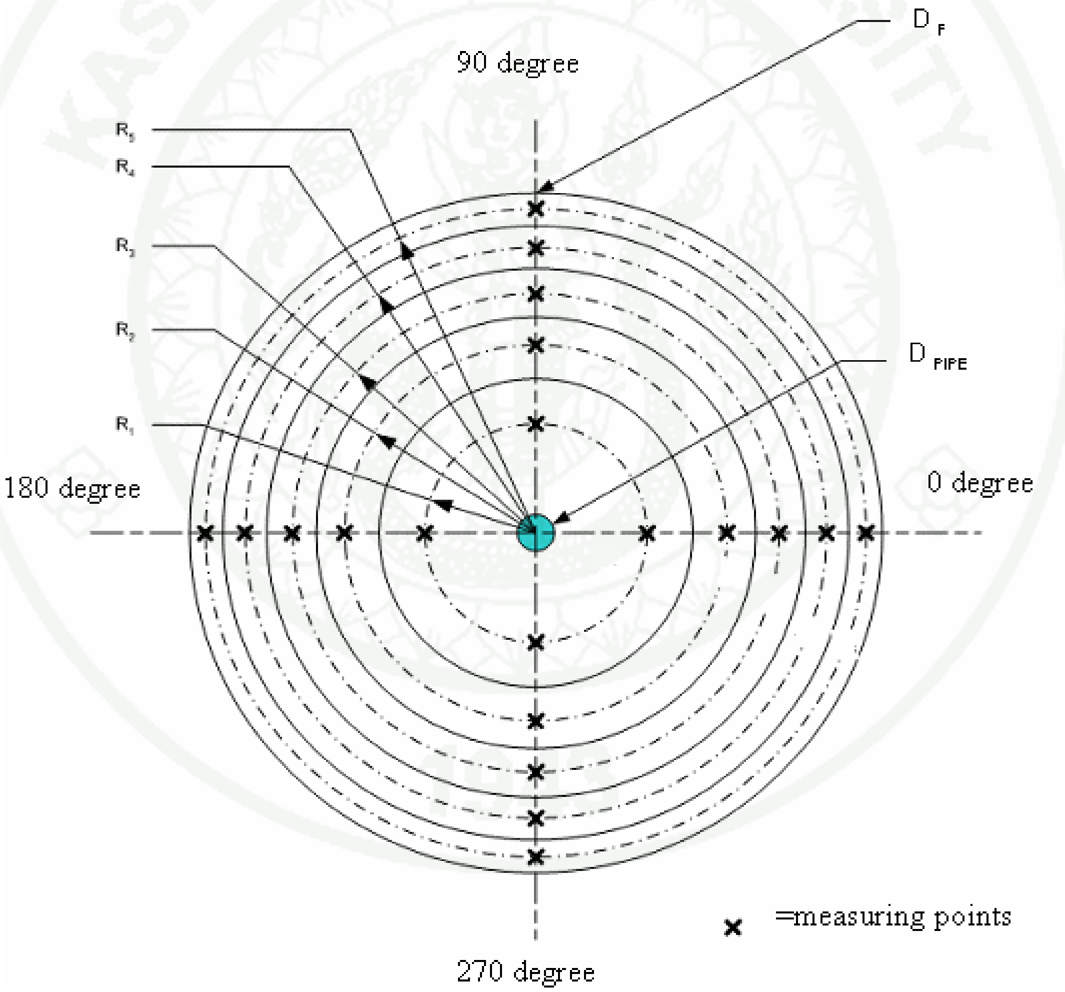
The Eq.(81) was used to predict the flow rate of water passing through the testing system of the cooling tower when you knew the different level of mercury in the manometer by the precision uncertainty of $\pm$ 6.5%, approximately.

Appendix C

Measurement of the Air Flow Rate for the Cooling Tower

Measurement of the Air Flow Rate for the Cooling Tower

In this experiment, the air flow rates of the cooling tower were measured by measuring air velocities at the top of packing. The anemometer was used to measure and record the air velocities. The air velocity at each position could be measured in accordance with CTI-standards (CTI PFM-143: 1994) about Recommended Practice for Air Testing of Cooling Tower. In the field testing, the CTI-standards Dictated the



Appendix Figure C1 Measured points on the free flow area of cooling tower.

measurement of air velocities on the cross section area of cooling tower (A_f) above the packing and net free flow area (A_{nf}) should be divided into 5 parts ($A_1, A_2, \ldots\ldots, A_5$). The given number of divided-area, the ratio area (A_{ratio}) is the ratio of the net free flow area to the double number of divided-area. In this case, the number of divided-areas is equal to 5 parts and the ratio area can be written as:

$$A_{ratio} = \frac{A_{nf}}{2x5} = \frac{A_{nf}}{10} \tag{82}$$

Therefore, the divided-area can be determined as following:

The fifth part; $A_5 = A_f - A_{ratio}$ with radius, $R_5 = \sqrt{\frac{A_5}{\pi}}$ (83)

The fourth part; $A_4 = A_5 - 2A_{ratio}$ with radius, $R_4 = \sqrt{\frac{A_4}{\pi}}$ (84)

The third part; $A_3 = A_4 - 2A_{ratio}$ with radius, $R_3 = \sqrt{\frac{A_3}{\pi}}$ (85)

The second part; $A_2 = A_3 - 2A_{ratio}$ with radius, $R_2 = \sqrt{\frac{A_2}{\pi}}$ (86)

The first part; $A_1 = A_2 - 2A_{ratio}$ with radius, $R_1 = \sqrt{\frac{A_1}{\pi}}$ (87)

The air velocity can be measured on 20 marked positions as shown in Appendix Figure C1 and the average velocity(V_{ave}) can be calculated.

The air flow rate can be written as:

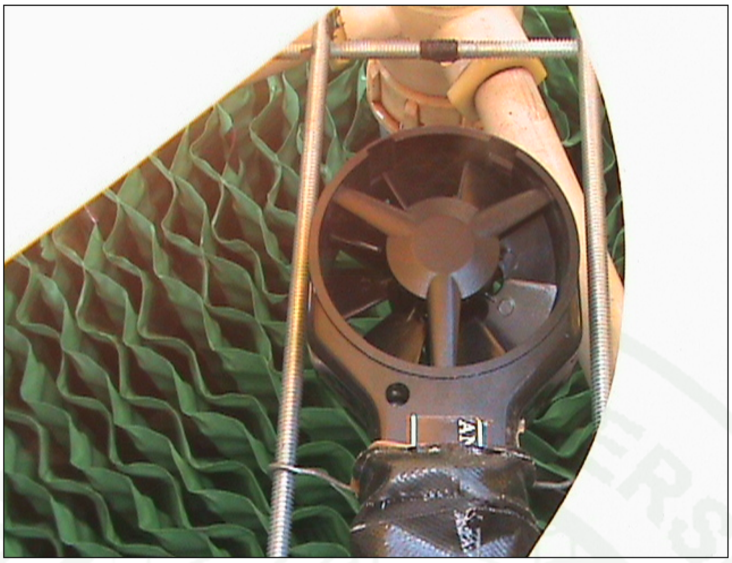
$$\dot{V}_a = A_{nf} V_{ave} \tag{88}$$

Details of cooling tower;

Packing diameter (D_{fill})	0.64	m
Water pipe diameter at the axis of cooling tower (D_{pipe})	0.060	m
Gross cross sectional area of the packing (A_f)	0.3217	m^2
Net free flow area of the packing (A_{nf})	0.3189	m^2
Ratio area ($A_{ratio} = A_{nf} / 2(5) = A_{nf} / 10$)	0.03189	

Appendix Table C1 Marked positions for measuring the air velocities on the cross sectional area of packing with a diameter of 64 cm.

Circle area (m^2)	Radius of measured positions (cm)	Distance from inside surface of cooling tower (cm) = 32 – R
A_5 = 0.28980	R_5= 30.37	1.63
A_4 = 0.22602	R_4= 26.82	5.18
A_3 = 0.16224	R_3= 22.73	9.27
A_2 = 0.09846	R_2= 17.70	14.30
A_1 = 0.03468	R_1= 10.51	21.49



Appendix Figure C2 Measured position of the anemometer on the cross sectional area of packing with a diameter of 64 cm.

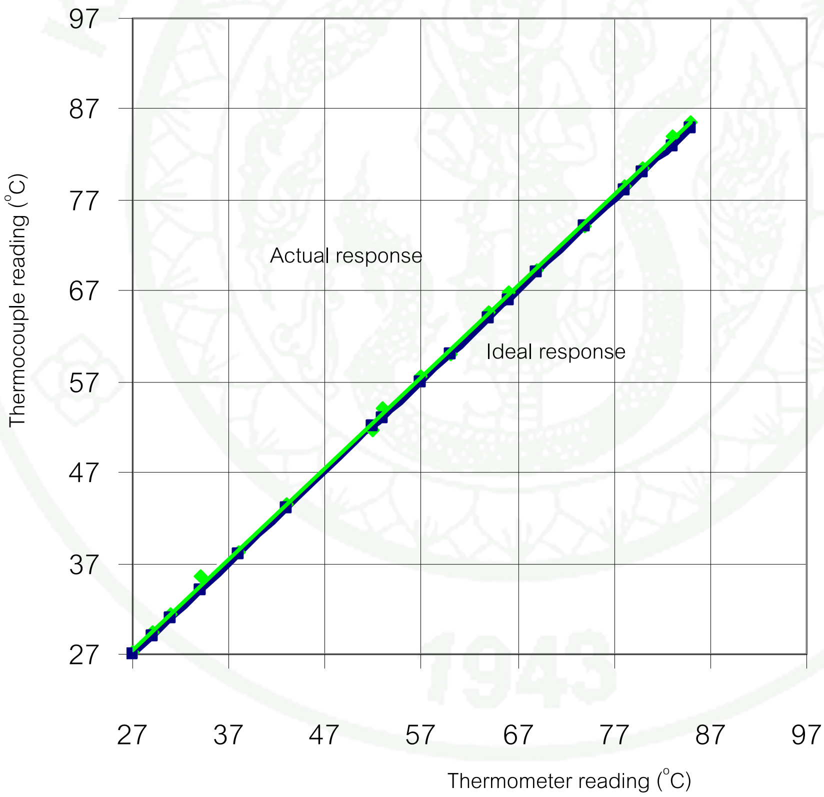
Appendix D

Calibration of the K-Type of Thermocouple and Analysis of

the Deviation of Temperatures

Calibration of the K-Type of Thermocouple and Analysis of
the Deviation of Temperatures

The temperatures of thermocouple reading were measured on comparing with the temperatures of thermometer reading. It was able to plot the temperatures of thermocouple reading versus on the temperatures of thermometer reading. These two fitted lines were considered to be the ideal response and the actual response, respectively. For the ideal response, it was found that the measured readings equal the true temperatures, $T_{measured} = T_{true}$. The actual response includes the zero-offset error (T_{offset}) and the scale error (β) so that it could obtain as $T_{measured} = \beta \cdot T_{true} + T_{offset}$.



Appendix Figure D1 Calibration of the K-type of thermocouple by comparing with the standard thermometer.

In Appendix Figure D1, the fitted line of actual response could be obtained by the least square method as $T_{measured} = 1.0008T_{true} + 0.4878$ with correlation $r^2 = 0.9996$. So, it was found that the scale error was $\beta = 1.0248$ and the zero-offset error was $T_{offset} = 0.2849^{\circ}$ C.

From the calibration by the comparison method, the true value of temperature could be determined in term of the milli-voltmeter of the K-type of thermocouple as:

$$T_{true} = \frac{T_{measured} - 0.4878}{1.0008} = \frac{[24.186(\_\_mV) + 1.012] - 0.4878}{1.0008} \tag{89}$$

The temperature difference of two typical readings could be considered the mean temperature deviation of the thermocouple reading and the standard thermometer reading. The upper and lower deviation values were calculated .

Appendix Table D1 Temperature Deviation of the thermocouple reading and the standard thermometer reading.

Thermocouple reading (^{o}C)	Thermometer reading (^{o}C)	Difference of two readings (^{o}C) ,D	D^2
27.2	27	0.2	0.04
29.5	29	0.5	0.25
31.5	31	0.5	0.25
35.5	34	1.5	2.25
38.3	38	0.3	0.09
43.5	43	0.5	0.25
51.6	52	-0.4	0.16
54	53	1	1
57.7	57	0.7	0.49
60.1	60	0.1	0.01

Appendix Table D1 (Continued)

Thermocouple reading (°C)	Thermometer reading (°C)	Difference of two readings (°C) ,D	D^2
64.7	64	0.7	0.49
66.8	66	0.8	0.64
69.3	69	0.3	0.09
74.2	74	0.2	0.04
78.6	78	0.6	0.36
80.6	80	0.6	0.36
84	83	1	1
85.5	85	0.5	0.25
		9.6	8.02

From Appendix Table D1, the mean temperature difference could be calculated

$$\overline{D} = 9.6/18 = 0.5333$$

and the standard deviation was used the relation of

$$SD = \sqrt{\frac{\sum D_i^2 - \frac{(\sum D_i)^2}{n}}{n-1}} \tag{90}$$

Substituting $\sum D_i = 9.6$, $\sum D_i^2 = 8.02$, and $n = 18$ into Eq.(90), it could obtain

$$SD = 0.41302$$

Within 95% confidence; $c = 0.95$, $\alpha = 1 - 0.95 = 0.05$, and $\upsilon = 18 - 1 = 17$

From Appendix Table H1, it could get $t_{\alpha/2,\upsilon} = 2.11$ and it could calculated as:

$$Uncertainty = \pm t_{0.025,17} \cdot \frac{SD}{\sqrt{n}} \tag{91}$$

Substituting $SD = 0.41302$ into Eq.(91), it obtained

$$Uncertainty = \pm(2.11)\frac{0.41302}{\sqrt{18}} = \pm 0.2054\ ^{o}C$$

The calibrated deviation could obtain as:

$$Calibration\ deviation = 0.5333 \pm 0.2054\ ^{o}C$$

Appendix Table D2 Deviation of the water temperatures at the vertical positions of packing under the same conditions at inlet dry bulb temperature of 35.5 °C, inlet wet bulb temperature of 27.4 °C, inlet water temperature of 40 °C, and the given L/G ratios of 0.553, 0.719 and 0.933.

Simulated results(°C) (1)	Merkel results(°C) (2)	Measured data(°C) (3)	Difference D_{13}	Difference D_{23}	D_{13}^2	D_{23}^2
31.9	30.8	30.7	1.2	0.1	1.44	0.01
33.07	32.64	32.57	0.5	0.07	0.25	0.0049
34.39	34.48	34.2	0.19	0.28	0.0361	0.0784
35.93	36.32	35.18	0.75	1.14	0.5625	1.2996
37.76	38.16	37.13	0.63	1.03	0.3969	1.0609
40	40	39.73	0.27	0.27	0.0729	0.0729

Appendix Table D2 (Continued)

Simulated results(°C) (1)	Merkel results(°C) (2)	Measured data(°C) (3)	Difference D_{13}	Difference D_{23}	D_{13}^{2}	D_{23}^{2}
32.35	31.5	31.27	1.08	0.23	1.1664	0.0529
33.45	33.2	32.9	0.55	0.3	0.3025	0.09
34.71	34.9	34.2	0.51	0.7	0.2601	0.49
36.17	36.6	35.5	0.67	1.1	0.4489	1.21
37.9	38.3	37.45	0.45	0.85	0.2025	0.7225
40	40	39.73	0.27	0.27	0.0729	0.0729
32.87	32.5	31.95	0.92	0.55	0.8464	0.3025
33.91	34	33.55	0.36	0.45	0.1296	0.2025
35.1	35.5	34.53	0.57	0.97	0.3249	0.9409
36.47	37	36.15	0.32	0.85	0.1024	0.7225
38.08	38.5	37.78	0.3	0.72	0.09	0.5184
40	40	39.73	0.27	0.27	0.0729	0.0729
		Summation =	**9.81**	**10.15**	**6.7779**	**7.9247**

From Appendix Table D2, the mean difference and the standard deviation could be calculated as:

$\overline{D}_{13} = 9.81/18 = 0.545$ and $\overline{D}_{23} = 10.15/18 = 0.564$

Substituting $\sum D_i = 9.81$, $\sum D_i^2 = 6.778$, , and $n = 18$ into Eq.(90), it could obtain $SD_{13} = 0.2902$.

Substituting $\sum D_i = 10.15$, $\sum D_i^2 = 7.9247$, , and $n = 18$ into Eq.(90), it could obtain $SD_{23} = 0.3598$.

At 95% confidence; $c = 0.95$, $\alpha = 1 - 0.95 = 0.05$, and $\upsilon = 18 - 1 = 17$

From Appendix Table H1, it could get $t_{\alpha/2,\upsilon} = 2.11$ and it could calculated from

Substituting $SD_{13} = 0.2902$ and $SD_{23} = 0.3598$ into Eq.(91), it obtained

$$Uncertaint\, y_{13} = \pm(2.11)\frac{0.2902}{\sqrt{18}} = \pm 0.1443$$

$$Uncertaint\, y_{23} = \pm(2.11)\frac{0.35984}{\sqrt{18}} = \pm 0.1790$$

Deviation of the simulated results and the measured data could obtain

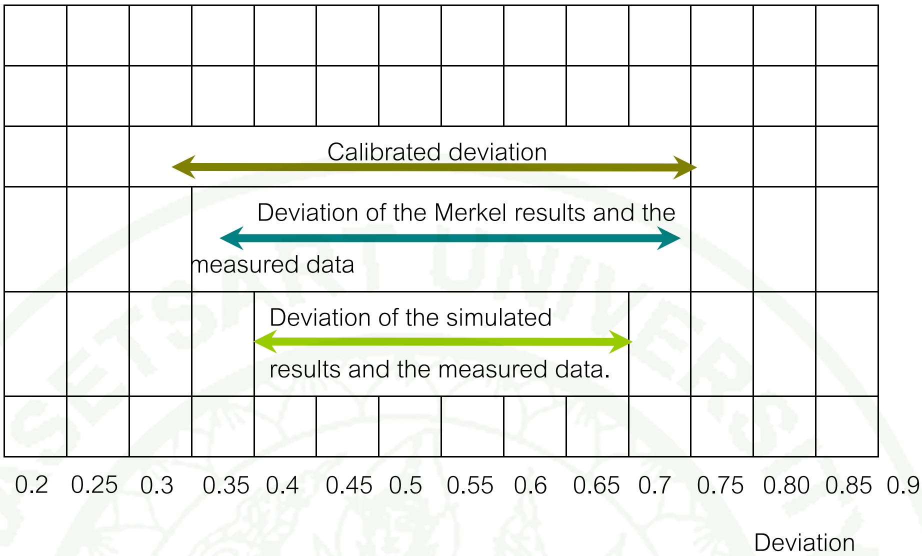
$$Mean\ Deviation_{13} = 0.5450 \pm 0.1443$$

Deviation of the Merkel's results and the measured data could obtain

$$Mean\ Deviation_{23} = 0.5639 \pm 0.1790$$

Accordingly, it was obvious that the deviation band of the calibrated deviation was nearly close to the deviation band of the deviation of simulated results and the measured data (including the deviation of the Merkel's results and measured data). Based on these data and the assumption that the parent population was normally distributed. The results could be used to estimate the interval containing 95% confidence of the 18 sets of data for determination of each deviation.

These deviation bands could be shown in Appendix Figure D2.



Appendix Figure D2 Deviation bands of the calibrated deviation, the deviation of Merkel results and measured data, and the deviation of simulated results and measured data.

Appendix E

Calculation of KaV/L by the Tchebycheff Method

Calculation of KaV/L by Tchebycheff Method

In this experiment ,the inlet hot water temperature and inlet wet bulb temperature could be maintained constant at 40 ^{o}C and 25.2 ^{o}C respectively by varying the water flow rates of 31.03 , 36.8 and 46.41 L/min (for three setting values L/G of 1.800 , 2.171 and 2.820). The outlet water temperature could be measured at 34.91 ,35.5 and 36.23 ^{o}C for each water flow rate respectively, it was seen that the KaV/L-values were calculated by Tchebycheff method as shown in Table E1, E2 and E3.

Appendix Table E1 Calculated KaV/L of the Tchebycheff method under the inlet wet bulb temperature at 25.2 ^{o}C, the inlet water temperature at 40 ^{o}C, the outlet water temperature at 34.91 ^{o}C , and the given L/G ratio of 1.800.

Water temperature (^{o}C)	h_s (kJ/kg)	h_a (kJ/kg)	Δh	$1/\Delta h$
T_2=34.91	-	77.41	-	-
T_A=35.42	131.83	80.97	50.86	0.0197
T_B=36.95	142.24	92.44	49.80	0.0201
T_C=37.96	149.51	100.09	49.42	0.0202
T_D=39.49	161.81	111.57	50.24	0.0199
T_1=40	-	115.39	-	-
				0.0799

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

$$= \frac{4.175(40 - 34.91)}{4}(0.0799) = 0.4244$$

Appendix Table E2 Calculated KaV/L of the Tchebycheff method under the inlet wet bulb temperature at 25.2 °C, the inlet water temperature at 40 °C, the outlet water temperature at 35.5 °C, and the given L/G ratio of 2.171.

Water temperature (°C)	h_s (kJ/kg)	h_a (kJ/kg)	Δh	$1/\Delta h$
T_2=35.5	-	77.41	-	-
T_A=35.95	135.38	81.22	54.16	0.0185
T_B=37.3	144.74	93.46	51.28	0.0195
T_C=38.2	151.85	101.61	50.24	0.0199
T_D=39.55	162.29	113.85	48.43	0.0206
T_1=40	-	117.93	-	-
				0.0785

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

$$= \frac{4.175(40 - 35.5)}{4}(0.0785) = 0.3688$$

Appendix Table E3 Calculated KaV/L of the Tchebycheff method under the inlet wet bulb temperature at 25.2 °C, the inlet water temperature at 40 °C, the outlet water temperature at 36.23 °C, and the given L/G ratio of 2.820.

Water temperature (°C)	h_s (kJ/kg)	h_a (kJ/kg)	Δh	$1/\Delta h$
T_2=36.23	-	77.14	-	-
T_A=36.61	139.88	81.58	58.3	0.0172
T_B=37.74	147.88	94.90	52.98	0.0189
T_C=38.49	154.03	103.77	50.26	0.0199
T_D=39.62	162.88	117.09	45.79	0.0218
T_1=40	-	121.53	-	-
				0.0778

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

$$= \frac{4.175(40 - 36.23)}{4}(0.0778) = 0.3060$$

Appendix F

Calculation of the Cold Water Temperature by the Merkel's Method

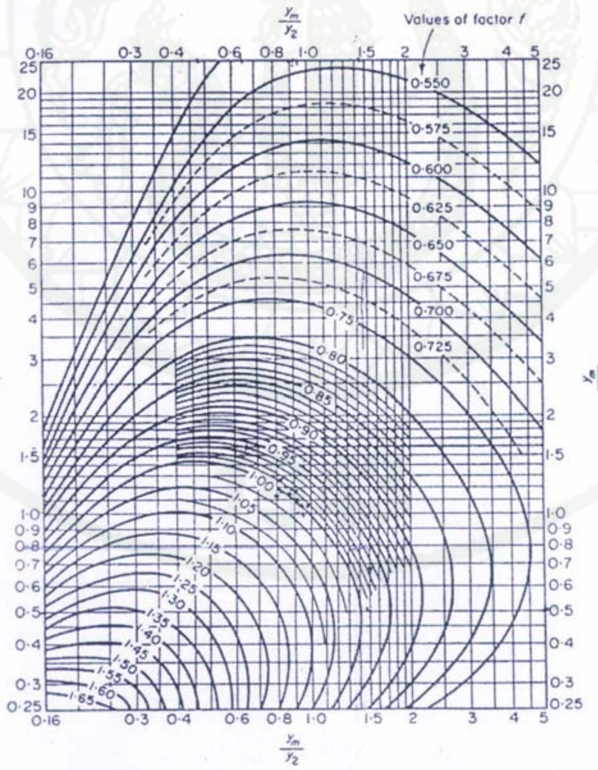
Merkel's Method

The procedure of Merkel's method could be determined as follows:

Required operating condition;

1) Hot water temperature HWT= 40 ^{o}C
2) Inlet wet bulb temperature WBT= 27.4 ^{o}C
3) Inlet dry bulb temperature DBT= 35.5 ^{o}C
4) Circulated water flow = …………… L/min
5) Air flow rate = …………… m^3/min

Characteristic equation of packing; $KaV/L= 0.8556(L/G)^{-0.6350}$

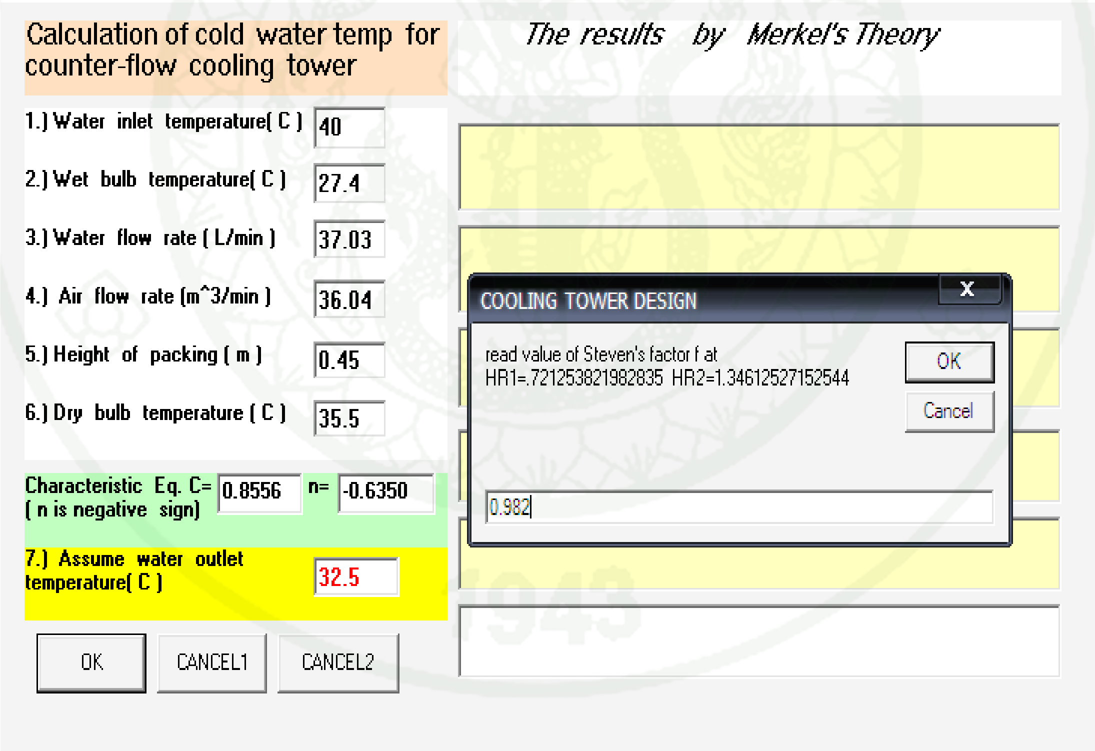


Appendix Figure F1 Steven's factor, f

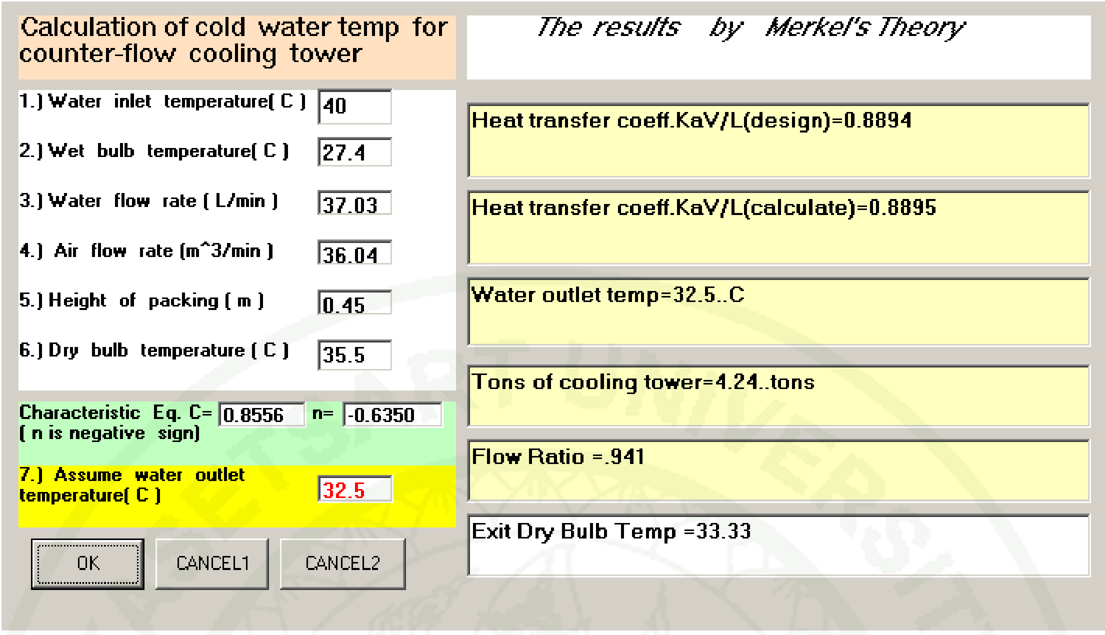
Steven's factor, f

Steven's factor, f could be determined from Appendix Figure F1 by knowing values of $\frac{y_m}{y_1} = \frac{\Delta h_m}{h_{s1} - h_{a1}}$ and $\frac{y_m}{y_2} = \frac{\Delta h_m}{h_{s2} - h_{a2}}$.

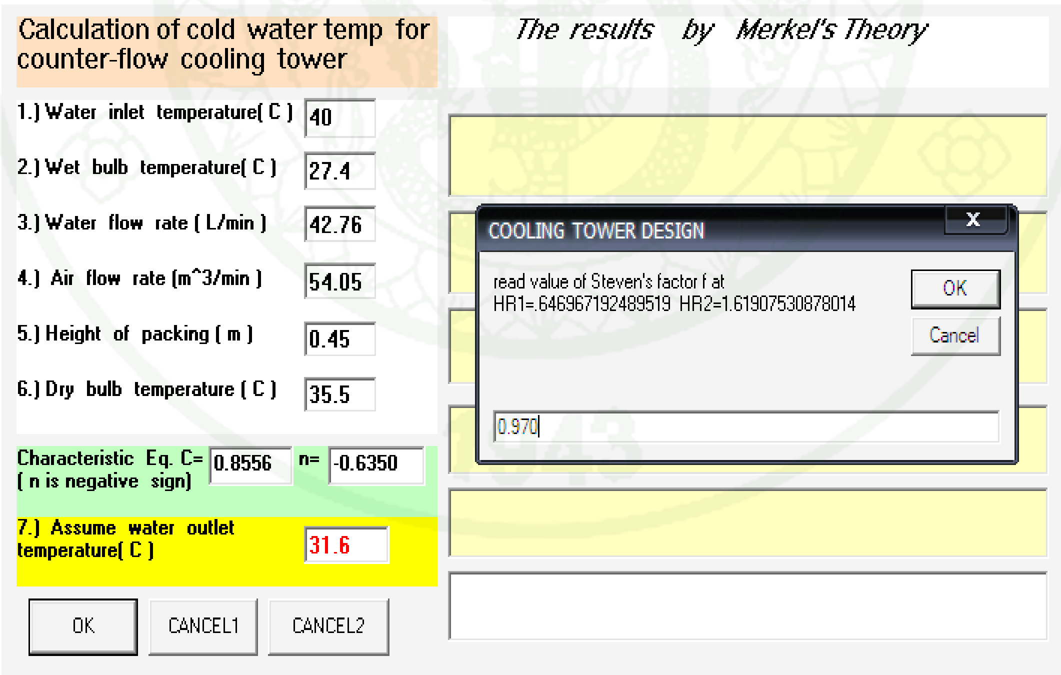
The procedure of the Merkel's method could be solved by the computer program. Under the same conditions at inlet water temperature of 40 °C, inlet dry bulb temperature of 35.5 °C,and inlet wet bulb temperature of 27.4 °C, it had three operating water to air flow ratios as (37.03 L/min, 36.04 m^3/min), (42.76 L/min, 54.05 m^3/min), and (50.9 L/min, 83.71 m^3/min),respectively.



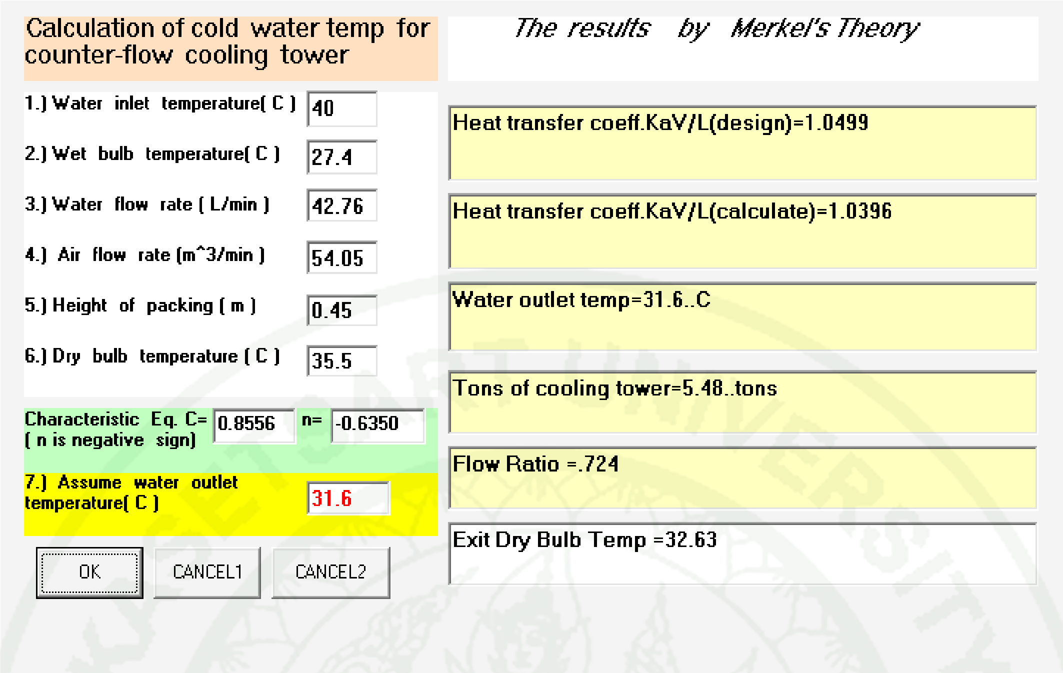
Appendix Figure F2 Steven's factor for the Merkel's method at the water flow rate of 37.03 L/min and the air flow rate of 36.04 m^3/min.



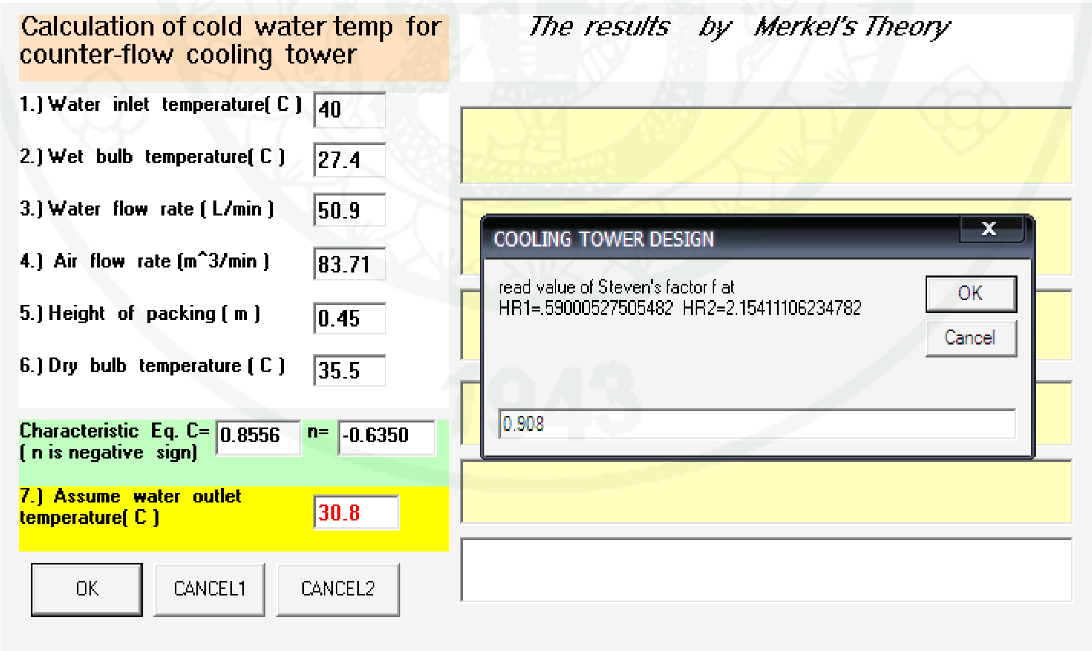
Appendix Figure F3 Results of the Merkel's method at the water flow rate of 37.03 L/min and the air flow rate of 36.04 m^3/min.



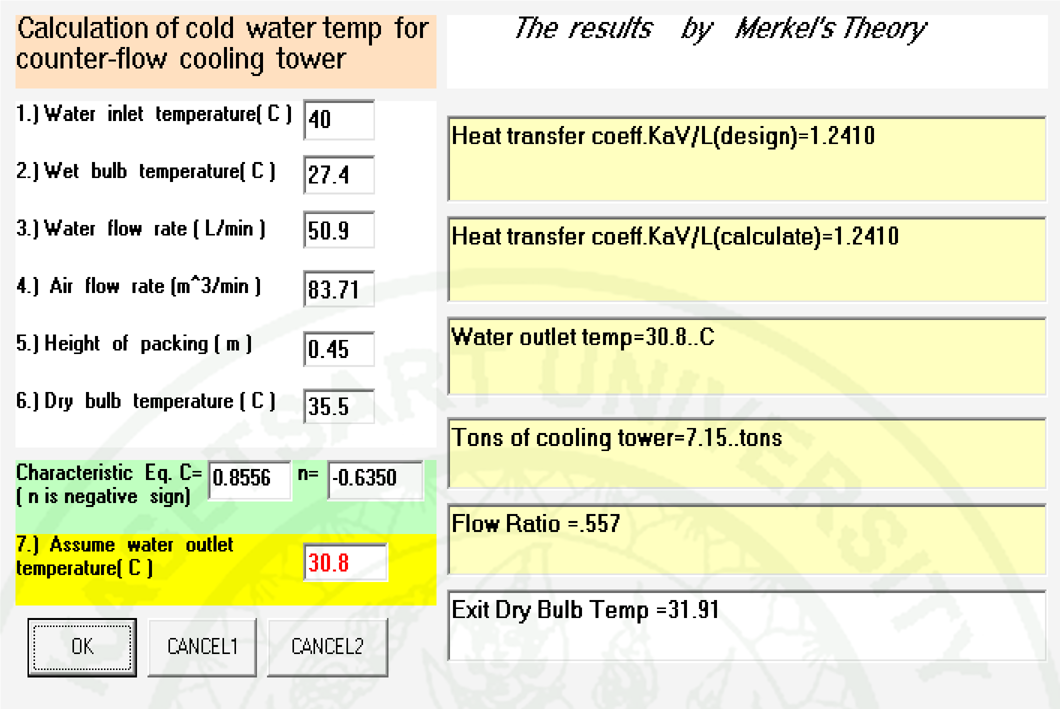
Appendix Figure F4 Steven's factor of the Merkel's method at the water flow rate of 42.76 L/min and the air flow rate of 54.05 m^3/min.



Appendix Figure F5 Results of Merkel's method at water flow rate of 42.76 L/min and air flow rate of 54.05 m^3/min.



Appendix Figure F6 Steven's factor of the Merkel's method at the water flow rate of 50.9 L/min and the air flow rate of 83.71 m^3/min.



Appendix Figure F7 Results of the Merkel's method at the water flow rate of 50.9 L/min and the air flow rate of 83.71 m^3/min.

The Steven's factor by the Merkel's theory could be illustrated (f = 0.982, 0.970 and 0.908) in Appendix Figure F2, F4 and F6, respectively.

The results by the Merkel's theory could be illustrated (water outlet temperature = 32.5, 31.6 and 30.8 $^{\circ}$C) in Appendix Figure F3, F5 and F7, respectively.

Appendix G

Enthalpy and Humidity Ratio of Saturated Air

in Temperature Range 1-60 ^{o}C

Enthalpy and Humidity Ratio of Saturated Air in Temperature Range 1-60 ^{o}C

Consideration on mathematical modeling predicted the heat and mass transfer phenomenon on the packing. It was necessary to use the humidity ratio of saturated air and the enthalpy of saturated air for calculating in the computer program as shown in Appendix Table G1.

Appendix Table G1 Enthalpy and humidity ratio of the saturated air in a temperature range of 1-60 ^{o}C.

T_a (^{o}C)	h_s (kJ / kg)	ω_S (kg-water / kg-dry air)
1	11.20	0.00413
2	12.98	0.00438
3	14.81	0.00469
4	16.70	0.00500
5	18.64	0.00538
6	20.65	0.00575
7	22.72	0.00619
8	24.86	0.00662
9	27.07	0.00713
10	29.35	0.00763
11	31.72	0.00818
12	34.18	0.00876
13	36.73	0.00933
14	39.37	0.00996
15	42.11	0.01059

Appendix Table G1 (Continued)

T_a (°C)	h_s (kJ / kg)	ω_S (kg-water / kg-dry air)
16	44.96	0.01135
17	47.93	0.01212
18	51.01	0.01288
19	54.21	0.01371
20	57.55	0.01467
21	61.03	0.01564
22	64.67	0.01667
23	68.47	0.01770
24	72.43	0.01881
25	76.56	0.02004
26	80.87	0.02129
27	85.36	0.02253
28	90.04	0.02405
29	94.93	0.02550
30	100.0	0.02711
31	105.3	0.02878
32	111.0	0.03053
33	116.8	0.03242
34	123.0	0.03439
35	129.4	0.03645
36	136.2	0.03865
37	143.2	0.04094
38	150	0.04338
39	158	0.04559
40	167	0.04876

Appendix Table G1 (Continued)

T_a (°C)	h_s (kJ / kg)	ω_s (kg-water / kg-dry air)
41	175	0.05162
42	184	0.05472
43	194	0.05793
44	205	0.06124
45	214	0.06480
46	225	0.06870
47	237	0.07250
48	249	0.07640
49	262	0.08100
50	275	0.08580
51	289	0.09140
52	304	0.09620
53	320	0.10120
54	337	0.10700
55	355	0.11380
56	374	0.11990
57	394	0.12600
58	415	0.13410
59	437	0.14230
60	460	0.15170

Source: Hill *et al*. (1990)

Appendix H

Student's t –Distribution (values of $t_{\alpha,\nu}$)

Student's t –Distribution (values of $t_{\alpha,\nu}$)

The t-distribution was qualitatively similar to the z-distribution. Student could calculate the probability distribution of the t-statistic under the assumption that the underlying population satisfied with the Gaussian distribution. The area beneath the t-distribution represented the percent of confidence as shown in Appendix Table H1 with a confidence of c %, the level of significance, $\alpha = 1 - c$ and the degree of freedom , $\nu = n - 1$ (where n was the number of data in the sample).

Appendix Table H1 Student's t –Distribution (values of $t_{\alpha,\nu}$)

ν	$t_{0.10}$	$t_{0.05}$	$t_{0.025}$	$t_{0.01}$	$t_{0.005}$	ν
1	3.078	6.314	12.706	31.821	63.657	1
2	1.886	2.920	4.303	6.925	9.925	2
3	1.638	2.353	3.182	4.541	5.841	3
4	1.533	2.132	2.776	3.747	4.604	4
5	1.476	2.015	2.571	3.365	4.032	5
6	1.440	1.943	2.447	3.143	3.707	6
7	1.415	1.895	2.365	2.998	3.499	7
8	1.397	1.860	2.306	2.896	3.355	8
9	1.383	1.833	2.262	2.821	3.250	9
10	1.372	1.812	2.228	2.764	3.169	10
11	1.363	1.796	2.201	2.718	3.106	11
12	1.356	1.782	2.179	2.681	3.055	12
13	1.350	1.771	2.160	2.650	3.012	13
14	1.345	1.761	2.145	2.624	2.977	14
15	1.341	1.753	2.131	2.602	2.947	15

Appendix Table H1 (Continued)

ν	$t_{0.10}$	$t_{0.05}$	$t_{0.025}$	$t_{0.01}$	$t_{0.005}$	ν
16	1.337	1.746	2.120	2.583	2.921	16
17	1.333	1.740	2.110	2.567	2.898	17
18	1.330	1.734	2.101	2.552	2.878	18
19	1.328	1.729	2.093	2.539	2.861	19
20	1.325	1.725	2.086	2.528	2.845	20
21	1.323	1.721	2.080	2.518	2.831	21
22	1.321	1.717	2.074	2.508	2.819	22
23	1.319	1.714	2.069	2.500	2.807	23
24	1.318	1.711	2.064	2.492	2.797	24
25	1.316	1.798	2.060	2.485	2.787	25
26	1.315	1.706	2.056	2.479	2.779	26
27	1.314	1.703	2.052	2.473	2.771	27
28	1.313	1.701	2.048	2.467	2.763	28
29	1.311	1.699	2.045	2.462	2.756	29
∞	1.282	1.645	1.960	2.326	2.576	∞

Source: Beckwith *et al*. (1993)

Appendix I

Source Code of the Computer Program for the Simulation

Source Code of the Computer Program

for the Simulation

```
Dim A1, A2, A3, A4, B1, B2, B3, B4, C1, C2, C3, C4, D1, D2, D3, D4, DELZ, ZR, TA, TF,
HF, HFG, PS, TWB, A, AM, GM, W, HW, HA, PER, H, CPA, WS, MDA, PG, MW, TFK,
ROF, MUF, NUF, ROF_MOL, AFR, P, REF, DELTA, VW, DH, THICK, REA, MUA, MUDA,
MUVAP, DIA, E, ROA, SC, DIFF, HSAT, L_HDIFF1, L_HDIFF2, HWW, ACT, DCT, VEL
Dim SUM(0 To 300), ZZ(0 To 300), ZZ2(0 To 300), TAA(0 To 300), TAA2(0 To 300),
TAA3(0 To 300), TFF2(0 To 300), ROAA2(0 To 300), ROAA3(0 To 300), WW3(0 To 300),
SUM2(0 To 300), SUM3(0 To 300), TFF3(0 To 300), TFF(0 To 300), WWS(0 To 300),
WWS2(0 To 300), WWS3(0 To 300), WW(0 To 300), MWW(0 To 300), MDAA(0 To 300),
ROAA(0 To 300), WW2(0 To 300), MWW2(0 To 300), MDAA2(0 To 300), MWW3(0 To
300), MDAA3(0 To 300), MAA3(0 To 300), MAA2(0 To 300), MAA(0 To 300),
Cal_WBT23(0 To 1000000), Cal_WW23(0 To 1000000), Cal_WW22(0 To 1000000),
Cal_WBT24(0 To 1000000), Cal_WW24(0 To 1000000), Cal_WBT(0 To 1000000),
Cal_WBT2(0 To 1000000), Cal_WW2(0 To 1000000)
Dim Gm_a, Fill_Pitch, Fill_Height, L_over_G, Plate_thickness, Plate_Width,
CT_Diameter, Cal_W, Cal_W2, Diff_W
Dim K As Integer,  I As Integer,  N As Integer
Public Function F1(TA, TF, W)
F1 = (1.005 + 1.88 * W) ^ -1 * (AFR * Gm_a / MDAA(0)) * (((1.005 + 1.88 * W) * (TF - TA)
/ (1 + W)) + ((WS - W) / ((1 + WS) * (1 + W))) * (2501 + 1.789 * TF + 0.00005337 * ((TF +
273.15) ^ 2 - 273.16 ^ 2) + 0.0000001952 * ((TF + 273.15) ^ 3 - 273.16 ^ 3) -
0.00000000005 * ((TF + 273.15) ^ 4 - 273.16 ^ 4)) - (2501 + 1.88 * TA) * (WS - W) / ((1 +
WS) * (1 + W)))
End Function
Public Function F2(TA, TF, W, MW)
F2 = (4.179 ^ -1) * (AFR * Gm_a / MW) * (((1.005 + 1.88 * W) * (TF - TA) / (1 + W)) +
((WS - W) / ((1 + WS) * (1 + W))) * (2501 + 1.789 * TF + 0.00005337 * ((TF + 273.15) ^ 2
```

```
- 273.16 ^ 2) + 0.0000001952 * ((TF + 273.15) ^ 3 - 273.16 ^ 3) - 0.00000000005 * ((TF
+ 273.15) ^ 4 - 273.16 ^ 4)) - (4.179 * TF + 0.4164) * (WS - W) / ((1 + WS) * (1 + W)))
End Function
Public Function F3(W)
F3 = AFR * Gm_a * (WS - W) / (MDAA(0) * (1 + WS) * (1 + W))
End Function
Public Function F4(W)
F4 = AFR * Gm_a * (WS - W) / ((1 + WS) * (1 + W))
End Function
Sub CMDSHOW_CLICK()
PI = 3.142857:  GCC = 9.807 m/s2
'Input type of packing(fill) and diameter of packing
Fill_Pitch = 235:  Fill_Height = 0.235    'm : ZR = Fill_Height
CT_Diameter = 0.55     'm
'Input water flow rate and air flow rate
VW = 46.41          ' L/min
VAIR = 14.66       'm3/min
'Input initial values
Z = 0: TA = 32.3: TWB = 25.2: TF = 36.26
'Input number of layer
N = 20
'Calculate increment of height
DELZ = ZR / N
'Calculate frontal area of packing
AFR = (PI / 4) * CT_Diameter ^ 2
'Calculate water temperature, density and mass flow rate of water
TFK = ((273.15 + TF) + (40 + 273.15)) / 2
ROF = 2.116235E-10 * TFK ^ 6 - 0.0000004052421 * TFK ^ 5 + 0.0003221635 * TFK ^ 4
- 0.136077 * TFK ^ 3 + 32.19895 * TFK ^ 2 - 4045.674 * TFK + 211816.2
MW = ROF * (0.001 * VW) / 60
```

```
'Calculation of mass flow rate of air
If TWB > 20  And  TWB < 45 Then
PS = (9 * 10 ^ -5) * TWB ^ 3 - 0.0017 * TWB ^ 2 + 0.1081 * TWB + 0.1614
Else
TxtOUTOFF.Text = "OUT OFF RANGE"
End If
If TWB >= 5 And TWB <= 60 Then
HF = 4.182 * TWB + 0.2293
HFG = 2501.8 - 2.387 * TWB
Else
End If
W = (1.005 * (TWB - TA) + (0.622 * PS / (101.325 - PS)) * HFG) / (2501.5 + 1.806 * TA - HF)
VA = (0.082 * TA + 22.4135) * ((1 / 29) + (W / 18)) / (1 + W)
ROA = 1 / VA
MA = ROA * VAIR / 60
MDA = MA / (1 + W)
……………………………Loop for Runge-Kutta simulation…………………………………
For I = 0 To N
ZZ(I) = Z
TAA(I) = TA
TFF(I) = TF
WW(I) = W
MWW(I) = MW
MDAA(I) = MDA
MAA(I) = MA
ROAA(I) = ROA
L_over_G = MWW(I) / MDAA(0)
'Calculate mass transfer per unit volume, Gm_a
If Fill_Pitch = 4.45 Then
```

```
P = Fill_Pitch / 100: Plate_thickness = 0.002: Plate_Width = 0.45
AFR = (NP - 1) * P * Plate_Width
C = 0.289: b = 0.7
Gm_a = C * (MW / AFR) * L_over_G ^ -b
ElseIf Fill_Pitch = 3.81 Then
P = Fill_Pitch / 100: Plate_thickness = 0.002: Plate_Width = 0.45
AFR = (NP - 1) * P * Plate_Width
C = 0.361: b = 0.72
Gm_a = C * (MW / AFR) * L_over_G ^ -b
ElseIf Fill_Pitch = 3.81 Then
P = Fill_Pitch / 100: Plate_thickness = 0.002: Plate_Width = 0.45
AFR = (NP - 1) * P * Plate_Width
C = 0.394: b = 0.76
Gm_a = C * (MW / AFR) * L_over_G ^ -b
ElseIf Fill_Pitch = 2.54 Then
P = Fill_Pitch / 100: Plate_thickness = 0.002: Plate_Width = 0.45
AFR = (NP - 1) * P * Plate_Width
C = 0.459: b = 0.73
Gm_a = C * (MW / AFR) * L_over_G ^ -b
ElseIf Fill_Pitch = 235 Then   'Fill height=235mm
AFR = (PI / 4) * CT_Diameter ^ 2
C = 0.8255: b = 0.7569
Gm_a = (C / Fill_Height) * (MW / AFR) * L_over_G ^ -b
ElseIf Fill_Pitch = 470 Then   'Fill height=470mm
AFR = (PI / 4) * CT_Diameter ^ 2
C = 0.5943: b = 0.7422
Gm_a = (C / Fill_Height) * (MW / AFR) * L_over_G ^ -b
ElseIf Fill_Pitch = 450 Then   'Fill height=450mm
AFR = (PI / 4) * CT_Diameter ^ 2
C = 0.8556: b = 0.6350
```

```
Gm_a = (C / Fill_Height) * (MW / AFR) * L_over_G ^ -b
End If
TFK = 273.15 + TF
ROF = 2.116235E-10 * TFK ^ 6 - 0.0000004052421 * TFK ^ 5 + 0.0003221635 * TFK ^ 4
- 0.136077 * TFK ^ 3 + 32.19895 * TFK ^ 2 - 4045.674 * TFK + 211816.2
HW = 4.179 * TF + 0.4164 'for water temp 25 C to 49 C
HA = 1.005 * TA + W * (2501 + 1.88 * TA)
PG = 0.0109 * TF ^ 2 - 0.4754 * TF + 8.7967
WS = 0.622 * PG / (101.325 - PG)
If TF >= 24 And TF <= 38 Then
HSAT = 0.1251 * TF ^ 2 - 2.232 * TF + 53.945
ElseIf TF > 38 And TF <= 48 Then
HSAT = 0.2412 * TF ^ 2 - 11.023 * TF + 220.96
End If
WWS(I) = WS
'Calculation of driving force
L_HDIFF1 = 1 / (HSAT - HA)
HWW = HW
'Calculation of wet bulb temperature
For J = 0 To 200000
Cal_WBT(0) = TWB
If Cal_WBT(J) > 20 And Cal_WBT(J) < 45 Then
PS = (9 * 10 ^ -5) * Cal_WBT(J) ^ 3 - 0.0017 * Cal_WBT(J) ^ 2 + 0.1081 * Cal_WBT(J) +
0.1614
ElseIf Cal_WBT(J) > 45 Then
J = 200000: I = N
TxtOUTOFF.Text = "OUT OFF RANGE"
End If
If Cal_WBT(J) > 5  And Cal_WBT(J) < 60 Then
HF = 4.182 * Cal_WBT(J) + 0.2293
```

```
HFG = 2501.8 - 2.387 * Cal_WBT(J)
End If
Cal_W = (1.005 * (Cal_WBT(J) - TA) + (0.622 * PS / (101.325 - PS)) * HFG) / (2501.5 +
1.806 * TA - HF)
Diff_W = Abs(Cal_W - W)
If Diff_W = 0.00001 Then
J = 200000
ElseIf Cal_W < W Then
Cal_WBT(J + 1) = Cal_WBT(J) + 0.0001
ElseIf Cal_W > W Then
Cal_WBT(J + 1) = Cal_WBT(J) - 0.0001
End If
Next J
'Cal_WBT2(0) = TWB
Cal_WBT2(I) = Cal_WBT(200000)
Cal_W2 = (1.005 * (Cal_WBT(200000) - TA) + (0.622 * PS / (101.325 - PS)) * HFG) /
(2501.5 + 1.806 * TA - HF)
Cal_WW2(I + 1) = Cal_W2
MSFlexGrid1.Col = 0          'for the zeroth column
MSFlexGrid1.Row = 1
MSFlexGrid1.Text = "Z(m)"
MSFlexGrid1.Row = I + 2      'row after the first row
MSFlexGrid1.Text = Round(Z, 3)
MSFlexGrid1.Col = 1          'for the first column
MSFlexGrid1.Row = 1
MSFlexGrid1.Text = "TA(C)"
MSFlexGrid1.Row = I + 2
MSFlexGrid1.Text = Round(TAA(I), 2)
MSFlexGrid1.Col = 2     'for the second column
MSFlexGrid1.Row = 1
```

```
MSFlexGrid1.Text = "WBT(C)"
MSFlexGrid1.Row = 2
MSFlexGrid1.Text = Round(TWB, 2)
MSFlexGrid1.Row = I + 2
MSFlexGrid1.Text = Round(Cal_WBT2(I), 2)
MSFlexGrid1.Col = 3     'for the third column
MSFlexGrid1.Row = 1
MSFlexGrid1.Text = "TF(C)"
MSFlexGrid1.Row = I + 2
MSFlexGrid1.Text = Round(TFF(I), 2)
MSFlexGrid1.Col = 4      'for the fourth column
MSFlexGrid1.Row = 1
MSFlexGrid1.Text = "W"
MSFlexGrid1.Row = I + 2
MSFlexGrid1.Text = Round(WW(I), 4)
MSFlexGrid1.Col = 5      'for the fifth column
MSFlexGrid1.Row = 1
MSFlexGrid1.Text = "MW(kg/s)"
MSFlexGrid1.Row = I + 2
MSFlexGrid1.Text = Round(MWW(I), 4)
MSFlexGrid1.Col = 6     'for the sixth column
MSFlexGrid1.Row = 1
MSFlexGrid1.Text = "KaV/L"
MSFlexGrid1.Row = I + 2
MSFlexGrid1.Text = Round(SUM(I), 4)
MSFlexGrid1.Col = 7    'for the seventh column
MSFlexGrid1.Row = 1
MSFlexGrid1.Text = "Cal_W"
MSFlexGrid1.Row = 2
MSFlexGrid1.Text = Round(WW(0), 4)
```

```
MSFlexGrid1.Row = I + 2
MSFlexGrid1.Text = Round(Cal_WW2(I + 1), 4)
MSFlexGrid1.Col = 8     'for the eighth column
MSFlexGrid1.Row = 1
MSFlexGrid1.Text = "WS"
MSFlexGrid1.Row = I + 2
MSFlexGrid1.Text = Round(WWS(I), 4)
A1 = DELZ * F1(TA, TF, W)
B1 = DELZ * F2(TA, TF, W, MW)
C1 = DELZ * F3(W)
D1 = DELZ * F4(W)
A2 = DELZ * F1(TA + A1 / 2, TF + B1 / 2, W + C1 / 2)
B2 = DELZ * F2(TA + A1 / 2, TF + B1 / 2, W + C1 / 2, MW + D1 / 2)
C2 = DELZ * F3(W + C1 / 2)
D2 = DELZ * F4(W + C1 / 2)
A3 = DELZ * F1(TA + A2 / 2, TF + B2 / 2, W + C2 / 2)
B3 = DELZ * F2(TA + A2 / 2, TF + B2 / 2, W + C2 / 2, MW + D2 / 2)
C3 = DELZ * F3(W + C2 / 2)
D3 = DELZ * F4(W + C2 / 2)
A4 = DELZ * F1(TA + A3, TF + B3, W + C3)
B4 = DELZ * F2(TA + A3, TF + B3, W + C3, MW + D3)
C4 = DELZ * F3(W + C3)
D4 = DELZ * F4(W + C3)
TA = TA + (A1 + 2 * A2 + 2 * A3 + A4) / 6
TF = TF + (B1 + 2 * B2 + 2 * B3 + B4) / 6
W = W + (C1 + 2 * C2 + 2 * C3 + C4) / 6
MW = MW + (D1 + 2 * D2 + 2 * D3 + D4) / 6
Z = Z + DELZ
HW = 4.179 * TF + 0.4164
HA = 1.005 * TA + W * (2501 + 1.88 * TA)
```

```
If TF >= 24 And TF <= 38 Then
HSAT = 0.1251 * TF ^ 2 - 2.232 * TF + 53.945
ElseIf TF > 38 And TF <= 48 Then
HSAT = 0.2412 * TF ^ 2 - 11.023 * TF + 220.96
End If
HDIFF_OFWATER = HW - HWW
L_HDIFF2 = 1 / (HSAT - HA)
'trapesoidal rule
SUM(0) = 0
SUM(I + 1) = SUM(I) + 0.5 * (L_HDIFF1 + L_HDIFF2) * HDIFF_OFWATER
Next I
.............................End of Loop for Runge-Kutta simulation................................
MSFlexGrid1.Col = 0
MSFlexGrid1.Row = N + 3
MSFlexGrid1.Text = "KaV/L"
MSFlexGrid1.Row = N + 4
MSFlexGrid1.Text = Round(SUM(N), 4) ' Use Sum(0)at z=0  ,Sum(N) @ Z=N
MSFlexGrid1.Col = 1
MSFlexGrid1.Row = N + 3
MSFlexGrid1.Text = "L/G"
MSFlexGrid1.Row = N + 4
MSFlexGrid1.Text = Round(MWW(N) / MDAA(0), 4)
MSFlexGrid1.Col = 2
MSFlexGrid1.Row = N + 3
MSFlexGrid1.Text = "LL(kg/m^2.s)"
MSFlexGrid1.Row = N + 4
MSFlexGrid1.Text = Round(MWW(N) / AFR, 4)          'base on frontal area
MSFlexGrid1.Col = 3
MSFlexGrid1.Row = N + 3
MSFlexGrid1.Text = "GG(kg/m^2.s)"
```

```
MSFlexGrid1.Row = N + 4
MSFlexGrid1.Text = Round(MDAA(0) / AFR, 4)
MSFlexGrid1.Col = 4
MSFlexGrid1.Row = N + 3
MSFlexGrid1.Text = "Va(m/s)"
MSFlexGrid1.Row = N + 4
MSFlexGrid1.Text = Round(MAA(N) / (ROAA(N) * AFR), 4)
```

Plot Graph

```
MSChart1.ColumnCount = 2
MSChart1.RowCount = N + 1
For I = 0 To N
MSChart1.Data = ZZ(I) * 10
Next I
For I = 0 To N
MSChart1.Data = TAA(I)
Next I
Cal_WBT2(0) = TWB
MSChart2.ColumnCount = 2
MSChart2.RowCount = N + 1
For I = 0 To N
MSChart2.Data = ZZ(I) * 100
Next I
For I = 0 To N
MSChart2.Data = Cal_WBT2(I)
Next I
MSChart3.ColumnCount = 2
MSChart3.RowCount = N + 1
For I = 0 To N
MSChart3.Data = TAA(I)
Next I
```

```
For I = 0 To N
MSChart3.Data = WW(I) * 100
Next I
txtP1 = "Vw=" & VW & "L/min"
```

……………………………………..PROGRAM 2……………………………………………

```
'Input type of packing(fill) and diameter of packing
Fill_Pitch = 235:  Fill_Height = 0.235    'm : ZR = Fill_Height
CT_Diameter = 0.55     'm
'Input water flow rate and air flow rate
VW = 36.8          ' L/min
VAIR = 15.12       'm3/min
'Input initial values
Z = 0: TA = 32.3: TWB = 25.2: TF = 35.54
'Input number of layer
N = 20
'Calculate increment of height
DELZ = ZR / N
'Calculate frontal area of packing
AFR = (PI / 4) * CT_Diameter ^ 2
'Calculate water temperature, density and mass flow rate of water
TFK = ((273.15 + TF) + (40 + 273.15)) / 2
ROF = 2.116235E-10 * TFK ^ 6 - 0.0000004052421 * TFK ^ 5 + 0.0003221635 * TFK ^ 4
- 0.136077 * TFK ^ 3 + 32.19895 * TFK ^ 2 - 4045.674 * TFK + 211816.2
MW = ROF * (0.001 * VW) / 60
'Calculation of mass flow rate of air
If TWB > 20 And TWB < 45 Then
PS = (9 * 10 ^ -5) * TWB ^ 3 - 0.0017 * TWB ^ 2 + 0.1081 * TWB + 0.1614
Else
End If
If TWB >= 5 And TWB <= 60 Then
HF = 4.182 * TWB + 0.2293
```

```
HFG = 2501.8 - 2.387 * TWB
Else
End If
W = (1.005 * (TWB - TA) + (0.622 * PS / (101.325 - PS)) * HFG) / (2501.5 + 1.806 * TA -
HF)
VA = (0.082 * TA + 22.4135) * ((1 / 29) + (W / 18)) / (1 + W)
ROA = 1 / VA
MA = ROA * VAIR / 60
MDA = MA / (1 + W)
......................................Loop for Runge-Kutta simulation....................................
For I = 0 To N
ZZ(I) = Z
TAA2(I) = TA
TFF2(I) = TF
WW2(I) = W
MWW2(I) = MW
MDAA2(I) = MDA
MAA2(I) = MA
ROAA2(I) = ROA
L_over_G = MWW2(I) / MDAA2(0)
'Calculate mass transfer per unit volume, Gm_a
If Fill_Pitch = 4.45 Then
P = Fill_Pitch / 100: Plate_thickness = 0.002: Plate_Width = 0.45
AFR = (NP - 1) * P * Plate_Width
C = 0.289: b = 0.7
Gm_a = C * (MW / AFR) * L_over_G ^ -b
ElseIf Fill_Pitch = 3.81 Then
P = Fill_Pitch / 100: Plate_thickness = 0.002: Plate_Width = 0.45
AFR = (NP - 1) * P * Plate_Width
C = 0.361: b = 0.72
```

```
Gm_a = C * (MW / AFR) * L_over_G ^ -b
ElseIf Fill_Pitch = 3.81 Then
P = Fill_Pitch / 100: Plate_thickness = 0.002: Plate_Width = 0.45
AFR = (NP - 1) * P * Plate_Width
C = 0.394: b = 0.76
Gm_a = C * (MW / AFR) * L_over_G ^ -b
ElseIf Fill_Pitch = 2.54 Then
P = Fill_Pitch / 100: Plate_thickness = 0.002: Plate_Width = 0.45
AFR = (NP - 1) * P * Plate_Width
C = 0.459: b = 0.73
Gm_a = C * (MW / AFR) * L_over_G ^ -b
ElseIf Fill_Pitch = 235 Then   'Fill height=235mm
AFR = (PI / 4) * CT_Diameter ^ 2
C = 0.8255: b = 0.7569
Gm_a = (C / Fill_Height) * (MW / AFR) * L_over_G ^ -b
ElseIf Fill_Pitch = 470 Then   'Fill height=470mm
AFR = (PI / 4) * CT_Diameter ^ 2
C = 0.5943: b = 0.7422
Gm_a = (C / Fill_Height) * (MW / AFR) * L_over_G ^ -b
ElseIf Fill_Pitch = 450 Then   'Fill height=450mm
AFR = (PI / 4) * CT_Diameter ^ 2
C = 0.8556: b = 0.6350
Gm_a = (C / Fill_Height) * (MW / AFR) * L_over_G ^ -b
End If
TFK = 273.15 + TF
ROF = 2.116235E-10 * TFK ^ 6 - 0.0000004052421 * TFK ^ 5 + 0.0003221635 * TFK ^ 4
- 0.136077 * TFK ^ 3 + 32.19895 * TFK ^ 2 - 4045.674 * TFK + 211816.2
HW = 4.179 * TF + 0.4164      'for water temp 25 C to 49 C
HA = 1.005 * TA + W * (2501 + 1.88 * TA)
PG = 0.0109 * TF ^ 2 - 0.4754 * TF + 8.7967
```

```
WS = 0.622 * PG / (101.325 - PG)
If TF >= 24 And TF <= 38 Then
HSAT = 0.1251 * TF ^ 2 - 2.232 * TF + 53.945
ElseIf TF > 38 And TF <= 48 Then
HSAT = 0.2412 * TF ^ 2 - 11.023 * TF + 220.96
End If
WWS2(I) = WS
'Calculation of driving force
L_HDIFF1 = 1 / (HSAT - HA)
HWW = HW
'Calculation of wet bulb temperature
HWW = HW
For J = 0 To 10000
Cal_WBT(0) = TWB
If Cal_WBT(J) > 20 And Cal_WBT(J) < 45 Then
PS = (9 * 10 ^ -5) * Cal_WBT(J) ^ 3 - 0.0017 * Cal_WBT(J) ^ 2 + 0.1081 * Cal_WBT(J) +
0.1614
ElseIf Cal_WBT(J) > 45 Then
J = 200000: I = N
TxtOUTOFF.Text = "OUT OFF RANGE"
End If
If Cal_WBT(J) >= 5 And Cal_WBT(J) <= 60 Then
HF = 4.182 * Cal_WBT(J) + 0.2293
HFG = 2501.8 - 2.387 * Cal_WBT(J)
End If
Cal_W = (1.005 * (Cal_WBT(J) - TA) + (0.622 * PS / (101.325 - PS)) * HFG) / (2501.5 +
1.806 * TA - HF)
Diff_W = Abs(Cal_W - W)
If Diff_W = 0 Then
J = 10000 '30000
```

```
ElseIf Cal_W < W Then
Cal_WBT(J + 1) = Cal_WBT(J) + 0.002225
ElseIf Cal_W > W Then
Cal_WBT(J + 1) = Cal_WBT(J) - 0.00088455
End If
Next J
'Cal_WBT23(0) = TWB
Cal_WBT23(I) = Cal_WBT(10000)
Cal_W2 = (1.005 * (Cal_WBT(10000) - TA) + (0.622 * PS / (101.325 - PS)) * HFG) /
(2501.5 + 1.806 * TA - HF)
Cal_WW22(I + 1) = Cal_W2
'Table results
MSFlexGrid1.Col = 0             'for the zeroth column
MSFlexGrid1.Row = N + 6
MSFlexGrid1.Text = "Z(m)"
MSFlexGrid1.Row = I + N + 7   'row after the first row
MSFlexGrid1.Text = Round(Z, 3)
MSFlexGrid1.Col = 1             'for the first column
MSFlexGrid1.Row = N + 6
MSFlexGrid1.Text = "TA(C)"
MSFlexGrid1.Row = I + N + 7
MSFlexGrid1.Text = Round(TAA2(I), 2)
MSFlexGrid1.Col = 2              'for the second column
MSFlexGrid1.Row = N + 6
MSFlexGrid1.Text = "WBT(C)"
MSFlexGrid1.Row = N + 7
MSFlexGrid1.Text = Round(TWB, 2)
MSFlexGrid1.Row = I + N + 7
MSFlexGrid1.Text = Round(Cal_WBT23(I), 2)
MSFlexGrid1.Col = 3              'for the third column
```

```
MSFlexGrid1.Row = N + 6
MSFlexGrid1.Text = "TF(C)"
MSFlexGrid1.Row = I + N + 7
MSFlexGrid1.Text = Round(TFF2(I), 2)
MSFlexGrid1.Col = 4               'for the fourth column
MSFlexGrid1.Row = N + 6
MSFlexGrid1.Text = "W"
MSFlexGrid1.Row = I + N + 7
MSFlexGrid1.Text = Round(WW2(I), 4)
MSFlexGrid1.Col = 5                'for the fifth column
MSFlexGrid1.Row = N + 6
MSFlexGrid1.Text = "MW(kg/s)"
MSFlexGrid1.Row = I + N + 7
MSFlexGrid1.Text = Round(MWW2(I), 4)
MSFlexGrid1.Col = 6               'for the sixth column
MSFlexGrid1.Row = N + 6
MSFlexGrid1.Text = "KaV/L"
MSFlexGrid1.Row = I + N + 7
MSFlexGrid1.Text = Round(SUM2(I), 4)
MSFlexGrid1.Col = 7               'for the seventh column
MSFlexGrid1.Row = N + 6
MSFlexGrid1.Text = "Cal_W"
MSFlexGrid1.Row = N + 7
MSFlexGrid1.Text = Round(WW2(0), 4)
MSFlexGrid1.Row = I + N + 7
MSFlexGrid1.Text = Round(Cal_WW22(I + 1), 4)
MSFlexGrid1.Col = 8               'for the eighth column
MSFlexGrid1.Row = N + 6
MSFlexGrid1.Text = "WS"
MSFlexGrid1.Row = I + N + 7
```

```
MSFlexGrid1.Text = Round(WWS2(I), 4)
A1 = DELZ * F1(TA, TF, W)
B1 = DELZ * F2(TA, TF, W, MW)
C1 = DELZ * F3(W)
D1 = DELZ * F4(W)
A2 = DELZ * F1(TA + A1 / 2, TF + B1 / 2, W + C1 / 2)
B2 = DELZ * F2(TA + A1 / 2, TF + B1 / 2, W + C1 / 2, MW + D1 / 2)
C2 = DELZ * F3(W + C1 / 2)
D2 = DELZ * F4(W + C1 / 2)
A3 = DELZ * F1(TA + A2 / 2, TF + B2 / 2, W + C2 / 2)
B3 = DELZ * F2(TA + A2 / 2, TF + B2 / 2, W + C2 / 2, MW + D2 / 2)
C3 = DELZ * F3(W + C2 / 2)
D3 = DELZ * F4(W + C2 / 2)
A4 = DELZ * F1(TA + A3, TF + B3, W + C3)
B4 = DELZ * F2(TA + A3, TF + B3, W + C3, MW + D3)
C4 = DELZ * F3(W + C3)
D4 = DELZ * F4(W + C3)
TA = TA + (A1 + 2 * A2 + 2 * A3 + A4) / 6
TF = TF + (B1 + 2 * B2 + 2 * B3 + B4) / 6
W = W + (C1 + 2 * C2 + 2 * C3 + C4) / 6
MW = MW + (D1 + 2 * D2 + 2 * D3 + D4) / 6
Z = Z + DELZ
HW = 4.179 * TF + 0.4164
HA = 1.005 * TA + W * (2501 + 1.88 * TA)
If TF >= 24 And TF <= 38 Then
HSAT = 0.1251 * TF ^ 2 - 2.232 * TF + 53.945
ElseIf TF > 38 And TF <= 48 Then
HSAT = 0.2412 * TF ^ 2 - 11.023 * TF + 220.96
End If
HDIFF_OFWATER = HW - HWW
```

```
L_HDIFF2 = 1 / (HSAT - HA)
'trapesoidal rule
SUM2(0) = 0
SUM2(I + 1) = SUM2(I) + 0.5 * (L_HDIFF1 + L_HDIFF2) * HDIFF_OFWATER
Next I
……………………………..End of Loop for Rung-Kutta simulation…………………………..
MSFlexGrid1.Col = 0
MSFlexGrid1.Row = 2 * N + 8
MSFlexGrid1.Text = "KaV/L"
MSFlexGrid1.Row = 2 * N + 9
MSFlexGrid1.Text = Round(SUM2(N), 4)
MSFlexGrid1.Col = 1
MSFlexGrid1.Row = 2 * N + 8
MSFlexGrid1.Text = "L/G"
MSFlexGrid1.Row = 2 * N + 9
MSFlexGrid1.Text = Round(MWW2(N) / MDAA2(0), 4)
MSFlexGrid1.Col = 2
MSFlexGrid1.Row = 2 * N + 8
MSFlexGrid1.Text = "LL(kg/m^2.s)"
MSFlexGrid1.Row = 2 * N + 9
MSFlexGrid1.Text = Round(MWW2(N) / AFR, 4) ' base on frontal area
MSFlexGrid1.Col = 3
MSFlexGrid1.Row = 2 * N + 8
MSFlexGrid1.Text = "GG(kg/m^2.s)"
MSFlexGrid1.Row = 2 * N + 9
MSFlexGrid1.Text = Round(MDAA2(0) / AFR, 4)
MSFlexGrid1.Col = 4
MSFlexGrid1.Row = 2 * N + 8
MSFlexGrid1.Text = "Va(m/s)"
MSFlexGrid1.Row = 2 * N + 9
```

```
MSFlexGrid1.Text = Round(MAA2(N) / (ROAA2(N) * AFR), 4)
```

Plot Graph

```
MSChart1.ColumnCount = 4
MSChart1.RowCount = N + 1
For I = 0 To N
MSChart1.Data = ZZ(I) * 10
Next I
For I = 0 To N
MSChart1.Data = TAA(I)
Next I
For I = 0 To N
MSChart1.Data = ZZ(I) * 10
Next I
For I = 0 To N
MSChart1.Data = TAA2(I)
Next I
Cal_WBT23(0) = TWB
MSChart2.ColumnCount = 4
MSChart2.RowCount = N + 1
For I = 0 To N
MSChart2.Data = ZZ(I) * 100
Next I
For I = 0 To N
MSChart2.Data = Cal_WBT2(I)
Next I
For I = 0 To N
MSChart2.Data = ZZ(I) * 100
Next I
For I = 0 To N
MSChart2.Data = Cal_WBT23(I)
```

```
Next I
MSChart3.ColumnCount = 4
MSChart3.RowCount = N + 1
For I = 0 To N
MSChart3.Data = TAA(I)
Next I
For I = 0 To N
MSChart3.Data = WW(I) * 100
Next I
For I = 0 To N
MSChart3.Data = TAA2(I)
Next I
For I = 0 To N
MSChart3.Data = WW2(I) * 100
Next I
MSChart4.ColumnCount = 4
MSChart4.RowCount = N + 1
For I = 0 To N
MSChart4.Data = ZZ(I) * 100
Next I
For I = 0 To N
MSChart4.Data = TFF(I)
Next I
For I = 0 To N
MSChart4.Data = ZZ(I) * 100
Next I
For I = 0 To N
MSChart4.Data = TFF2(I)
Next I
txtP2 = "Vw=" & VW & "L/min"
```

………………………………………..PROGRAM 3……………………………………………

```
'Input type of packing(fill) and diameter of packing
Fill_Pitch = 235:  Fill_Height = 0.235    'm : ZR = Fill_Height
CT_Diameter = 0.55     'm
'Input water flow rate and air flow rate
VW = 31.03         ' L/min
VAIR = 15.4       'm3/min
'Input initial values
Z = 0: TA = 32.3: TWB = 25.2: TF = 34.96
'Input number of layer
N = 20
'Calculate increment of height
DELZ = ZR / N
'Calculate frontal area of packing
AFR = (PI / 4) * CT_Diameter ^ 2
'Calculate water temperature, density and mass flow rate of water
TFK = ((273.15 + TF) + (40 + 273.15)) / 2
ROF = 2.116235E-10 * TFK ^ 6 - 0.0000004052421 * TFK ^ 5 + 0.0003221635 * TFK ^ 4
- 0.136077 * TFK ^ 3 + 32.19895 * TFK ^ 2 - 4045.674 * TFK + 211816.2
MW = ROF * (0.001 * VW) / 60
'Calculation of mass flow rate of air
If TWB > 20 And TWB < 45 Then
PS = (9 * 10 ^ -5) * TWB ^ 3 - 0.0017 * TWB ^ 2 + 0.1081 * TWB + 0.1614
ElseIf Cal_WBT(J) > 45 Then
J = 200000: I = N
TxtOUTOFF.Text = "OUT OFF RANGE"
End If
If TWB >= 5 And TWB <= 60 Then
HF = 4.182 * TWB + 0.2293
HFG = 2501.8 - 2.387 * TWB
Else
```

```
End If
W = (1.005 * (TWB - TA) + (0.622 * PS / (101.325 - PS)) * HFG) / (2501.5 + 1.806 * TA -
HF)
VA = (0.082 * TA + 22.4135) * ((1 / 29) + (W / 18)) / (1 + W)
ROA = 1 / VA
MA = ROA * VAIR / 60
MDA = MA / (1 + W)
……………………………..Loop for Runge-Kutta simulation………………………………
For I = 0 To N
ZZ(I) = Z
TAA3(I) = TA
TFF3(I) = TF
WW3(I) = W
MWW3(I) = MW
MDAA3(I) = MDA
MAA3(I) = MA
ROAA3(I) = ROA
L_over_G = MWW3(I) / MDAA3(0)
'Calculate mass transfer per unit volume, Gm_a
If Fill_Pitch = 4.45 Then
P = Fill_Pitch / 100: Plate_thickness = 0.002: Plate_Width = 0.45
AFR = (NP - 1) * P * Plate_Width
C = 0.289: b = 0.7
Gm_a = C * (MW / AFR) * L_over_G ^ -b
ElseIf Fill_Pitch = 3.81 Then
P = Fill_Pitch / 100: Plate_thickness = 0.002: Plate_Width = 0.45
AFR = (NP - 1) * P * Plate_Width
C = 0.361: b = 0.72
Gm_a = C * (MW / AFR) * L_over_G ^ -b
ElseIf Fill_Pitch = 3.81 Then
```

```
P = Fill_Pitch / 100: Plate_thickness = 0.002: Plate_Width = 0.45
AFR = (NP - 1) * P * Plate_Width
C = 0.394: b = 0.76
Gm_a = C * (MW / AFR) * L_over_G ^ -b
ElseIf Fill_Pitch = 2.54 Then
P = Fill_Pitch / 100: Plate_thickness = 0.002: Plate_Width = 0.45
AFR = (NP - 1) * P * Plate_Width
C = 0.459: b = 0.73
Gm_a = C * (MW / AFR) * L_over_G ^ -b
ElseIf Fill_Pitch = 235 Then   'Fill height=235mm
AFR = (PI / 4) * CT_Diameter ^ 2
C = 0.8255: b = 0.7569
Gm_a = (C / Fill_Height) * (MW / AFR) * L_over_G ^ -b
ElseIf Fill_Pitch = 470 Then   'Fill height=470mm
AFR = (PI / 4) * CT_Diameter ^ 2
C = 0.5943: b = 0.7422
Gm_a = (C / Fill_Height) * (MW / AFR) * L_over_G ^ -b
ElseIf Fill_Pitch = 450 Then   'Fill height=450mm
AFR = (PI / 4) * CT_Diameter ^ 2
C = 0.8556: b = 0.6350
Gm_a = (C / Fill_Height) * (MW / AFR) * L_over_G ^ -b
End If
TFK = 273.15 + TF
ROF = 2.116235E-10 * TFK ^ 6 - 0.0000004052421 * TFK ^ 5 + 0.0003221635 * TFK ^ 4
- 0.136077 * TFK ^ 3 + 32.19895 * TFK ^ 2 - 4045.674 * TFK + 211816.2
HW = 4.179 * TF + 0.4164                  'for water temp 25 C to 49 C
HA = 1.005 * TA + W * (2501 + 1.88 * TA)
PG = 0.0109 * TF ^ 2 - 0.4754 * TF + 8.7967
WS = 0.622 * PG / (101.325 - PG)
If TF >= 24 And TF <= 38 Then
```

```
HSAT = 0.1251 * TF ^ 2 - 2.232 * TF + 53.945
ElseIf TF > 38 And TF <= 48 Then
HSAT = 0.2412 * TF ^ 2 - 11.023 * TF + 220.96
End If
WWS3(I) = WS
'Calculation of driving force
L_HDIFF1 = 1 / (HSAT - HA)
HWW = HW
'Calculation of wet bulb temperature
For J = 0 To 10000
Cal_WBT(0) = TWB
If Cal_WBT(J) > 20 And Cal_WBT(J) < 45 Then
PS = (9 * 10 ^ -5) * Cal_WBT(J) ^ 3 - 0.0017 * Cal_WBT(J) ^ 2 + 0.1081 * Cal_WBT(J) +
0.1614
Else
End If
If Cal_WBT(J) >= 5 And Cal_WBT(J) <= 60 Then
HF = 4.182 * Cal_WBT(J) + 0.2293
HFG = 2501.8 - 2.387 * Cal_WBT(J)
End If
Cal_W = (1.005 * (Cal_WBT(J) - TA) + (0.622 * PS / (101.325 - PS)) * HFG) / (2501.5 +
1.806 * TA - HF)
Diff_W = Abs(Cal_W - W)
If Diff_W = 0 Then
J = 10000 '30000
ElseIf Cal_W < W Then
Cal_WBT(J + 1) = Cal_WBT(J) + 0.002225
ElseIf Cal_W > W Then
Cal_WBT(J + 1) = Cal_WBT(J) - 0.00088455
End If
```

```
Next J
Cal_WBT24(I) = Cal_WBT(10000)
Cal_W2 = (1.005 * (Cal_WBT(10000) - TA) + (0.622 * PS / (101.325 - PS)) * HFG) /
(2501.5 + 1.806 * TA - HF)
Cal_WW24(I + 1) = Cal_W2
'Table results
MSFlexGrid1.Col = 0            'for the zeroth column
MSFlexGrid1.Row = 2 * N + 11
MSFlexGrid1.Text = "Z(m)"
MSFlexGrid1.Row = I + 2 * N + 12
MSFlexGrid1.Text = Round(Z, 3)
MSFlexGrid1.Col = 1            'for the first column

MSFlexGrid1.Row = 2 * N + 11
MSFlexGrid1.Text = "TA(C)"
MSFlexGrid1.Row = I + 2 * N + 12
MSFlexGrid1.Text = Round(TAA3(I), 2)
MSFlexGrid1.Col = 2            'for the second column
MSFlexGrid1.Row = 2 * N + 11
MSFlexGrid1.Text = "WBT(C)"
MSFlexGrid1.Row = 2 * N + 12
MSFlexGrid1.Text = Round(TWB, 2)
MSFlexGrid1.Row = I + 2 * N + 12
MSFlexGrid1.Text = Round(Cal_WBT24(I), 2)
MSFlexGrid1.Col = 3            'for the third column
MSFlexGrid1.Row = 2 * N + 11
MSFlexGrid1.Text = "TF(C)"
MSFlexGrid1.Row = I + 2 * N + 12
MSFlexGrid1.Text = Round(TFF3(I), 2)
MSFlexGrid1.Col = 4            'for the fourth column
```

```
MSFlexGrid1.Row = 2 * N + 11
MSFlexGrid1.Text = "W"
MSFlexGrid1.Row = I + 2 * N + 12
MSFlexGrid1.Text = Round(WW3(I), 4)
MSFlexGrid1.Col = 5          'for the fifth column
MSFlexGrid1.Row = 2 * N + 11
MSFlexGrid1.Text = "MW(kg/s)"
MSFlexGrid1.Row = I + 2 * N + 12
MSFlexGrid1.Text = Round(MWW3(I), 4)
MSFlexGrid1.Col = 6          'for the sixth column
MSFlexGrid1.Row = 2 * N + 11
MSFlexGrid1.Text = "KaV/L"
MSFlexGrid1.Row = I + 2 * N + 12
MSFlexGrid1.Text = Round(SUM3(I), 4)
MSFlexGrid1.Col = 7          'for the seventh column
MSFlexGrid1.Row = 2 * N + 11
MSFlexGrid1.Text = "Cal_W"
MSFlexGrid1.Row = 2 * N + 12
MSFlexGrid1.Text = Round(WW3(0), 4)
MSFlexGrid1.Row = I + 2 * N + 12
MSFlexGrid1.Text = Round(Cal_WW24(I + 1), 4)
MSFlexGrid1.Col = 8          'for the eighth column
MSFlexGrid1.Row = 2 * N + 11
MSFlexGrid1.Text = "WS"
MSFlexGrid1.Row = I + 2 * N + 12
MSFlexGrid1.Text = Round(WWS3(I), 4)
A1 = DELZ * F1(TA, TF, W)
B1 = DELZ * F2(TA, TF, W, MW)
C1 = DELZ * F3(W)
D1 = DELZ * F4(W)
```

```
A2 = DELZ * F1(TA + A1 / 2, TF + B1 / 2, W + C1 / 2)
B2 = DELZ * F2(TA + A1 / 2, TF + B1 / 2, W + C1 / 2, MW + D1 / 2)
C2 = DELZ * F3(W + C1 / 2)
D2 = DELZ * F4(W + C1 / 2)
A3 = DELZ * F1(TA + A2 / 2, TF + B2 / 2, W + C2 / 2)
B3 = DELZ * F2(TA + A2 / 2, TF + B2 / 2, W + C2 / 2, MW + D2 / 2)
C3 = DELZ * F3(W + C2 / 2)
D3 = DELZ * F4(W + C2 / 2)
A4 = DELZ * F1(TA + A3, TF + B3, W + C3)
B4 = DELZ * F2(TA + A3, TF + B3, W + C3, MW + D3)
C4 = DELZ * F3(W + C3)
D4 = DELZ * F4(W + C3)
TA = TA + (A1 + 2 * A2 + 2 * A3 + A4) / 6
TF = TF + (B1 + 2 * B2 + 2 * B3 + B4) / 6
W = W + (C1 + 2 * C2 + 2 * C3 + C4) / 6
MW = MW + (D1 + 2 * D2 + 2 * D3 + D4) / 6
Z = Z + DELZ
HW = 4.179 * TF + 0.4164
HA = 1.005 * TA + W * (2501 + 1.88 * TA)
If TF >= 24 And TF <= 38 Then
HSAT = 0.1251 * TF ^ 2 - 2.232 * TF + 53.945
ElseIf TF > 38 And TF <= 48 Then
HSAT = 0.2412 * TF ^ 2 - 11.023 * TF + 220.96
End If
HDIFF_OFWATER = HW - HWW
L_HDIFF2 = 1 / (HSAT - HA)
'trapesoidal rule
SUM3(0) = 0
SUM3(I + 1) = SUM3(I) + 0.5 * (L_HDIFF1 + L_HDIFF2) * HDIFF_OFWATER
Next I
```

……………………………End of Loop for Runge-Kutta simulation………………………

```
MSFlexGrid1.Col = 0
MSFlexGrid1.Row = 3 * N + 13
MSFlexGrid1.Text = "KaV/L"
MSFlexGrid1.Row = 3 * N + 14
MSFlexGrid1.Text = Round(SUM3(N), 4)
MSFlexGrid1.Col = 1
MSFlexGrid1.Row = 3 * N + 13
MSFlexGrid1.Text = "L/G"
MSFlexGrid1.Row = 3 * N + 14
MSFlexGrid1.Text = Round(MWW3(N) / MDAA3(0), 4)
MSFlexGrid1.Col = 2
MSFlexGrid1.Row = 3 * N + 13
MSFlexGrid1.Text = "LL(kg/m^2.s)"
MSFlexGrid1.Row = 3 * N + 14
MSFlexGrid1.Text = Round(MWW3(N) / AFR, 4) ' base on frontal area
MSFlexGrid1.Col = 3
MSFlexGrid1.Row = 3 * N + 13
MSFlexGrid1.Text = "GG(kg/m^2.s)"
MSFlexGrid1.Row = 3 * N + 14
MSFlexGrid1.Text = Round(MDAA3(0) / AFR, 4)
MSFlexGrid1.Col = 4
MSFlexGrid1.Row = 3 * N + 13
MSFlexGrid1.Text = "Va(m/s)"
MSFlexGrid1.Row = 3 * N + 14
MSFlexGrid1.Text = Round(MAA3(N) / (ROAA3(N) * AFR), 4)
```

Plot Graph

```
Cal_WBT2(0) = TWB:  Cal_WBT23(0) = TWB:  Cal_WBT24(0) = TWB
MSChart1.ColumnCount = 6
MSChart1.RowCount = N + 1
```

```
For I = 0 To N
MSChart1.Data = TAA(I)
Next I
For I = 0 To N
MSChart1.Data = Cal_WBT2(I)
Next I
For I = 0 To N
MSChart1.Data = TAA2(I)
Next I
For I = 0 To N
MSChart1.Data = Cal_WBT23(I)
Next I
For I = 0 To N
MSChart1.Data = TAA3(I)
Next I
For I = 0 To N
MSChart1.Data = Cal_WBT24(I)
Next I
Cal_WBT24(0) = TWB
MSChart2.ColumnCount = 12
MSChart2.RowCount = N + 1
'Wet Bulb Temp  6 set of data
For I = 0 To N
MSChart2.Data = ZZ(I) * 100
Next I
For I = 0 To N
MSChart2.Data = Cal_WBT2(I)
Next I
For I = 0 To N
MSChart2.Data = ZZ(I) * 100
```

```
Next I
For I = 0 To N
MSChart2.Data = Cal_WBT23(I)
Next I
For I = 0 To N
MSChart2.Data = ZZ(I) * 100
Next I
For I = 0 To N
MSChart2.Data = Cal_WBT24(I)
Next I
For I = 0 To N
MSChart2.Data = ZZ(I) * 100
Next I
For I = 0 To N
MSChart2.Data = TAA(I)
Next I
For I = 0 To N
MSChart2.Data = ZZ(I) * 100
Next I
For I = 0 To N
MSChart2.Data = TAA2(I)
Next I
For I = 0 To N
MSChart2.Data = ZZ(I) * 100
Next I
For I = 0 To N
MSChart2.Data = TAA3(I)
Next I
MSChart3.ColumnCount = 6
MSChart3.RowCount = N + 1
```

```
For I = 0 To N
MSChart3.Data = TAA(I)
Next I
For I = 0 To N
MSChart3.Data = WW(I) * 100
Next I
For I = 0 To N
MSChart3.Data = TAA2(I)
Next I
For I = 0 To N
MSChart3.Data = WW2(I) * 100
Next I
For I = 0 To N
MSChart3.Data = TAA3(I)
Next I
For I = 0 To N
MSChart3.Data = WW3(I) * 100
Next I
For I = 0 To N
MSChart3.Data = TAA(I)
Next I
For I = 0 To N
MSChart3.Data = WWS(I) * 100
Next I
For I = 0 To N
MSChart3.Data = TAA2(I)
Next I
For I = 0 To N
MSChart3.Data = WWS2(I) * 100
Next I
```

```
For I = 0 To N
MSChart3.Data = TAA3(I)
Next I
For I = 0 To N
MSChart3.Data = WWS3(I) * 100
Next I
MSChart4.ColumnCount = 6
MSChart4.RowCount = N + 1
For I = 0 To N
MSChart4.Data = ZZ(I) * 100
Next I
For I = 0 To N
MSChart4.Data = TFF(I)
Next I
For I = 0 To N
MSChart4.Data = ZZ(I) * 100
Next I
For I = 0 To N
MSChart4.Data = TFF2(I)
Next I
For I = 0 To N
MSChart4.Data = ZZ(I) * 100
Next I
For I = 0 To N
MSChart4.Data = TFF3(I)
Next I
Cal_WBT2(0) = TWB: Cal_WBT23(0) = TWB: Cal_WBT24(0) = TWB
MSChart5.ColumnCount = 6
MSChart5.RowCount = N + 1
For I = 0 To N
```

```
MSChart5.Data = Cal_WBT2(I)
Next I
For I = 0 To N
MSChart5.Data = TFF(I)
Next I
For I = 0 To N
MSChart5.Data = Cal_WBT23(I)
Next I
For I = 0 To N
MSChart5.Data = TFF2(I)
Next I
For I = 0 To N
MSChart5.Data = Cal_WBT24(I)
Next I
For I = 0 To N
MSChart5.Data = TFF3(I)
Next I
MSChart6.ColumnCount = 6
MSChart6.RowCount = N + 1
For I = 0 To N
MSChart6.Data = ZZ(I) * 1000
Next I
For I = 0 To N
MSChart6.Data = SUM(I) * 1000
Next I
For I = 0 To N
MSChart6.Data = ZZ(I) * 1000
Next I
For I = 0 To N
MSChart6.Data = SUM2(I) * 1000
```

```
Next I
For I = 0 To N
MSChart6.Data = ZZ(I) * 1000
Next I
For I = 0 To N
MSChart6.Data = SUM3(I) * 1000
Next I
txtP3 = "Vw=" & VW & "L/min"
End Sub
```

…………………………………Present Results on Excel's Window……………………………….

```
Private Sub Command1_Click()
Dim resultChart1 As Object
Set result = CreateObject("excel.application")
result.Visible = True
result.Workbooks.Add
With result
    .Cells(1, 1).Value = CStr("   Z")
    .Cells(1, 2).Value = CStr("  DBT(C)")
    .Cells(1, 3).Value = CStr("  WBT(C)")
    .Cells(1, 4).Value = CStr("TF(C)")
    .Cells(1, 5).Value = CStr("MW..kg/s")
    .Cells(1, 6).Value = CStr("W...kg-vap/kg-da")
    .Cells(1, 7).Value = CStr("  NTU")
    .Cells(1, 8).Value = CStr("WS...kg-vap/kg-da")
End With
For I = 0 To 20
With result
    .Cells(I + 2, 1).Value = Round(ZZ(I), 3)
    .Cells(I + 2, 2).Value = Round(TAA(I), 2)
    .Cells(I + 2, 3).Value = Round(Cal_WBT2(I), 2)
```

```
        .Cells(I + 2, 4).Value = Round(TFF(I), 2)
        .Cells(I + 2, 5).Value = Round(MWW(I), 4)
        .Cells(I + 2, 6).Value = Round(WW(I), 4)
        .Cells(I + 2, 7).Value = Round(SUM(I), 4)
        .Cells(I + 2, 8).Value = Round(WWS(I), 4)
        .Cells(22, 10).Value = CStr(" L/G=")
        .Cells(22, 11).Value = Round(MWW(N) / MDAA(0), 3)
End With
Next I
For I = 0 To 20
With result
        .Cells(I + 2 + 22, 1).Value = Round(ZZ(I), 3)
        .Cells(I + 2 + 22, 2).Value = Round(TAA2(I), 2)
        .Cells(I + 2 + 22, 3).Value = Round(Cal_WBT23(I), 2)
        .Cells(I + 2 + 22, 4).Value = Round(TFF2(I), 2)
        .Cells(I + 2 + 22, 5).Value = Round(MWW2(I), 4)
        .Cells(I + 2 + 22, 6).Value = Round(WW2(I), 4)
        .Cells(I + 2 + 22, 7).Value = Round(SUM2(I), 4)
        .Cells(I + 2 + 22, 8).Value = Round(WWS2(I), 4)
        .Cells(44, 10).Value = CStr(" L/G=")
        .Cells(44, 11).Value = Round(MWW2(N) / MDAA2(0), 3)
End With
Next I
For I = 0 To 20
With result
        .Cells(I + 2 + 44, 1).Value = Round(ZZ(I), 3)
        .Cells(I + 2 + 44, 2).Value = Round(TAA3(I), 2)
        .Cells(I + 2 + 44, 3).Value = Round(Cal_WBT24(I), 2)
        .Cells(I + 2 + 44, 4).Value = Round(TFF3(I), 2)
        .Cells(I + 2 + 44, 5).Value = Round(MWW3(I), 4)
```

```
    .Cells(I + 2 + 44, 6).Value = Round(WW3(I), 4)
    .Cells(I + 2 + 44, 7).Value = Round(SUM3(I), 4)
    .Cells(I + 2 + 44, 8).Value = Round(WWS3(I), 4)
    .Cells(66, 10).Value = CStr(" L/G=")
    .Cells(66, 11).Value = Round(MWW3(N) / MDAA3(0), 3)
End With
Next I
End Sub
```

……………………………………………End of Program……………………………………………

Appendix J

Source Code of the Computer Program for the Merkel's Method

Source Code of the Computer Program for the Merkel's Method

```
Dim T(1 To 280), H(1 To 280), TM(1 To 25), RO(1 To 25), TDB2(1 To 100000), TDBB(1 To 100000), W2(1 To 100000), PG2(1 To 100000), Diff(1 To 100000), PGG2(1 To 100000)
Dim T1, T2, TWB, N, A, W, CP, E, H1, H2, V, L, F, VW, C, M, G, U, Q, Z, T3, KaVL, ROA, W1, HFG, PS, RH, L_over_G
Dim I As Integer, J As Integer, S As Integer, Y As Integer, K As Integer
Private Sub CMDCANCEL1_CLICK()
TxtT1.Text = ""
TXTT2.Text = ""
TXTTWB.Text = ""
TXTVW.Text = ""
TXTVA.Text = ""
TXTN.Text = ""
TXTLE.Text = ""
TXTC.Text = ""
TXTTDB.Text = ""
End Sub
Private Sub CMDCANCEL2_CLICK()
TXTA1.Text = ""
TXTKA.Text = ""
TXTT2.Text = ""
TXTKA1.Text = ""
TXTQT.Text = ""
TXTL_Over_G.Text = ""
TXTTDBB.Text = ""
End Sub
Private Sub CMDOK_CLICK()
T1 = TxtT1.Text
```

```
T2 = TXTT2.Text
TWB = TXTTWB.Text
VA = TXTVA.Text
TDB = TXTTDB.Text
VW = TXTVW.Text
C = TXTC.Text
N = TXTN.Text
LE = TXTLE.Text
CP = 4.175
If T2 <= TWB Then
TXTKA.Text = "Be impossible to calculate size"
Else
T1 = 273 + T1: T2 = 273 + T2
T3 = (T1 + T2) / 2: T3 = T3 - 273
F = 0
For S = 1 To 25
W = 1
RO(1) = 997: RO(2) = 997: RO(3) = 997: RO(4) = 997: RO(5) = 997: RO(6) = 997: RO(7) = 997: RO(8) = 997: RO(9) = 997: RO(10) = 996: RO(11) = 996: RO(12) = 995: RO(13) = 995: RO(14) = 995: RO(15) = 994: RO(16) = 994: RO(17) = 993: RO(18) = 993: RO(19) = 993: RO(20) = 992: RO(21) = 992: RO(22) = 992: RO(23) = 991: RO(24) = 991: RO(25) = 991
For Y = 1 To 25
If Y = S Then
Else
TM(1) = 21: TM(2) = 22: TM(3) = 23: TM(4) = 24: TM(5) = 25: TM(6) = 26: TM(7) = 27: TM(8) = 28: TM(9) = 29: TM(10) = 30: TM(11) = 31: TM(12) = 32: TM(13) = 33: TM(14) = 34: TM(15) = 35: TM(16) = 36: TM(17) = 37: TM(18) = 38: TM(19) = 39: TM(20) = 40: TM(21) = 41: TM(22) = 42: TM(23) = 43: TM(24) = 44: TM(25) = 45
W = W * (T3 - TM(Y)) / (TM(S) - TM(Y))
```

```
End If
Next Y
F = F + W * RO(S)
Next S
L = (VW * F * 0.001) / 60
HFG = -2.4396 * TWB + 2503
HF = 4.175 * TWB + 0.1429
PS = 0.007 * TWB ^ 2 - 0.1721 * TWB + 3.0622
W1 = (1.005 * (TWB - TDB) + (0.622 * PS / (101.325 - PS)) * HFG) / (2501.5 + 1.8055 * TDB - HF)
ROA = 1 / ((0.082 * TDB + 22.4135) * ((1 / 28.9) + (W1 / 18)))
G = ROA * VA / (60 * (1 + W1))
KaVL = C * (L / G) ^ N
T1 = T1 - 273
T2 = T2 - 273
H1 = 0: HW1 = 0: HW2 = 0: HWM = 0
For J = 1 To 280
V = 1: U = 1: Q = 1: Z = 1
H(1) = 72.18: H(2) = 72.58: H(3) = 72.98: H(4) = 73.39: H(5) = 73.8: H(6) = 74.21: H(7) = 74.62: H(8) = 75.03: H(9) = 75.44: H(10) = 75.86: H(11) = 76.28: H(12) = 76.7: H(13) = 77.12: H(14) = 77.54: H(15) = 77.97: H(16) = 78.39: H(17) = 78.82: H(18) = 79.25: H(19) = 79.69: H(20) = 80.12: H(21) = 80.56: H(22) = 81: H(23) = 81.44: H(24) = 81.88: H(25) = 82.32: H(26) = 82.77: H(27) = 83.22: H(28) = 83.67: H(29) = 84.12: H(30) = 84.57: H(31) = 85.03: H(32) = 85.49: H(33) = 85.95: H(34) = 86.41: H(35) = 86.87: H(36) = 87.34: H(37) = 87.81: H(38) = 88.28: H(39) = 88.75: H(40) = 89.22
: H(41) = 89.7: H(42) = 90.18: H(43) = 90.66: H(44) = 91.14: H(45) = 91.63: H(46) = 92.11: H(47) = 92.6: H(48) = 93.09: H(49) = 93.59: H(50) = 94.08: H(51) = 94.58: H(52) = 95.08: H(53) = 95.5: H(54) = 96.09: H(55) = 96.6: H(56) = 97.11: H(57) = 97.62: H(58) = 98.13: H(59) = 98.65: H(60) = 99.17: H(61) = 99.69: H(62) = 100.21: H(63) = 100.74: H(64) = 101.26: H(65) = 101.79: H(66) = 102.33: H(67) = 102.86: H(68) = 103.4: H(69) =
```

103.94: H(70) = 104.48: H(71) = 105.03: H(72) = 105.57: H(73) = 106.12: H(74) = 106.68: H(75) = 107.23: H(76) = 107.79: H(77) = 108.35: H(78) = 108.91: H(79) = 109.48:

H(80) = 110.04: H(81) = 110.61: H(82) = 111.19: H(83) = 111.76: H(84) = 112.34: H(85) = 112.92: H(86) = 113.5: H(87) = 114.09: H(88) = 114.68: H(89) = 115.27: H(90) = 115.86: H(91) = 116.46: H(92) = 117.06: H(93) = 117.66: H(94) = 118.27: H(95) = 118.88: H(96) = 119.49: H(97) = 120.1: H(98) = 120.72: H(99) = 121.34: H(100) = 121.96: H(101) = 122.59: H(102) = 123.21: H(103) = 123.84: H(104) = 124.48: H(105) = 125.11: H(106) = 125.75: H(107) = 126.4: H(108) = 127.04: H(109) = 127.69: H(110) = 128.34: H(111) = 129: H(112) = 129.66: H(113) = 130.32: H(114) = 130.98: H(115) = 131.65: H(116) = 132.32: H(117) = 132.99: H(118) = 133.67:

H(119) = 134.35: H(120) = 135.03: H(121) = 135.72: H(122) = 136.41: H(123) = 137.1: H(124) = 137.8: H(125) = 138.5: H(126) = 139.2: H(127) = 139.91: H(128) = 140.62: H(129) = 141.33: H(130) = 142.05: H(131) = 142.77: H(132) = 143.49: H(133) = 144.21: H(134) = 144.94: H(135) = 145.68: H(136) = 146.41: H(137) = 147.16: H(138) = 147.9: H(139) = 148.65: H(140) = 149.4: H(141) = 150.15: H(142) = 150.91: H(143) = 151.67: H(144) = 152.44: H(145) = 153.21: H(146) = 153.98: H(147) = 154.76: H(148) = 155.54: H(149) = 156.32: H(150) = 157.11: H(151) = 157.9: H(152) = 158.7: H(153) = 159.5: H(154) = 160.3: H(155) = 161.11: H(156) = 161.92: H(157) = 162.73: H(158) = 163.55: H(159) = 164.37: H(160) = 165.2:

H(161) = 166.03: H(162) = 166.387: H(163) = 167.71: H(164) = 168.55: H(165) = 169.4: H(166) = 170.25: H(167) = 171.1: H(168) = 171.96: H(169) = 172.83: H(170) = 173.69: H(171) = 174.57: H(172) = 175.44: H(173) = 176.32: H(174) = 177.21: H(175) = 178.1: H(176) = 178.99: H(177) = 179.89: H(178) = 180.79: H(179) = 181.7: H(180) = 182.61: H(181) = 183.53: H(182) = 184.45: H(183) = 185.37: H(184) = 186.3: H(185) = 187.24: H(186) = 188.18: H(187) = 189.12: H(188) = 190.07: H(189) = 191.02: H(190) = 191.98: H(191) = 192.94: H(192) = 193.91: H(193) = 194.88: H(194) = 195.86: H(195) = 196.84: H(196) = 197.83: H(197) = 198.82: H(198) = 199.82: H(199) = 200.82: H(200) = 201.82: H(201) = 202.84: H(202) = 203.85:

H(203) = 204.87: H(204) = 205.9: H(205) = 206.93: H(206) = 207.97: H(207) = 209.01: H(208) = 210.06: H(209) = 211.11: H(210) = 212.17: H(211) = 213.24: H(212) = 214.31: H(213) = 215.38: H(214) = 216.46: H(215) = 217.55: H(216) = 218.64: H(217) = 219.73: H(218) = 220.84: H(219) = 221.94: H(220) = 223.06: H(221) = 224.18: H(222) = 225.3: H(223) = 226.43: H(224) = 227.57: H(225) = 228.71: H(226) = 229.86: H(227) = 231.01: H(228) = 232.17: H(229) = 233.34: H(230) = 234.51: H(231) = 235.69: H(232) = 236.87: H(233) = 238.06: H(234) = 239.26: H(235) = 240.46: H(236) = 241.67: H(237) = 242.88: H(238) = 244.1: H(239) = 245.33: H(240) = 246.56: H(241) = 247.8: H(242) = 249.05: H(243) = 250.3: H(244) = 251.56: H(245) = 252.83: H(246) = 254.1:

H(247) = 255.38: H(248) = 256.67: H(249) = 257.96: H(250) = 259.26: H(251) = 260.57: H(252) = 261.88: H(253) = 263.2: H(254) = 264.53: H(255) = 265.86: H(256) = 267.2: H(257) = 268.55: H(258) = 269.9: H(259) = 271.27: H(260) = 272.64: H(261) = 274.01: H(262) = 275.4: H(263) = 276.79: H(264) = 278.19: H(265) = 279.59: H(266) = 281.01: H(267) = 282.43: H(268) = 283.86: H(269) = 285.29: H(270) = 286.74: H(271) = 288.19: H(272) = 289.65: H(273) = 291.12: H(274) = 292.59: H(275) = 294.08: H(276) = 295.57: H(277) = 297.07: H(278) = 298.57: H(279) = 300.09: H(280) = 301.61

For I = 1 To 280

If I = J Then

Else

T(1) = 24: T(2) = 24.1: T(3) = 24.2: T(4) = 24.3: T(5) = 24.4: T(6) = 24.5: T(7) = 24.6: T(8) = 24.7: T(9) = 24.8: T(10) = 24.9: T(11) = 25: T(12) = 25.1: T(13) = 25.2: T(14) = 25.3: T(15) = 25.4: T(16) = 25.5: T(17) = 25.6: T(18) = 25.7: T(19) = 25.8: T(20) = 25.9: T(21) = 26: T(22) = 26.1: T(23) = 26.2: T(24) = 26.3: T(25) = 26.4: T(26) = 26.5: T(27) = 26.6: T(28) = 26.7: T(29) = 26.8: T(30) = 26.9: T(31) = 27: T(32) = 27.1: T(33) = 27.2: T(34) = 27.3: T(35) = 27.4: T(36) = 27.5: T(37) = 27.6: T(38) = 27.7: T(39) = 27.8: T(40) = 27.9: T(41) = 28:

T(42) = 28.1: T(43) = 28.2: T(44) = 28.3: T(45) = 28.4: T(46) = 28.5: T(47) = 28.6: T(48) = 28.7: T(49) = 28.8: T(50) = 28.9: T(51) = 29: T(52) = 29.1: T(53) = 29.2: T(54) = 29.3: T(55) = 29.4: T(56) = 29.5: T(57) = 29.6: T(58) = 29.7: T(59) = 29.8: T(60) = 29.9: T(61) = 30: T(62) = 30.1: T(63) = 30.2: T(64) = 30.3: T(65) = 30.4: T(66) = 30.5: T(67) = 30.6:

T(68) = 30.7: T(69) = 30.8: T(70) = 30.9: T(71) = 31: T(72) = 31.1: T(73) = 31.2: T(74) = 31.3: T(75) = 31.4: T(76) = 31.5: T(77) = 31.6: T(78) = 31.7: T(79) = 31.8: T(80) = 31.9: T(81) = 32: T(82) = 32.1: T(83) = 32.2: T(84) = 32.3: T(85) = 32.4: T(86) = 32.5:

T(87) = 32.6: T(88) = 32.7: T(89) = 32.8: T(90) = 32.9: T(91) = 33: T(92) = 33.1: T(93) = 33.2: T(94) = 33.3: T(95) = 33.4: T(96) = 33.5: T(97) = 33.6: T(98) = 33.7: T(99) = 33.8: T(100) = 33.9: T(101) = 34: T(102) = 34.1: T(103) = 34.2: T(104) = 34.3: T(105) = 34.4: T(106) = 34.5: T(107) = 34.6: T(108) = 34.7: T(109) = 34.8: T(110) = 34.9: T(111) = 35: T(112) = 35.1: T(113) = 35.2: T(114) = 35.3: T(115) = 35.4: T(116) = 35.5: T(117) = 35.6: T(118) = 35.7: T(119) = 35.8: T(120) = 35.9: T(121) = 36: T(122) = 36.1: T(123) = 36.2: T(124) = 36.3: T(125) = 36.4: T(126) = 36.5: T(127) = 36.6: T(128) = 36.7: T(129) = 36.8: T(130) = 36.9: T(131) = 37: T(132) = 37.1: T(133) = 37.2: T(134) = 37.3: T(135) = 37.4:

T(136) = 37.5: T(137) = 37.6: T(138) = 37.7: T(139) = 37.8: T(140) = 37.9: T(141) = 38: T(142) = 38.1: T(143) = 38.2: T(144) = 38.3: T(145) = 38.4: T(146) = 38.5: T(147) = 38.6: T(148) = 38.7: T(149) = 38.8: T(150) = 38.9: T(151) = 39: T(152) = 39.1: T(153) = 39.2: T(154) = 39.3: T(155) = 39.4: T(156) = 39.5: T(157) = 39.6: T(158) = 39.7: T(159) = 39.8: T(160) = 39.9: T(161) = 40: T(162) = 40.1: T(163) = 40.2: T(164) = 40.3: T(165) = 40.4: T(166) = 40.5: T(167) = 40.6: T(168) = 40.7: T(169) = 40.8: T(170) = 40.9: T(171) = 41: T(172) = 41.1: T(173) = 41.2: T(174) = 41.3: T(175) = 41.4: T(176) = 41.5: T(177) = 41.6: T(178) = 41.7: T(179) = 41.8: T(180) = 41.9: T(181) = 42: T(182) = 42.1: T(183) = 42.2: T(184) = 42.3: T(185) = 42.4: T(186) = 42.5: T(187) = 42.6: T(188) = 42.7: T(189) = 42.8: T(190) = 42.9: T(191) = 43: T(192) = 43.1: T(193) = 43.2: T(194) = 43.3: T(195) = 43.4:

T(196) = 43.5: T(197) = 43.6: T(198) = 43.7: T(199) = 43.8: T(200) = 43.9: T(201) = 44: T(202) = 44.1: T(203) = 44.2: T(204) = 44.3: T(205) = 44.4: T(206) = 44.5: T(207) = 44.6: T(208) = 44.7: T(209) = 44.8: T(210) = 44.9: T(211) = 45: T(212) = 45.1: T(213) = 45.2: T(214) = 45.3: T(215) = 45.4: T(216) = 45.5: T(217) = 45.6: T(218) = 45.7: T(219) = 45.8: T(220) = 45.9: T(221) = 46: T(222) = 46.1: T(223) = 46.2: T(224) = 46.3: T(225) = 46.4: T(226) = 46.5: T(227) = 46.6: T(228) = 46.7: T(229) = 46.8: T(230) = 46.9: T(231) = 47: T(232) = 47.1: T(233) = 47.2: T(234) = 47.3: T(235) = 47.4: T(236) = 47.5: T(237) = 47.6: T(238) = 47.7: T(239) = 47.8: T(240) = 47.9: T(241) = 48: T(242) = 48.1: T(243) = 48.2: T(244) = 48.3: T(245) = 48.4: T(246) = 48.5:

```
T(247) = 48.6: T(248) = 48.7: T(249) = 48.8: T(250) = 48.9: T(251) = 49: T(252) = 49.1:
T(253) = 49.2: T(254) = 49.3: T(255) = 49.4: T(256) = 49.5: T(257) = 49.6: T(258) = 49.7:
T(259) = 49.8: T(260) = 49.9: T(261) = 50: T(262) = 50.1: T(263) = 50.2: T(264) = 50.3:
T(265) = 50.4: T(266) = 50.5: T(267) = 50.6: T(268) = 50.7: T(269) = 50.8: T(270) = 50.9:
T(271) = 51: T(272) = 51.1: T(273) = 51.2: T(274) = 51.3: T(275) = 51.4: T(276) = 51.5:
T(277) = 51.6: T(278) = 51.7: T(279) = 51.8: T(280) = 51.9
V = V * (TWB - T(I)) / (T(J) - T(I))
U = U * (T1 - T(I)) / (T(J) - T(I))
Q = Q * (T2 - T(I)) / (T(J) - T(I))
Z = Z * (T3 - T(I)) / (T(J) - T(I))
End If
Next I
H1 = H1 + V * H(J)
HW1 = HW1 + U * H(J)
HW2 = HW2 + Q * H(J)
HWM = HWM + Z * H(J)
Next J
H2 = H1 + CP * (L / G) * (T1 - T2)
HM = (H1 + H2) / 2
DH1 = HW1 - H2
DH2 = HW2 - H1
DHM = HWM - HM
RT1 = DHM / DH1: RT2 = DHM / DH2
FF = InputBox("read value of Steven's factor f at HR1=" & RT1 & "  HR2=" & RT2)
DHM1 = FF * DHM
KAVL1 = CP * (T1 - T2) / DHM1
QT = L * CP * (T1 - T2) / 4.53
TXTKA.Text = "Heat transfer coeff.KaV/L(design)=" & Format(KaVL, "0.0000")
TXTKA1.Text = "Heat transfer coeff.KaV/L(calculate)=" & Format(KAVL1, "0.0000")
TXTA1.Text = "Water outlet temp=" & T2 & "..C"
```

```
TXTQT.Text = "Tons of cooling tower=" & Format(QT, "0.00") & "..tons"
TXTL_Over_G = "Flow Ratio =" & Round(L / G, 3)
End If
End Sub
```

CURRICULUM VITAE

NAME : Mr. Montri Pirunkaset

BIRTH DATE : August 20, 1958

BIRTH PLACE : Chiangrai, Thailand

EDUCATION :

YEAR	INSTITUTION	DEGREE
1983	Kasetsart Univ.	B.E. (Mechanical Engineering)
1986	KMIT(Thonbury)	M.S. (Mechanical Engineering)

POSITION/TITLE : Associate Professor

WORK PLACE : Faculty of Engineering, Kasetsart University

SCHOLARSHIP/AWARD : -