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THE BEHAVIOR OF LEWIS NUMBER IN FINNED TUBE COOLING COILS UNDER HIGHLY MOIST INLET AIR CONDITIONS

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ABSTRACT

The objective of this research was to study the effects of highly moist inlet air conditions such as temperature, relative humidity, and frontal air velocity on the value of the Lewis number (Le) in the cooling and dehumidifying process of air. A finned tube cooling coil was tested under ranges of temperature, relative humidity and frontal velocity. It was found that the Lewis number (Le) varied within the range of 0.92–1.62 and that the increase in inlet air relative humidity tends to decrease the Lewis number (Le). Based on the experimental, a correlation for predicting the Lewis number (Le) was also established in this article. The correlation has the mean absolute error (MAE) of 3.04% and covers 98.07% of the data where a discrepancy within ± 10%.

Keywords: Cooling coils; Dehumidifying process; Lewis number; Moist air

1. INTRODUCTION

The condensation process will occur when the moist air reaches a dew point which higher than the surface temperature of the cooling coil through which it flows. In this process, heat and mass transfer are occurs simultaneously, so the air temperature will drop and water vapor in moist air will transfer to the cooling coil surface. The parameter which is used to explain this phenomenon is Lewis number (Le). This parameter is very important for the prediction of specific humidity of the outlet air, especially in a cooling coil model which uses the enthalpy difference method (Threlkeld, 1972). This method has been employed by some researchers including Theerakulpisut and Priprem (1998), Xia et al. (2010) and Mansour (2016).

Several researchers studied the values of Lewis number (Le). For example, Kusuda (1963) proposed the Lewis number (Le) of the moist air, saturate surface temperature range of 10-60°C was the range of 0.87–0.90. Seshimo et al. (1988) reported the value Lewis number at 1.1 and Eckels and Rabas (1987) gave values of Lewis number between 1.1–1.2; in addition, Hong and Webb (1996) showed values in the range of 0.7–1.1. Moreover, Wang and Chang (1998) also tested the cooling coil and presented the correlation of the Lewis number (Le), but the correlation did not include the effect of relative humidity. Furthermore, Pirompugd et al. (2006) reported the value of the Lewis number (Le) from experimental data at the range of 0.6–1.1.

The present literature review reveals that research on the influence of air inlet conditions on the Lewis number is rather limited. The purpose of this work is therefore to test a cooling coil

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under different inlet air conditions defined by inlet air temperature, relative humidity, and velocity to determine the influence of these parameters on the Lewis number (Le).

2. EXPERIMENTAL SETTING

2.1. Experimental Rig

The experimental rig used in this study is depicted in Figure 1. It consists of an air blower, controlled by a variable speed drive, a 9.0-kW air heater with a temperature controller, a humidifier, a 13.5-kW steam boiler for feeding steam to the humidifier, a test coil, a chilled-water unit, measuring equipment, and a data acquisition system.

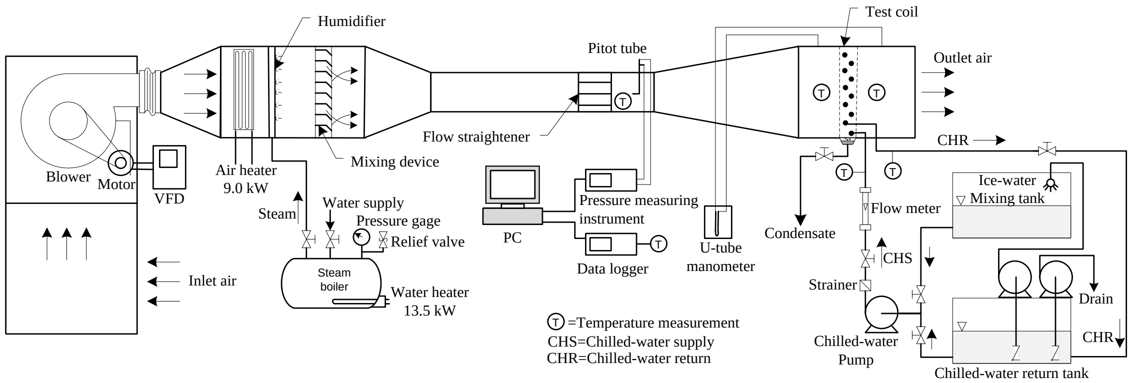


Figure 1 Experimental rig and measuring equipment

Chilled-water unit produces chilled water by mixing iced water and chilled water returning from the test coil. Chilled water is supplied at a constant temperature of 7°C to the test coil by a pump through a flow meter (rotameter) with an accuracy of ± 50 l/h. Measuring equipment employs type-T thermocouples with an accuracy of ± 0.2°C for measuring air temperatures before entering and after leaving the test coil, and chilled water temperatures at the inlet and the exit of the test coil.

The measurement of temperatures of the air entering the test coil using a thermocouple grid consists of nine thermocouples according to ASHRAE 41.1 (ASHRAE, 1986). The average of these nine readings was taken as the dry-bulb temperature of the inlet air. For the inlet air, wet-bulb temperature was measured at the mid-point of the flow section. Measurement of wet-bulb temperatures followed the ASHRAE 41.1 (ASHRAE, 1986), and calculation of moist air properties was carried out according to ASHRAE 41.6 (ASHRAE, 1994). All readings of thermocouples with an accuracy of ± 0.2°C were recorded by Agilent data logger, Model 34972A.

Mass flow rate of air was obtained by using a Pitot tube and a pressure measuring device, Testo 435-4 with an accuracy of ±2 Pa, to measure the velocity after the flow straightener. Positions of velocity measurement were determined by the Log-linear Method (ISO, 2008). All pressure readings were recorded by a computer. The average velocity was calculated according to ASHRAE 41.2 (ASHRAE, 1987). The calculated uncertainties of the measuring parameters are listed in Table 1

Table 1 Calculated uncertainties of parameters

Parameters	Estimates uncertainties (±%)	
	Minimum	Maximum
Le	2.35%	23.74%
RH_{ai}	1.75%	3.01%
Re_{Dc}	1.78%	14.82%

2.2. Cooling Coil Specifications

The cooling coil used in this study is a finned-tube type with copper tubes and aluminium wavy fins. Some of features of the coil are depicted in Figure 2 with its specifications in Table 2.

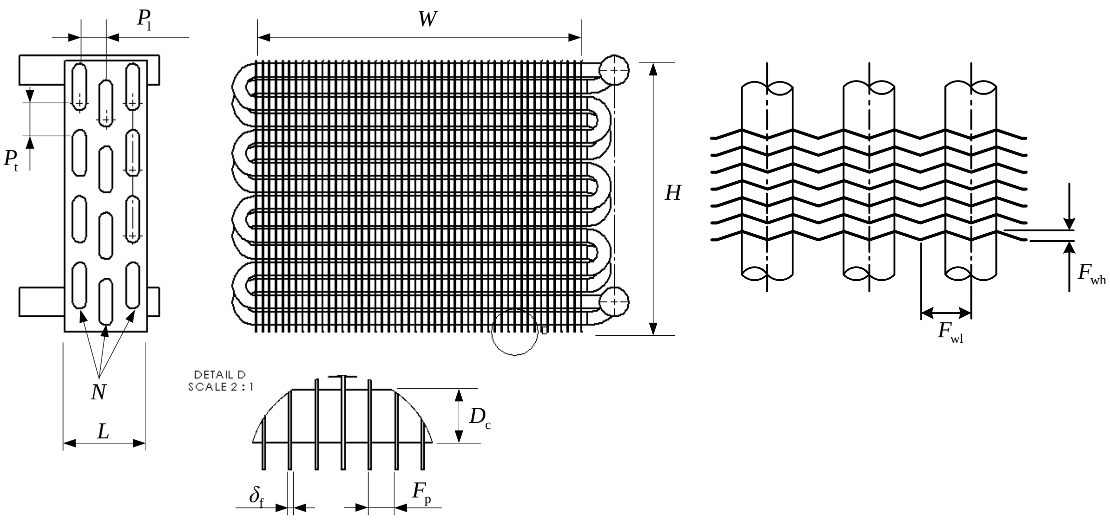


Figure 2 Test cooling coil

Table 2 Cooling coil specifications

Parameters	Specifications
Coil face width (W)	545 mm
Coil face height (H)	204 mm
Coil deep (L)	57 mm
Number of tube row (N)	3
Number of tube per row	8
Tube arrangement	Staggered
Transverse tube pith (P_t)	25.40 mm
Longitudinal tube pith (P_l)	19.00 mm
Tube outside diameter (D_o)	9.70 mm
Tube inside diameter (D_i)	8.40 mm
Collar diameter (D_c)	10.09 mm
Fin thickness (F_t)	0.15 mm
Fin pith (F_p)	2.09 mm
Number of fin	259
Wave length of fin (F_{wt})	9.00 mm
Wave height of fin (F_{wh})	0.60 mm

2.3. Experimentation

Table 3 shows the conditions of inlet air and inlet chilled water used in testing the cooling coil in this study. It is important to mention that there were only 69 runs of experiment instead of 72 due to some difficulty in attaining 90%, and 100% *RH* at the inlet air temperature of 35°C and 40°C. It should be noted that for all the test conditions listed in the table, the cooling coil surface was totally wet. In each test, three sets of the best steady-state data were selected for analysis. Selection of the data was based on the agreement of the calculated values of air-side and water-side heat transfer rates. The data sets which gave these two heat transfer rates being closest to each other and within 5% (ASHRAE, 1978) of their average value were selected for analysis.

Table 3 Inlet air and water conditions

Parameters	Inlet conditions
Inlet air dry-bulb temperature	27, 30, 35, 40 (°C)
Inlet air relative humidity	50, 60, 70, 80, 90, 100 (%)
Air frontal velocity	1, 2, 3 (m/s)
Inlet chilled water temperature	7 (°C)
Chilled-water flow rate	800 l/h (0.2232 kg/s)

2.4. Experimentation

Lewis number (Le) in a cooling process of moist air was calculated from the relationship which was proposed by Threlkeld (1972) as shown in Equation 1. His relationship shows the change of humidity ratio with respect to the change of the enthalpy of the air.

$$\frac{\mathrm{d}\omega}{\mathrm{d}h_{\mathrm{a}}} = \left[Le\left(\frac{h_{\mathrm{a}} - h_{\mathrm{aswm}}}{\omega_{\mathrm{a}} - \omega_{\mathrm{aswm}}} \right) + \left(h_{\mathrm{g}} - 2501Le \right) \right]^{-1} \tag{1}$$

For “not deep” cooling coil, $\mathrm{d}\omega/\mathrm{d}h_{\mathrm{a}}$ can be approximated in Equation 2 below:

$$\Delta\omega/\Delta h_{\mathrm{a}} = \left(\omega_{\mathrm{ai}} - \omega_{\mathrm{ao}}\right)/\left(h_{\mathrm{ai}} - h_{\mathrm{ao}}\right) \tag{2}$$

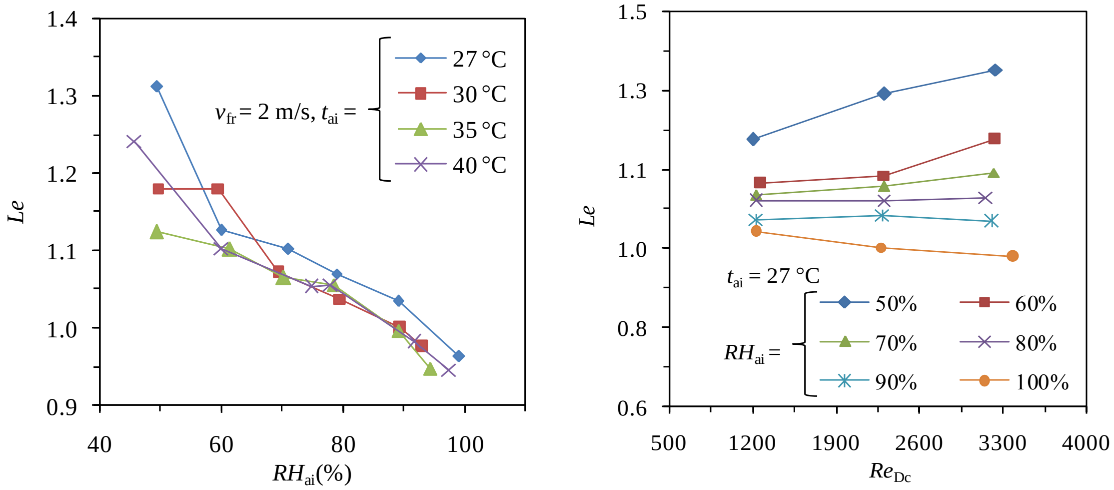
Parameters h_{aswm} and ω_{aswm} represent saturated enthalpy and specific humidity of the air, respectively, which are evaluated at the mean temperature of water film. The calculation procedure of both parameters were descripted in Theerakulpisut and Priprem (1998).

3. RESULTS AND DISCUSSION

Figure 3a shows plots of Lewis number (Le) against the inlet relative humidity (RH_{ai}) at different values of inlet air temperature. From Figure 3a, it is evident that the Lewis number (Le) decreases as the RH_{ai} increases. The increase in RH_{ai} causes more mass transfer to occur. However the increase in the heat transfer coefficient is much less. Hence, the Lewis number (Le) decreases as the RH_{ai} increases. It was noted that the Lewis number at 27°C tends to be slightly higher than those of higher inlet air temperature at the other inlet air temperature.

In addition, the increase of Reynolds number (Re_{Dc}), at the inlet air temperature of 27°C, and 50% of RH_{ai}, causes the Lewis number to increase as illustrated in Figure 3b. For the RH_{ai} range of 60-90%, an increase in Reynolds number (Re_{Dc}) causes little change to the Lewis number (Le), which is similar to the test results of Hong and Webb (1996) and Wang and

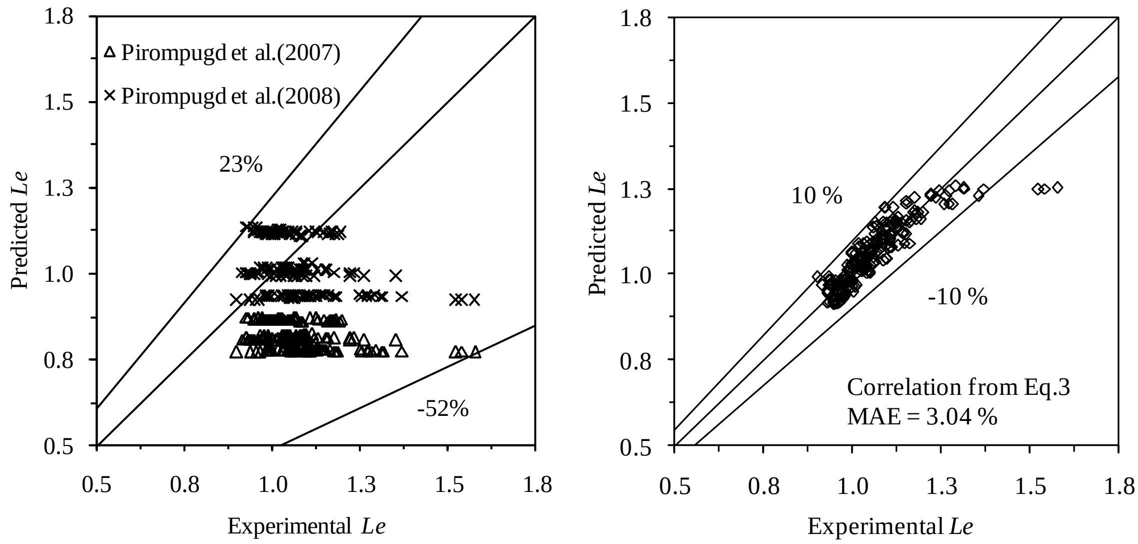
Chang (1998). However, when the RH_{ai} is about 100%, the Lewis number (Le) decreases as the Reynolds number (Re_{Dc}) increases.



(a) **(b)**

Figure 3 Influence of: (a) inlet air relative humidity; (b) Reynolds number (Re_{Dc}) on Lewis number (Le)

Figure 4a shows the plots of predicted Lewis number (Le) and experimental data by using the correlations of Pirompugd et al. (2007; 2008). The correlations gives larger error of Lewis number (Le) ranging from -52 to 23%. This is largely thought to be due to the absence of inlet air relative humidity and temperature.



(a) **(b)**

Figure 4 Comparison of predicted Lewis number (Le) with this experimental data: (a) using from Pirompugd's correlation; and (b) using from Equation 3

It is obvious from the aforementioned discussion that Lewis number (Le) is a function of relative humidity, Reynolds number (Re_{Dc}), and inlet air temperature. As previously discussed, the sixty nine (69) runs of present experiment were conducted and three sets of experimental data from each run were used to calculate the Lewis number (Le). Correlation of the Lewis number (Le) as the function of relevant parameters was formulated by using multiple linear regression to yield Equation 3.

$$Le = 3.373 Re_{\mathrm{Dc}}^{0.05768} RH_{\mathrm{ai}}^{-0.3441} \left[\frac{t_{\mathrm{ai}}}{t_{\mathrm{ri}}} \right]^{-0.06699} \quad (3)$$

The comparison between predicted values by Equation 4 and the experimental data is illustrated in Figure 4b. The mean absolute error (MAE) of the correlation which is calculated using Equation 4 is 3.04% and the correlation covers 98.07% of the data with a discrepancy of ±10%.

$$MAE = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{x_p - x_{exp}}{x_{exp}} \right| \times 100 \quad (4)$$

4. CONCLUSION

The dependence of the Lewis number (Le) on inlet air temperature, relative humidity and frontal velocity of air was studied. It was found that the Lewis number (Le) depends strongly on the inlet air relative humidity. A correlation for predicting the value of the Lewis number (Le) was also proposed. The correlation gives values in good agreement with the experimental results and can be used under the conditions commonly encountered in air conditioning system.

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6. NOMENCLATURE

h	enthalpy (kJ/kg$_{\mathrm{da}}$)	t	temperature ($^{\mathrm{o}}$C)
Le	Lewis number	x	data point
Re	Reynolds number	ω	specific humidity (kg$_{\mathrm{water}}$/kg$_{\mathrm{da}}$)
RH	relative humidity [%]		

Subscripts

a	air	i	inlet, inside	p	prediction
Dc	collar diameter	l	longitudinal	r	chilled water
da, g	dry air	m	mean value, measurement	s	saturate
exp	experiment	o	outlet, outer	w	wet surface, water film

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