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Governing Equation of Heat And Mass Transfer In Wet-Cooling Tower Fills.

Ms. Shruti B.Mehta[*1], Prof. Amitesh Paul[2], Dr. G.R.Selokar[3]
Shru.mecher@yahoo.co.in

Abstract

A wet-cooling tower fill performance evaluation model developed by Reuter is derived in Cartesian coordinates for a rectangular cooling tower and compared to cross- and counterblow Merkel, e-NTU and Popped models. The Reuter model is found to effectively give the same results as the Popped method for cross- and counter flow fill configuration as well as the Merkel and e-NTU method if the assumptions as made by Merkel are implemented. A second order upwind discretization method is applied to the Reuter model for increased accuracy and compared to solution methods generally used to solve cross- and counter flow Merkel and Popped models. First order methods used to solve the Reuter model and cross flow Merkel and Popped models are found to need cell sizes four times smaller than the second order method to obtain the same results

Keyword: Anisotropic , Popped Models, Discretization

Introduction

Merkel developed a method to predict fill performance in counterflow wet cooling towers. The method is relatively simple and can be used to cooling tower performance with basic hand calculations. Jaber and Webb (2) later developed a way to use the effectiveness-NTU approach directly to wet-cooling towers, similar to the e-NTU method normally used for heat exchangers. The e-NTU method has an advantage over the Merkel method, which is it can calculate cooling for cross- or counterflow with equal effort. The Merkel and e-NTU methods make the following simplifying assumptions: change in water flow rate from evaporation is negligible in the energy balance; the air leaving the fill is saturated with water vapour and the Lewis factor is equal to unity. Despite these assumptions the methods allow for an accurate evaluation of water outlet temperature. However, the prediction of air outlet temperature and humidity is inaccurate. For cooling towers with plume abatements like hybrid towers it is essential to determine the conditions of the air leaving the fill correctly. Poppe and Rögener (1) developed the Poppe method which does not make the same simplifying assumptions as Merkel and can be solved for cross- or counterflow. The Poppe method is not as simple as the e-NTU and Merkel methods and requires solving multiple differential equations. It can be solved one-dimensionally for counterflow but requires a two-dimensional calculation for crossflow.

In cooling towers with anisotropic fill resistance such as trickle and splash fills, the air flow through the fill can, as previously mentioned in chapter 1, be oblique or in cross-counterflow to the water flow, particularly at a cooling tower inlet and when the fill loss coefficient is small Reuter(3) and Kröger, (4). With CFD models, the oblique flow field in the fill can be modelled. The Merkel, e-NTU and Poppe methods cannot predict cooling tower performance for cross-counterflow. Reuter (3), however developed a method that can evaluate fill performance of wet-cooling tower in cross-, counter- and cross-counterflow conditions. The method gives the same result as would be obtained in an equivalent CFD model. The method is new and therefore no information exists on transfer characteristics for cooling tower fills determined by the method. Reuter (3) derived the governing fundamental partial differential equation to determine the cooling water temperature, water evaporation rate, air temperature and air humidity ratio in a two-dimensional cross-counter flow fill for unsaturated and supersaturated air. The equations are presented in cylindrical co-ordinates for circular sectioned axis-symmetric cooling towers. Governing equations are also given for a rectangular sectioned cooling tower in Cartesian co-ordinates. In this chapter a derivation is given for the Reuter model for a rectangular cooling tower, as well as a description of the e-NTU, Merkel and Poppe methods. A sample case used by Kröger (4) and Kloppers (5), in a cross- and counterflow fill analysis is used as a comparison of performance prediction with the different methods.

Governing differential equations of heat and mass transfer in a cross-, counter-, and cross-counterflow fill based on the Merkel assumptions

The following derivations are adopted from Reuter (3), nomenclature and structure of derivation is kept similar for coherency. Consider the elementary cross-section through a rectangular cooling tower fill with cross-counterflow,in

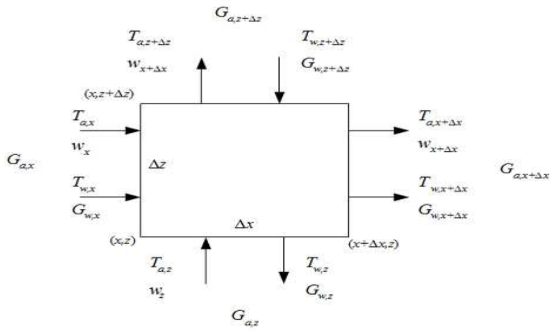

Figure 1: Elementary cross-section through a fill region of a rectangular cooling tower (3)

Merkel assumed a Lewis factor equal to unity (Le_f =1) and the evaporative loss to be negligible ($\partial G_w / \partial z$=0 and $\partial w/\partial z$=0) in the energy balance. By applying these assumptions only the governing differential equation for the water temperature and air enthalpy remain. In the energy balanced of water and air, the equation for water temperature simplifies to,

$$\frac{\partial Tw}{\partial z} = \frac{1}{CnwGw}\left[C_{pma} h_d a_{fi}(T_w - T_a) + i_{v(T_w)} h_d a_{fi}(w_{sw} - w)\right]$$

1

This equation is often written in terms of enthalpies, instead of temperature andhumidity. By assuming that the difference in specific heat evaluated at the different temperatures is minimal, the following equations can be obtained,

$$i_{masw} - i_{ma} \approx c_{pma}(T_w - T_a) + i_v(w_{sw} - w)$$

2

By substituting Eq. (2) into Eq. (1), the governing differential equation for water temperature can be written in terms of enthalpy in the following form,

$$\frac{\partial T_w}{\partial z} = \frac{1}{c_{pw}} \frac{h_d a_{fi}}{G_w}(i_{masw} - i_{ma}) \qquad 3$$

Similarly the governing differential equation for enthalpy can be written as,

$$\frac{\partial i_{ma}}{\partial z} = \frac{h_d a_{fi}}{G_{a,z}}(i_{masw} - i_{ma}) \qquad 4$$

For crossflow the governing differential equations for enthalpy becomes,

$$\frac{\partial i_{ma}}{\partial x} = \frac{h_d a_{fi}}{G_{a,x}}(i_{masw} - i_{ma})$$

5

To determine the properties of the air leaving the fill, Merkel assumed that the air is saturated with water vapour. By applying this last assumption for a counterflow fill, Eq. (3) and (4) can be combined to form the following,

$$Me = \frac{h_d a_{fi} L_{fi}}{G_w} = \int_{T_{wo}}^{T_{wi}} \frac{c_{pw} dT_w}{i_{masw} - i_{ma}}$$

6

For crossflow the governing differential equations for enthalpy becomes,

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6

The above equation is the most traditional form of the governing equations for counterflow wet-cooling towers and is commonly referred to as the Merkel equation (4). The Merkel equation can be solved with any numerical integration method, but is generally solved by the means of the Chebychev method. Zivi and Brand derived and solved the two governing equations for the Merkel method in crossflow. The governing equations for crossflow have to be solved in a two dimensional domain and usually require an iterative procedure.One of the advantages of the Reuter model is that it can do cross-, counter- or cross-counterflow by only changing the values and . It can also be useful to switch between Poppe and Merkel assumptions without altering the governing differential equation substantially. Consider the following form of the governing differential equation for the water temperature,

$$\frac{\partial T_w}{\partial z} = \frac{c_{pma}}{c_{pw}} \frac{h_d a_{fi}}{G_w}\left[Le_f(T_w - T_a) + \frac{i_{fg(Tw)} + \beta_{Me} c_{pw} T_w}{c_{pma}}(w_{sw} - w)\right]$$

7

where $\beta M_e = 0$ is for Poppe assumption and $\beta M_e = 1$ is for Merkel assumption of the evaporative loss in the energy balance. Using $\beta M_e = 1$ and $Le_f = 0$ therefore gives the Merkel assumption, whereas $\beta M_e = 0$ and the Bosnjakovic relation for the Lewis factor gives the Poppe assumptions. By solving the governing equations for humidity as well, this form can be implemented in CFD models to give results equivalent of the common Merkel method. A comparison of performance prediction using the Reuter model with Merkel assumption.

The effectiveness-NTU method

Jaber and Webb (1) developed the effectiveness-NTU method to be directly applied to crossflow or counterflow wet-cooling towers. The e-NTU method is very useful for crossflow due to its simplicity compared to other crossflow methods. Kröger (4) gives a detailed derivation of e-NTU method along with a sample calculation for a counterflow case. The e-NTU method makes the same simplifying assumption as Merkel for evaporation, Lewis factor and air outlet conditions.

The e-NTU method resembles the common e-NTU heat exchanger equation

$$\frac{\partial(i_{masw}-i_{ma})}{i_{masw}-i_{ma}} = h_d\left(\frac{\partial i_{masw}/\partial T_w}{m_w c_{pw}} - \frac{1}{m_a}\right)\partial A$$

8

Two cases can be consider for a wet-cooling tower,

Case 1: $m_a > m_w c_{pw}/(\partial i_{masw}/\partial T_w)$

Where $C_{emin} = m_w c_{pw}/(\partial i_{masw}/\partial T_w)$ and $C_{emax} = m_a$

Case 2: $m_a < m_w c_{pw}/(\partial i_{masw}/\partial T_w)$

Where $C_{emin} = m_a$ and $C_{emax} = m_w c_{pw}/(\partial i_{masw}/\partial T_w)$

The gradient of the saturated air enthalpy temperature curve is

$$\frac{\partial i_{masw}}{\partial T_w} = \frac{i_{maswi}-i_{maswo}}{T_{wi}-T_{wo}}$$

9

$$c = \frac{C_{emin}}{C_{emax}}$$

10

The effectiveness ratio is given by

$$e = \frac{Q}{Q_{max}} = \frac{m_w c_{pw}(T_{wi}-T_{wo})}{C_{emin}(i_{maswi}-\lambda-i_{mai})}$$

11 where Lambda (λ) is a correction factor proposed by Berman (1961) and is defined by

$$\lambda = (i_{maswo} + i_{maswi} - 2i_{maswm})/4$$

12

Depending on the flow configuration the effectiveness-NTU formula is given in different forms. For a counterflow the effectiveness formula is given by

$$e = \frac{1-exp[-NTU(1-C)]}{1-C\, exp[-NTU(1-C)]}$$

13

For crossflow configurations the effectiveness can be defined as

$$e = 1 - exp\{NTU^{0.22}[exp(-C\, NTU^{0.78}) - 1]\}/C$$

14

The Merkel number in the effectiveness-NTU method can be determined by

$$Me = \frac{c_{emin}}{m_w} NTU$$

15

If a Merkel number is known for a given fill, the number of transfer units (NTU) can be determined from Eq. (15). With the capacity, the effectiveness can be determined and water outlet temperature can be solved from the effectiveness, Eq. (11). When a Merkel number is to be determined from measured test data, the effectiveness is first determined from Eq. (11). The number of transfer units can then be solved from the effectiveness formulas and the Merkel number determined from Eq. (15).

Cross- and counterflow models with Poppe assumptions

Poppe and Rögener (2) developed a way to predict the performance of fills without making the simplifying assumptions of Merkel. This approach is normally referred to as the Poppe method. Consider the following governing differential equation for a crossflow Poppe method with unsaturated air,

$$\frac{\partial G_w}{\partial z} = h_d a_{fi}(w_{sw} - w)$$

16

$$G_a \frac{\partial w}{\partial x} = h_d a_{fi}(w_{sw} - w)$$

17

$$\frac{\partial T_w}{\partial z} = \frac{h_d a_{fi}}{c_{pw} G_w}\left[(w_{sw} - w)c_{pw}T_w - B_{us}\right]$$

18

$$G_a \frac{\partial i_{ma}}{\partial x} = h_d a_{fi}(T_w - T_a)B_{us}$$

19

Where,

$$B_{us} = i_{masw} - i_{ma} + (Le_f - 1)[i_{masw} - i_{ma} - i_v(w_{sw} - w)]$$

20

For supersaturated air the equations become,

$$\frac{\partial G_w}{\partial z} = h_d a_{fi}(w_{sw} - w_{sa})$$

21

$$G_a \frac{\partial w}{\partial x} = h_d a_{fi}(w_{sw} - w_{sa})$$

22

$$\frac{\partial T_w}{\partial z} = \frac{h_d a_{fi}}{c_{pw} G_w}[(w_{sw} - w_{sa})\, c_{pw}\, T_w - B_{ss}]$$

23

$$G_a \frac{\partial i_{ma}}{\partial x} = h_d a_{fi}(T_w - T_a)B_{ss}$$

24

$$B_{ss} = i_{masw} - i_{ma,ss} + (Le_f - 1)[i_{masw} - i_{ma,ss} - i_v(w_{sw} - w_{sa})] + Le_f c_{pw} T_w(w - w_{sa})$$

25

The main difference between this form of governing equation and the Reuter model in full crossflow is that it is derived fully in terms of air enthalpy instead of air temperature. A check must be made to determine whether the air is unsaturated or supersaturated, which requires an iterative procedure. The above governing differential equations can be solved with the same solution methods as the Reuter model. The counterflow Poppe method has been presented in another form where the governing equations are derived in terms of water temperature as opposed to the spatial coordinates. Kloppers and Kröger (6) derive this form of the Poppe method, where governing equations for unsaturated air are presented as,

$$\frac{m_w}{m_a} = \frac{m_{wi}}{m_a}\left(1 - \frac{m_a}{m_{wi}}(w_o - w)\right)$$

26

$$\frac{dw}{dT_w} = \frac{c_{pw}\frac{m_w}{m_a}(w_{sw} - w)}{B_{us} - (w_{sw} - w)c_{pw}T_w}$$

27

$$\frac{di_{ma}}{dT_w} = \frac{m_w c_{pw}}{m_a}\left[1 + \frac{(w_{sw} - w)c_{pw}T_w}{B_{us} - (w_{sw} - w)c_{pw}T_w}\right]$$

28

$$\frac{dMe_p}{dT_w} = \frac{c_{pw}}{B_{us} - (w_{sw} - w)c_{pw}T_w}$$

29

where B_{us} is according to Eq. (20). For supersaturated air the governing equations are,

$$\frac{m_w}{m_a} = \frac{m_{wi}}{m_a}\left(1 - \frac{m_a}{m_{wi}}(w_o - w_{sa})\right)$$

30

$$\frac{dw}{dT_w} = \frac{c_{pw}\frac{m_w}{m_a}(w_{sw} - w_{sa})}{B_{ss}}$$

31

$$\frac{di_{ma}}{dT_w} = \frac{m_w c_{pw}}{m_a}\left[1 + \frac{(w_{sw} - w_{sa})c_{pw}T_w}{B_{ss}}\right]$$

32

$$B_{ss} = i_{masw} - i_{ss} + (Le_f - 1)[i_{masw} - i_{ss} - (w_{sw} - w_{sa})i_v + (w - w_{sa})c_{pw}T_w] + (w - w_{sw})c_{pw}T_w$$

33

Note that B_{ss} is not the same as before. These governing equations can be solved numerically by dividing the inlet-outlet water temperature difference in to intervals or cells. Kloppers and Kröger (6) present a detailed discretization for solving the equations by 4th order Runge-Kutta numerical scheme.

Model comparison

Kröger (4) presents two sample calculations for an expanded metal fill (trickle fill) in a wet-cooling tower counterflow test facility where Merkel numbers are determined by the Merkel method and the e-NTU method of analysis. Measured parameters for the test case are given in Table 1.This case has a measured cooling range of $\Delta T_W = 11.90$°C and Merkel numbers per meter fill height of $Me/L_{fi} = 0.365$m^{-1} using the Merkel equation and $Me/L_{fi} = 0.361$ m^{-1} using the e-NTU method. Kloppers (5) uses the same case for a sample calculation of the counterflow Poppe method, with a 4thorder Runge-Kutta numerical scheme, as well as giving crossflow Merkel numbers and outlet conditions for e-NTU, Merkel and Poppe method. This particular case can therefore be verified and is used to illustrate differences from using the Reuter model with Merkel andPoppeapproaches

Table 1: Measured data for an expanded metal fill Kröger(4),

Measured conditions	
Atmospheric pressure (P_a)	101712 N/m^2
Air inlet temperature (T_{ai})	9.70 °C
Air inlet temperature(T_{wb})	8.23 °C
Dry air mass flow rate(m_a)	4.134 kg/s
Water inlet temperature(T_{wi})	39.67 °C
Water outlet temperature(T_{wo})	27.77 °C
Water mass flow rate(m_w)	3.999 kg/s
Static pressure drop across fill	4.5 N/m^2
Fill heigh(L_{fi})	1.878 m
Fill length and depth	1.5 m

Table 2.: Cross- and counterflow Merkel numbers per meter fill height obtained by the e-NTU, Merkel, Poppe and the Reuter model

				Ruter model	
Method	e-NTU	Merkel	Poppe	with Merkel $\beta_{Me} = 1, Le_f = 1$	with Poppe $\beta_{Me} = 1, Le_f = Bosjir$
Counterflow	0.361	0.365	0.392	0.364	0.391
Crossflow	0.394	0.395	0.427	0.394	0.425

To obtain a Merkel number from the Reuter model with Merkel assumptions, the evaporation is neglected $(\beta_{Me} = 1)$ in the governing equations for water temperature, Eq. (7), and the Lewis factor is equal to unity $(Le_f = 1)$. .For

Poppe assumptions the evaporation is not neglected $(\beta_{Me} = 0)$ and the Bosnjakovic relation is used for the Lewis factor. To vary between cross and counterflow the inlet air flow angle is varied from 0° for crossflow and 90° for counterflow. The Merkel numbers obtained correspond well with Merkel numbers determined by the other methods. The e-NTU and Merkel method determine outlet conditions of the air by assuming the air leaving the fill is saturated. Temperature and humidity are therefore determined by applying this assumption to the enthalpy of the outlet air stream. The Poppe and Reuter model do not make this assumption and solve unsaturated or supersaturated governing equations. Table 3 and4 give the difference in air properties across the fill for different methods and approaches with the Merkel numbers obtained in Table 2.

Table 3: Counterflow results for air properties using the e-NTU, Merkel, Poppe and Reuter models

				Ruter model	
Method	e-NTU	Merkel	Poppe	with Merkel $\beta_{Me} = 1, Le_f = 1$	with Poppe $\beta_{Me} = 1, Le_f = Bosjin$
M_e/L_{fi}, m[-1]	0.361	0.365	0.392	0.364	0.391
ΔT_a, °C	14.58	14.58	15.00	14.45	14.97
Δw, kg/kg	0.01305	0.01305	0.01535	0.01422	0.01516

Table 4: Cross flow results for air properties using the e-NTU, Merkel, Poppe and Reuter models

				Ruter model	
Method	e-NTU	Merkel	Poppe	with Merkel $\beta_{Me} = 1, Le_f = 1$	with Poppe $\beta_{Me} = 1, Le_f = Bosjin$
M_e/L_{fi}, m[-1]	0.394	0.395	0.427	0.394	0.426
ΔT_a, °C	14.58	14.60	14.85	14.25	14.80
Δw, kg/kg	0.01305	0.01308	0.01521	0.01430	0.01522

It can be seen from Tables 3 and 4 that the difference between the Poppe method and the Reuter model with Poppe assumptions is insignificant. Whereas the Merkel and e-NTU methods have a significant difference in air temperature and humidity compared with the Reuter model with both the Poppe and Merkel assumptions. The difference is caused by the equation describing rate of change in water temperature being adjusted for Merkel assumptions, but equations for rate of change in water mass flow, air temperature and humidity. The energy balance for the Poppe assumptions is 0.3% whereas, it is -4.7% for the Merkel assumptions. Despite this difference there is a small difference in water cooling. It should be noted that theoretically the Poppe method should give perfect energy balance. The energy balance is not 0% mainly because fluid properties in the models are calculated from empirical equations, and second order terms are neglected. Accurate predictions of air outlet temperature are usually only important when hybrid systems are considered. The humidity is equally important for hybrid and normal cooling towers to predict total evaporation from the water stream. Predicting the humidity accurately is therefore very important to determine the amount of makeup water needed. The Reuter model with Merkel assumptions predicts humidity closer to the Poppe method than the e-NTU and Merkel method. From Tables 3 and 4 it can be seen that differences in Merkel numbers and outlet conditions between the e-NTU and Merkel method and Reuter model with corresponding assumptions is small. One way of determining the effects of this difference is to use Merkel numbers obtained by the e-NTU, Merkel and Poppe methods directly in the Reuter model to determine outlet conditions. Tables 5 and 6 give the resulting difference in properties for the case in Table 1.

Table 5: Counterflow results using the Reuter model with Merkel numbers obtained by the e-NTU, Merkel and Poppe models

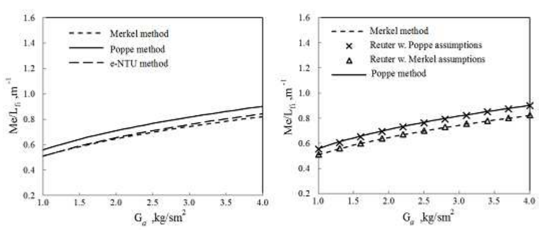
	with Merkel assumption		with Poppe assumption
Method	(e-NTU)	(Merkel eq.)	(Poppe method)
M_e/L_{fi}, m[-1]	0.394	0.395	0.427
ΔT_w, °C	11.91	11.92	11.91
ΔT_a, °C	14.4	14.48	14.99

	0		
Δw, kg/kg	0.01 417	0.0142 5	0.01518

Table 6: Crossflow results using the Reuter model with Merkel numbers obtained by the e-NTU, Merkel and Poppe models

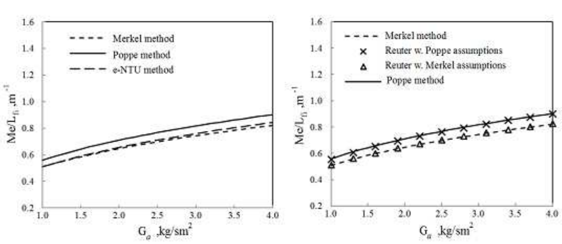
with Merkel assumption			with Poppe assumption
Method	(e-NTU)	(Merkel eq.)	(Poppe method)
M_e/L_{fi} ,m[-1]	0.36 1	0.365	0.392
ΔT_w , °C	11.8 5	11.92	11.92
ΔT_a , °C	14.2 6	14.27	14.84
Δw, kg/kg	0.01 431	0.01432	0.01521

Tables 5 and 6 show that Merkel numbers obtained by a different method can be used directly in Reuter model and predict the same performance. To determine if this applies for different conditions than given in Table 1, Merkel numbers are determined with the Merkel, e-NTU, Poppe and Reuter methods for a series of experiments presented in Figures 2 and 3 show Merkel numbers per meter fill using the correlations obtained for the different methods. The curve fit constants, correlation and plot with curve fit and experimental data for all themethods



(a) e-NTU, Merkel and Poppe Methods (b) Merkel, Poppe and Reuter model

Figure 2: Performance curves for a trickle fill in counterflow configuration



(a) e-NTU, Merkel and Poppe Methods (b) Merkel, Poppe and Reuter model

Figure 3: Performance curves for a trickle fill in crossflow configuration with Gw = 3 kg/s m^2 and Twi = 40°C

The Merkel and Poppe give the same results as the Reuter model with Merkel and Poppe assumptions. The e-NTU method gives a similar result as the Merkel method and Reuter model with Merkel assumptions. The difference between the e-NTU and Merkel increases as the air flow increases. When the airflow becomes two and a half times the water flow the difference between the two starts to increase, see performance graphs in When this is the case, Merkel numbers from the e-NTU method should be used with caution and cannot always be expected to give the same or similar results as the Merkel method or the Reuter model with Merkel assumptions.

Conclusion and summary

The Reuter model is derived for unsaturated and supersaturated air for a rectangular cooling tower fill. Governing equations for the cross- and counterflow Merkel methods as well as cross-counterflow Merkel method are given. Necessary changes to the derivation by Reuter, to predict performance equivalent to the Merkel method are given. Descriptions of cross and counterflow e-NTU and Poppe methods are presented. Sample case by Kröger (4) is presented to illustrate the differences in predicting outlet conditions and performance with these different methods for cross and counterflow. Differences in Merkel numbers are given with varying air flow rate and constant water inlet conditions where the Merkel numbers were determined using curve fit equations obtained from experimental test data presented Main results from employing the different methods were the following: If the appropriate assumptions are made, the Reuter model results in the same Merkel number and outlet water temperature as the Merkel and e-NTU methods for cross- and counterflow. For the same Lewis factor the Reuter model results in the same Merkel number and outlet conditions of water and air as the Poppe method for cross- and counterflow. Outlet conditions of air determined by the Reuter model with Merkel approach will not be the same as for the Merkel and e-NTU method. The e-NTU method gives the same result as the Reuter model with Merkel assumptions for most cases. In some cases the e-NTU method can differ significantly, particularly when the airflow rate is two to three times the water flow rate. This is not the case for the Merkel method, as it gives consistently the same result as the Reuter model with Merkel assumptions The Merkel method has been around for a long time and is relatively simple for a counterflow case. Therefore, extensive information exists for performance prediction for different fill materials. The same applies for the e-NTU method except it is equally simple for cross- and counterflow. Therefore, information on performance prediction exists for both counter- and crossflow. The traditional Poppe methods are more complex, similar to the Reuter method and less information exists on performance prediction with the Poppe method. The Reuter model is new and no information is available where the Reuter model is applied directly. New experiment for various different cooling tower fill materials would be time consuming and expensive. As has been shown with a comparison, the cross-counterflow model can use transfer characteristics obtained with Merkel or Poppe method if the right assumption and modification are made.

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