A Study on the Performance of Cooling Ceiling Panel

Dr. Chirdpun Vitooraporn[1] and Aryut Wattanawanichakorn[2]

[1] Lecturer at Building Technology and Environment Laboratory,

[2] Former graduate student

Mechanical Engineering Department, Chulalongkorn University,

Phyathai Rd, Patumwan, Bangkok, Thailand, 10330

Tel: 662-2218-6622 Fax: 662-2252-2889 E-mail: chirdpun@chula.com[1]

Abstract

In this research the performance of cooling ceiling panel in transferring heat is studied. The parameters considered in the experiment are supplied chilled water temperature, supplied chilled water flow rate, and the cooling performance of the panel. From the experiment, it is found that supplied chilled water temperature has an effect on the surface temperature of the panel, the room temperature and the heat transfer rate of the panel at the steady state condition. Low supplied chilled water temperature increases the heat transfer rate of the panel, and, at the same time, decreases the surface temperature of the panel as well as the room temperature. In the contrary, the supplied chilled water flow rate does not significantly affect the surface temperature of the panel, the room temperature, and the heat transfer rate of the panel at the steady state condition. However, the supplied chilled water flow rate has an effect on the time gradient required for the surface temperature of the panel, the room temperature and the heat transfer rate of the panel to approach the steady state condition. The surface temperature of the panel, the room temperature and the heat transfer rate of the panel approach the steady state condition faster as the supplied chilled water flow rate increases. Furthermore, heat load also plays an important effect on the surface temperature of the panel and the room temperature at the steady state condition. Higher heat load results in higher surface temperature of the panel and room temperature at the steady state condition. Results from experiment are used to derive the equations that represent the cooling performance of the panel at the steady state condition.

1. Introduction

The cooling ceiling panel transfers heat to or from a room by convection and radiation. The radiant loads from the wall as well as from the persons and objects within the room are treated directly. The natural convection occurs at the air layer near the cooling ceiling panel. This heated air then moves and mixes with the air inside the room under the buoyancy force. This mechanism happens because of the low panel temperature. The panel is the metal ceiling panel bonded to the copper tube. The tube contains the re-circulated cooling media which is water. The combined radiant and convection heat transfer is then transferred to the panel through the conduction heat transfer happened at the tubes. Water inside the tube is then gradually heated up and circulated back to the chiller where all the heat contained is dissipated.

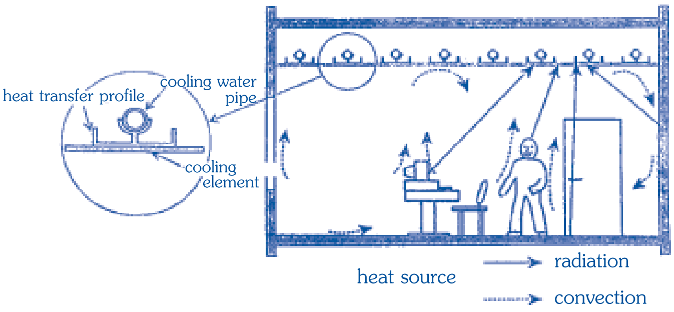

Figure 1 *Heat transfer mechanism of the cooling ceiling panel*

2. Related Theory

The cooling loads considered for the cooling ceiling panel in this research are radiation load from floors and walls, natural convection load, and heat load from lighting fixtures.

2.1 Radiation Heat Transfer

The radiation heat transfer rate for the cooling ceiling panel is calculated using the equation from Walton (1980). The mean radiant temperature (MRT) method is used to calculate the radiation heat transfer in the multi-surface enclosure. This multi-surface enclosure is reduced to a two-surface approximation. For radiant interchange in a room, one surface is occupied by the cooling ceiling panel where the average surface temperature is t_p. The other surface is occupied by other multi-surface enclosure. This surface is assumed to be a fictitious surface that has an area emissivity and temperature giving, t_r, about the same heat transfer from the surface as the real multi-surface enclosure. The MRT equation is shown in equation (1)

$$q_r = \sigma F_r \left[t_p^4 - t_r^4 \right] \qquad (1)$$

where

F_r = Radiation interchange factor (dimensionless)

σ = Stefan-Boltzman constant = 5.669×10^{-8} (W/m^2-K^4)

q_r = Net radiation heat transferred by cooling ceiling panel (W/m^2)

The fictitious surface temperature, t_r, is calculated by using the weighted average temperature and the emissivity of all un-cooled surfaces. When the emissivities of un-cooled surfaces are closely equal then the fictitious surface temperature, t_r, can be approximated from the weighted surface temperature of all un-cooled surfaces.

In practice, the emissivity of nonmetallic or painted metal nonreflecting surfaces is about 0.9. When this emissivity is used, the radiation interchange factor is about 0.87 for most rooms. Therefore equation (1) can be rewritten as follow;

$$q_r = 5 \times 10^{-8}\left[(AUST + 273)^4 - (t_p + 273)^4\right] \quad (2)$$

where

t_p = Surface temperature of the cooling ceiling panel (°C)

AUST = Area-weighted average temperature of un-cooled surfaces in room (°C)

2.2 Natural Convection Heat Transfer

The convection heat transfer in the cooling ceiling panel system is normally natural. The air motion is generated by the cooling of the boundary layer of air near the panel. However, in practice, many factors such as, infiltration or the movement of persons may interfere and affect natural convection or even induces forced convection.

The convection heat transfer for the cooling ceiling panel is calculated by using the equation from Schutrum and Vouris (1954). Schutrum and Vouris also showed that the room size normally has no significant effect to the rate of natural convection heat transfer except for the very large size of room. Therefore the natural convection heat transfer rate for the panel is calculated as follow;

$$q_c = 2.12(t_a - t_p)^{1.31} \quad (3)$$

where

q_c = Heat transfer by natural convection (W/m^2)

t_p = Surface temperature of the panel (°C)

t_a = Air temperature (°C)

2.3 Radiation Heat Transfer from Lighting Fixtures

The heat load inside the set up room in this research comes from the 40 W light fixture. The number of light fixture used are varied depended on each case study. This heat load can be calculated from

$$q_b = n_b A_{b\text{-}p} \varepsilon_b \sigma (t_b^4 - t_p^4) \quad (4)$$

where

q_b = Radiation heat transfer from light fixture to panel (W/m$_2$)

t_b = Surface temperature of light fixture (K)

t_p = Surface temperature of the panel (K)

$A_{b\text{-}p}$ = Surface area of light fixture (m^2)

n_b = No. of light fixture per unit area (set/m^2)

ε_b = Emissivity of light fixture surface

σ = Stefan-Boltzman constant = 5.669x10^{-8} W/(m^2-K^4)

3. Experimental Set Up

The set up room is 1x2 m. with 1 m. in height. Eight ceiling cooling panels with size 50x50 cm. are installed inside the room. Closed cell insulation is used to cover the top of the panel. Details of the panel is shown in fig. 2. Figure 3 shows the chilled water circuit used in the experiment. The supplied chilled water temperature, supplied chilled water flow rate, and heat load inside the room are varied in order to study the effect of these parameters to the cooling performance of the panel. Five case studies are set up where the supplied chilled water temperature to the panel is 6.3, 8.5, 11.1, 14.4, and 16.3 °C. Seven additional sub-case studies for each constant supplied chilled water temperature are also set up as shown in table 1. Therefore the no. of experiment is in total of thirty five case studies.

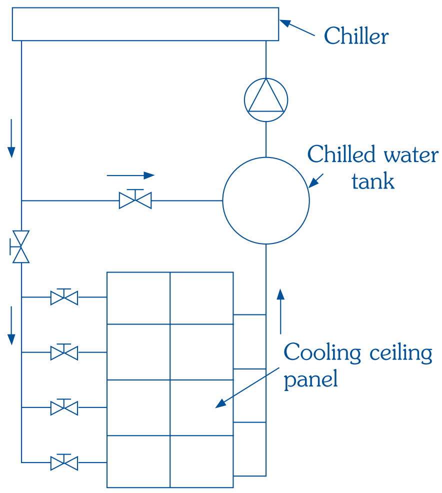

Figure 2 *Details of cooling ceiling panel*

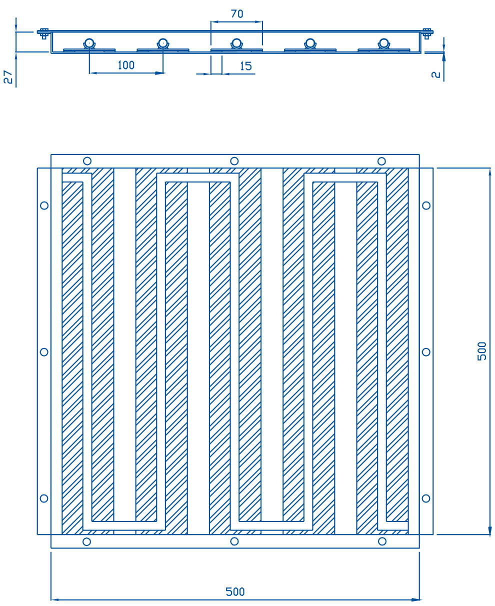

Figure 3 *Chilled water circuit*

Table 1 7 sub case studies for each constant supplied chill water temperature

No.	Flow rate	Internal heat load
1	0.5 liter/min.	-
2	1.0 liter/min.	-
3	1.5 liter/min.	-
4	1.5 liter/min.	1 set of 40 watt light fixture
5	1.5 liter/min.	2 sets of 40 watt light fixture
6	1.5 liter/min.	3 sets of 40 watt light fixture
7	1.5 liter/min.	4 sets of 40 watt light fixture

In each experiment, the following parameters are measured at various time until they reach the steady state condition, ie. surface temperature of the panel, floor and internal wall temperature, supplied and return chilled water temperature to the panel, and room temperature.

4. Data Analysis

4.1 Chilled Water Temperature Effect to the Cooling Performance of the Panel

Results from the experiment in all cases show that the panel surface temperature decreases rapidly at the beginning. After that the rate is slow down and the temperature becomes constant. It is also found that lower supplied chilled water temperature results in lower panel surface temperature provided that the internal heat load is unchanged. The supplied chilled water temperature also affects the rate of change of panel surface temperature at the beginning, ie. at low supplied chilled water temperature, the panel surface temperature changes faster than that at high supplied chilled water temperature as shown in fig. 4.

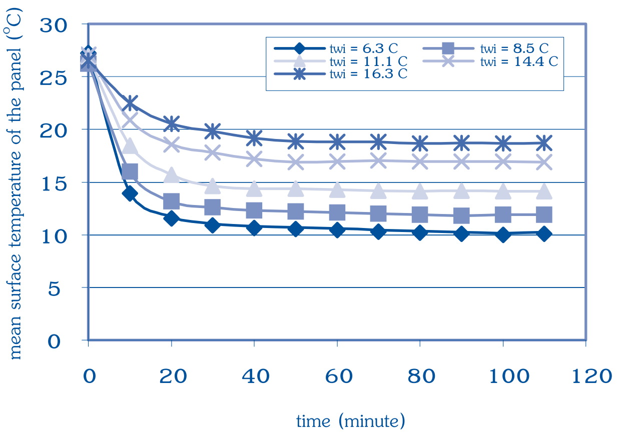

Figure 4 *Comparison of mean panel surface temperature for various chilled water temperature at 1.5 liter/min. with 2 light fixtures at 40 W. each*

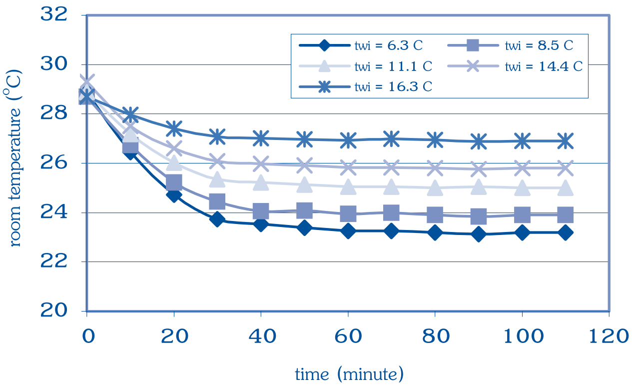

Figure 5 *Comparison of room temperature for various supplied chilled water temperature at 1.5 liter/min. with 2 light fixtures at 40 W. each*

The effect of supplied chilled water temperature to room temperature is shown in fig. 5. With the same heat load, low supplied chilled water provides lower room temperature at steady state condition than that at high supplied chilled water temperature. The supplied chilled water temperature also has an effect to the rate of change of room temperature, ie: with low supplied chilled water temperature, the room temperature changes faster than that at high supplied chilled water temperature.

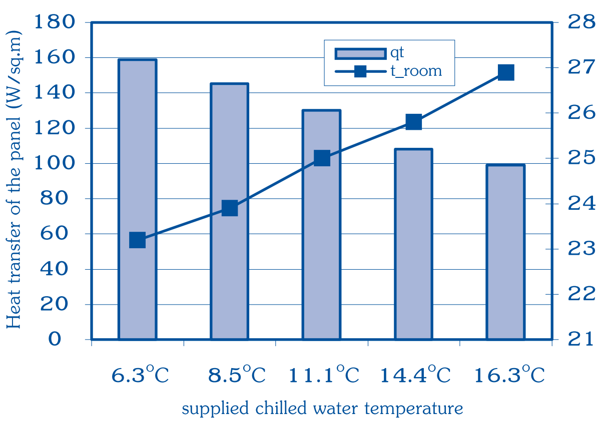

Figure 6 *Comparison of heat transfer amount of the cooling ceiling panel and room temperature at steady state condition for supplied chilled water temperature 6.3, 8.5, 11.1,14.4, and 16.3 °C at 1.5 liter/min and 2 light fixtures with 40 W each.*

The effect of supplied chilled water temperature to the rate of heat transfer of the panel is shown in fig. 6. With the same heat load, low supplied chilled water temperature provides higher rate of heat transfer of the panel than that at high supplied chilled water temperature. This is because the panel surface temperature at steady state condition is lower at low supplied chilled water temperature as mentioned earlier. The cooling performance of the panel increases as the panel surface temperature decreases. Since the cooling performance of the panel increases when supplied chilled water temperature is low, then the panel can maintain lower room temperature than that in the case of high supplied chilled water temperature for the same internal heat load.

4.2 Effect of Chilled Water Flow Rate to the Cooling Performance of the Panel

Supplied chilled water flow rate has an important effect to the time required for the panel surface temperature to approach the steady state condition. With constant supplied chilled water temperature, the panel surface temperature approaches the steady state condition faster at high supplied chilled water flow rate than that at low supplied chilled water flow rate. However, supplied chilled water flow rate plays no effect to the panel surface temperature at steady state condition as shown in fig. 7. Similar effect also occurs for the room temperature as shown in fig. 8.

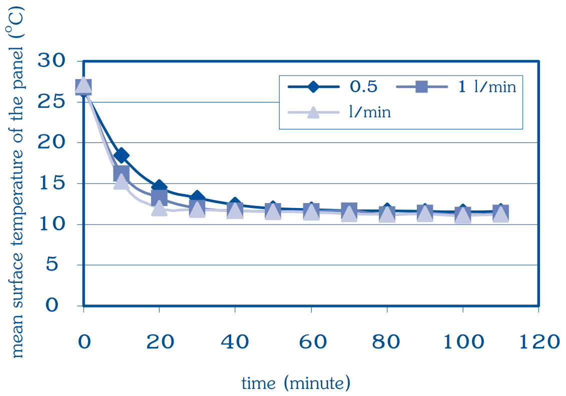

Figure 7 *Comparison of mean panel surface temperature when supplied chilled water temperature is 8.5 °C at 0.5, 1, and 1.5 liter/min with no internal heat load*

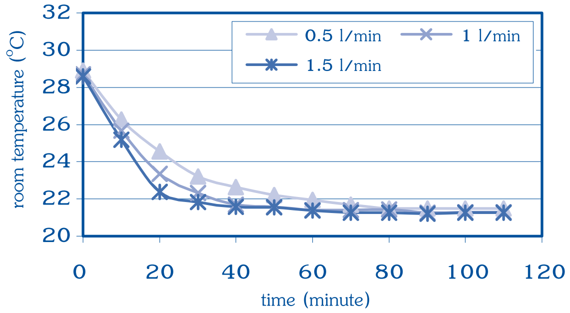

Figure 8 *Comparison of room temperature when supplied chilled water temperature is 8.5 °C at 0.5, 1, 1.5 liter/min with no internal heat load*

Fig.9. shows the effect of supplied chilled water flow rate to the heat transfer rate of the panel. There is no vivid effect of supplied chilled water flow rate to the amount of heat transfer of the panel at steady state condition since the supplied chilled water flow rate has no effect to the panel surface temperature at steady state condition as mentioned earlier.

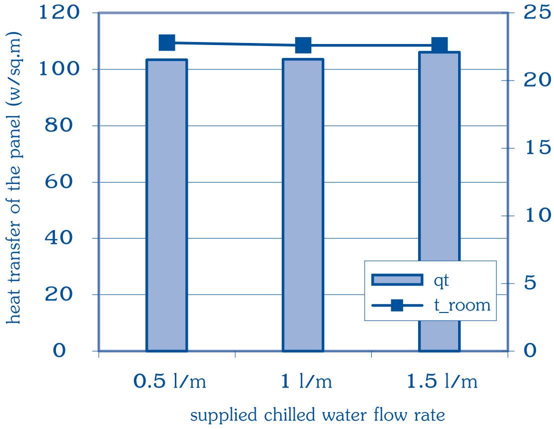

Figure 9 *Comparison of heat transfer amount of the panel and room temperature at steady state condition when supplied chilled water flow rate is 0.5, 1, 1.5 liter/min at 11.1 °C with no internal heat load*

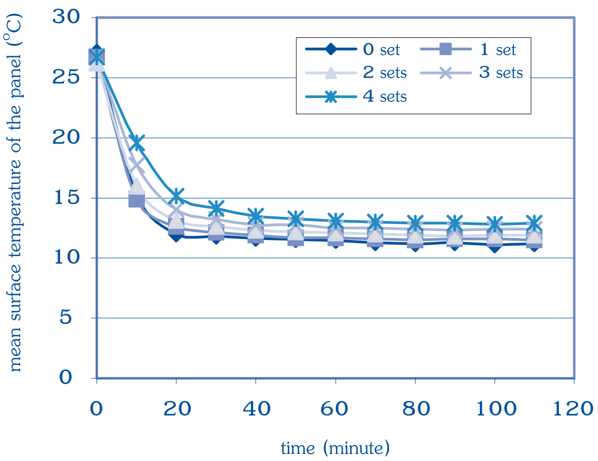

Figure 10 *Comparison of mean panel surface temperature with 0, 1, 2, 3, and 4 light fixtures at 40 W. each for 8.5 °C and 1.5 liter/min. supplied chilled water flow rate*

4.3 Effect of Internal Heat Load to the Cooling Performance of the Panel

The amount of internal heat load has an effect to the panel surface temperature at steady state condition. The panel surface temperature is higher at high amount of internal heat load while the rate of change of panel surface temperature is slower at high internal heat load as shown in fig. 10

The internal heat load also affects the room temperature at steady state condition as shown in fig. 11. The room temperature approaches the steady state condition at higher temperature for high internal heat load. The amount of internal heat load also affects the rate of change of room temperature at the beginning. The room temperature changes slower when high amount of internal heat load is applied.

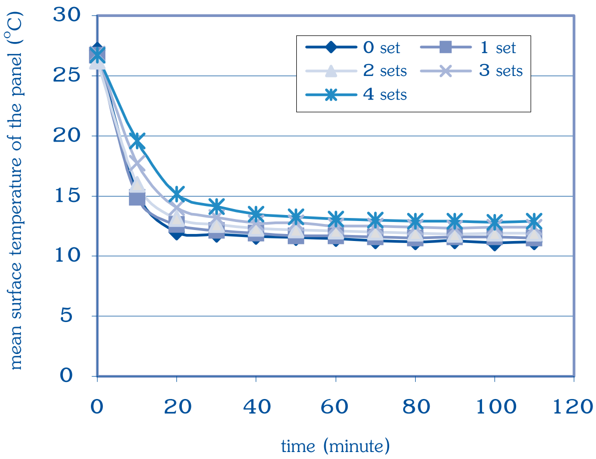

Figure 10 *Comparison of room temperature for 0, 1, 2, 3, and 4 light fixtures at 40 W. each at 8.5 °C and 1.5 liter/min. of supplied chilled water flow rate*

5. Derivation of Equations

Data received from the experiment are used to develop the equations for the panel. The equations developed are proposed to use as a guideline to design the cooling ceiling panel.

5.1 Equation for Calculating the Surface Temperature of the Panel

Since conduction heat transfer occurs between the surface of the panel and chilled water inside the tube, therefore the main parameter is the total thermal resistance of the panel (R_u). It is the result from the thermal resistance of the tube wall (r_t), the thermal resistance between the chilled water tube and the panel (r_p)

Consider the total thermal resistance of the panel per unit area

$$R_u = Mr_t + Mr_s + r_p \qquad (5)$$

where

R_u = Total thermal resistance of the panel (m^2-K/W)

r_t = Thermal resistance of the tube wall per unit distance between the tube (m-K/W)

r_s = Thermal resistance between the tube and panel per unit distance between the tube (m-K/W)

r_p = Thermal resistance of the panel (m^2-K/W)

M = Distance between the tubes measured from center of the tube (m)

r_t and r_p of the panel can be calculated using the following equations;

$$r_t = ln(D_o/D_i)/2\pi k_t \qquad (6)$$

$$r_p = X_p/k_p \qquad (7)$$

where

D_o, D_i = Inside and outside diameter of the tube (m)

k_p = Thermal conductivity of the panel (W/m-K)

x_p = Thickness of the panel (m)

For the thermal resistance between the tube and panel per unit distance between the tubes, ASHRAE (1992) indicates that the thermal resistance depends on the installed configuration of the tube to the panel which has no relation to the tube diameter. Therefore this thermal resistance can be calculated by developing the relationship between the difference of panel surface temperature and mean chilled water temperature, ie. Δt_m shown in equation 8, and the amount of heat transfer through the panel at steady state condition (q_t) . The result is shown in equation 9

$$\Delta t_m = t_p - 0.5(t_{wi} + t_{wo}) \qquad (8)$$

where

t_p = Mean surface temperature of the panel (°C)

t_{wi} = Inlet chilled water temperature (°C)

t_{wo} = Outlet chilled water temperature (°C)

$$qt = k\Delta t_m \quad \text{or}$$

$$qt = \Delta t_m/R_u \qquad (9)$$

where k is the constant value determined from the regression analysis and equal to 47.46943 W/m^2-°C. This k value is in fact the total heat transfer coefficient of the panel (U) or

$$R_u = I/U \qquad (10)$$

where U is equal to 0.02107 m^2-°C/W

The total thermal resistance is then used, along with the r_t and r_p, to calculate the thermal resistance between the tube and the panel according to equation 5. Its value is 0.2106 m^2-°C/W.

Equation 5 is then rearranged along with Δt_m from equation 8, r_t and r_p from equation 6 and 7 such that the surface temperature of the panel is in the left hand side of the equation. The new arranged equation, equation 11, can be used to predict the surface temperature of the panel at steady state condition when the dimension related to the panel and the chilled water temperature are known.

$$t_p = q_t[M(ln(D_o/D_i)/2\pi k_t)+ 0.2106M+(x_p/k_p)]+t_{w\_avg} \quad (11)$$

where

t_p = Mean surface temperature of the panel at steady state condition (°C)

q_t = Heat flux of the panel at steady state condition (W/m²)

t_{w_avg} = Mean chilled water temperature = 0.5 (twi + two) (°C)

M = Distance between the tube measured from center of the tube (m)

D_o = Outside diameter of the tube (m)

D_i = Inside diameter of the tube (m)

k_t = Thermal conductivity of the tube (W/m-K)

x_p = Thickness of the panel (m)

k_p = Thermal conductivity of the panel (W/m-K)

The equation above is then used to develop the equation for calculating the cooling performance of the panel.

5.2 Equation for Calculating the Cooling Performance of the Panel at Steady State Condition

Results from the experiment are used to find the relation among the cooling performance of the panel, the surface temperature of the panel, and room temperature at steady state condition. The relation found is shown in equation below

$$q_t = A(t_r-t_p)^B \quad (12)$$

where

q_t = Heat flux of the panel at steady state condition (W/m²)

t_r = Room temperature at steady state condition (°C)

t_p = Mean surface temperature of the panel at steady state condition (°C)

A, B = Constants to be found from the experimental results

The coefficient A and B found from the experimental results are equal to 7.9194 and 1.1675 respectively. Therefore equation (12) is then

$$q_t = 7.9194(t_r-t_p)^{1.1675} \quad (13)$$

Substitute t_p from equation 11 into equation 13

$$q_t = 7.9194[t_r-\{q_t[M(ln(D_o/D_i)2\pi k_t) +0.2106M+(x_p/k_p)]+t_{w\_avg}\}]^{1.675} \quad (14)$$

The equation above can be used to calculate the cooling performance of the panel when knowing the configuration of the tube inside the panel.

6. Conclusion

Result from the experiment can be concluded as follow;

1. Supplied chilled water temperature has an effect to the surface temperature of the panel and room temperature at steady state condition. Low supplied chilled water temperature results in lower surface temperature of the panel and room temperature at the same internal heat load.

2. Supplied chilled water flow rate has no vivid effect to the level of surface temperature of the panel and room temperature at steady state condition. However it affects the time for the panel surface temperature and room temperature to approach the steady state condition. High supplied chilled water flow rate to the panel results in faster approaching time for the surface temperature of the panel and room temperature to reach the steady state condition.

3. The amount of internal heat load has an effect to the level of surface temperature of the panel and room temperature at steady state condition. Higher internal heat load results in higher surface temperature of the panel and room temperature at steady state condition.

4. Total rate of heat transfer of the panel depends on the level of supplied chilled water temperature. Low supplied chilled water temperature results in higher rate of heat transfer of the panel. In the contrary, supplied chilled water flow rate has no vivid effect to the rate of heat transfer of the panel at steady state condition.

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