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Comparison of a 2D axisymmetric CFD model of a natural draft wet cooling tower and a 1D model

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Abstract

The performance predictions of a simple one-dimensional natural draft wet cooling tower (NDWCT) model and a two-dimensional axisymmetric numerical model are compared under a range of design parameters. The two-dimensional model has the ability to resolve radial non-uniformities across the tower which the one-dimensional model only computes as a bulk averaged value. The difference between the overall cooling range predicted by the two models is generally less than 2%, with no divergence in the agreement between the methods with respect to any design parameter.

Keyword: Natural draft wet cooling tower

1. Introduction

Wet cooling tower performance modelling and design has changed little in the last 50 years. Traditional practices employ a one-dimensional heat and mass transfer model such as the Merkel method [1,2] or a NTU style approach [3].

These methods now form the cornerstone of the cooling tower industry. The heat and mass transfer mechanics of the methods have been thoroughly reviewed with the shortfalls of the methods well documented [1,4–11]. It is now generally accepted that the Merkel method provides accurate results if the methods used to derive the empirical transfer coefficient correlations for a fill type are replicated in any subsequent performance calculations [4]. Merkel's approach is still the standard approach recommended in many reference texts [1,2,12] and most fill transfer coefficient correlations are obtained using this method.

The original Merkel model [1] simplifies the one-dimensional heat and mass transfer equations down to an enthalpy difference by neglecting the reduction in water mass flow rate caused by evaporation and taking the Lewis factor [13] to be unity. This allows the differential equations to be numerically integrated through the tower with a simple hand calculation. Poppe and Rogener [14] later proposed a complete and more accurate set of equations accounting for the evaporation of water but requiring the simultaneous numerical integration of three differential equations through the heat transfer region.

Cooling towers come in many shapes and configurations, from small forced draft counter-flow units to larger counter-flow natural draft cooling towers [1]. The mechanics of these heat and mass transfer methods are identical whether applied to a small wet forced draft mechanical cooling tower or a much larger natural draft wet cooling tower (NDWCT) although the air flow patterns in the tower change considerably.

The coupling of the heat transfer calculations with the rest of the model requires some additional simplifications and assumptions. In the Merkel model the air must be assumed to be saturated at the outlet of the mass transfer zones as no information about humidity is retained in the calculation. In practice this assumption is very reasonable

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Nomenclature

A	wetted contact area (m^2)
C_p	specific heat (kJ/kg K)
D_m	diffusion coefficient of water vapor (m^2/s)
H	height (m)
h	heat transfer coefficient (W/m^2 K)
h_m	mass transfer coefficient (kg/m^2 s)
i	enthalpy of air (kJ/kg)
i''	enthalpy of saturated air (kJ/kg)
K	loss coefficient
K_P	loss coefficient for the Poppe model
Le_f	Lewis factor
L_{fi}	depth of the fill (m)
Me	Merkel number
Me_P	Merkel number from Poppe equations
m	flow rate in the fill ($kg/s/m^2$)
S_c	Schmidt number, $S_c = \mu/\rho D$
T	temperature (K)
T_{range}	tower range temperature, $T_{range} = T_{w,i} - T_{w,o}$ (K)
V	velocity in the fill (m/s)
z	axial coordinate (m)

Greek symbol

ρ	density (kg/m^3)

Subscripts

a	air
cts	cooling tower supports
de	drift eliminators
fi	fill
i	inlet
ma	air water mixture
o	outlet
sz	spray zone
w	water
wdn	water distribution network

except in very hot dry conditions as shown by Kloppers [4]. In some cases such as in hybrid wet/dry towers where this assumption is invalid, the Poppe model is used.

If the air flow is to be computed via a one-dimensional model as well then several assumptions must be made to simplify the air flow and geometry, especially in a large NDWCT. In the one-dimensional model described in Kröger [1], the air flow in the fill is assumed to be uniform across the tower. The inlet losses and losses through the fill, rain zone, spray zone, drift eliminators, spray nozzles and other components are represented using empirical loss coefficients.

In a large NDWCT the air flows radially into the tower through what is known as the rain zone. The air is then drawn axially into the fill where it is constrained to vertical flow between the parallel plates. Locally across a small section of the fill the air flow is approximately one-dimensional and is well described by a one-dimensional volumetric heat transfer model. Across the tower as a whole however, there is some radial profile to the air flow [1,15–18].

In the rain zone (see Fig. 1) the air is in direct contact with the water and heat and mass transfer occurs such that there is a radial variation in the air temperature and humidity. In a previous study [16], the authors found that the water outlet temperature can vary by more than 6 K (~40%) between the tower center and the exterior.

In Kröger's model [1], the heat and mass transfer in the rain zone is taken as a bulk averaged value in a similar manner to the fill. A semi-empirical transfer coefficient is

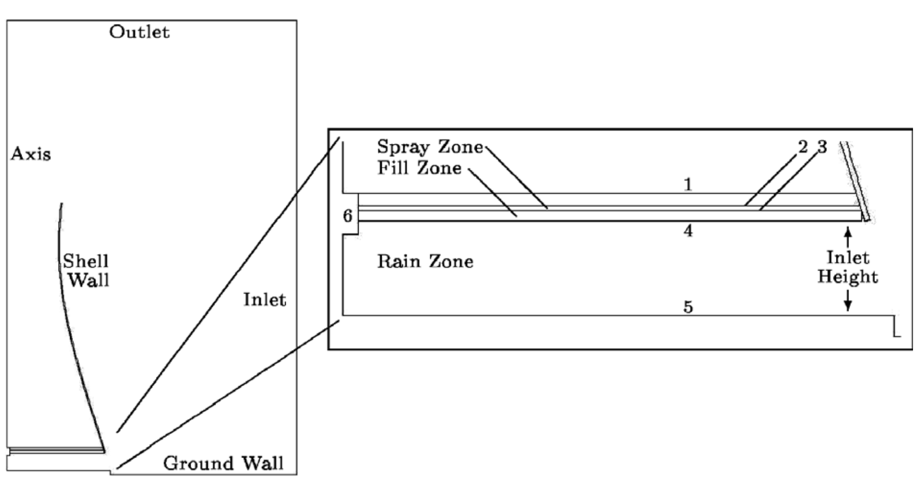

Fig. 1. Computational domain (left) with heat and mass transfer region detail enlarged on right: (1) drift eliminators, (2) spray nozzles, (3) fill water inlet (or fill air outlet), (4) fill water outlet (or fill air inlet), (5) basin, (6) causeway.

used to account for the part cross-flow, part counter-flow air/water flow in this region. This in essence assumes that the air enthalpy at the bottom of the fill is uniform across the tower.

The effects of these one-dimensional flow assumptions and the lumped heat transfer approach on the accuracy of a one-dimensional model of a NDWCT have not been examined to date. In this study these assumptions are examined by comparing a two-dimensional axisymmetric computational fluid dynamics (CFD) model with a one-dimensional model akin to that described by Kröger under a range of design parameters.

A range of CFD models of NDWCTs have appeared in the literature [16,20–24]. These models are generally very similar. None of the models reported on to date explicitly model the fill, instead researchers have employed source terms to model the effect of the fill on the continuous phase. Usually empirical transfer coefficients are used based on traditional heat and mass transfer methods. The Merkel model is commonly used with the transfer coefficient and loss coefficients written in terms of the air water flow rate. These coefficients are evaluated locally across the tower.

Radosavljevic [21] developed both an axisymmetric and a three-dimensional CFD model of a NDWCT employing an algebraic turbulence model. In this model the heat and mass transfer in the spray and rain regions was computed in the same manner as in the fill, with transfer characteristics specified to calculate the overall source terms. Fournier and Boyer [22] developed a three-dimensional CFD model where the fill region was represented using source terms as functions of either the Poppe or Merkel equations. The heat and mass transfer in the rain region were modelled in a similar fashion, with the water droplets assumed to travel in the vertical direction only and their effect on the air flow expressed entirely through the axial momentum equation. Hawlader and Liu [23] developed a two-dimensional axisymmetric NDWCT model where the heat and mass transfer in the fill was represented with the source terms as functions of the Merkel model. The spray zone was neglected. The droplet flow in the rain zone was modelled using one-dimensional Lagrangian particle tracking, with source terms coupling the heat, mass and momentum with the gas phase. The authors employed an algebraic turbulence model. In that study, the computational domain did not extend beyond the tower inlet or tower outlet, resulting in probable errors in prediction of tower outlet pressure and rain zone inlet air velocity profile. Al-Waked and Behnia [24,25] developed both a three-dimensional model of a NDDCT (natural draft dry cooling tower) and a NDWCT to examine the effect of cross wind on tower performance. In the NDWCT model the authors used a Lagrangian scheme, to model both the water flow in the fill and the droplet phase, using the commercial CFD package *FLUENT* [26].

The model employed by the authors in this study is the steady two-dimensional axisymmetric numerical model presented in Williamson et al. [16,27]. This model is an advance on previous models, with the generality of the empirical correlations used and the detail to which condensation is represented, improved over previous efforts. The water flow in the rain and spray zones has been modelled in more detail with two-dimensional Lagrangian particle motion and the droplet distribution in the rain zone represented. The model is described more completely in Section 3.

2. Reference parameters

The reference tower (located at Mt. Piper Power Station (Delta Electricity), NSW, Australia; Designed by Hamon-Sobelco LTD South Africa) which is used as the base case for this investigation has a tower height of 131 m, fill base diameter of 98 m, total water flow rate of 15,000 kg/s at 313 K, a tower inlet height of 8.577 m and a fill depth of 1 m. During the study additional fill depths of 1.2 m, 0.9 m and 0.6 m were tested, along with water flow rates of 12,500 kg/s, 22,500 kg/s and 30,000 kg/s and tower inlet heights of 6.777 m and 4.977 m.

A 2.8 m wide causeway runs through the center of the tower. This has been represented by a 1.4 m wide blockage in the axisymmetric model here (see Fig. 1) and is captured in the loss coefficients in the one-dimensional model [1].

3. CFD model

The CFD model presented here is that reported and validated in Williamson et al. [16,27]. The model is an axisymmetric representation of the natural draft cooling tower. The steady RANS equations are solved, closed with the k–ϵ turbulence model. This model represents the water flow in the rain and spray zone with Lagrangian droplet trajectories. Poppe style heat and mass transfer coefficients are used.

The computational domain extends 90 m beyond the cooling tower inlet and 90 m above the cooling tower outlet as shown in Fig. 1. The domain is discretised with approximately 500,000 two-dimensional unstructured mesh elements, with cell sizes ranging between 0.1 m and 1.0 m and mesh growth rates of 4%.

The fill is represented with source terms which solve basic heat and mass transfer equations including the release of latent heat with condensation. The heat and mass transfer coefficients are found from the Poppe Merkel number (Eqs. (1)–(4)) for the fill. The implementation of this method has been compared to the one-dimensional method used to derive the correlations and found to return accurate results with ten computational nodes through the depth of the fill.

Kloppers [4] developed correlations for the Poppe Merkel numbers at three discrete fill depths. These are given per unit fill depth below in Eqs. (1)–(3). No correlation was available for a fill depth of 1.0 m (the design depth of the reference tower) so a general correlation was developed from the data in Kloppers' work [4]. This correlation gives the Poppe Merkel number as a function of fill depth (Eq. (4)) as first reported in [16].

$$\frac{Me_{\mathrm{P,0.6\,m}}}{L_{\mathrm{fi}}} = \frac{h_{\mathrm{m}}A}{m_{\mathrm{w}}L_{\mathrm{fi}}} = 1.497125 m_{\mathrm{w}}^{0.276216} m_{\mathrm{a}}^{0.665735} - 0.589942 m_{\mathrm{w}}^{0.634757} m_{\mathrm{a}}^{0.622408} \quad (1)$$

$$\frac{Me_{\mathrm{P,0.9\,m}}}{L_{\mathrm{fi}}} = \frac{h_{\mathrm{m}}A}{m_{\mathrm{w}}L_{\mathrm{fi}}} = 1.526182 m_{\mathrm{w}}^{0.078237} m_{\mathrm{a}}^{0.695680} - 0.556982 m_{\mathrm{w}}^{0.419584} m_{\mathrm{a}}^{0.675151} \quad (2)$$

$$\frac{Me_{\mathrm{P,1.2\,m}}}{L_{\mathrm{fi}}} = \frac{h_{\mathrm{m}}A}{m_{\mathrm{w}}L_{\mathrm{fi}}} = 1.380517 m_{\mathrm{w}}^{0.112753} m_{\mathrm{a}}^{0.698206} - 0.517075 m_{\mathrm{w}}^{0.461071} m_{\mathrm{a}}^{0.681271} \quad (3)$$

$$\frac{Me_{\mathrm{P,gen}}}{L_{\mathrm{fi}}} = \frac{h_{\mathrm{m}}A}{m_{\mathrm{w}}L_{\mathrm{fi}}} = 1.118 \mathrm{m}_{\mathrm{w}}^{-0.389} m_{\mathrm{a}}^{0.735} L_{\mathrm{fi}}^{-0.280} \quad (4)$$

L_{fi} is the depth of the fill in (m), m_{a} and m_{w} are the air and water flow rates in the fill, respectively (kg/s/m^2), A is the wetted contact area (m^2) and h_{m} is the mass transfer coefficient (kg/m^2 s).

The heat and mass transfer in the rain and spray zones is described in detail in Williamson et al. [16]. In the spray and rain regions the water flows in droplet form. Here the droplet flow has been represented with Lagrangian particle tracking with coupled heat and mass transfer between the droplets and the continuous phase.

The spray nozzle characteristics implemented here have been taken from Bellagamba et al. [28]. A uniform droplet size of 2.8 mm has been used with the initial radial velocity varying linearly between −6.3 m/s and +6.3 m/s and the initial axial velocity of 0 m/s. The injection points have been spaced at intervals consistent with the full scale tower. Each spray nozzle is represented by 20 droplet trajectories.

The droplet distribution in the rain zone was taken from Kröger [1], which has a sauter mean diameter of 3.26 mm. In the rain zone approximately 7000 droplet trajectories are computed, with the droplet distribution represented by 15 trajectories per injection point.

The following loss coefficient correlations, Eqs. (5)–(7), have been taken from Kloppers' work [4,19]. These equations have been used for the runs with corresponding fill depths. For the computational runs with a fill depth of 1.0 m, a combination of the original correlations have been used, by applying an interpolation function, Eq. (8). This was found to give a smoother fit to the data in the range of air and water flow rates considered here than a single general correlation developed for all fill depths and water flow rates as given by Kloppers [4].

$$K_{\mathrm{P,fi,0.6\,m}} = (0.003132 m_{\mathrm{w}}^{4.755218} m_{\mathrm{a}}^{-3.631669} + 17.238242 m_{\mathrm{w}}^{0.349702} m_{\mathrm{a}}^{-0.030826}) L_{\mathrm{fi}}, \quad (5)$$

$$K_{\mathrm{P,fi,0.9\,m}} = (1.561219 m_{\mathrm{w}}^{1.276792} m_{\mathrm{a}}^{-3.931459} + 16.173258 m_{\mathrm{w}}^{0.287875} m_{\mathrm{a}}^{0.011599}) L_{\mathrm{fi}}, \quad (6)$$

$$K_{\mathrm{P,fi,1.2\,m}} = (3.859490 m_{\mathrm{w}}^{0.782298} m_{\mathrm{a}}^{-2.119420} + 15.295976 m_{\mathrm{w}}^{0.215311} m_{\mathrm{a}}^{0.080546}) L_{\mathrm{fi}}, \quad (7)$$

$$K_{\mathrm{P,fi,1.0\,m}} = K_{\mathrm{P,fi,0.9\,m}} f + K_{\mathrm{P,fi,1.2\,m}} (1 - f), \quad (8)$$

where the smoothing factor $f = \frac{(1.2 - L_{\mathrm{fi}})}{(1.2 - 0.9)}$.

The pressure loss due to the tower shell supports, the spray piping network and the drift eliminators were modelled in a manner similar to the fill. The loss coefficients used were $K_{\mathrm{cts}} = 0.5$, $K_{\mathrm{wdn}} = 0.5$ and $K_{\mathrm{de}} = 3.5$, respectively, as taken from [1].

4. One-dimensional model

The one-dimensional model presented here is based on Kröger's [1] and Kloppers' [4] models. These models represent a heat and mass transfer system coupled with a simple hydraulic flow calculation where the system losses are represented with loss coefficients. Here the driving force for air flow is the tower draft calculated simply as

$$\Delta P = (\rho_\infty - \rho_{\mathrm{ai}}) g H_{\mathrm{tower}} = \sum_{i=1}^{n} K_i \frac{\rho V^2}{2}, \quad (9)$$

where the density ρ and the velocity V are referred to fill inlet conditions in a similar manner to that described in Kröger [1]. This simple model neglects an atmospheric lapse rate, as does the CFD model.

The Merkel heat transfer methods have been implemented here in the one-dimensional model as the transfer characteristics for the rain and spray zones are not available for the Poppe method, only the Merkel method. The fill transfer coefficients for the Poppe method used in the CFD model are derived from the same experimental data as the Merkel transfer correlations below. When implemented in the appropriate model they calculate the same result. The loss coefficients used here (Eqs. (17)–(19)) are different to the Poppe loss coefficients given above as the density used to interpret the data is different in each case [4].

The method requires the numerical integration of Eqs. (10) and (11), which can be combined to form Eq. (12):

$$\frac{\mathrm{d}i_{\mathrm{ma}}}{\mathrm{d}z} = \frac{h_{\mathrm{m}}A}{m_{\mathrm{a}}} (i''_{\mathrm{ma}(T_{\mathrm{w}})} - i_{\mathrm{ma}}), \quad (10)$$

$$\frac{\mathrm{d}T_{\mathrm{w}}}{\mathrm{d}z} = \frac{m_{\mathrm{a}}}{m_{\mathrm{w}}} \frac{1}{C_{p_{\mathrm{w}}}} \frac{\mathrm{d}i_{\mathrm{ma}}}{\mathrm{d}z}, \quad (11)$$

$$Me_{\mathrm{m}} = \frac{h_{\mathrm{m}}A}{m_{\mathrm{w}}} = \int_{T_{\mathrm{w,o}}}^{T_{\mathrm{w,i}}} \frac{C_{p_{\mathrm{w}}} \mathrm{d}T_{\mathrm{w}}}{(i''_{\mathrm{ma}(T_{\mathrm{w}})} - i_{\mathrm{ma}})}, \quad (12)$$

where $i''_{\mathrm{ma}(T_{\mathrm{w}})}$ is the enthalpy of saturated air at the water temperature T_{w}, i_{ma} the enthalpy of the air water mixture at any location in the fill z. $T_{\mathrm{w,i}}$ and $T_{\mathrm{w,o}}$ are the water temperature at the inlet and outlet of the heat transfer zones, respectively.

4.1. Empirical correlations

All empirical transfer coefficient correlations and loss coefficient correlations used in the one-dimensional model are contained in the Appendix. The fill transfer coefficient correlations (Eqs. (13)–(16)) and loss coefficient correlations (Eqs. (17)–(19)) employed here are all taken from Kloppers [4]. Eq. (20) has been employed in the same manner as Eq. (8).

The transfer coefficient and loss coefficient for the rain zone are taken from de Villers and Kröger [29] and are given in Eqs. (21) and (22), respectively. The correlations are a function of rain zone height, droplet diameter, humidity and air velocity in the fill. They are derived assuming uniform air flow through the fill. The sauter mean diameter d_d of the droplet distribution in the CFD simulation is 3.26 mm. The spray zone transfer correlation (Eq. (23)) and loss coefficient (Eq. (24)) are also taken from Kröger [1] based on experimental results in [15]. The other system losses for the drift eliminators, water distribution pipes and tower supports are the same as those in the

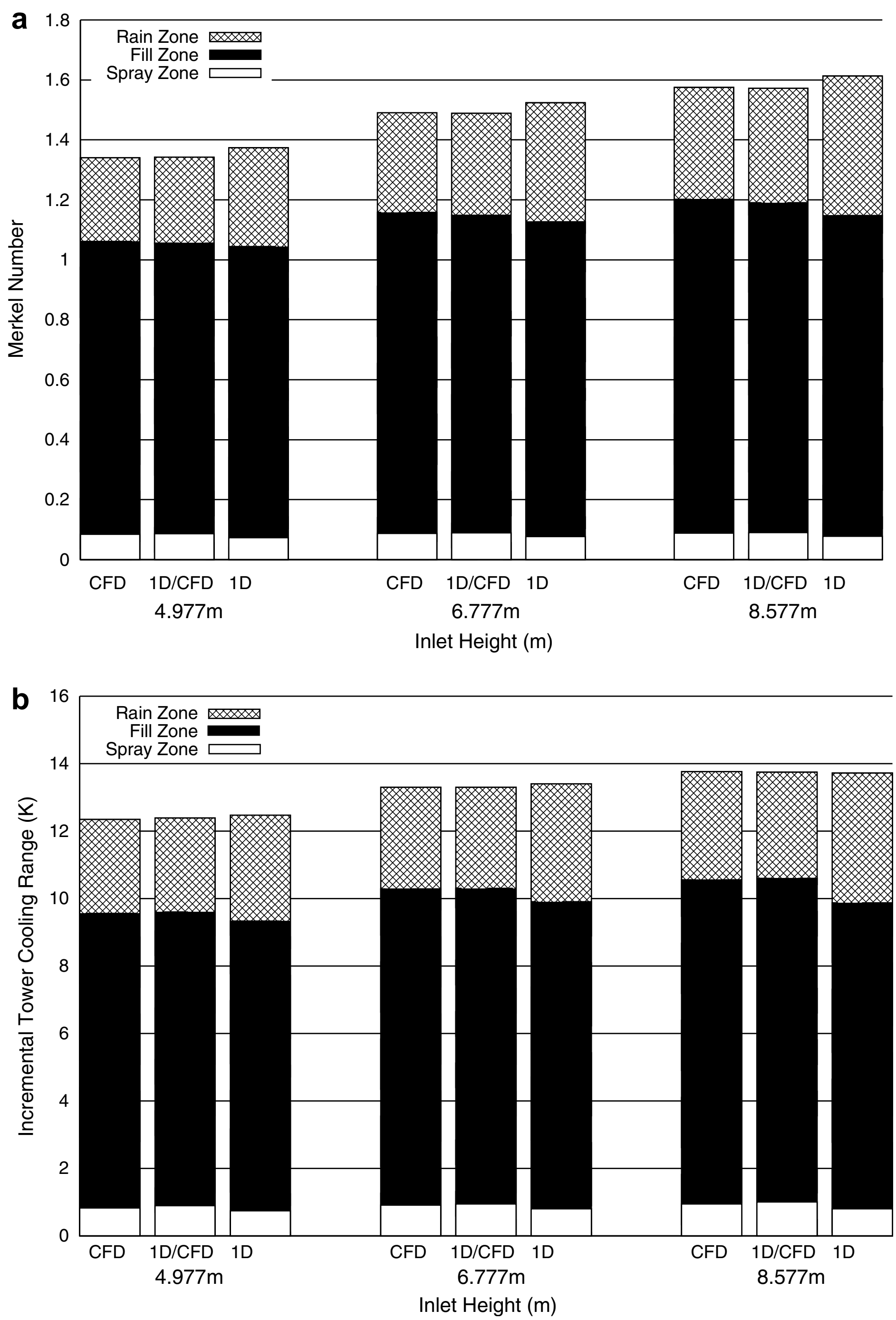

Fig. 2. Incremental Merkel number (a) and incremental cooling range (b) plotted against inlet height with a water flow rate of 15,000 kg/s and fill depth of 1.0 m.

CFD model. In addition, the tower inlet losses, expansion losses after the fill and rain zone losses are represented using the correlations described in Kloppers [4].

5. Results and discussion

A comparison has been made between the CFD and one-dimensional methods under a range of design parameters. The one-dimensional methods are comprised of two components, the heat and mass transfer solution following the Merkel method and the draft equation. In order to separate the effects of each calculation, two comparisons have been made:

(1) Standard design method with draft equation solved and the Merkel method used for the heat/mass transfer (denoted by – 1D).
(2) Instead of solving the draft equation the air flow is taken from the CFD model. The Merkel method is used but the transfer coefficients (Merkel numbers)

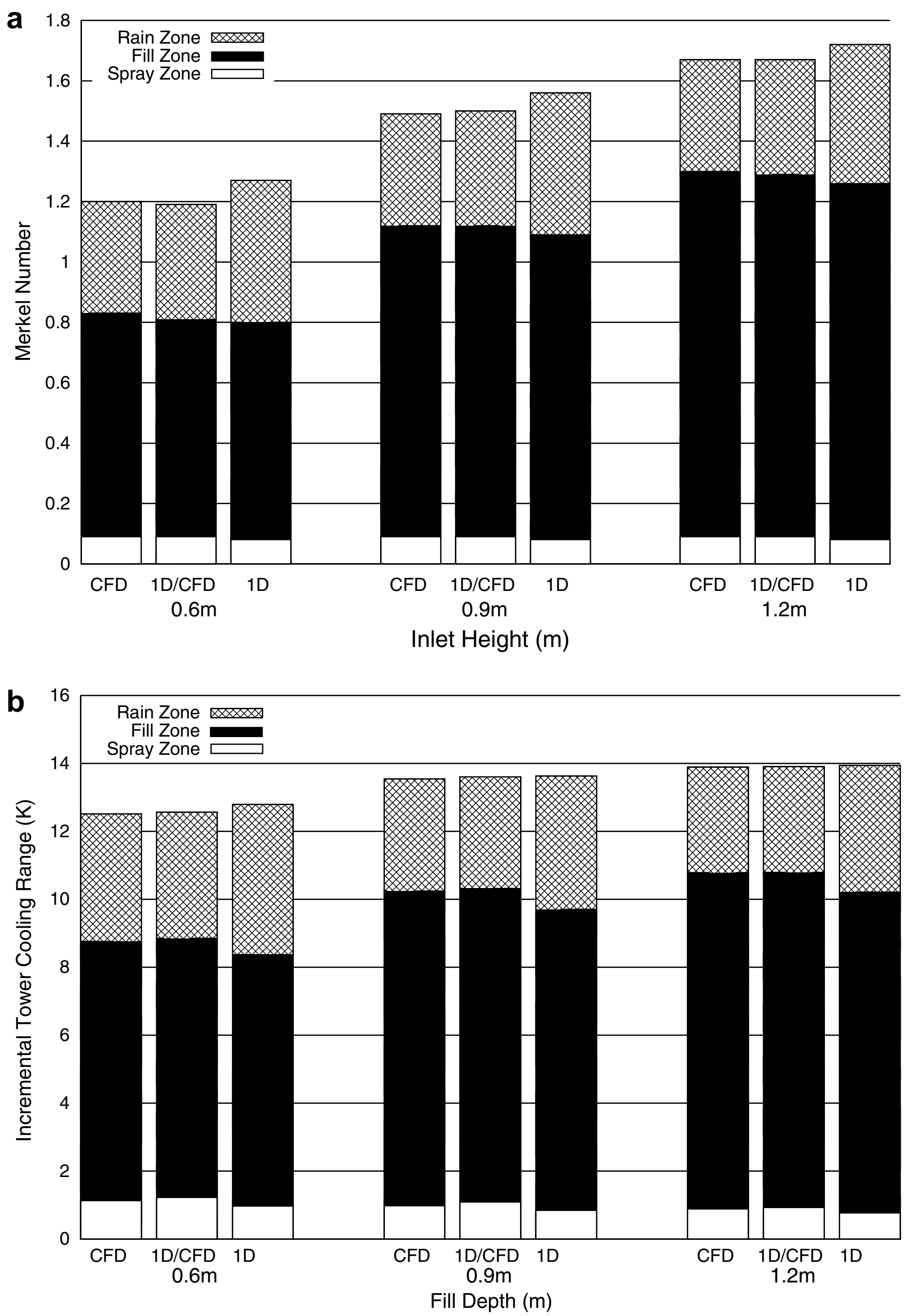

Fig. 3. Incremental Merkel number (a) and incremental cooling range (b) plotted against fill depth with a water flow rate of 15,000 kg/s and inlet height of 8.577 m.

for the rain and spray zones are taken from the CFD model to eliminate any difference in their evaluation (denoted by – 1D/CFD).

The comparison between the methods is shown on a series of bar plots detailing the Merkel number and the temperature drop (zone T_{range}) across each transfer zone. The Merkel numbers have been derived from the CFD results using the one-dimensional methods assuming uniform air flow and averaged inlet conditions.

5.1. Inlet height

Fig. 2 shows the Merkel number and the cooling range through the transfer zones for the CFD, 1D/CFD and 1D methods over a range of inlet heights. The Merkel numbers compare well in all cases although the rain zone transfer coefficient for the 1D case is slightly larger compared to the CFD result. At all inlet heights the comparisons between the methods are similar. The rain zone contributes approximately 23% of the tower range. The difference

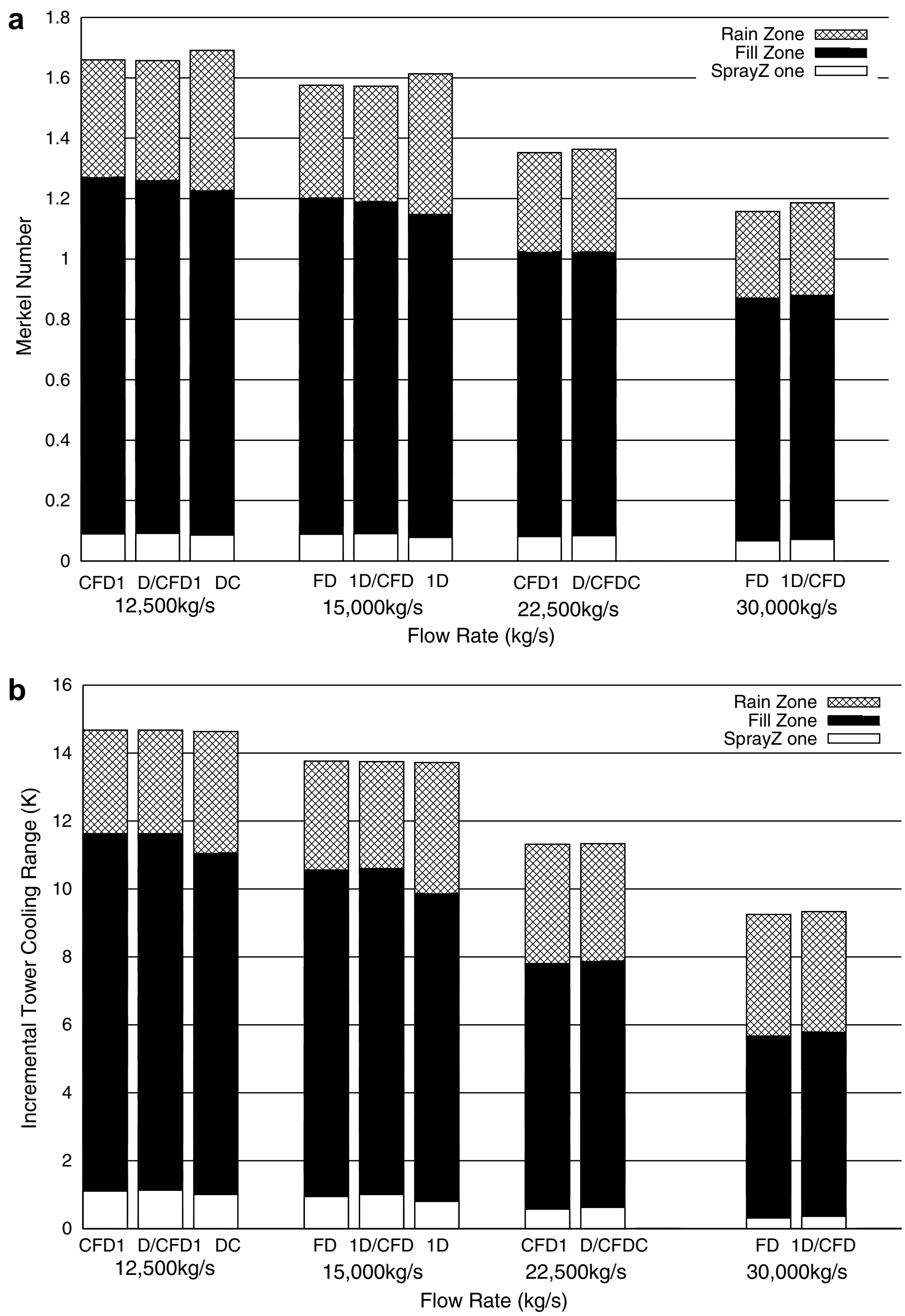

Fig. 4. Incremental Merkel number (a) and incremental cooling range (b) plotted against water flow rate with fill depth of 1.0 m and inlet height of 8.577 m.

between the rain zone Merkel number predicted from the CFD results and the one-dimensional correlation is approximately 15% rising to about 21% at an inlet height of 8.577 m. The air mass flow rate predicted by the 1D method is within 0.2% of the CFD result at an inlet height of 4.977 m but the difference rises to 3% at an inlet height of 8.577 m. The tower range is well predicted in all cases. The difference decreases from 0.9% (0.1 K) between the CFD and the 1D model at an inlet height of 4.977 m to 0.3% (0.04 K) at an inlet height of 8.577 m. For the 1D/CFD model the difference decreases from 0.3% (0.04 K) at an inlet height of 4.977 m to 0.08% (0.01 K) at an inlet height of 8.577 m. This extraordinarily close comparison is largely due to the insensitivity of the tower cooling to the Merkel number at high Merkel numbers. The slight over prediction of the rain zone transfer coefficient makes little difference to the end result. The close agreement of both the one-dimensional and the 1D/CFD models with the CFD approach also suggests that the one-dimensional assumptions of uniform flow and averaged inlet conditions incur no dicernable penalty in accuracy under the range of inlet heights tested.

5.2. Fill depth

Fig. 3 shows the Merkel number and the cooling range through the transfer zones for the CFD, 1D/CFD and 1D methods over a range of fill depths. The trends observed over a range in fill depths are similar to those observed for the variable tower inlet height. The difference in the tower range between the CFD result and the 1D/CFD runs is less than 0.4% (0.05 K) for all fill depths. The difference in tower range between the CFD and 1D result ranges between 0.4% (0.05 K) at a height of 1.2 m to 2% (0.3 K) at a height of 0.6 m. The difference between the CFD predicted air flow and the 1D models predicted air flow ranges between 1% and 2%. The predicted rain zone Merkel number is about 23% larger in the one-dimensional method than the CFD results which explains the slightly larger tower range predicted by the 1D method. These results appear consistent across all three inlet heights tested with the relative difference between the CFD results and the standard 1D methods perhaps slightly better at the larger fill depths.

5.3. Water flow rate

Fig. 4 shows the Merkel number and the cooling range through the transfer zones for the CFD, 1D/CFD and 1D methods over a range of water flow rates. The correlation for the loss coefficient for the tower inlet is only valid for water flow rates between 1 and 3 $kg/m^2/s$ [4] so the correlation is not valid for the flow rate of 22,500 kg/s and 30,000 kg/s. In addition, the rain zone loss coefficient and transfer coefficient are not valid over this range. In these cases the one-dimensional method has not been solved, only the 1D/CFD method and the CFD method.

The difference in tower range predicted by the CFD model and the 1D model is insignificant in the two design cases of 12,500 kg/s and 15,000 kg/s (∼0.3%). The CFD predicted air flow rate is approximately 3% larger than the 1D models predictions for both the 12,500 kg/s and 15,000 kg/s runs. The comparison between the 1D/CFD model and the CFD model is the same with the difference in tower range less than 0.2% for the three lower flow rates but 0.9% for the 30,000 kg/s case. These results suggest that the 1D methods would work just as well at higher water flow rates if the correlation for the transfer coefficient for rain zone and the loss coefficients for the tower inlet could be extended into these regions.

6. Rain zone

The rain zone transfer coefficient offers the most discrepancy between the two models here so the following additional tests have been performed to determine the degree of disagreement between the correlations under a range of droplet sizes. The difference between the rain zone Merkel number predicted by Eq. (21) and that predicted by the CFD models, are given in Fig. 5. The CFD results for the rain zone with a droplet distribution with a sauter mean diameter of 3.26 mm are given at the three inlet heights. For comparison, further CFD results are given with a uniform droplet distribution at an inlet height of 8.577 m.

The CFD results for the uniform droplet diameter are slightly higher than those for the model with a droplet distribution. Eq. (21) is plotted with the air flow rate calculated in the CFD models (with droplet distribution) but this has only a very small influence as the air flow rates are very similar. The plot indicates that the agreement between the models decreases with droplet diameter. The effective sauter mean diameter of the reference tower distri-

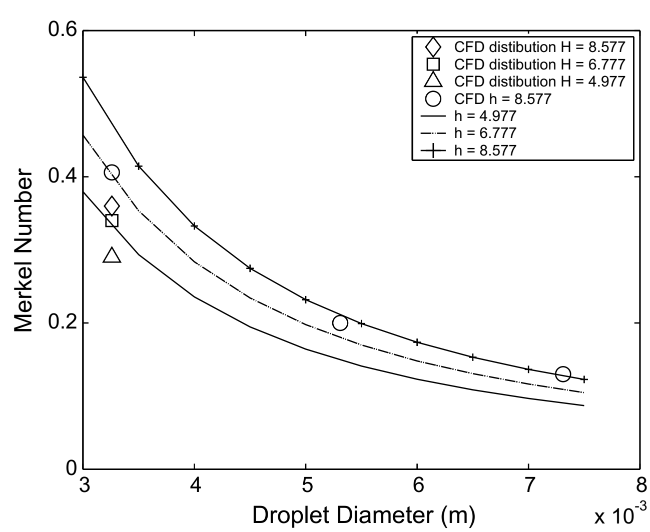

Fig. 5. Merkel number for the rain zone as predicted by Eq. (21) and CFD results with fixed droplet diameter and droplet distribution.

bution here is quite low so this illustrates the source of the disagreement shown in the bar plots above. Detailed experimental results are needed to verify the above predictions. Both models rely on general droplet empirical heat and mass transfer correlations. The CFD model is a more detailed representation of air flow and droplet trajectory integration however.

7. Conclusion

A comparison has been made between a one-dimensional NDWCT model and a two-dimensional CFD model. The difference between the predictions of tower cooling range is very low, generally around 1–2%. The small difference there is largely due to the correlations for the transfer coefficient for the rain zone. The difference in the prediction of the tower draft is generally less than 3%. A comparison of the CFD results with a one-dimensional method using the CFD draft and CFD transfer coefficients for the rain zone and spray zone was used to test the one-dimensional assumptions of uniform air flow through the fill and averaged inlet air conditions. The difference between the tower range predicted by the two models has been shown to be less than 0.4% in most cases. This extraordinarily close comparison supports these assumptions.

Furthermore under the range of parameters tested here the difference between the CFD model predictions and those of the one-dimensional models remained fairly constant suggesting that there is no particular case where the flow becomes so skewed or non-uniform that the one-dimensional model predictions begin to fail.

In all cases the predicted water outlet temperatures are very close in all methods in spite of quite noticeable differences in the Merkel numbers of the towers. This is largely because the sensitivity of the tower range to Merkel number decreases with increasing Merkel number. Increasing the Merkel number from 1.6 to 1.7 results in an increase in water outlet temperature of about only 0.1 K under standard tower design conditions. The study has been repeated using a one-dimensional method employing Poppe heat and mass transfer equations with approximations for the spray and rain zone transfer coefficients. The results are similar to these detailed above.

Appendix A. Empirical correlations for the one-dimensional method

Fill transfer coefficients:

$$\frac{Me_{0.6\,\mathrm{m}}}{L_{\mathrm{fi}}} = \frac{h_{\mathrm{m}}A}{m_{\mathrm{w}}L_{\mathrm{fi}}} = 1.638988m_{\mathrm{w}}^{0.282648}m_{\mathrm{a}}^{0.682887} - 0.802755m_{\mathrm{w}}^{0.560711}m_{\mathrm{a}}^{0.644229}, \quad (13)$$

$$\frac{Me_{0.9\,\mathrm{m}}}{L_{\mathrm{fi}}} = \frac{h_{\mathrm{m}}A}{m_{\mathrm{w}}L_{\mathrm{fi}}} = 1.625618m_{\mathrm{w}}^{0.091940}m_{\mathrm{a}}^{0.702913} - 0.735958m_{\mathrm{w}}^{0.376496}m_{\mathrm{a}}^{0.6665399}, \quad (14)$$

$$\frac{Me_{1.2\,\mathrm{m}}}{L_{\mathrm{fi}}} = \frac{h_{\mathrm{m}}A}{m_{\mathrm{w}}L_{\mathrm{fi}}} = 1.357391m_{\mathrm{w}}^{0.110577}m_{\mathrm{a}}^{0.712196} - 0.567207m_{\mathrm{w}}^{0.443165}m_{\mathrm{a}}^{0.669846}, \quad (15)$$

$$\frac{Me_{\mathrm{gen}}}{L_{\mathrm{fi}}} = \frac{h_{\mathrm{m}}A}{m_{\mathrm{w}}L_{\mathrm{fi}}} = 1.019766m_{\mathrm{w}}^{-0.432896}m_{\mathrm{a}}^{0.782744}L_{\mathrm{fi}}^{-0.292870}. \quad (16)$$

Fill loss coefficients:

$$K_{\mathrm{fi},0.6\,\mathrm{m}} = (0.00819m_{\mathrm{w}}^{5.465533}m_{\mathrm{a}}^{-3.666315} + 17.545503m_{\mathrm{w}}^{0.345860}m_{\mathrm{a}}^{-0.036969})L_{\mathrm{fi}}, \quad (17)$$

$$K_{\mathrm{fi},0.9\,\mathrm{m}} = (1.633204m_{\mathrm{w}}^{1.250268}m_{\mathrm{a}}^{-3.873083} + 16.170094m_{\mathrm{w}}^{0.288861}m_{\mathrm{a}}^{0.012429})L_{\mathrm{fi}}, \quad (18)$$

$$K_{\mathrm{fi},1.2\,\mathrm{m}} = (3.897830m_{\mathrm{w}}^{0.777271}m_{\mathrm{a}}^{-2.114727} + 15.327472m_{\mathrm{w}}^{0.215975}m_{\mathrm{a}}^{0.079696})L_{\mathrm{fi}}, \quad (19)$$

$$K_{\mathrm{fi},1.0\,\mathrm{m}} = K_{\mathrm{fi},0.9\,\mathrm{m}}f + K_{\mathrm{fi},1.2\,\mathrm{m}}(1-f). \quad (20)$$

Rain zone transfer coefficient and loss coefficient:

$$\begin{aligned} Me_{\mathrm{rz}} = {} & 12\left(\frac{D_m}{V_{\mathrm{ma,f}}d_{\mathrm{d}}}\right)\left(\frac{H_{\mathrm{i}}}{d_{\mathrm{d}}}\right)\left(\frac{P_t}{\rho_{\mathrm{wo}}R_{\mathrm{v}}T_{\mathrm{ai}}}\right)S_c^{0.33} \\ & \times\left[\left(\ln\frac{w_{s,\mathrm{Two}}+0.622}{w_{\mathrm{i}}+0.622}\right)\Big/(w_{s,\mathrm{Two}}-w_{\mathrm{i}})\right] \\ & \times[0.90757a_p\rho_{\mathrm{av,i}} - 30341.04a_\mu\mu_{\mathrm{av}} - 0.37564 \\ & + 4.04016([0.55+41.7215(a_Ld_{\mathrm{d}})^{0.80043}] \\ & \times[0.713+3.741(a_LH_{\mathrm{i}})^{-1.23456}] \\ & \times[3.11\mathrm{e}^{(0.15a_{\mathrm{v}}V_{\mathrm{ma,f}})}-3.13] \\ & \times\exp[5.3759\mathrm{e}^{(-0.2092a_LH_{\mathrm{i}})} \\ & \times\ln(0.3719\mathrm{e}^{(0.0019055a_Ld_{\mathrm{i}})}+0.55)])], \end{aligned} \quad (21)$$

$$\begin{aligned} K_{\mathrm{rz}} = {} & 3a_{\mathrm{v}}V_{\mathrm{w,o}}(H_{\mathrm{i}}/d_{\mathrm{d}})[0.2246 - 0.31467a_p\rho_{\mathrm{a}} + 5263.04a_\mu\mu_{\mathrm{a}} \\ & + 0.775526(1.4824163\exp(71.52a_Ld_{\mathrm{d}}) - 0.91) \\ & \times(0.39064\exp(0.010912a_Ld_{\mathrm{i}}) - 0.17) \\ & \times(2.0892(a_{\mathrm{v}}V_{\mathrm{av,o}})^{-1.3944} + 0.14) \\ & \times\exp((0.8449\log(a_Ld_{\mathrm{i}}/2) - 2.312) \\ & \times(0.3724\log(a_{\mathrm{v}}V_{\mathrm{av,o}}) \\ & + 0.7263)\log(206.757(a_LH_{\mathrm{i}})^{-2.8344} + 0.43))], \end{aligned} \quad (22)$$

where, $a_\mu = 3.061\times10^{-6}\left(\frac{\rho_{\mathrm{w}}^4g^9}{\sigma_{\mathrm{w}}}\right)^{0.25}$, $a_p = 998/\rho_{\mathrm{w}}$, $a_{\mathrm{v}} = 73.298(g^5\sigma_{\mathrm{w}}^5/\rho_{\mathrm{w}}^3)^{0.25}$ and $a_L = 6.122(g\sigma_{\mathrm{w}}/\rho_{\mathrm{w}})^{0.25}$. $V_{\mathrm{ma,f}}$ is the velocity of the air leaving the rain zone and entering the fill, v_{w} is the velocity of the water in the fill.

Spray zone transfer coefficient and loss coefficient:

$$Me_{\mathrm{sz}} = 0.2L_{\mathrm{sz}}(m_{\mathrm{a}}/m_{\mathrm{w}})^{0.5}, \quad (23)$$

$$K_{\mathrm{sz}} = L_{\mathrm{sz}}(0.4(m_{\mathrm{w}}/m_{\mathrm{a}})+1), \quad (24)$$

where L_{sz} is the depth of the spray zone, which is 0.45 m in this case.

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