International Journal of Thermal Sciences 48 (2009) 2159–2164

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

A modified logarithmic mean enthalpy difference (LMED) method for evaluating the total heat transfer rate of a wet cooling coil under both unit and non-unit Lewis Factors

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ARTICLE INFO

Article history:
Received 29 September 2008
Received in revised form
11 February 2009
Accepted 5 April 2009
Available online 7 May 2009

Keywords:
Modified LMED method
Total heat transfer rate
Wet cooling coil
Lewis Factors

ABSTRACT

The logarithmic mean enthalpy difference, (LMED) method has been extensively used in evaluating the thermal performance of an air cooling coil under wet condition. The LMED method has been developed based on the assumption of unit Lewis Factor, i.e., $\mathrm{Le}^{2/3} = 1$. However, a number of previous studies have suggested that the Lewis Factor can actually deviate from being 1. Consequently, errors can be resulted in when calculating the total heat transfer rate of a wet cooling coil using the LMED method. Therefore, a modified LMED (m-LMED) method has been developed for calculating the total heat transfer rate under both unit and non-unit Lewis Factors and is reported in this paper. This m-LMED method has been validated by comparing its prediction of the total heat transfer rate to that from numerically solving the fundamental governing equations of heat and mass transfer of a wet cooling coil. The m-LMED method can therefore replace the LMED method for calculating the total heat transfer rate of a wet cooling coil under both unit and non-unit Lewis Factors.

1. Introduction

Air cooling and dehumidifying coils have been widely used in air-conditioning systems. For an air cooling coil, if its surface temperature is below the dew point temperature of incoming air, simultaneous heat and mass transfer takes place on its air side, or the cooling coil is operated under wet condition.

The total heat transfer rate of an air cooling and dehumidifying coil under wet condition has been evaluated based on the enthalpy difference:

$$\mathrm{d}q = \frac{h_\mathrm{a}\mathrm{d}A_\mathrm{a}}{C_\mathrm{pa}}(i_\mathrm{a} - i_\mathrm{sur}) \tag{1}$$

where $\mathrm{d}q$ and $\mathrm{d}A_\mathrm{a}$ are the total heat transfer rate and air side surface area in a micro-scale element of a cooling coil; h_a, C_pa the air side sensible heat transfer coefficient and specific heat of air; i_a and i_sur the enthalpy of bulk air and the saturated air enthalpy at coil surface temperature, respectively. When establishing Eq. (1), the Lewis Analogy and the assumption of unit Lewis Factor were used, as follows.

$$\frac{h_\mathrm{a}}{h_\mathrm{m}C_\mathrm{pa}} = \mathrm{Le}^{2/3} = 1 \tag{2}$$

where h_m is the mass transfer coefficient.

Eq. (1) was originally proposed by Threlkeld [1] for simplifying the calculation of the total heat transfer rate in a wet cooling coil. The LMED method was developed from Eq. (1), as follows.

$$q = HA_\mathrm{a}\Delta i_\mathrm{lm} \tag{3}$$

where Δi_lm is the logarithmic mean enthalpy difference; H the overall heat transfer coefficient based upon the enthalpy difference.

Because of simplicity and convenience in determining the total heat transfer rate of a wet cooling coil, the LMED method has been extensively applied since its establishment, for investigating the simultaneous heat and mass transfer in both chilled water cooling coils [2–7] and direct expansion cooling coils [8–13] under different operating conditions.

It can be seen that the assumption of unit Lewis Factor is a prerequisite when establishing the LMED method. However, a number of previous related studies have suggested that Lewis Factor may well deviate from being one. For example, the experimental results by Hong and Webb [14] suggested that Lewis Factor was between 0.7 and 1.1. Seshimo et al. [15] suggested a value of 1.1. Eckels and Rabas [16] also reported a similar value of 1.1–1.2 based on their test

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doi:10.1016/j.ijthermalsci.2009.04.002

Nomenclature

A	area, m^2
b	the linear coefficient relating the enthalpy of saturated moist air to air temperature
C_p	specific heat, kJ/(kg K)
D_o	outside tube diameter, mm
h	heat transfer coefficient, $\mathrm{W/(K\,m^2)}$
h_m	mass transfer coefficient, $\mathrm{kg/(m^2\,s)}$
h_fg	latent heat of vaporization of water, kJ/kg
H	overall heat transfer coefficient in the LMED method
H_M	overall heat transfer coefficient in the m-LMED method
i	air enthalpy, kJ/kg
k	thermal conductivity, W/(K m)
L	length of fin, mm
Le	Lewis Number, defined as a ratio between thermal diffusivity and mass diffusivity of humid air
M	a parameter defined by Eq. (22), m^{-1}
N	number of tube rows
p_l	longitudinal tube pitch, mm
p_t	transverse tube pitch, mm
q	heat transfer rate, kW
R_o	equivalent radius defined by Eq. (23), mm
r	radius, mm
S_f	fin spacing, mm
T	temperature, °C
t	fin thickness, mm
W	fin width, mm
w	humidity ratio, kg/kg

Greek letters

η	fin efficiency
Φ	a parameter defined in Equation (21)

Subscripts

1	air side inlet of a cooling coil
2	air side outlet of a cooling coil
a	air side
c	cooling medium side
l	latent heat transfer
m	mass transfer
M	modified
o	overall or outside
s	sensible heat transfer
sur	air side surface of cooling coil
t	coil tube

results of fin-and-tube cooling coils having plain fin geometry. Wang et al. [17] suggested that Lewis Factor ranged from 0.6 to 1.1. In addition, Lewis Factor would slightly decrease as the Reynolds Number increased [18].

Therefore, errors can be resulted in when evaluating the total heat transfer rate of a wet cooling coil using the LEMD method. Xia and Jacobi [19] pointed out that a difference of 8% could be introduced in evaluating the total heat transfer rate, under the operating condition of a sensible heat ratio of 50%, as the value of Lewis Factor changed from 1 to 1.16.

A modified LMED (m-LMED) method for calculating the total heat transfer rate under both non-unit and unit Lewis Factors has been therefore developed and is reported in this paper. This m-LMED method has been validated by comparing its predictions of the total heat transfer rate to that from numerically solving the fundamental governing equations of the heat and mass transfer in a wet cooling coil.

Furthermore, the calculation results of the total heat transfer rates from using both the LMED and the m-LMED methods under the same operating conditions have been compared to indicate the errors resulted in where unit Lewis Factor is used, instead of actual Lewis Factor values which may not be equal to 1.

2. Development of the m-LMED method

The difference between the enthalpies of bulk air and the saturated moist air at coil surface temperature could be calculated as:

$$i_\mathrm{a} - i_\mathrm{sur} = C_\mathrm{pa}(T_\mathrm{a} - T_\mathrm{sur}) + h_\mathrm{fg}(w_\mathrm{a} - w_\mathrm{sur}) \tag{4}$$

where i_a and i_sur are the enthalpy of bulk air and the enthalpy of saturated moist air at coil surface temperature, respectively; T_a and T_sur, the temperatures of bulk air and coil surface, respectively; w_a and w_sur, the specific humidity ratio of bulk air and the saturated air humidity ratio at T_sur, respectively; C_pa and h_fg, the specific heat of air and the latent heat of vaporization of water, respectively.

Eq. (4) could be transformed to:

$$i_\mathrm{a} - i_\mathrm{sur} = \frac{C_\mathrm{pa}}{h_\mathrm{a}}\left[h_\mathrm{a}(T_\mathrm{a} - T_\mathrm{sur}) + \frac{h_\mathrm{a}}{C_\mathrm{pa}}h_\mathrm{fg}(w_\mathrm{a} - w_\mathrm{sur})\right] \tag{5}$$

The Lewis Analogy is:

$$\frac{h_\mathrm{a}}{C_\mathrm{pa}h_\mathrm{m}} = \mathrm{Le}^{2/3} \tag{6}$$

In Eqs. (5) and (6), h_a and h_m are the air side heat and mass transfer coefficients, respectively; Le, the Lewis Number and $\mathrm{Le}^{2/3}$, the Lewis Factor.

Applying the Lewis Analogy to Eq. (5) yields:

$$i_\mathrm{a} - i_\mathrm{sur} = \frac{C_\mathrm{pa}}{h_\mathrm{a}}\left[h_\mathrm{a}(T_\mathrm{a} - T_\mathrm{sur}) + \mathrm{Le}^{2/3}h_\mathrm{m}h_\mathrm{fg}(w_\mathrm{a} - w_\mathrm{sur})\right] \tag{7}$$

or:

$$\begin{aligned} i_a - i_{sur} = \frac{C_\mathrm{pa}}{h_\mathrm{a}}\Big[&h_\mathrm{a}(T_\mathrm{a} - T_\mathrm{sur}) + h_\mathrm{m}h_\mathrm{fg}(w_\mathrm{a} - w_\mathrm{sur}) \\ &+ (\mathrm{Le}^{2/3} - 1)h_\mathrm{m}h_\mathrm{fg}(w_\mathrm{a} - w_\mathrm{sur})\Big] \end{aligned} \tag{8}$$

The total heat transfer rate is calculated by:

$$\mathrm{d}q = \left[h_\mathrm{a}(T_\mathrm{a} - T_\mathrm{sur}) + h_\mathrm{m}h_\mathrm{fg}(w_\mathrm{a} - w_\mathrm{sur})\right]\mathrm{d}A_\mathrm{a} \tag{9}$$

where q and A_a are the total heat transfer rate and total air side coil surface area, respectively; $\mathrm{d}q$ the heat transfer rate in the surface area on the air side of a micro-scale element of the cooling coil, $\mathrm{d}A_\mathrm{a}$.

Combining Eqs. (8) and (9) for calculating $\mathrm{d}q$:

$$\mathrm{d}q = \frac{h_\mathrm{a}}{C_\mathrm{pa}}(i_\mathrm{a} - i_\mathrm{sur})\mathrm{d}A_\mathrm{a} - (\mathrm{Le}^{2/3} - 1)h_\mathrm{m}h_\mathrm{fg}(w_\mathrm{a} - w_\mathrm{sur})\mathrm{d}A_\mathrm{a} \tag{10}$$

Following the assumption that the ratio between the sensible heat transfer rate and the latent heat transfer rate remains constant in the entire coil, which was adopted previously [19], the following equation holds:

$$\frac{dq_s}{dq_l} = \frac{q_s}{q_l} \tag{11}$$

where q_s and q_l are the sensible and latent heat transfer rates in the entire coil; dq_s and dq_l, the sensible and latent heat transfer rates in the micro-scale element of the cooling coil.

Based on Eq. (11), the ratio between $(T_a - T_{sur})$ and $(w_a - w_{sur})$ could be determined by:

$$\frac{(T_a - T_{sur})}{(w_a - w_{sur})} = \frac{h_m h_{fg}}{h_a}\cdot\frac{dq_s}{dq_l} = \frac{h_m h_{fg}}{h_a}\cdot\frac{q_s}{q_l} \tag{12}$$

where h_m is the mass transfer coefficient for bulk air moisture content.

From Eqs. (4) and (12), the ratio between $(i_a - i_{sur})$ and $(w_a - w_{sur})$ could be calculated by:

$$\frac{(i_a - i_{sur})}{(w_a - w_{sur})} = \frac{h_{fg}}{Le^{2/3}}\,\frac{q_s}{q - q_s} + h_{fg} \tag{13}$$

Then $(w_a - w_{sur})$ could be evaluated by:

$$(w_a - w_{sur}) = \frac{(i_a - i_{sur})}{\frac{h_{fg}}{Le^{2/3}}\,\frac{q_s}{q - q_s} + h_{fg}} \tag{14}$$

Combining Eqs. (14) and (10) and the Lewis Analogy, i.e., Eq. (6), gives:

$$dq = \frac{h_a dA_a}{C_{pa}}\left[1 - \frac{\left(Le^{2/3} - 1\right)}{\frac{q_s}{q - q_s} + Le^{2/3}}\right]\cdot(i_a - i_{sur}) \tag{15}$$

Comparing Eq. (15) with Eq. (1), it can be seen that the linear relationship between dq and $(i_a - i_{sur})$ remains unaltered, with the linear coefficient being different, due to the fact that Lewis Factor, $Le^{2/3}$, may deviate from being 1. However, if $Le^{2/3} = 1$, Eq. (15) is exactly the same as Eq. (1).

Therefore, the m-LMED method can be established when replacing Eq. (1) with Eq. (15). Follow the same approach used in deriving LMED method [1], the m-LMED method can be shown as:

$$q = H_M A_a \Delta i_{lm} \tag{16}$$

where H_M is the modified overall heat transfer coefficient based on enthalpy and Δi_{lm}, the logarithmic mean enthalpy difference.

Normally the heat transfer resistances due to tube metal and condensate film on the external surface of the cooling coil are small compared to those on both air side and cooling medium side, thus negligible. With this assumption, H_M can be evaluated by:

$$H_M = \frac{1}{A_a}\cdot\left[\frac{b}{A_c h_c} + \frac{C_{pa}}{\eta_o A_a h_a}\left(1 - \frac{Le^{2/3} - 1}{\frac{q_s}{q - q_s} + Le^{2/3}}\right)^{-1}\right]^{-1} \tag{17}$$

where b is a linear coefficient relating the enthalpy of saturated moist air to air temperature.

For the LMED method, the overall heat transfer coefficient based upon enthalpy, H, is calculated by:

$$H = \frac{1}{A_a}\cdot\left(\frac{b}{A_c h_c} + \frac{C_{pa}}{\eta_o A_a h_a}\right)^{-1} \tag{18}$$

Comparing Eq. (17) with Eq. (18), it can be seen that when Lewis Factor is 1, H_M should be equal to H, and the m-LMED method is the same as the LMED method. Hence, the LMED method can be regarded as a special case of the m-LMED method when $Le^{2/3} = 1$.

In Eq. (17), the overall fin efficiency, η_o, is calculated by:

$$\eta_o = 1 - \frac{A_f}{A_a}(1 - \eta) \tag{19}$$

where fin efficiency, η, is calculated by Hong–Webb equation [14]:

$$\eta = \frac{\tan h(Mr_o\phi)\cos(0.1Mr_o\phi)}{Mr_o\phi} \tag{20}$$

where Φ and M are evaluated by the following two equations:

$$\phi = \left(\frac{R_o}{r_o} - 1\right)\left[1 + 0.35\ln\left(\frac{R_o}{r_o}\right)\right] \tag{21}$$

$$M = \left[\frac{2h_a}{kt}\left(1 + \frac{dq_l}{dq_s}\,\frac{h_{fg}}{C_{pa}}\right)\right]^{1/2} \tag{22}$$

In Eq. (21), r_o is the outside radius of the tube and the equivalent radius, R_o, of a plate fin is calculated by:

$$R_o = 1.28W(L/W - 0.2)^{1/2} \tag{23}$$

where W and L are the width and length of the fin.

3. Validation of the m-LMED method

The m-LMED method reported in Section 2 has been validated by comparing its prediction of the total heat transfer rate to that from numerically solving the fundamental governing equations of the heat and mass transfer in a wet cooling coil. The numerical solution (NS) has been widely regarded as the most accurate solution to the fundamental governing equations and hence is used as the basis for comparison.

3.1. Numerical solution to the fundamental governing equations

The m-LMED method can be applicable to both counter-flow and parallel-flow air cooling and dehumidifying coils. In this paper,

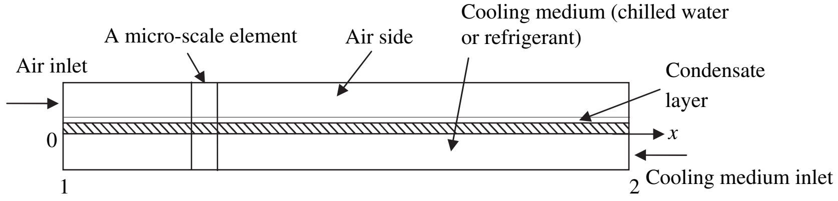

Fig. 1. Schematics of a counter-flow air cooling and dehumidifying coil under study.

a counter-flow air cooling coil whose schematic diagram is shown in Fig. 1 has been studied. In Fig. 1, “1” and “2” are used to denote the two ends of the air cooling coil, respectively.

For the micro-scale element shown in Fig. 1, the fundamental equations governing the simultaneous heat and mass transfer, and energy conservation are as follows.

$$\mathrm{d}q_\mathrm{s} = h_\mathrm{a}(T_\mathrm{a} - T_\mathrm{sur})\eta_\mathrm{o}\mathrm{d}A_\mathrm{a} \tag{24}$$

$$\mathrm{d}q_\mathrm{l} = \frac{h_\mathrm{a}}{C_\mathrm{pa}\mathrm{Le}^{2/3}}h_\mathrm{fg}(w_\mathrm{a} - w_\mathrm{sur})\eta_\mathrm{o,m}\mathrm{d}A_\mathrm{a} \tag{25}$$

$$\mathrm{d}q_\mathrm{s} = -m_\mathrm{a}C_\mathrm{pa}\mathrm{d}T_\mathrm{a} \tag{26}$$

$$\mathrm{d}q_\mathrm{l} = -m_\mathrm{a}h_\mathrm{fg}\mathrm{d}w_\mathrm{a} \tag{27}$$

$$\mathrm{d}q = h_\mathrm{c}(T_\mathrm{sur} - T_\mathrm{c})\mathrm{d}A_\mathrm{c} \tag{28}$$

$$\mathrm{d}q = \mathrm{d}q_\mathrm{s} + \mathrm{d}q_\mathrm{l} = -m_\mathrm{c}C_\mathrm{pc}\mathrm{d}T_\mathrm{c} \tag{29}$$

where η_o and $\eta_\mathrm{o,m}$ are the overall heat and mass transfer fin efficiencies, respectively.

The fundamental governing Eqs. (24–29) can be transformed to differencing equations and solved using one-order discrete method to obtain the numerical solutions of $T_\mathrm{a,1}$, $T_\mathrm{a,2}$, $w_\mathrm{a,1}$, $w_\mathrm{a,2}$, $T_\mathrm{c,1}$, $T_\mathrm{c,2}$, q, q_s and q_l, for a specific cooling coil under a given operating condition.

3.2. The procedure for applying the m-LMED method

Applying the m-LMED method to the air cooling and dehumidifying coil shown in Fig. 1 yields:

$$q = H_\mathrm{M}A_\mathrm{a}\frac{(i_\mathrm{a,1} - i_\mathrm{c,1}) - (i_\mathrm{a,2} - i_\mathrm{c,2})}{\ln\left(\frac{i_\mathrm{a,1} - i_\mathrm{c,1}}{i_\mathrm{a,2} - i_\mathrm{c,2}}\right)} \tag{30}$$

where $i_\mathrm{c,1}$ and $i_\mathrm{c,2}$ are the enthalpies of saturated moist air at the temperatures of $T_\mathrm{c,1}$ and $T_\mathrm{c,2}$; the overall heat transfer coefficient, H_M, can be determined by Eq. (17).

For calculating the total heat transfer rate using the m-LMED method, the results of $i_\mathrm{a,1}$, $i_\mathrm{a,2}$, $i_\mathrm{c,1}$ and $i_\mathrm{c,2}$ obtainable from the NS to the fundamental governing equations were used as inputs to Eq. (30). The total heat transfer rate calculated by using the m-LMED method was compared to that from the NS to validate the m-LMED method.

For calculating the overall heat transfer coefficient, H_M, the value of $q_\mathrm{s}/(q - q_\mathrm{s})$ should be assumed firstly. Consequently, the calculation procedure for using the m-LMED method is shown as follows.

(i) Assuming an initial value of $q_\mathrm{s}/(q - q_\mathrm{s})$.
(ii) Calculating the total heat transfer rate, q, by using the m-LMED method with input $i_\mathrm{a,1}$, $i_\mathrm{a,2}$, $i_{\mathrm{c},1}$ and $i_\mathrm{c,2}$, which are calculated from the NS of $T_\mathrm{a,1}$, $T_\mathrm{a,2}$, $w_\mathrm{a,1}$, $w_\mathrm{a,2}$, $T_\mathrm{c,1}$ and $T_\mathrm{c,2}$; and then calculating the sensible heat transfer rate, q_s, by using the logarithmic mean temperature difference (LMTD) method, noting that in Eq. (22), the value of M is evaluated by using the assumed value of $q_\mathrm{s}/(q - q_\mathrm{s})$.
(iii) Calculating a new value of $q_\mathrm{s}/(q - q_\mathrm{s})$ based on the calculated results of q and q_s using Eq. (30) and the LMTD method. Comparing the originally assumed and calculated values of $q_\mathrm{s}/(q - q_\mathrm{s})$, the calculation procedure for the m-LMED method ends when a convergence arrives, otherwise, assuming a new value of $q_\mathrm{s}/(q - q_\mathrm{s})$ and repeating (ii) and (iii).

Table 1
Operating conditions for validating the m-LMED method.

Mass flow rate of chilled water, kg/s	0.35
Inlet temperature of chilled water to the cooling coil, °C	8
Mass flow rate of air, kg/s	0.6
Inlet air temperature, °C	24
Inlet air humidity ratio, kg/kg	0.016

Table 2
Geometrical parameters of the air cooling coil for validating the m-LMED method.

Overall air side heat transfer area, m^2	24
Overall cooling medium side heat transfer area, m^2	1.25
Overall fin surface area, m^2	22.5
Fin length, m	0.013
Fin width, m	0.011
Fin thickness, mm	0.115
Outside diameter of the cooling medium tube, mm	9.52
Length of the cooling coil along the air flow direction, m	0.5

3.3. Validation of the m-LMED method

To validate the m-LMED method, the total heat transfer rate calculated by using the m-LMED method was compared to that obtained from numerically solving the fundamental governing Eqs. (24–29), under the operating conditions shown in Table 1, for a chilled water air cooling coil whose geometrical parameters are shown in Table 2. The thermal properties of air and chilled water are shown in Table 3.

Based on the results of previous studies on the actual Lewis Factors for a wet cooling coil [14–17], the Lewis Factors were set at 0.6, 0.8, 1.0, 1.2 and 1.4, in the validation process, so that errors that may be resulted in under non-unit Lewis Factors can be evaluated.

Fig. 2 shows the results of the total heat transfer rates calculated respectively by the m-LMED method and from numerically solving the fundamental equations. It can be seen that the variations trends of the total heat transfer rates calculated by the m-LMED method and from the NS are identical as the Lewis Factor changes from 0.6 to 1.4. With the increase of the Lewis Factor, the total heat transfer rate decreases.

In Fig. 2, the total heat transfer rates calculated by the LMED method where unit Lewis Factors were applied regardless the actual values of the Lewis Factor, are also included in to illustrate the errors resulted in where unit Lewis Factor was used across the board, instead of actual non-unit Lewis Factor values which may not be equal 1. For example, in Fig. 2, Point *a* represents the calculated total heat transfer rate by using the LMED method, where the numerical values of all other operating parameters, except Lewis Factor, obtained from the NS at 0.6 Lewis Factor were input to the LMED method. For Lewis Factor, instead of using its actual value of 0.6, unit Lewis Factor, i.e., $\mathrm{Le}^{2/3} = 1$, are used. Similar approaches were applied to all other Points of *b*, *c* and *d*, where the actual Lewis Factors were 0.8, 1.2 and 1.4, respectively.

The sensible heat transfer rates calculated by the m-LMED method and from the NS are shown in Fig. 3. It can also be seen

Table 3
Thermal properties of air and chilled water.

Specific heat of chilled water, kJ/(kg K)	4193
Specific heat of air, kJ/(kg K)	1007
Convective heat transfer coefficient of chilled water, W/(K m^2)	8000
Convective heat transfer coefficient of air in wet condition, W/(K m^2)	70
Total number of the micro-scale elements	100
Atmosphere pressure, kPa	101.325

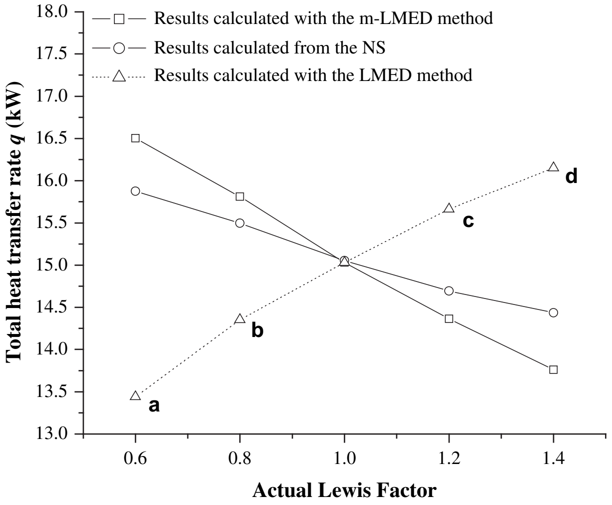

Fig. 2. The total heat transfer rates calculated by the LMED, m-LMED methods and from the numerical solutions under different actual Lewis Factors.

from Fig. 3 that the variation trends for the sensible heat transfer rates calculated from both calculation approaches agree well.

The Relative Deviations of the total heat transfer rate calculated by the m-LMED method from that obtained from numerically solving the fundamental governing equations is defined as follows:

$$\text{Relative Deviation} = \left|\frac{q_{\text{m-LMED}} - q_{\text{numerical solution}}}{q_{\text{numerical solution}}}\right| \tag{31}$$

where $q_{\text{m-LMED}}$ and $q_{\text{numerical solution}}$ are the total heat transfer rates calculated by the m-LMED method and from the NS, respectively.

The Relative Deviations for the sensible heat transfer rate, q_s, under different Lewis Factors are also calculated by substituting q with q_s in Eq. (31). The Relative Deviations for both q and q_s calculated by the m-LMED method and the Relative Deviations for q calculated by the LMED method under different Lewis Factors are shown in Table 4.

As seen in Table 4, the highest RD for q is about 5%; and that for q_s is about 1% when using the m-LMED method. Therefore, the m-LMED method is validated.

Furthermore, it can be seen from Table 4 that the Relative Deviations for both q and q_s increase when the Lewis Factor deviates from 1.

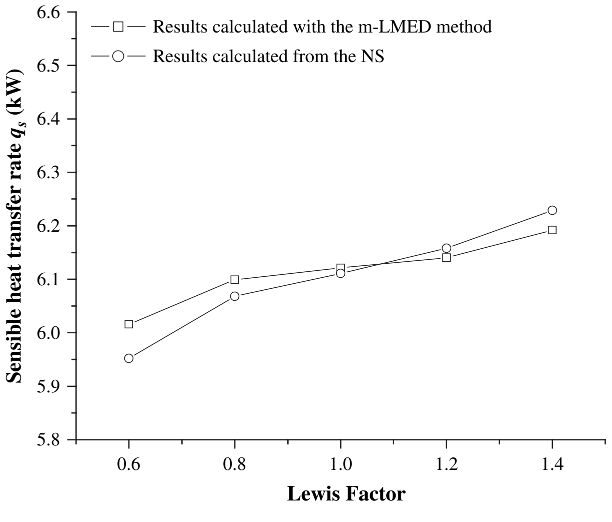

Fig. 3. The sensible heat transfer rates calculated by the m-LMED method and from the numerical solutions under different actual Lewis Factors.

Table 4
Relative deviations (RDs) for the total heat transfer rate (q) and sensible heat transfer rate (q_s) calculated by the m-LMED method and LMED method, respectively.

For the m-LMED method					
Lewis Factor	0.6	0.8	1.0	1.2	1.4
RD of q (%)	3.94	2.03	0.14	2.23	4.68
RD of q_s (%)	1.08	0.51	0.16	0.36	0.59
For the LMED method					
Lewis Factor	0.6	0.8	1.0	1.2	1.4
RD of q (%)	18.13	7.97	0.14	6.20	14.62

4. Discussions

When actually applying the m-LMED method to a wet cooling coil, the Lewis Factor should be firstly determined. Pirompugd et al. [7] provided the following equation for calculating the Lewis Factor of a wet cooling coil:

$$\mathrm{Le}^{2/3} = 2.282N^{0.2393}\left(\frac{S_\mathrm{f}}{D_\mathrm{o}}\right)^{(0.0239N+0.4332)}\left(\frac{A_\mathrm{a}}{A_\mathrm{a,t}}\right)^{(0.0321N+0.0747)} \mathrm{Re}_{D_\mathrm{o}}^{\left(-0.01833N-0.1094\frac{S_\mathrm{f}}{D_\mathrm{o}}-0.0026\frac{p_\mathrm{l}}{D_\mathrm{o}}-0.03012\frac{p_\mathrm{t}}{D_\mathrm{o}}+0.0418\right)} \tag{32}$$

where N is the number of the tube rows of an air cooling coil; S_f and D_o, the fin spacing and outside tube diameter; $A_\mathrm{a,t}$, the outside tube area; p_l and p_t; the longitudinal and transverse tube pitch.

After obtaining $\mathrm{Le}^{2/3}$, the procedure of applying the m-LMED method as detailed in Section 3.2 may be then followed.

The use of the m-LMED method will require additional computational efforts than the LMED method, as an iterative process is involved. This is justified because a higher accuracy in evaluating the total heat transfer rate in a wet cooling coil can be attained. However, the additional computational effort is much less than that involved in numerically solving the fundamental equations governing the heat and mass transfer in a wet cooling coil, as the discretization of the governing differential equations as well as the iterative solving process are involved.

5. Conclusions

In this paper, a modified LMED method has been developed and is reported. The m-LMED method can be applied to calculating the total heat transfer rate in a wet cooling coil under both unit and non-unit Lewis Factors' operating conditions.

The m-LMED method has been validated by comparing its predictions of the total heat transfer rate to that from numerically solving the fundamental governing equations of the heat and mass transfer of a wet cooling coil, with less than 5% deviation. Therefore, the m-LMED method can replace the LMED method for evaluating the thermal performance of a wet cooling coil operated with both unit and non-unit Lewis Factors.

Acknowledgements

The authors acknowledge the funding supports from the Hong Kong Polytechnic University (GU271) and The Research Grant Council of Hong Kong (B-Q11U).

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