primary air is cooled by convection heat transfer from the plate surface. This wet operation is formulated by Equation 1. On the other hand, the sensible heat is exchanged during dry operation as in Equation 2.

$$\dot{q}_{wet} = U_{wet} A(t_{pi} - t_{si}^{wb}) \tag{1}$$

$$\dot{q}_{dry} = U_{dry} A(t_{pi} - t_{si}) \tag{2}$$

where, $\dot{q}$ is the heat transfer rate [kW], U is the overall heat transfer coefficient [W/m^{2}C], A is the heat transfer area [m^2], t and t^{wb} are the dry-bulb and wet-bulb temperature [C], respectively. Subscript *pi* and *si* indicate the primary and secondary air inlet channels, respectively. The overall heat transfer coefficient under wet operation (U_{wet}) and dry operation (U_{dry}) is estimated by Equation (3) and (4), respectively.

$$U_{wet} = \left(\frac{1}{h_{a,p}} + \frac{a_{pl}}{k_{pl}} + \frac{a_{w,s}}{k_{w,s}} + \frac{c_{p,si}}{c_{w,si} h_{si}} \right)^{-1} \tag{3}$$

$$U_{dry} = \left(\frac{1}{h_{a,p}} + \frac{a_{pl}}{k_{pl}} + \frac{a_{s}}{k_{s}} + \frac{1}{h_{a,s}} \right)^{-1} \tag{4}$$

The effectiveness of IEC for counter flow can be estimated by Equation (5) using the ε-NTU method.

$$\varepsilon_{IEC,x} = \left[1 - \exp\left\{ \frac{NTU_x^{0.22}}{C_x} \left(\exp\left(- C_x \cdot NTU_x^{0.78} \right) \right) - 1 \right\} \right] \tag{5}$$

where, NTU is the number of transfer units calculated by $NTU_x = \frac{U_x A}{\dot{m}_p c_p}$. The subscript x means wet operation (wet) and dry operation (dry). The value of C_x is estimated by $C_{wet} = \frac{\dot{m}_p c_{p,pi}}{\dot{m}_s c_{w,si}}$ and $C_{dry} = \frac{\dot{m}_p c_{p,pi}}{\dot{m}_s c_{p,si}}$. $\dot{m}$ is the mass transfer coefficient [kg/s], c_p is the specific heat of air [kJ/kg C]. Using Equation (5), the outlet dry-bulb temperature of the primary channel can be obtained using Equation (6) and Equation

(7).

$$\varepsilon_{IEC,wet} = \frac{t_{pi} - t_{po}}{t_{pi} - t_{si}^{wb}} \tag{6}$$

$$\varepsilon_{IEC,dry} = \frac{t_{pi} - t_{po}}{t_{pi} - t_{si}} \tag{7}$$

SIMPLIFIED IEC MODEL

(1) Derivation of simplified IEC model

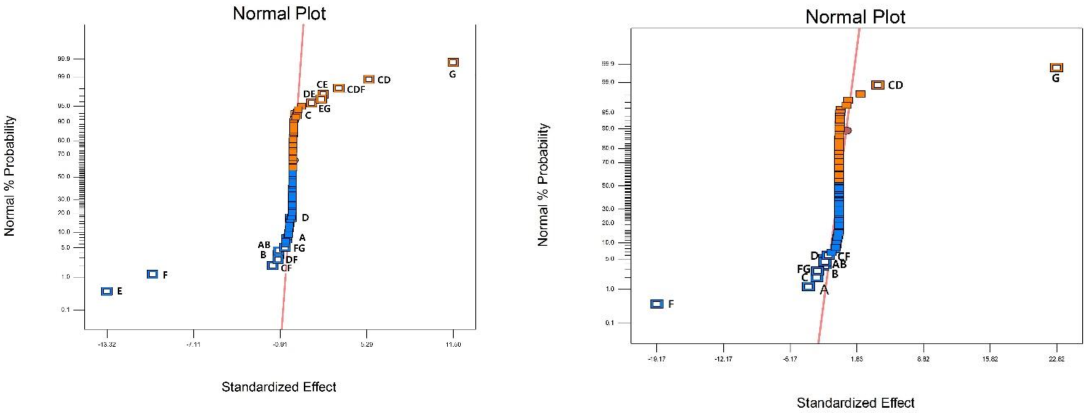
In order to estimate the impact of design parameters, and their interactions, on the effectiveness of wet coil IEC, the 2k factorial experiment design method was applied. Using this experiment design method, the parameters and interactions that have the most influence were obtained and then linear regression equations were derived. In order to derive the simplified model for predicting the effectiveness of wet coil IEC, seven parameters were selected as design variables for a simple IEC design. The high and low value for deriving the model using the 2k factorial design method was obtained from the manufacturer’s data (Table 1). The selected major design parameters were dry-bulb temperature of primary air (t_{pi}), relative humidity of primary air (RH_{pi}), dry-bulb temperature of secondary air (t_{si}), relative humidity of secondary air (RH_{si}), mass flow rate of primary air (m_p), mass flow rate ratio of primary to secondary air (m_{ratio}), Ratio of heat transfer area to primary air mass flow rate (ma_{ratio}).

Table 1. *Experimental data from literatures*

Label	Parameter	Symbol	Type	Unit	Low	High
A	Dry-bulb temperature of primary channel	t_{pi}	Numeric	℃	20 (wet) -20 (dry)	40
B	Relative humidity of primary channel	RH_{pi}	Numeric	%	10	100
C	Dry-bulb temperature of secondary channel	t_{si}	Numeric	℃	10	40
D	Relative humidity of secondary channel	RH_{si}	Numeric	%	10	100
E	Mass flow rate of primary channel	$\dot{m}_p$	Numeric	kg/s	0.05	2
F	Mass flow ratio of primary to secondary channel	m_{ratio}	Numeric		0.5	2
G	Ratio of heat transfer area to primary air mass flow rate (* NTU: 0.5~6)	ma_{ratio}	Numeric	m^2s/m	50	500

For deriving these simplified models, a full factorial experiment was selected and 2^7(=128) simulations were also conducted. As shown in Figure 2, the high impact individual parameters and interactions on the effectiveness of wet coil IEC under wet operation (Fig. 2(a)) and dry operation (Fig. 2(b)) were selected on the normal probability plot of standardized effect. The results show that there are 12 and 10 high impact parameters and interactions, respectively.

Table 2 shows the selected parameters and percentage contribution of each parameter. The contribution of the selected parameters were 0.07~37.76% on the wet operation and 0.15~55.32% on the dry operation. The terms of A and D were hierarchically selected in the wet operation model, even for the less than 0.07% contribution, for two-factor and three factor interactions of AB, CD, DE, DF, and CDF. From this result, first order linear regression equations for returning the effectiveness of IEC during wet and dry operation was derived as a function of selected single parameters and two or three-factor interactions. The model Prob>F values are less than 0.0001, which indicate model terms are significant, and the R^2 values for both the proposed models for wet and dry operations were 0.99.



(a) wet operation (b) Dry operation

***Figure 1**. Normal probability plot of effects on response result*

***Table 2.** Selected parameters and percent contribution*

wet operation								
7 single parameters								
Label	A	B	C	D	E	F	G	
Parameter	t_{pi}	RH_{pi}	t_{si}	RH_{si}	$\dot{m}_p$	m_{ratio}	ma_{ratio}	
Contribution [%]	0.04	0.22	0.01	0.004	37.76	21.45	28.13	
8 two-factor interactions								
Label	AB	CD	CE	CF	DE	DF	EG	FG
Parameter	$t_{pi} \cdot RH_{pi}$	$t_{si} \cdot RH_{si}$	$t_{si} \cdot \dot{m}_p$	$t_{si} \cdot m_{ratio}$	$RH_{si} \cdot \dot{m}_p$	$RH_{si} \cdot m_{ratio}$	$\dot{m}_p \cdot ma_{ratio}$	$m_{ratio} \cdot ma_{ratio}$
Contribution [%]	0.21	6.36	1.00	0.45	0.39	0.23	0.90	0.07
1 three-factor interactions								
Label	CDF							
Parameter	$t_{si} \cdot RH_{si} \cdot m_{ratio}$							
Contribution [%]	2.33							
Dry operation								
6 single parameters								
Label	A	B	C	D	F	G		
Parameter	t_{pi}	RH_{pi}	t_{si}	RH_{si}	m_{ratio}	ma_{ratio}		
Contribution [%]	1.11	0.24	0.58	0.23	39.03	55.32		
4 two-factor interactions								
Label	AB	CD	CF	FG				

Parameter	$t_{pi} \cdot RH_{pi}$	$t_{si} \cdot RH_{si}$	$t_{si} \cdot m_{ratio}$	$m_{ratio} \cdot ma_{ratio}$
Contribution [%]	0.23	1.72	0.15	0.55

$$\begin{aligned}\varepsilon_{IEC,wet} &= \alpha_0 + \alpha_1(t_{pi}) + \alpha_2(RH_{pi}) + \alpha_3(t_{si}) + \alpha_4(RH_{si}) + \alpha_5(\dot{m}_p) + \alpha_6(m_{ratio}) + \alpha_7(ma_{ratio}) \\ &+ \alpha_8(t_{pi} \cdot RH_{pi}) + \alpha_9(t_{si} \cdot RH_{si}) + \alpha_{10}(t_{si} \cdot \dot{m}_p) + \alpha_{11}(t_{si} \cdot m_{ratio}) + \alpha_{12}(RH_{si} \cdot \dot{m}_p) \\ &+ \alpha_{13}(RH_{si} \cdot m_{ratio}) + \alpha_{14}(\dot{m}_p \cdot ma_{ratio}) + \alpha_{15}(m_{ratio} \cdot ma_{ratio}) + \alpha_{16}(t_{si} \cdot RH_{si} \cdot m_{ratio})\end{aligned}$$

……………………………………………… (8)

$$\begin{aligned}e_{IEC,dry} &= b_0 + b_1(t_{pi}) + b_2(RH_{pi}) + b_3(t_{si}) + b_4(RH_{si}) + b_5(m_{ratio}) + b_6(ma_{ratio}) \\ &+ b_7(t_{pi} \times RH_{pi}) + b_8(t_{si} \times RH_{si}) + b_9(t_{si} \times m_{ratio}) + b_{10}(m_{ratio} \times ma_{ratio})\end{aligned}$$

……………………………………………… (9)

EXPERIMENTAL RESULTS

(1) Wet coil IEC pilot unit

The pilot system of wet coil IEC was a cross-counter flow heat exchanger which has a U-shaped air flow on the secondary air side and straight flow on the primary air side. The pilot system consists of PolyEthylene (Tere)-Phthalate (PET) air-to-air sensible heat exchanger and a 0.192mm thick evaporative cooling pad, to hold the water to make a water film, is attached on the secondary channel. The dimension of the SHE is 450×560×450 mm.

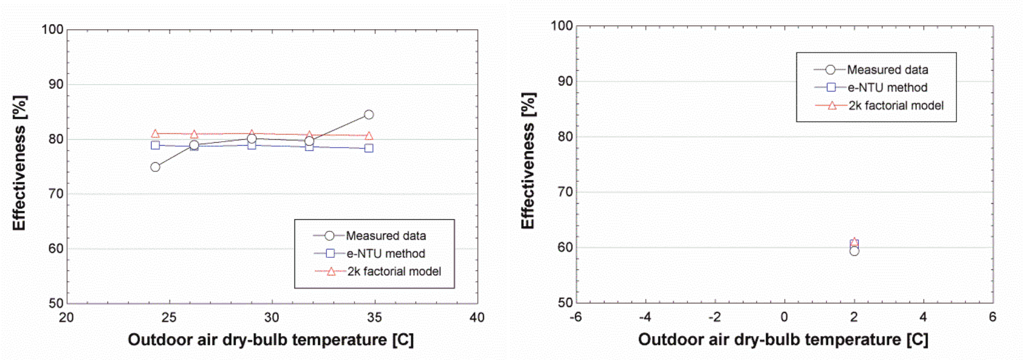
The two groups of tests were conducted to investigate the primary channel outlet air temperature under various primary channel inlet air conditions. In Test 1, five temperature levels (35, 32, 29, 26, and 24℃) and two relative humidity levels (40 and 50%) were used on the primary channel inlet air conditions. Test 1 was conducted for wet operation in the summer season. The selected temperature is based on TMY2 weather data. The returned air condition was 24℃ and 50%, and the 5 tests were conducted on each dry-bulb temperature difference. During the tests, the air flow of the primary and secondary air channel was 500m^3/h. During test 2, a 2℃ dry bulb temperature is supplied in the primary channel and the returned air condition was 22℃ and 40%. Each test is measured over 35minutes and the measuring data is saved at 1 minute interval. The corresponding air flow rate of the primary and secondary channels, and the inlet and outlet dry-bulb and wet bulb temperatures of each state were measured to observe the thermal performance of the wet coil IEC.

(2) Test results

The results for Test 1, as shown in Fig. 2(a), when the inlet temperature of the primary air (i.e. outdoor air) decreased from 35℃ to 24℃, show that the effectiveness of the pilot unit also decreases but significant variation was seldom observed. In addition, the outlet relative humidity of the primary air reached nearly 95%, but condensation or dehumidification on the plate was not shown in this tests. Test 2, Fig. 2(b), shows that the induced 2℃ of outdoor air is pre-heated to 14.6℃ at about 59% of heat reclaiming effectiveness from the 22℃ of return air temperature.

The absorbing material for improving evaporative cooling is attached to the secondary channel of the pilot system. This improves the evaporative cooling efficiency (to about 80%) under wet operation but it also reduces heat transfer efficiency (to about 60%) under dry operation, caused by decreasing the overall U-value of the heat exchanger.

The test results were compared with the acquired model in Equation (8) and (9) for verification. Fig. 2 also show the comparison of the measured and estimated values by the ε-NTU method as well as the predicted effectiveness and outlet temperature of the primary channel under the various primary side inlet temperatures. One can see that the predicted models are well matched with the measured values with under 10% deviation.



(a) Wet operation (b) Dry operation

Figure 2. Normal probability plot of effects on response result

CONCLUSIONS

In this research, practical effectiveness estimation models for a wet coil IEC were proposed, these can be applied to simulate the annual energy performance and design of the wet coil IEC at initial phase. The proposed models are derived based on the ε-NTU method. The models use a form of first-order linear equation and return the effectiveness of wet and dry operation. In order to validate the proposed models, a pilot unit wet coil IEC was built and tests were conducted under various environment conditions in an environment chamber. The test results show that over 75% and 59% effectiveness can be obtained during wet and dry operation, respectively. During wet operation obtaining this high effectiveness, even in hot and humid OA condition, is mainly the result of relatively cool and dry RA being used in the secondary channel. It was also shown that the proposed models and experimental results agree well with less than 10% deviation during both wet and dry operation.

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