Parametric analysis of a counter-flow dew point evaporative cooler

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Abstract: *Dew point evaporative cooling (DPEC), a type of indirect evaporative cooling where a single stream of air flows sequentially through the dry and wet channels, can cool air theoretically to its dew point temperature. In this study, the effects of design parameters, operating parameters, and inlet air condition to the cooling performance of a counter-flow DPEC was investigated. It has been shown that for the nominal condition of channel length = 1m, channel height = 5mm, inlet air velocity = 1.5 m/s, and working air ratio = 0.3, the inlet air with temperature of 30°C and humidity of 0.010 kg/kg da was cooled to 19.3 °C which is lower that its wet bulb temperature of 19.6 °C. The temperature can be cooled further by increasing the channel length, decreasing the channel height, decreasing the inlet air velocity, or increasing the working air ratio.*

Keywords: dew point; dew point evaporative cooling; evaporative cooling; Maisotsenko cycle; thermal comfort

1. INTRODUCTION

Evaporative cooling is a greener and cheaper alternative to compressor-based air conditioners. The driving force in evaporative cooling is the vapor pressure difference between the air and water. During evaporative cooling, water evaporates due to the vapor pressure difference between the air and the water. As water evaporates, it absorbs energy from its surroundings which produces a cooling effect equivalent to the latent heat of evaporation of water. Generally, evaporative cooling can be classified as direct evaporative cooling (DEC) or indirect evaporative cooling (IEC) [1]. In DEC, water evaporation occurs adiabatically wherein temperature decrease corresponds to an equivalent humidity increase. Due to the increase in moisture content, direct evaporative cooling is deemed not be suitable for many applications. In IEC, the cooling effect in the evaporation channel is transferred to an adjacent channel without increasing its humidity. For both DEC and IEC, the minimum achievable temperature is the dew point temperature of the air. In recent years, a modification to the IEC, which is called in many names such as dew point evaporative cooling (DPEC), Maisotsenko cycle, wet surface heat exchanger, and regenerative evaporative cooler was developed. In DPEC, air flow sequentially from the dry channel to the wet channel. As air flows in the dry channel, its temperature decreases due to the cooling effect in the adjacent wet channel. Due to the sequential flow of the single air stream, the theoretical minimum achievable temperature is the dew point temperature, much lower than both DEC and IEC [1], [2]. Dew point evaporative coolers are thus considered an effective sensible cooler which can provide up to 80% electricity savings [3].

In this study, the design and operating parameters affecting the performance of a counter-flow DPEC is studied numerically. This study is essential to better understand the effects of various parameters to the performance of the cooler.

2. METHODOLOGY

2.1 Numerical model

In this study, a 1-dimensional model based on energy and mass balance inside the DPEC was developed. Fig. 2 shows the four control volumes namely dry channel air, plate, water film, and wet channel air, and their corresponding energy and mass flows. The governing equations used in the study are as follows [2], [4]:

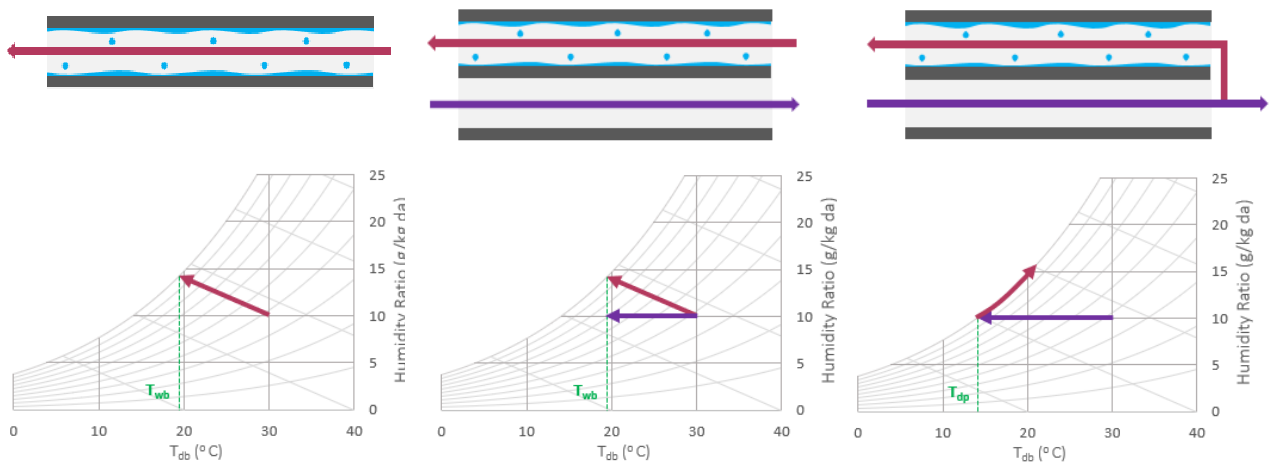

Fig. 1. Schematic and psychrometric representation of DEC (left), IEC (middle), and DPEC (right)

$$\rho_{da}c_{pda}\frac{\partial T_{da}}{\partial t} = -\frac{h_{da}}{z_{da}/2}(T_{da} - T_{pl}) - \rho_{da}c_{pda}u_{da}\frac{\partial T_{da}}{\partial x} \quad (1)$$

$$\rho_{pl}c_{ppl}\frac{\partial T_{pl}}{\partial t} = \frac{k_{da}}{d_{da}d_{pl}}(T_{da} - T_{pl}) - \frac{k_{pl}}{d_{pl}d_{wf}}(T_{pl} - T_{wf}) \quad (2)$$

$$\rho_{wf}c_{wf}\frac{\partial T_{wf}}{\partial t} = \frac{h_{da}}{d_{wf}}(T_{da} - T_{wf}) + \frac{h_{wa}}{d_{wf}}(T_{wa} - T_{wf}) - \frac{\bar{h}_{wa}}{d_{wf}}(\rho_{vsat,wa} - \rho_{v,wa})(H_{wf}) \quad (3)$$

$$\rho_{wa}c_{pwa}\frac{\partial T_{wa}}{\partial t} = -\frac{h_{wa}}{z_{wa}/2}(T_{wa} - T_{wf}) + \rho_{wa}c_{pwa}u_{wa}\frac{\partial T_{wa}}{\partial x} + u_{wa}\frac{\partial \rho_{v,wa}}{\partial x}H_{wa} + \frac{\bar{h}_{wa}}{z_{wa}/2}(\rho_{vsat,wa} - \rho_{v,wa})H_{wf} \quad (4)$$

$$\frac{\partial \rho_{v,wa}}{\partial t} = u_{wa}\frac{\partial \rho_{v,wa}}{\partial x} + \frac{\bar{h}_{wa}}{z_{wa}/2}(\rho_{vsat,wa} - \rho_{v,wa}) \quad (5)$$

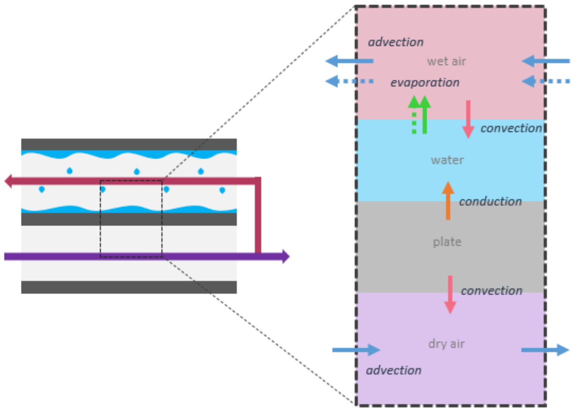

Fig. 2. Energy and mass flows in DPEC.

The humidity ratio of air is related to the vapor pressure according to:

$$Y = \frac{M_w}{M_a}\frac{\varphi P_s}{(P - \varphi P_s)} \quad (6)$$

where M_w and M_a represents the molar masses of water and air, respectively. The vapor density of the air is calculated as:

$$\rho_{air} = \frac{P_w}{R_{wv}T} \quad (7)$$

The saturation pressure in kPa is calculated using the Goff-Gratch equation as follows:

$$\log P_{w,s} = C_1(T' - 1) + C_2 \log T' + C_3\left(10^{C_4\left(1-\frac{1}{T'}\right)} - 1\right) + C_5\left(10^{C_6(T'-1)} - 1\right) + C_7 \quad (8)$$

where T' = 373.16/T; C_1 = -7.90298; C_2 = 5.02808; C_3 = -1.3816x10^{-7}; C_4 = 11.344; C_5 = 8.1328x10^{-3}; C_6 = -3.49149; C_7 = log(1013.246).

The convective heat transfer coefficients in the dry and wet channels were calculated as:

$$h_{da} = \frac{Nu_{da}k_{da}}{d_h} \quad (9)$$

$$h_{wa} = \frac{Nu_{wa}k_{wa}}{l_e} \quad (10)$$

whereas the convective mass transfer coefficient in the wet channel is calculated from its heat transfer coefficient as:

$$\frac{h_{wa}}{\bar{h}_{wa}} = \rho_a c_p Le^{2/3} \quad (11)$$

where Lewis number $Le = \frac{\alpha}{D_{AB}}$.

The Nusselt number in the dry channel is estimated accordingly for an internal flow in a flat plate [5]:

$$Nu_{da} = 7.54 \quad (12)$$

while the Nusselt number in the wet channel is calculated as:

$$Nu_{wa} = 0.10\left(\frac{l_e}{\delta}\right)Re^{0.8}Pr^{1/2} \quad (13)$$

where $l_e = \frac{V}{A}$; V is the volume occupied by the water absorbing wick material whereas A is its surface area. δ represents the thickness of the water film and the heat transfer plate combined.

The solution for the system of equations were solved numerically via implicit backward finite difference method in Python.

2.2 Simulation conditions

In this study, the nominal and the range of the investigated operating and design parameters are summarized in Table 1.

Table 1. Nominal and investigated range of operating and design parameters.

	Nominal	Range
Design parameters		
Channel length, mm	1000	800 – 1200
Channel height, mm	5	4 – 6
Channel width, mm	100	
Plate thickness, mm	0.25	
Water film thickness, mm	0.25	
Operating parameters		
Inlet air velocity, m/s	1.5	1.0 – 2.0
Working air ratio	0.3	0.1 – 0.5
Air Condition		
Inlet air temperature, °C	30	25 – 35
Inlet air humidity, g/kg da	10	5 - 15

where working air ratio, r, is the fraction of the air that is used for in the wet channel for evaporative cooling .

2.3 Initial and boundary conditions

The initial and boundary conditions used in the simulation are listed in Table 2.

Table 2. Initial and boundary conditions for the numerical simulation.

	Temperature	Humidity
Initial Condition	$T_{da}(x,0) = T_{water}$ $T_{wf}(x,0) = T_{water}$ $T_{wa}(x,0) = T_{water}$	$Y_{da}(x,0) = Y_{water,sat}$ $Y_{wa}(x,0) = Y_{water,sat}$
Boundary Condition	$T_{da}(0,t) = T_{hf}(0,t)$ $T_{wa}(L,t) = T_{da}(L,t)$	$Y_{da}(x,t) = Y_{a}(L,t)$ $Y_{wa}(L,t) = Y_{da}(L,t)$

2.4 Performance indices

The performance indices used to evaluated the DPEC are cooling capacity, wet bulb effectiveness (ε_{wb}), and dew point effectiveness (ε_{dp}) using the following equations:

$$Cooling\ Capacity = m_{pa}c_{p,pa}T_{pa} - m_{ia}c_{p,ia}T_{ia} \quad \text{Eq. 14}$$

$$\varepsilon_{wb} = \frac{T_{pa} - T_{ia}}{T_{wb} - T_{ia}} \quad \text{Eq. 15}$$

3. Results and discussion

3.1. General features of a DPEC

The temperature and humidity distribution of a DPEC operating at nominal condition and at steady state is illustrated in Fig. 3. As dry air enters the dry channel, its temperature decreases along the channel length with its humidity remaining constant. The enthalpy from the dry air is transferred sensibly to the adjacent wet channel. As cold unsaturated air enters the wet channel, it cools slightly further until it reaches saturation. The sensible heat from the dry channel increases the temperature and thus the vapor pressure of the wet air promoting evaporation. In DPEC, a fraction of the inlet dry air is sensibly cooled, theoretically approaching the dew point, while the remaining fraction exits as a saturated exhaust air.

3.2. Parametric analysis

3.2.1. Effect of Design Parameters

The effect of channel length on the performance of a DPEC is shown in Fig. 4. Product air temperature decreases as the channel length increases. The improved performance of the DPEC as increasing channel length is due to the longer period for mass and energy transfer. At nominal condition, the product air temperature surpasses the wet bulb temperature at channel length greater than 0.8m.

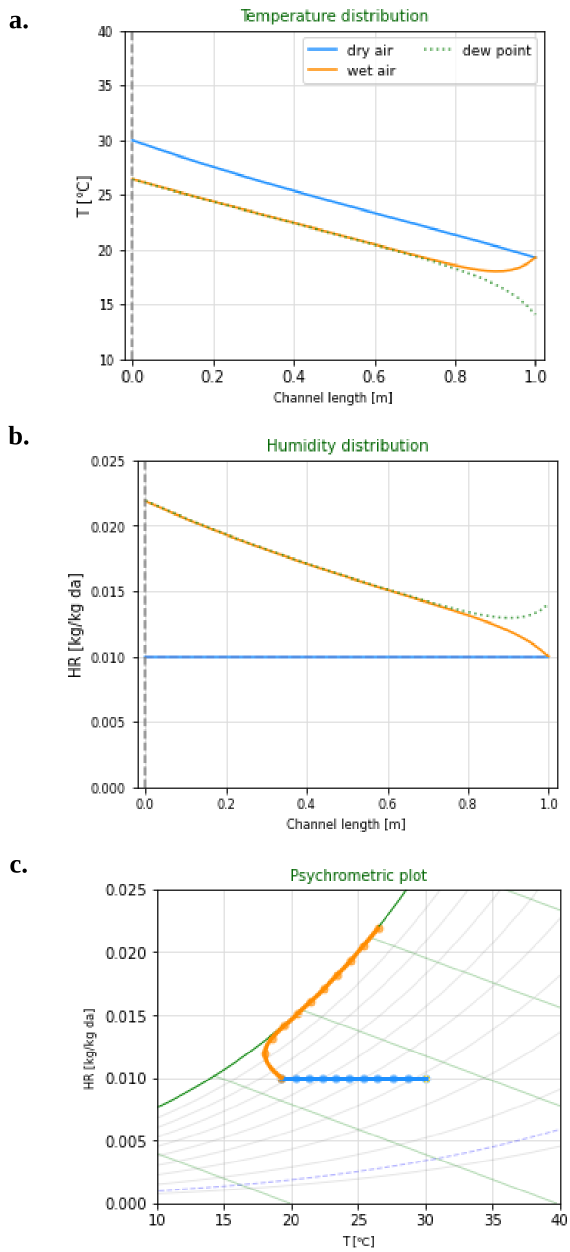

Fig. 3. Steady state (a) temperature distribution; (b) humidity distribution, and (c) psychrometric plot of a DPEC operating at nominal condition.

The effect of channel height on the performance of a DPEC is shown in Fig. 5. Product air temperature decreases as the height of the DPEC channel is decreased. This effect is attributed to the better convective heat and mass transfer associated with smaller channel height. At nominal condition, the product air temperature surpass the wet bulb temperature when channel height is smaller than 5mm.

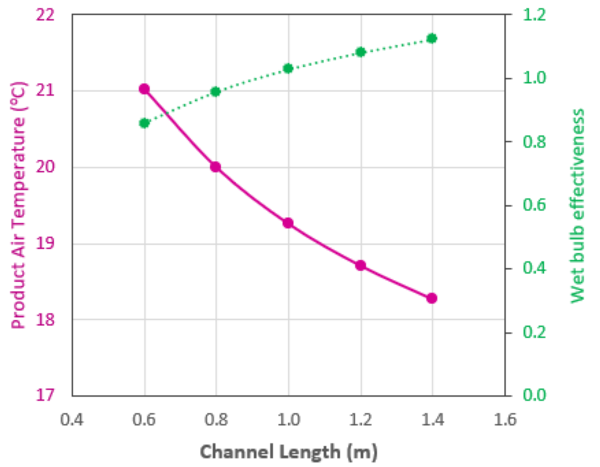

Fig. 4. Effect of channel length on DPEC product air temperature and wet bulb effectiveness.

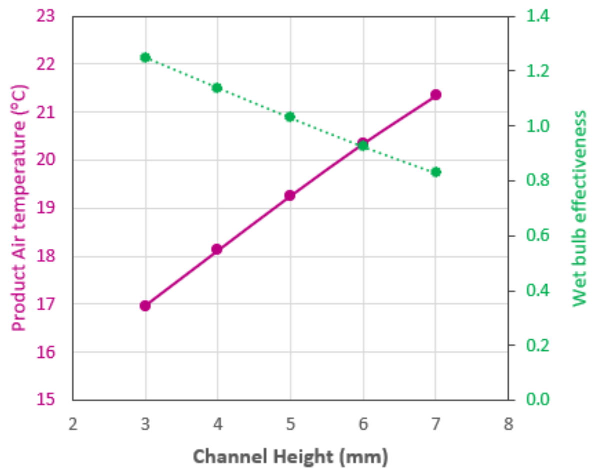

Fig. 5. Effect of channel height on DPEC product air temperature and wet bulb effectiveness.

3.2.2. Effect of Operating Parameters

The effect of working air ratio on the performance of a DPEC is shown in Fig. 6. As the working ratio increases, more air is diverted into the wet channel which causes more evaporation and hence more cooling. However, this reduces the amount of product air available for use and thus affecting the cooling capacity of the cooler. A balance between lowering the product air temperature while maintaining an acceptable cooling capacity must be considered when selecting an appropriate working air ratio.

The effect of inlet air velocity on the performance of a DPEC is shown in Fig. 7. As the inlet air increases, the time for heat and mass transfer becomes less and hence the air cannot be cooled well enough thereby increasing the temperature at the outlet. At nominal condition, product air temperature lower than the wet bulb can be achieved with an inlet air velocity of 1.5 m/s or less. On the other hand, increasing the inlet air velocity increases the cooling capacity of the cooler due to the increased mass flowrate. Similarly, a balance between product air temperature and cooling capacity must be considered when setting the inlet air velocity during operation of a DPEC.

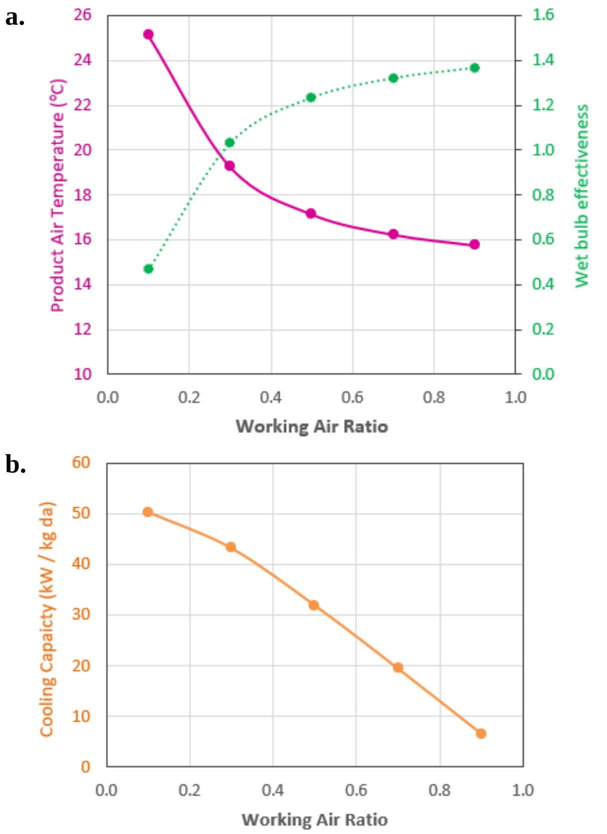

Fig. 6. Effect of channel length on DPEC product air (a) temperature and wet bulb effectiveness; and (b) cooling capacity.

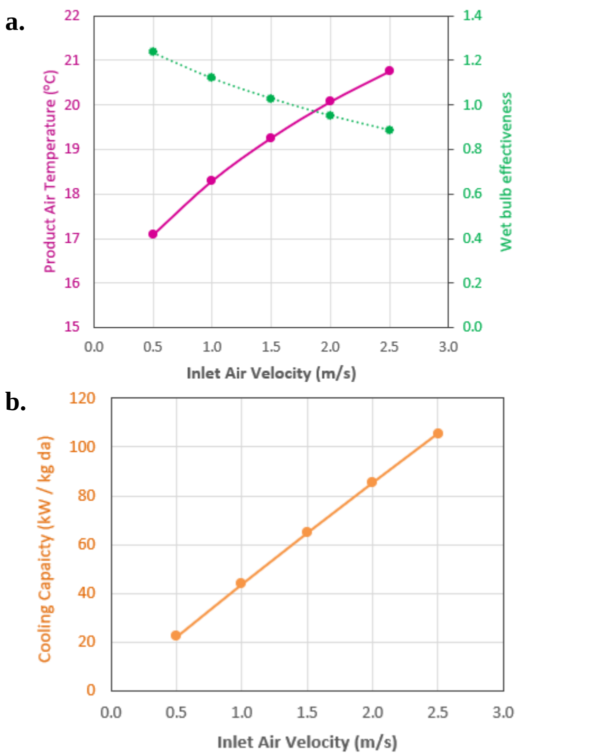

Fig. 7. Effect of inlet air velocity on DPEC product air (a) temperature and wet bulb effectiveness; and (b) cooling capacity

3.2.3. Effect of Inlet Air Condition

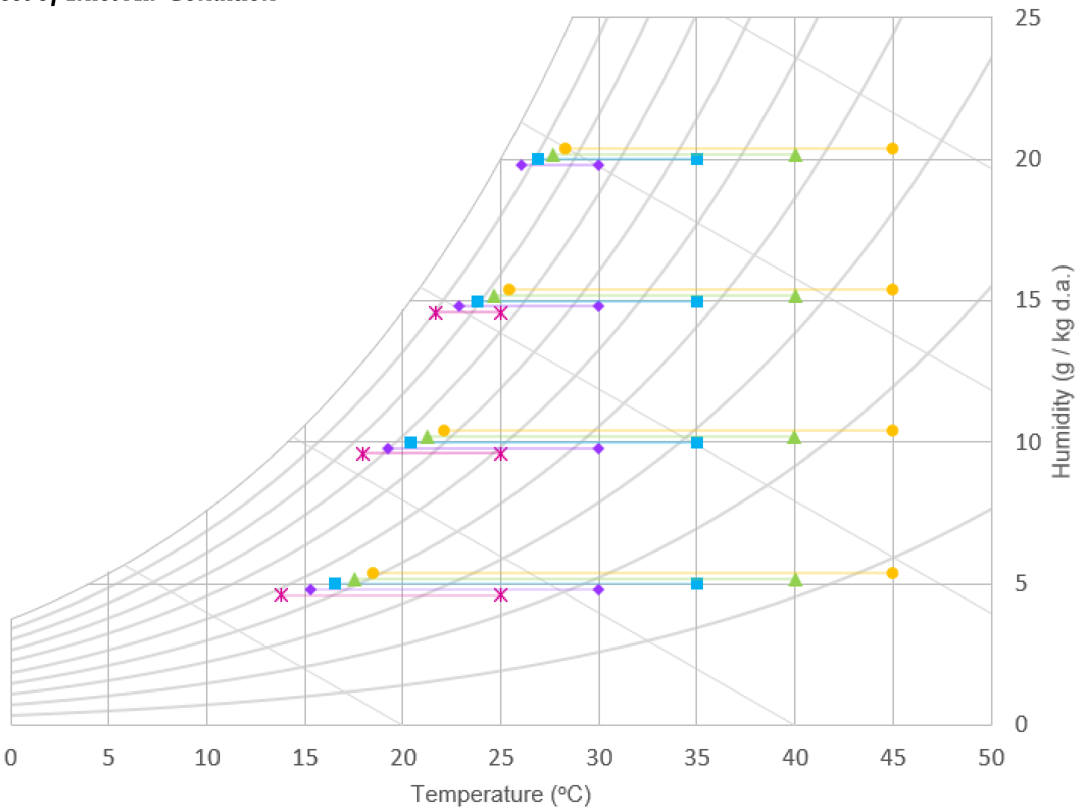

Fig. 8. Effect of inlet air temperature and humidity on the product air temperature (right markers – inlet/outdoor condition; left markers – product air).

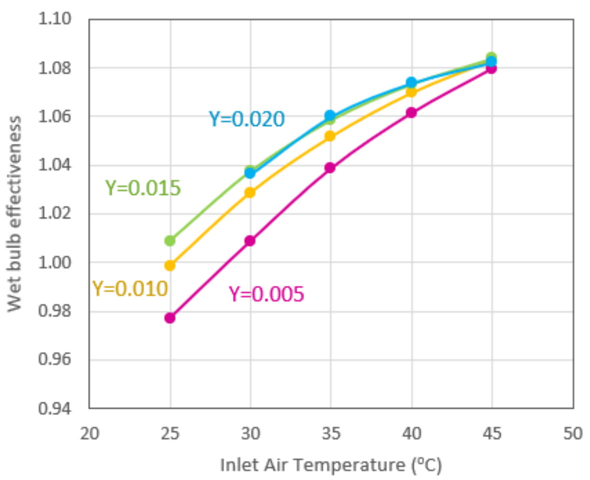

Fig. 9. Effect of inlet air temperature and humidity on DPEC wet bulb effectiveness.

The effect of the temperature and humidity to the product air is shown in the psychrometric chart in Fig. 8. And the corresponding effectiveness in Fig. 9. Generally, it can be observed that the product air temperature becomes lower as the humidity of the inlet air decreases. This is due to the higher vapor pressure driving force for evaporation. It can also be observed that, while the product air temperature is higher at higher inlet temperatures, the temperature drop from the inlet air to the product air becomes larger which in effect giving greater wet bulb effectiveness at higher temperature. This shows that a counter-flow DPEC is effective in reducing the temperature of air to beyond its wet bulb temperature especially at higher inlet temperatures.

4. Conclusion

Dew point evaporative cooling (DPEC) has been shown to effectively reduce the temperature of air beyond its wet bulb temperature without increase in humidity. In a counter-flow DPEC, the product air temperature can be reduced further by increasing channel length, decreasing channel height, increasing working air ratio, and decreasing air velocity. Lower inlet air humidity and temperature has also shown to give lower product air temperature. However, higher air temperature and humidity has shown to give higher wet bulb effectiveness.

Nomenclature

Symbols

c_p	isobaric specific heat, J/kg
d	thickness, mm
d_h	hydraulic diameter, m
ε	effectiveness
h	convective heat transfer coefficient W/m^2 K
ħ	convective mass transfer coefficient, m/s
H	heat of vaporization, J/kg
k	thermal conductivity, W/m-K
L	length, m
Le	Lewis number
le	characteristic length, m
M	molar mass, g/mol
P	pressure, kPa
Pr	Prandtl number
P_v	vapor pressure, kPa
ρ	density, kg/m

ρ_v	vapor density, kg/m^3
φ	relative humidity
Re	Reynolds number
T	temperature, ^oC
t	time, s
u	velocity, m/s
Y	humidity ratio, kg/kg da
z	channel height, m

Subscripts

da	dry channel air
ia	inlet air
pa	product air
pl	plate
s	saturation
v	vapor
wa	wet channel air in DPEC
wf	water film

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