Effects and Usefulness of Evaporative Cooling in Malaysia

Ir. Julian Saw
Green Quarter Sdn Bhd
No. 93A, Jalan Rukun 2, Taman Happy Garden
58200 Kuala Lumpur, Malayisa
juliansaw@greenquarter.biz

Ong Rui Fong
Green Quarter Sdn Bhd
No. 93A Jalan Rukun 2, Taman Happy Garden
58200 Kuala Lumpur, Malaysia
ruifong@greenquarter.biz

Abstract*—This paper analyses weather data in Malaysia and the thermal comfort parameters that would make evaporative cooling a useful and effective solution. A case study was then conducted where a data logging activity was conducted in a warehouse that is equipped with an evaporative cooler system. The data collected from this exercise was then used to evaluate the effectiveness of evaporative cooling in providing human thermal comfort based on two models, Fanger's Predicted Mean Vote – Predicted Percentage Dissatisfied (PMV-PPD) method and Adaptive model in compliance with ASHRAE 55. The results show that the evaporative cooler is able to reduce dry bulb temperature up to a maximum of 6.6°C. And measured air properties at occupant zone show 50% of the time complying with ASHRAE Standard 55 PMV-PPD method and 80% of the time complying with the Adaptive method. Evaporative cooling systems may be a possible cooling solution in Malaysia given the space has low heat gains.

Keywords—evaporative cooling, tropical climate, thermal comfort

I. Introduction

Malaysia, located 3°08'20.4"N latitude and 101°41'12.8"E longitude is an equatorial country with tropical climate conditions. A tropical climate country has fairly consistent weather conditions throughout the year, where average daytime dry bulb temperature, wet bulb temperature, and relative humidity is 32°C, 25°C and 62% respectively [1]. The lower relative humidity of daytime hours is indicative that evaporative cooling systems can potentially be used to lower indoor temperatures [2].

The need for indoor cooling in Malaysia is imperative for thermal comfort and conventional air conditioning system is used in majority of buildings. Air conditioning energy consumption accounts for 49% of total energy consumption in a typical office building in Malaysia [1]. Therefore, there is a need to study alternative cooling solutions that require lower operational energy, and evaporative coolers are a candidate. Direct evaporative coolers consist of a fan that actively passes air through a wet cooling pad; this effectively lowers the dry bulb temperature and aids thermal comfort. The process is considered adiabatic, meaning there is no heat gain, or heat loss, because sensible heat is converted to latent heat.

Feasibility index, F*, of evaporative cooling is defined as [3]:

$$F^{*} = T_w - (T_1 - T_w) \quad (1)$$

T_1 = Inlet dry bulb temperature
T_w = Wet bulb temperature

The smaller the F* number, the more feasible the evaporative cooling system. It indicates the evaporative cooling potential to give thermal comfort. According to Watt, J. R [4], $F^* \leq 10$ for comfort cooling; $11 \leq F^* \leq 16$ for relief (lenitive) cooling and for $F^* > 16$ not recommended for the use of evaporative cooling systems. In Malaysia, average daytime F* is 18, just outside the recommended margins. Therefore, it seems that Malaysian climate conditions are not favorable for evaporative cooling systems. This exercise seeks to study the effectiveness of direct evaporative cooling in providing thermal comfort.

This paper identifies the performance of the evaporative cooler in terms of temperature drop, and relative humidity increase; before and after the cooler. The usefulness and effectiveness of the cooler is then determined using Fanger's Predicted Mean Vote – Predicted Percentage Dissatisfied (PMV-PPD) Thermal Comfort model and Adaptive Thermal Comfort model in compliance with ASHRAE 55. The PMV-PPD model is a generally accepted model when predicted thermal comfort of a given air-conditioned zone. The PMV-PPD model uses heat balance principles to relate the six key factors for thermal comfort; six factors being metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity [5]. The Adaptive model on the other hand is intended to predict occupant-controlled naturally conditioned spaces are those spaces where the thermal conditions of the space are regulated primarily by the occupants through opening and closing of windows. Mechanical ventilation with unconditioned air may be also utilized [6].

The measured data in the case study of this paper is obtained from a warehouse with direct evaporative coolers. The warehouse is also naturally ventilated. Hence both PMV-PPD model and Adaptive thermal comfort models are discussed in this paper.

II. Background

The data logging exercise was conducted in a warehouse in Puchong, Malaysia. The historical weather data in Malaysia was first analysed before conducting the data logging exercise. The weather data from 1972 to 1998 was used, and the average temperature and RH values over the period was collected for this study. The warehouse has operating hours of typical office hours, thus we only take into account the time the building is occupied from 8:00 to 18:00. The average hourly temperature and relative humidity in Malaysia is shown in TABLE I.

TABLE I. RECORDS OF DAILY AVERAGE AND RELATIVE HUMIDITY OF MALAYSIA FROM 1972 TO 1998 [7]

Time	Temperature (°C)	Relative Humidity, RH (%)
08:00	25.63	92.2
09:00	27.52	82.0
10:00	29.21	74.6
11:00	30.39	70.1
12:00	30.01	67.5
13:00	31.23	67.0
14:00	30.98	68.5
15:00	30.21	71.8
16:00	29.20	75.6
17:00	28.09	79.3
Average	***29.25***	***74.86***

The case study was carried out in an 860 m^2 warehouse. The built up of the warehouse is shown below in Fig. 1. The warehouse is used as a storage for household products. The warehouse is fitted with two exhaust fans (YET Industrial Propeller Exhaust Fan, Model GLF9.5) on one side of the building while there are three evaporative air coolers installed. Air coolers installed were YET Evaporative Cooler, Model KF200 [9]. The evaporative cooler is based on the principle of converting sensible heat to latent heat with a consequent decrease in space temperature [3]. Evaporative cooling can be achieved through direct and indirect cooling methods. The direct evaporative cooling method is based on the movement of air through a moist medium (usually a wetted pad) where both evaporation and cooling can occur. From this, the moist and cool air will directly move into where it is needed to cool the space down [3]. On the contrary, an indirect evaporative cooling utilizes a heat exchanger that employs the cool and moist air produced from the direct method. This method is used to lower the temperature of drier air. The dry air that is cooled will then be expelled into the environment and expel the cool moist air in the process [3]. The schematic diagram of the direct evaporative cooler method is shown below in Fig. 2.

The warehouse where the activity was carried out is based on the direct evaporative cooling method. Each evaporative air cooler installed has a 1.1 kW capacity. The diagram of the evaporative air cooler used in the warehouse is shown in Fig. 3. Additionally, the technical specifications of the evaporative cooler at the warehouse is summarized in TABLE II.

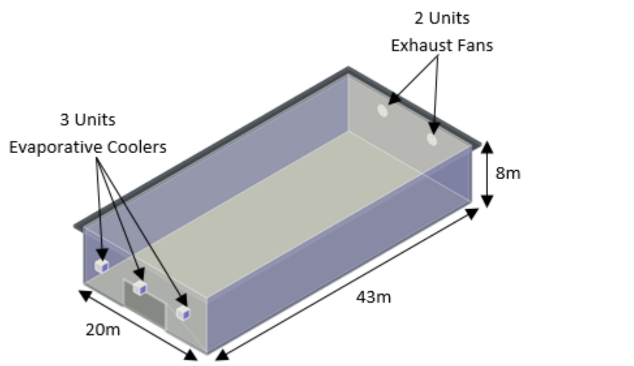

Fig. 1. Layout of warehouse with the evaporative coolers where the data logging exercise was conducted

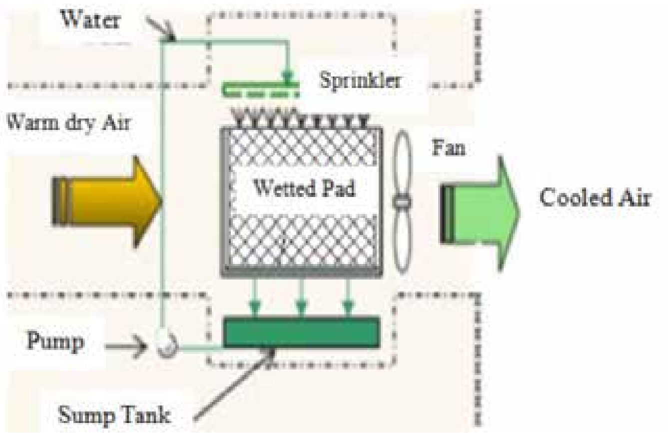

Fig. 2. Schematic diagram of direct evaporative cooler [8]

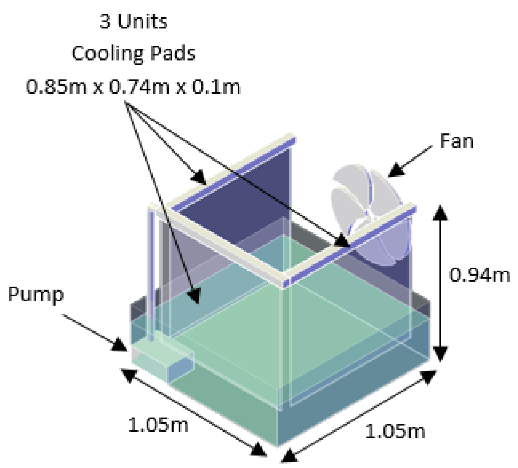

Fig. 3. Diagram showing the dimensions of the evaporative cooler installed at the warehouse

TABLE II. TECHNICAL SPECIFICATIONS OF THE YET EVAPORATIVE COOLER, MODEL KF200 T/B/S [9]

Description	Specifications
Air Flow	20000 m^3/h
Air Pressure	180 Pa

Description	Specifications
Effective Area	80 – 100 m^3
Power Supply	230 V, 50 Hz
Motor Power	1.1 kW
Noise	≤ 68 dB
Water Consumption	18 – 24 L/h
Speed	12
Net Weight	65 kg
Fan Type	Axial Fan
Send Wind Distance	15 – 18 m
Arise Tuyere Size	670 x 670 mm

The evaporative cooler is fitted with three cooling pads made with water that is supplied by a pump. The water will gradually trickle down the pad. The outdoor air that is warm and humid is then drawn into the evaporative cooler by the fan. A wet filter pad will filter the impurities and dust in the air. Water gains sensible heat from the dry air and converts it to latent heat that evaporates the water within the air. This will reduce the dry bulb temperature and increase the humidity of the air. This process is an adiabatic process as no heat gain or loss occurs, but sensible heat is converted to latent heat in the added vapour. This latent heat is then diffused into the air as water vapour [4]. There is a lower temperature of the exit air compared to the ambient air due to the evaporation process that has occured.

The saturation or cooling efficiency of the evaporative pad is based on the following formula [3]:

$$\varepsilon = 1 - \exp\left(-\frac{h_1 A_W}{m_a C_{P_a}}\right) = \frac{\Delta T}{T_1 - T_W} \qquad (2)$$

h_1: Convective heat transfer coefficient, in W/m^{2}K
A_W: Total wetted surface area
m_a: Air flow rate, in kg/s
C_{P_a}: Specific heat of air, in J/kgK
ΔT: Difference between inlet and outlet dry-bulb temperatures
T_1: Inlet dry bulb temperature
T_W: Wet bulb temperature

Thus, the efficiency of the evaporative cooling is dependent on the difference between the two temperatures. A larger temperature difference will result in a greater evaporative cooling effect.

III. Methodology

The data logging exercise was carried out over two different time periods at the same warehouse. The first period where data was collected was between 9th to 13th February 2018, and the second period of data was collected between 20th to 22nd February 2018. The first-time period included two control days where the evaporative air cooler was not turned on.

Three data loggers were used to collect the dry-bulb temperatures and relative humidity at 5-minute intervals. The three locations were:

- Inside occupant zone; the air conditions inside the warehouse, measured at occupant height and 11 m from the outlet of the evaporative cooler
- Outside, before cooler; the inlet temperature of the evaporative cooler, outdoor air conditions
- Inside, after cooler grille; the outlet temperature of the evaporative cooler, located right after the grille

The evaporative coolers were turned on each day at full capacity during operation hours, from 8:00 to 18:00. Based on the air flow of the evaporative cooler, 9 air change per hour (ACH) was expected during this time. The results collected was then analysed and averaged to the hourly data of a typical day. This was then compared to the thermal comfort parameters to determine the usefulness and effectiveness of evaporative cooling in Malaysia.

IV. Results

The data was collected and tabulated in excel before sorting into the average hourly data during operational hours. The summary these results is shown in TABLE III. From the results, the average temperature and relative humidity for each area was plotted on a graph to compare the results between the different areas. These plots are shown below in Fig. 4 and Fig. 5. All results calculation and graph plots were done on Microsoft Excel.

TABLE III. Temperature and Relative Humidity results collected from data loggers in average hours for each area

Time	Inside Occupant Zone		Outside, Before Cooler		Inside, After Cooler Grille	
	T_0 (°C)	RH_0	T_1 (°C)	RH_1	T_2 (°C)	RH_2
8:00	28.5	70.0	27.2	72.9	26.0	80.6
9:00	28.4	69.9	28.2	70.5	25.1	86.5
10:00	28.9	67.1	29.9	61.4	25.4	83.2
11:00	29.8	63.8	31.1	56.5	25.8	80.9
12:00	30.7	58.6	32.5	50.5	26.1	77.8
13:00	31.2	57.9	32.7	51.0	26.8	76.4
14:00	31.6	58.9	33.3	51.4	27.1	78.4
15:00	32.1	57.9	34.4	49.1	27.7	76.5
16:00	32.5	57.6	33.8	52.5	27.9	77.8
17:00	31.7	62.3	31.6	62.1	27.3	82.1

The trends from Fig. 4 show that the average hourly temperature increases during the day from the morning and starts to decrease from 16:00 onwards. This is the general trend for all three areas. The inlet temperature is lower than the occupant zone temperature in the morning when the evaporative air cooler is just switched on. As the evaporative cooler begins to run, the temperature of the occupant zone is lowered and becomes lower than the inlet temperature. This typically occurs from 9:00, about an hour after the evaporative cooler has been running. This trend continues and there is about a 2 ºC difference between the inlet and occupant temperatures. The peak temperature difference between the inlet and outlet temperature is 6.6 ºC and occurs between 12:00 to 15:00.

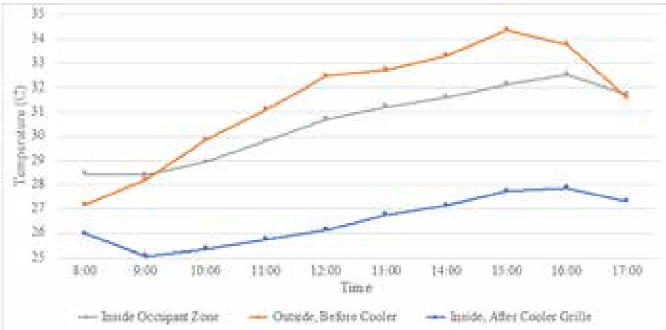

Fig. 4. Average temperature during operational hours

Fig. 5 shows that the relative humidity has an inverse trend in comparison to the temperature graph. This is because the relative humidity is dependent on the dry bulb temperature. The relative humidity decreases as the dry bulb temperature increases. Thus, relative humidity is lowest between 12:00 to 15:00. The inlet relative humidity is generally lower than the occupant zone relative humidity. However, the relative humidity of the outlet is relatively high and constant at 80% due to the air being cooled by the wetted pad.

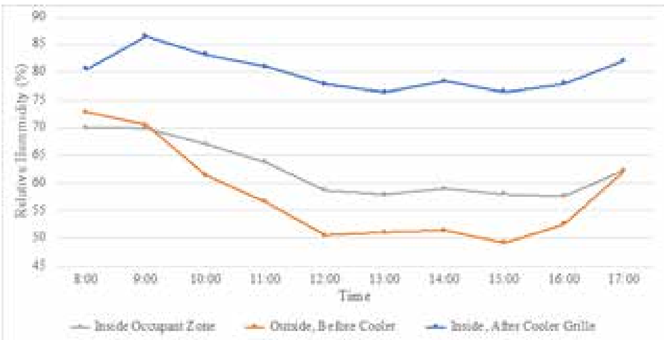

Fig. 5. Average relative humidity during operational hours

The average hourly dry-bulb temperature and relative humidity results was then used to obtain the inlet wet-bulb temperatures, T_w, based on psychometric formulas and calculated on Microsoft excel. The wet-bulb temperature is required to determine the feasibility index, F*, discussed in (1) and the saturation efficiency, ε, of the evaporative cooler based on (2) discussed earlier in the background. T_w and ε was calculated and tabulated in TABLE IV. From this, the graph of average hourly saturation efficiency of the evaporative cooler, ΔT and the Feasibility Index, F* is plotted and shown in Fig. 6. This allows us to observe the trends of the saturation efficiency against the difference in inlet and outlet dry-bulb temperatures.

TABLE IV. AVERAGE HOURLY SATURATION EFFICIENCY AND FEASIBILITY INDEX RESULTS FOR THE EVAPORATIVE COOLER

Time	T_1 (°C)	T_2 (°C)	T_w (°C)	ΔT (°C)	T_1-T_w (°C)	ε (%)	F*
8:00	27.2	26.0	23.6	1.2	3.6	33.9	20.0
9:00	28.2	25.1	24.2	3.1	4.0	77.9	20.2
10:00	29.9	25.4	24.3	4.5	5.6	80.9	18.7
11:00	31.1	25.8	24.6	5.4	6.6	81.9	18.0
12:00	32.5	26.1	24.6	6.3	7.8	80.7	16.8
13:00	32.7	26.8	24.9	6.0	7.8	76.5	17.2
14:00	33.3	27.1	25.5	6.2	7.8	78.9	17.7
15:00	34.4	27.7	25.9	6.6	8.4	78.9	17.5
16:00	33.8	27.9	26.1	5.9	7.7	77.1	18.4
17:00	31.6	27.3	25.9	4.3	5.7	75.1	20.2
Average	***31.5***	***26.5***	***25.0***	***4.9***	***6.5***	***74.2***	***18.5***

The average saturation efficiency is relatively constant once the evaporative cooler is switched on for a typical sunny day in Malaysia. The saturation efficiency of the cooler is typically between 75% – 82% throughout the day, with the more efficient times of the cooler found to be during 10:00 to 12:00.

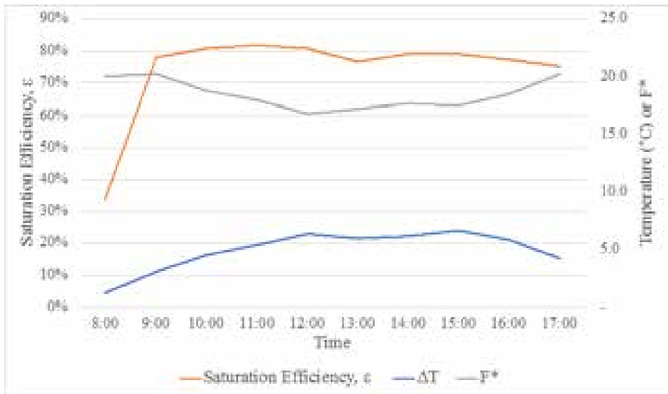

Fig. 6. Average hourly saturation efficiency curve for the evaporative cooler, ΔT and F*

V. DISCUSSION

A. *Effectiveness of the Evaporative Cooler*

Effectiveness of the cooler depends on two major factors; feasibility index, F*, and cooler saturation efficiency, ε. F* gives an indication of the feasibility based on local outdoor ambient air parameters, as discussed in [3] and [4]. For this case study, effectiveness of the cooler is indicated by ΔT. The greater the ΔT, the better the effectiveness of the cooler.

Based on measured average values from TABLE IV, F* is 18.5, which compares well with average Malaysian daytime F* of 18.0. F* remains relatively constant from 8:00 to 17:00 ranging from 16.8 to 20. From Fig. 6, F* peaks at 20 at early and late in the day. The lower the F* number, the more feasible evaporative cooling becomes. Hence the most effective time for evaporative cooler operation is during late morning to late afternoon, from 10:00 to 16:00. In other words, the greater the difference between T1 and Tw the greater the evaporative cooling effects.

TABLE IV shows that the average temperature difference from the inlet to outlet of the cooler (ΔT) is 4.9 °C and has a maximum temperature difference of 6.6 °C. This is a significant drop in temperature which directly correlates to the efficiency of the evaporative cooler in this exercise. Average saturation efficiency is 74%. Fig. 6 shows saturation efficiency and ΔT relationship with hourly readings. It can be seen that at 8am, saturation efficiency is low, hence ΔT is also low. As efficiency increases, ΔT correlates. This compares well with [10]. It is also noted that the evaporative cooler used in this exercise is about 3 years old which may affect equipment efficiency. Saturation efficiency depends on cooler equipment's wetted cooling pad area and air flow rate.

B. Thermal Comfort Analysis using ASHRAE Standard 55

TABLE III. and Fig. 4 shows temperature and RH measurements at occupant level. The CBE Thermal Comfort Tool [11] was used to quantify the usefulness of the evaporative cooler in providing thermal comfort. Occupant zone air parameters for each hour were plotted on the psychrometric chart and shown in Fig. 7. The chart shows measured points in compliance with ASHRAE Standard 55-2017 based on the PMV-PPD index. Hourly points were plotted using measured air temperature and relative humidity measurements. For the purposes of this study, mean radiant temperature, air speed, metabolic rate, and clothing level are fixed with the values shown below;

- Mean radiant temperature: 29 °C
- Air speed: 1.2 m/s (elevated air speed with ceiling fans)
- Metabolic rate: 1.1
- Clothing level: 0.5 (typical summer indoor)

Elevated air speed was fixed at 1.2 m/s in this exercise. Ceiling fans are commonly used in non-air conditioned and naturally ventilated spaces in Malaysia. Air speed of 1.2 m/s is an acceptable value for ceiling fans at medium setting as tested on a range of fans [12] [13]. The air speed of 1.2 m/s at the head level is able to provide comfort for conditions 30 °C and 80% RH [12].

Fig. 7 shows that hours from 8am to 12pm comply, while hours from 1pm to 5pm do not comply. On average, 50% of the time complies with ASHRAE's PMV-PPD method. The increasing sensible heat from solar gain increases dry bulb temperature within the warehouse in the afternoon. Given the lack of passive insulation on the walls and roof, temperature increases to beyond the comfortable zone. Hence for evaporative cooling to be useful, passive insulation on the building needs to good.

Fig. 8 shows occupant zone hourly measurements in compliance with the Adaptive method of ASHRAE Standard 55-2017. Prevailing mean outdoor temperature was fixed at 26.9 °C, as indicated in [1] for Malaysia. Again, air speed is fixed at 1.2 m/s. Fig. 8 shows that hours from 8:00 to 15:00 comply, while hours from 16:00 to 17:00 do not comply. This is also attributed to the increasing sensible heat from solar gain increases dry bulb temperature within the warehouse in the afternoon. On average, 80% of the time complies with ASHRAE's Adaptive Method. The adaptive method is also used here because the front door of the warehouse was opened all throughout the testing and measurement period. Hence allowing the space to be naturally ventilated. Although occupants did not have any controls of openable windows.

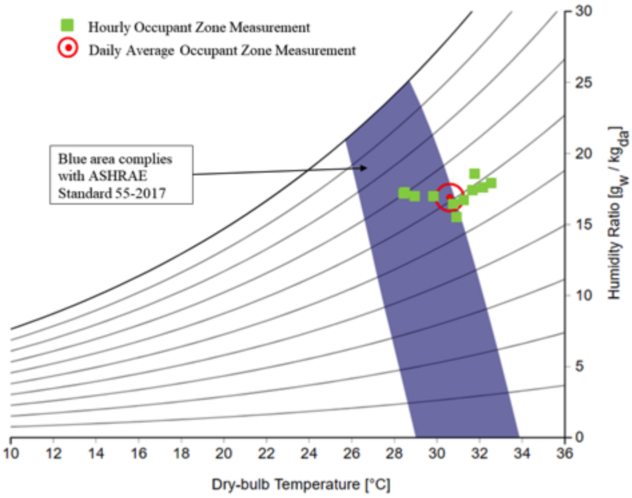

Fig. 7. Occupant zone hourly measurement in compliance with ASHRAE Standard 55-2017 PMV-PPD method

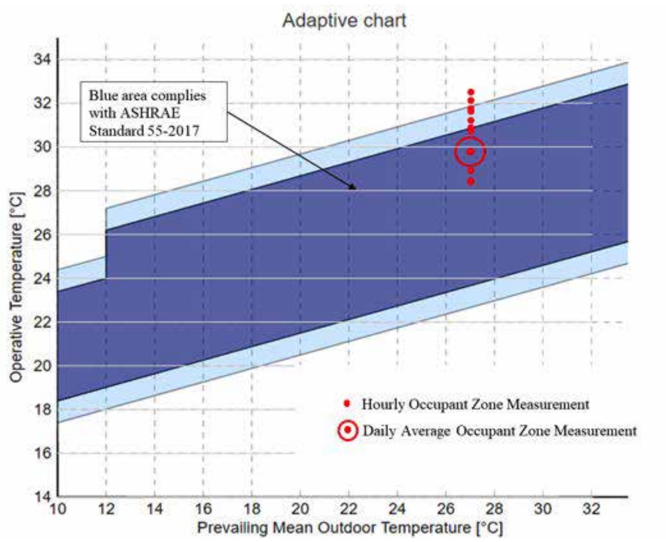

Fig. 8. Occupant zone hourly measurement in compliance with ASHRAE 55-2017 Adaptive method

C. Psychometry Chart Analysis

Fig. 9 shows the evaporative cooling process for the average hour of 11:00, when the cooler is most efficient. The three points plotted on the psychrometric chart are; Outside before cooler, Inside after cooler griller, and Inside at Occupant Zone. Fig. 9 shows that the cooler is effective in lowering dry bulb temperature from 31 °C to 25.8 °C. However due to sensible heat gain in the warehouse, inside occupant zone temperature increases up to 29.8 °C. This heat gain is mainly from solar gain, as the warehouse is used for storage of items with very few people. Therefore, equipment gain and people gain are low. Also, the front door of the warehouse was open during testing and measurement period allowing outside air to ventilate the area.

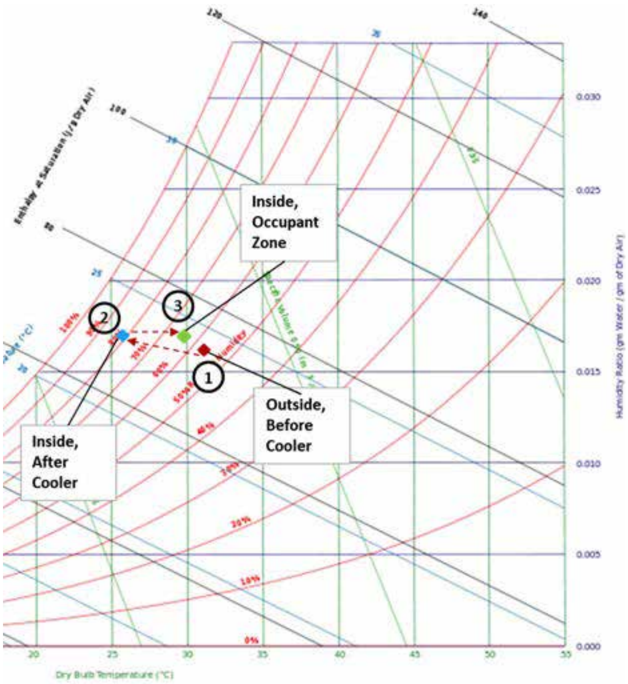

Fig. 9. Process of evaporative cooling for 11:00 on a psychomeric chart

VI. CONCLUSION

This paper presents the results of a direct evaporative cooler system in a warehouse in Malaysia. The effectiveness of the cooler was analyzed in providing thermal comfort to the space. From the exercise, the following conclusions were drawn:

1. The evaporative cooler is able to reduce dry bulb temperature up to a maximum of 6.6 °C or a daily average of 4.9 °C.

2. The effectiveness of the cooler in decreasing dry bulb temperature depends on feasibility index (F*), the greater the difference between T_1 and T_w the greater the evaporative cooling effects. The most effective hours are within 10:00 to 16:00.

3. Effectiveness of the cooler also depends on saturation efficiency (ε) of the cooler. Saturation efficiency reaches a maximum of 82% in this study. The greater the efficiency, the evaporative cooling effect. Saturation efficiency depends on cooler equipment's wetted cooling pad area and air flow rate.

4. Measured air properties at occupant zone show 50% of the time complying with ASHRAE Standard 55 PMV-PPD method and 80% of the time complying with ASHRAE Standard 55 Adaptive method. Hours that are not complying were at late afternoon when solar heat gain is greatest.

5. Evaporative cooler for human thermal comfort in Malaysia is useful for buildings with very low heat gains and must be well insulated from solar heat gain.

ACKNOWLEDGMENT

Green Quarter Sdn Bhd thanks Ben and the team at YET Air Cooling System Sdn Bhd and Living Depot warehouse for allowing us to carry out the data logging activity on the evaporative coolers installed at the warehouse.

REFERENCES

[1] C.K. Tang and N. Chin, Building Energy Efficiency Technical Guidelines for Passive Design, 1st ed. Kuala Lumpur: Building Sector Energy Efficiency Project (BSEEP), 2013, pp. 32-35.

[2] K.P. Arandara, R.A. Attalage and M.T.R. Jayasinghe, "Thermal Comfort with Evaporative Cooling for Tropical Climates", International Conference on Sustainable Built Environment (ICSBE-2010), December 2010.

[3] R. Poku, T. W. Oyinki and E. A. Ogbonnaya, "The Effects of Evaporative Cooling in Tropical Climate", American Journal of Mechanical Engineering, vol. 5, no. 4, pp. 145-150, 2017.

[4] Watt, J. R. (1963) Evaporative air conditioning. New York: The Industrial Press, p.300.

[5] ASHRAE Standard 55, 2004 ed, pp. 4.

[6] ASHRAE Standard 55, 2004 ed, pp. 9.

[7] M.M. Talbi, B. Agnew, Exergy analysis: an absorption refrigerator using lithium bromide and water as the working fluids, Appl. Therm. Eng. J., 20 (2000) 619–630.

[8] Xuan, Y. M., Xiao, F., Niu, X. F., Huang, X. and Wang, S. W. (2012) Research and Application of Evaporative Cooling in China: A Review (I)–Research. Renewable and Sustainable Energy Reviews, Elsevier. Issue 16, pp. 3535-3546.

[9] "Industrial Evaporative Air Cooler (Mounted) - YET | The best there is", YET, 2018. [Online]. Available: http://yet.com.my/products/industrial-evaporative-air-cooler/industrial-evaporative-air-cooler-system/. [Accessed: 14- Mar- 2018].

[10] D. Bishoyi and K. Sudhakar, "Experimental performance of a direct evaporative cooler in composite climate of India", Energy and Buildings, vol. 153, pp. 190-200, 2017.

[11] "CBE Thermal Comfort Tool for ASHRAE-55", Comfort.cbe.berkeley.edu, 2018. [Online]. Available: http://comfort.cbe.berkeley.edu. [Accessed: 05-Mar-2018].

[12] Y. Zhai, Y. Zhang, H. Zhang, W. Pasut, E. Arens and Q. Meng, "Human comfort and perceived air quality in warm and humid environments with ceiling fans", Building and Environment, vol. 90, pp. 178-185, 2015.

[13] K. Schmidt and D. Patterson, "Performance results for a high efficiency tropical ceiling fan and comparisons with conventional fans", Renewable Energy, vol. 22, no. 1-3, pp. 169-176, 2001.