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Modelling of cooling tower splash pack

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Abstract—A mathematical model and a computer simulation program have been developed for the modelling of counterflow cooling tower splash pack thermal performance. The one-dimensional model uses basic aerodynamic, hydrodynamic and heat/mass transfer information to predict the performance of the packing material without depending on cooling tower test data. The predicted transfer characteristics and pressure drop data obtained with the simulation program are compared with experimental data. It has been found that the model predicts the correct trends for both the transfer characteristics and the pressure drop across the packing material. Quantitatively the simulation program was found to over-predict the transfer characteristics slightly and possible reasons for the differences are discussed. The predicted pressure drop data agreed closely to the experimental data. The program was used to obtain rough guidelines for optimum splash pack layout. The program was also employed to study the effect of reduced surface tension (resulting in smaller drops) on the thermal performance of splash pack.

INTRODUCTION

In a counterflow cooling tower, the hot process water which is to be cooled is sprayed into an upward flowing air stream. Due to heat and mass transfer, the water temperature is reduced while the air enthalpy is increased. In order to increase the interface area between the air and the water, packing material is placed inside the cooling tower. Three types of packing material are commonly used: splash pack; film pack; and film-grid pack. Splash packing material consists of horizontal wooden, plastic or metal slats and grids which break up the drops falling through the tower, thereby reducing the average velocity and size of the drops. The smaller drop size and lower drop velocities result in increased interface area and increased drop residence time in the tower. Film packing material consists of large, thin sheets of asbestos, plastic or metal which spread the water into thin films flowing down the sides of these sheets. Film-grid packs fall between the splash and film packs discussed above. As in the case of splash pack, the grids tend to break up the falling water drops while the relatively large grid surface area (in comparison with splash packs) is covered with a thin water film which contributes significantly to the total interface area.

In order to obtain thermal and pressure drop design data on a given packing material, it is normally necessary to obtain the required information experimentally. To minimize wall effects, it is necessary to conduct these tests using large test sections, which requires large amounts of energy for the heating of the inlet water. It is often difficult to compare results obtained for the same packing material by different researchers due to differences in the water distribution systems and sizes of the spray and rain zones above and below the pack. Development of new types of pack requires many prototypes to be built and evaluated, resulting in very high development costs.

This study is aimed at developing a mathematical model to describe the performance of splash packing material using basic aerodynamic, hydrodynamic and heat/mass transfer information without depending on empirically determined data from cooling tower testing. A mathematical model that predicts the performance of splash packing material accurately could be used to optimize the layout of splash packing material. Such a model would also make it possible to study the effects of different types of water distribution systems on the performance of a given pack. A model that correctly predicts the drop size and velocity distributions through the pack zone would also allow accurate prediction of the performance of the rain zone below the pack.

LITERATURE REVIEW

Cooling tower theory

The total heat transfer rate between a water layer with an interface temperature of T_i and air at T_a and a vapour content of w_a can be expressed as

$$\partial \dot{Q} = h_c(T_i - T_a)\,\partial A + K(w_{asi} - w_a) i_v\,\partial A. \quad (1)$$

Merkel [2] assumed a Lewis factor of unity $[Le_f = (h_c/c_{pav}K) \approx 1]$ and negligible water mass loss (due to evaporation) to simplify this relation to

$$\partial \dot{Q} \approx K(i_{asi} - i_a)\,\partial A. \quad (2)$$

Noting that $\dot{m}_a \partial i_a = \dot{m}_w c_{pw} \partial T_w$ and assuming that the water interface temperature is equal to the bulk water temperature (i.e. $T_i \approx T_w$), integration of equation (2) between the water inlet and outlet positions of a cooling tower yields the following integral

NOMENCLATURE

a pack density, surface area per unit volume, [$m^2\ m^{-3}$]
A area [m^2]
b horizontal distance from the edge of the slat to the outer edge of a drop experiencing cutting [m]
c_p specific heat (heat capacity) [$J\ kg^{-1}\ K^{-1}$]
C_D drag coefficient
d diameter (characteristic length) [m]
d_{32} Sauter mean diameter, $d_{32} = \sum Nd^3/\sum Nd^2$ [m]
d_{50} mass median diameter, drop size above (or below) which 50% of the total mass of a given distribution would lie [m]
d_m maximum stable drop size [m]
d_{RR} scale parameter for Rosin–Rammler distribution, $d_{RR} = d_{50}(0.6931^{-(1/n_{RR})})$ [m]
F force [N]
f_c cutting fraction, ratio of the mass of drops formed by cutting to that of the incoming drop
f_s splash fraction, ratio of the mass of splash drops to that of the incoming drop
g gravitational acceleration [$m\ s^{-2}$]
h_c convection heat transfer coefficient [$W\ m^{-2}\ K^{-1}$]
i enthalpy [$J\ kg^{-1}$]
k thermal conductivity [$W\ m^{-1}\ K^{-1}$]
K mass transfer coefficient [$kg\ m^{-2}\ s^{-1}$]
$K_{\Delta p}$ pressure loss coefficient (number of velocity heads)
$Ka/\dot{M}_w$ transfer characteristic per metre of fill [m^{-1}]
$KaZ/\dot{M}_w$ transfer characteristic of fill
KE kinetic energy, $0.5mv^2$ [J]
L length of slat [m]
Le_f Lewis factor, h_c/Kc_{pav}
m mass [kg]
$\dot{m}$ mass flow rate [$kg\ s^{-1}$]
$\dot{M}$ mass flux, $\dot{m}/A_{fr}$ [$kg\ m^{-2}\ s^{-1}$]
N number
$\dot{N}$ number per second [s^{-1}]
n_{RR} shape (or skewness) parameter of Rosin–Rammler distribution
Nu Nusselt number, $h_c d/k$
Δp pressure drop [Pa]
$\dot{Q}$ heat transfer rate [W]
R cumulative mass fraction
t time [s]
T temperature [°C]
v velocity [$m\ s^{-1}$]
V volume [m^3]
$\dot{V}$ volume flow rate [$m^3\ s^{-1}$]
w humidity ratio (kg water per kg dry air)
W width of slat [m]
We Weber number, $\rho v^2 d/\sigma$
x distance from centreline of slat [m]
z vertical height or fall distance [m]
Z packing thickness [m].

Greek symbols
β porosity, ratio of open area to total frontal area of a grid
δ thickness of the water film on the top surface of a splash grid [m]
μ dynamic viscosity [$kg\ m^{-1}\ s^{-1}$]
ρ density [$kg\ m^{-3}$]
σ surface tension [$N\ m^{-1}$]
ϕ mixing ratio defined by equation (28)
Φ 'thermal function' defined by Nottage and Boelter [1] [s^{-1}]
Ψ 'dynamic function' defined by Nottage and Boelter [1] [$m\ s^{-1}$].

Subscripts
a air
as saturated air
asi air saturated at T_i
asw air saturated at T_w
av moist air (air and vapour)
c cutting
crit critical
d dripping or drop
f film
fr frontal
i inlet, interface or incoming
o outlet
s splashing
T terminal
v vapour
w water
wb wet bulb.

$$\frac{KaZ}{\dot{M}_w} = \int_Z \frac{c_{pw}\,\partial T_w}{(i_{asw} - i_a)}. \tag{3}$$

Since the relation between air saturation enthalpy and temperature is not a simple linear function of temperature, numerical integration is usually required to solve this integral. The Tchebycheff integration method (see Cale [3] or Johnson [4]) allows approximate evaluation of this relation. The effect of the assumption that the water interface temperature is equal to the bulk water temperature has been investigated by Baker and Shryock [5], Webb [6] and Marseille *et al.* [7].

The non-dimensional term, $KaZ/\dot{M}_w$, is known as the Merkel number or the transfer characteristic of the packing. If the transfer characteristic of a given cooling tower is known, it is possible to use the above theory to calculate the performance of the cooling tower under various air and water inlet conditions. Similarly, if the tower performance is known for specific inlet conditions (from measurements), it is possible to calculate the transfer characteristic by solution of equation (3).

In determining the operating point of natural draft cooling towers, the condition of the air leaving the pack zone is required to facilitate the calculation of the draft potential. When modelling the operation of a cooling tower with the Merkel theory, only the water temperature and the air enthalpy are known at every position in the cooling tower and it is usual to assume that the outlet air is saturated. This assumption allows the calculation of the temperature and density of the air leaving the pack.

In his 1972 thesis, Poppe rewrote equation (1) without resorting to the Merkel assumptions for heat and mass transfer between the water and non-saturated air in an element as [8]

$$\partial \dot{Q} = K(Le_f(i_{asi} - i_a) + (1 - Le_f)i_v(w_{asi} - w_a))\,\partial A. \quad (4)$$

The complete Poppe model includes differential equations describing the air humidity, water temperature and water mass flow rate changes in an imaginary element of cooling tower packing. Poppe also derived separate equations describing the heat and mass transfer between a water surface and saturated or supersaturated air, since the driving potential for mass transfer to saturated air ($w_{asi} - w_{as}$) differs from the driving potential for mass transfer to non-saturated air ($w_{asi} - w_a$). Various other models based on a similar approach to that of Poppe have been proposed for the mathematical modelling of cooling towers, e.g. refs. [6, 9–11]. When using one of the accurate models for cooling tower design purposes, it is important to use transfer characteristics which have been calculated from experimental data using the same model. If the Merkel model was used to calculate the transfer characteristics from experimental data, the Merkel model should be employed when using these data to predict the performance of a cooling tower. The Merkel model employing transfer characteristic data determined with the Merkel model can be expected to yield better results than a more accurate model using the same transfer characteristic data (based on the Merkel model).

Empirical splash pack design data

The experimentally determined values for the transfer characteristic of a given type of cooling tower packing material can usually be correlated by relations of the form

$$\frac{Ka}{\dot{M}_w} = c_1\left(\frac{\dot{M}_w}{\dot{M}_{av}}\right)^{c_2} \quad \text{or} \quad \frac{Ka}{\dot{M}_w} = c_3\dot{M}_w^{c_4}\dot{M}_{av}^{c_5}. \quad (5)$$

The pressure loss coefficient for a given packing is usually expressed as

$$K_{\Delta p,\text{fill}} = \frac{\Delta p/Z_{\text{fill}}}{0.5\rho_a v_a^2} = c_6\dot{M}_w^{c_7}\dot{M}_{av}^{c_8}. \quad (6)$$

Various researchers measured and correlated experimental transfer characteristic and pressure loss data for different types of splash pack [3, 4, 12]. A comprehensive summary of the data available in open literature is given by Dreyer [13]. No indication of the initial drop size distribution was given for any of these studies. For many of the cases, the sizes of the spray zone and the rain zone below the packing was not given.

Mathematical modelling from basic principles

Very little published literature on the modelling of cooling tower splash pack from first principles could be found. Several authors discussed the operating principles of splash packing without proposing mathematical prediction models. Limited published literature is available on the mathematical modelling of heat/mass transfer from free-falling sprays of large drops. The modelling of the cooling/heating (and evaporation) of small drops, as found in fuel injection systems, has received more attention. The simpler models for describing drop cooling invariably assume that the drop distribution can be expressed by a single representative drop size, e.g. Sauter mean drop diameter. The Sauter mean diameter of a distribution of drop sizes is that drop diameter which has the same ratio of surface area to mass as the complete distribution.

Hollands and Goel [14] showed analytically that it is not generally possible to use a mean drop diameter to model the cooling/heating of a distribution of drops. They found that a mean drop size can be used in the following cases: (i) when the particles move through the heat/mass exchanger so rapidly that they do not change appreciably in temperature (low efficiency systems); or (ii) when the drops are very small and represent a small mass in comparison with the airstream (in which case the drops quickly reach the local air wet bulb temperature).

Nottage and Boelter [1] developed a semi-graphical method to determine the cooling of monodisperse sprays (sprays of uniform drop size) accelerating under gravity through an upward flowing airstream. The transfer in such a spray was described using a so-called 'dynamic function', Ψ, and a 'thermal function', Φ. Lowe and Christie [12] noted that the 'thermal function' defined by Nottage and Boelter was in error. Lowe and Christie showed that the relation between the conventional cooling tower transfer characteristic and the 'dynamic function' for drops at terminal velocity can be expressed as

$$\frac{Ka}{\dot{M}_w} = \frac{c_{pw}k_a}{c_{pa}k_w(v_T - v_a)}\Psi = \frac{c_{pw}k_a}{c_{pa}k_w v_{rel}}\Psi. \quad (7)$$

Berman [15] described an approximate method to determine the relative contributions of the large drops dripping below the slats, the spray or splash drops and the films on the slats to the total air/water interface area and heat transfer rate for counterflow cooling tower splash packs. For a numerical example based on a typical splash pack with $a_{slats} = 4.4$ m^2 m^{-3}, Berman found that, although the spray drops constituted only about 20% of the interface area, they were responsible for approximately 65% of the heat/mass transfer.

Hollands [16] modelled the operation of a spray tower (cooling tower without any packing material) mathematically using basic aerodynamic, hydrodynamic and heat/mass transfer information to describe the cooling of a polydisperse spray of drops falling down through the tower. In conventional cooling tower modelling using empirically determined volumetric transfer coefficients, it is assumed that the water at any height has a uniform temperature distribution. Using this assumption, Hollands proposed an approximate model which uses a fixed drop size and does not require stepwise integration along the tower height. Factors to correct the simplified model predictions are given in graphical form for all the pertinent non-dimensional groups.

Benton and Rehberg [17], Benocci *et al.* [18] and Hoffmann and Kröger [19] used numerical models to calculate the drop motion and cooling in the rain zones below the packing in large natural cooling towers. These models all use a single drop diameter to represent the distribution of actual drop sizes and, as expected, the solutions are very sensitive to the choice of drop size.

MATHEMATICAL MODELLING

In this section the computer program for the simulation of cooling tower splash packing material is described with specific reference to the algorithms required. The different options for modelling drop acceleration, heat/mass transfer from drops, splash drop distribution, dripping drop formation below the slats, etc. based on information from the literature are described. The simulation program, SPSIM (splash pack simulation), was written in Borland Turbo Pascal on an IBM compatible personal computer.

Modelling principles

The following assumptions are made in the mathematical modelling of a counterflow cooling tower splash pack.

1. The enthalpy potential model for simultaneous heat and mass transfer, proposed by Merkel [2], is valid. This implies that $Le_f = 1$ and that evaporation is negligible.
2. The air is thoroughly mixed, i.e. the air enthalpy is constant in any given horizontal plane.
3. Radiation effects are negligible.
4. The initial drop size distribution and drop velocities are known at the water inlet side.
5. The transient problem of modelling accelerating drops may be approximated as a succession of steady states (see Yao [20]).
6. The drop drag coefficients and heat/mass transfer coefficients experienced by each drop in the splash pack is not influenced by the proximity of other drops (see Dreyer [13]).
7. The effect of free stream turbulence on the drag and heat/mass transfer from individual drops is assumed to be negligible.

For integration purposes, the packing zone is divided into a number of layers. The number of layers corresponds to the number of splash grids. These imaginary layers in the packing are selected in such a way as to ensure that every grid (if any) falls on the boundary of a layer. If a rain and a spray zone are to be evaluated as well, they each represent another layer (layers 0 and $N_{grids}+1$), as shown in Fig. 1. Every layer is subdivided into a number of elements, each with a thickness of ∂z.

For a typical element, the following governing equation for the total heat transfer from the water to the air can be derived from the Merkel theory:

$$\partial \dot{Q} = K \partial A (i_{asw} - i_a) = Ka\, A_{fr}\, \partial z (i_{asw} - i_a). \quad (8)$$

The temperature drop of the water and the air enthalpy gain in an element can be calculated by combining this equation with the energy balance, i.e.

$$\partial \dot{Q} = \dot{m}_a\, \partial i_a = \dot{m}_w c_{pw}\, \partial T_w. \quad (9)$$

In cooling tower design calculations, the value of K (or Ka) in equation (8) is usually known from experimental data and the solution of the governing equations in each element is relatively straightforward. In this study, however, the equation of motion of a given drop falling through an element is solved to determine the average velocity of the drop through the element. The drop velocity is then used to calculate the heat and mass transfer coefficients. From these coefficients, the cooling rate of the drop in the element is calculated. As the drops fall through the packing, they strike the slats and this changes the drop size distribution. Small drops are formed by the splashing action on top of the slats, while relatively large drops drip from below the slats.

It is convenient to start the integration process at the top of the packing zone (at the water inlet side)

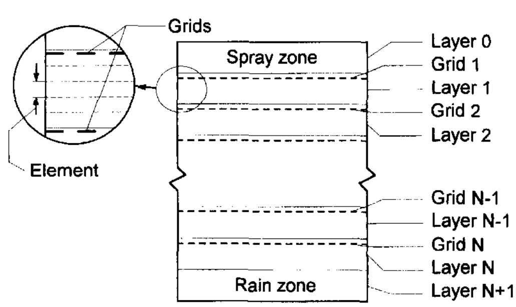

Fig. 1. Layout of the imaginary integration elements along the packing height.

since the initial drop size and velocity distributions are known there. The outlet air enthalpy, i_{ao}, is not known and an initial value of i_{ao} has to be assumed. The initial choice of air outlet enthalpy must be less than the smaller of the two extreme values: $i_{as}(T_{wi})$ and $i_{ai}+(\dot{m}_w c_{pw}(T_{wi}-T_{aiwb})/\dot{m}_a)$.

After the integration downwards through the packing, the calculated air inlet enthalpy should correspond with the ambient inlet air enthalpy (if the initial choice of i_{ao} was correct). If it does not agree, a new value of air outlet enthalpy has to be assumed and the integration process repeated until a solution is reached. Upon completion of the integration process (after reaching the air inlet side with the correct choice of outlet air enthalpy), the average outlet water temperature can be calculated. The overall transfer characteristic, or $KaZ/\dot{M}_w$, of the packing can then be calculated by using any conventional cooling tower integration procedure.

The calculation procedure is shown in Fig. 2. The algorithms required for the evaluation of the free fall zones and the influence of the splash grids are described in more detail below.

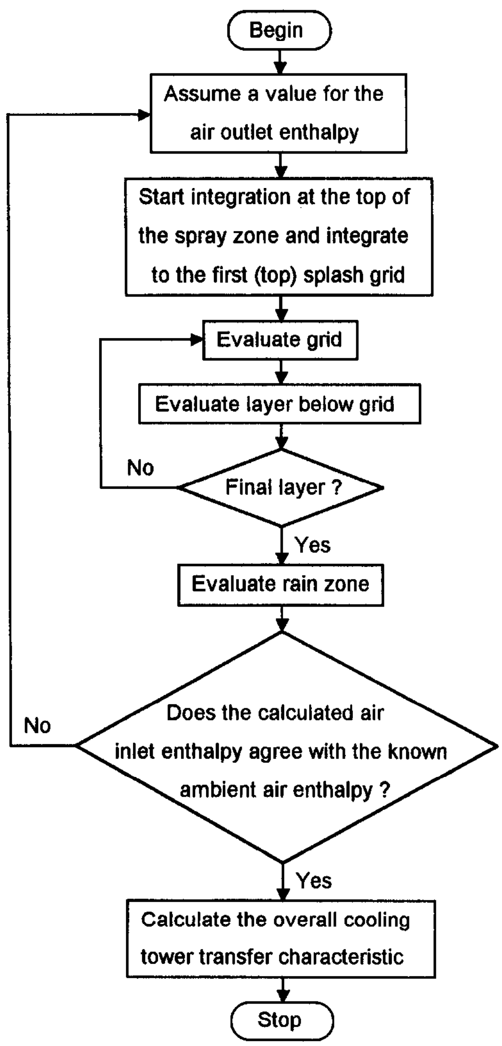

Fig. 2. Flow diagram showing the main calculation steps in the splash pack simulation program.

Packet concept

Any drop size distribution can be represented by distributing the drops in a range of fixed drop size intervals (or classes). Since large water drops are inherently unstable in free fall, it is assumed that the drop distribution has an upper limit, d_{max}. The drop size intervals can be linearly or logarithmically spaced between d_{min} and d_{max}. If it is assumed that d_{min} = 0 mm, d_{max} = 10 mm and that there are 20 equal-sized classes, it follows that the first drop class is represented by drops with diameters of 0.25 mm, the next 0.75 mm, etc. At the top of the range, the ratio of class width to drop size, $\Delta d/d$, is 0.05 (0.5/9.75), while it is equal to 2 (0.5/0.25) at the low end of the size range. In order not to lose resolution at the low end of the range, the drop size classes can be logarithmically distributed.

To simplify and reduce the number of calculations required to evaluate a given element, the collection of drops in each element is divided into discrete packets. These packets allow drops of similar diameter, temperature and velocity to be lumped together. Each packet represents a unique combination of drop size, velocity and temperature. To specify the number of drops per packet, the mass flow rate represented by each packet is used. The discrete packet modelling approach has the following advantages: (i) the equation of motion and the heat/mass transfer is only evaluated once per element per packet, thus reducing the number of calculations significantly; and (ii) since the numbers of packets are relatively small (compared with the number of drops) in a given element, the computer memory required to store the packet information is not excessive.

Free fall zone evaluation

The major part of the total energy transfer in a splash pack takes place in the free fall zones between the grids. The drop residence times and velocities in a particular free fall zone are governed by the upward air velocity, the initial drop velocities and the drag forces on the individual drops. The drop velocity is not only important in controlling the drop cooling, but it also controls the splashing phenomenon occurring on the grids below.

Figure 3 shows the sequence of steps used in the simulation program to describe the heat/mass transfer, drop motion, etc. for each packet of water drops falling between the grids in a cooling tower splash pack. The modelling of the individual steps is described in more detail below.

Drop motion. The motion of a drop in a counterflow air stream is governed by the following forces: drag, buoyancy and gravity. The drop acceleration or deceleration can be determined from the nett force balance on the drop using the following relation

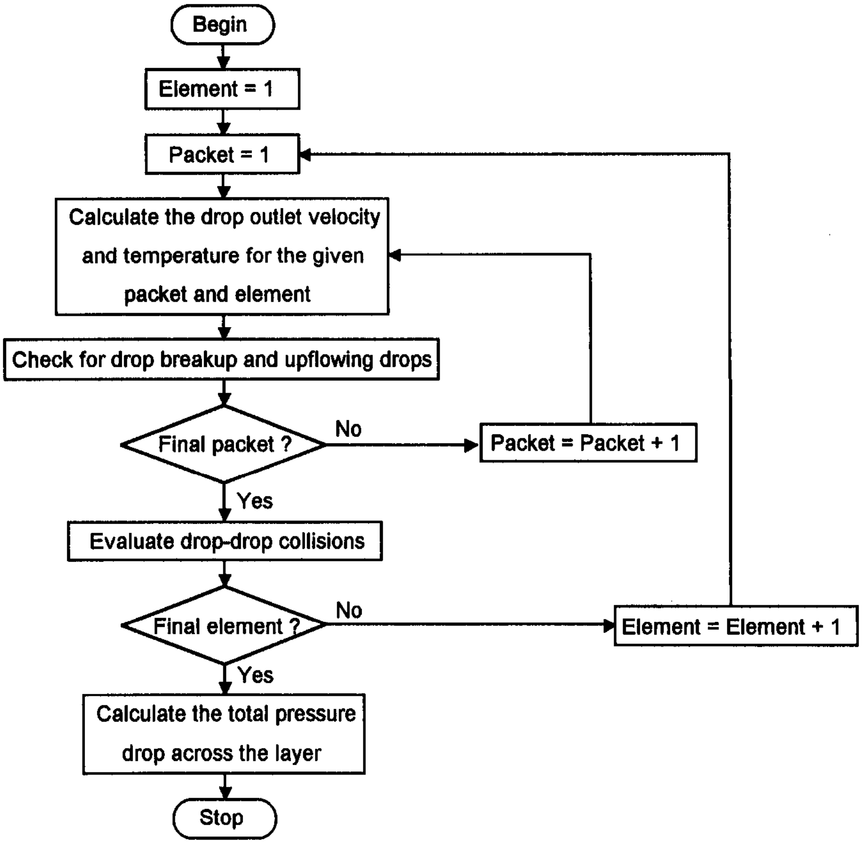

Fig. 3. Flow diagram showing the calculation steps required to evaluate a typical free fall zone between grids.

$$m\left(\frac{\partial v}{\partial t}\right) = m\left(\frac{(\rho_w - \rho_a)g}{\rho_w}\right) - 0.5\rho_a(v_d + |v_a|)^2 A_{fr} C_D. \quad (10)$$

Note that the positive direction is chosen as vertically downwards, thus a falling drop has a positive velocity and an upward flowing drop has a negative velocity. Since the airflow is always upwards, it is convenient to assume $v_a = |v_a|$ and to implement it as such in the governing equations. Also note that the velocities are always expressed relative to a fixed reference frame unless specifically stated otherwise. Since very small drops can be dragged upwards by the air stream, it may be necessary to divide the packing into smaller elements to prevent numerical problems in the element where a small drop starts moving upwards.

Heat and mass transfer from drop. The simulation program allows the user to select one of three drag models: (i) no drag ($C_D = 0$); (ii) drop drag calculated from solid sphere drag data; and (iii) drop drag calculated using the model which takes drop deformation into account. The drag coefficient for solid spheres can be calculated using the correlation by Turton and Levenspiel [21]. The effect of acceleration on the drag experienced by an accelerating solid sphere is assumed to be negligible. The model developed by Dreyer [13] and Dreyer and Erens [22] is used to calculate the drag experienced by deformable water drops during acceleration.

The average Nusselt number can be calculated from the known drop size, the average velocity relative to the airstream, etc. The simulation program allows the user to select any one of the Nusselt number correlations listed by Dreyer [13], e.g. the well-known Ranz and Marshall [23] correlation. From the analogy between heat and mass transfer, it follows that

$$K = \frac{h_c}{Le_f\, c_{pav}} = \frac{Nu\, k_a}{Le_f\, c_{pav} d}. \quad (11)$$

The number of drops of any given packet with drop diameter, d, and velocity, v, in an element can be found from

$$N = (\text{number of drops per second})$$
$$(\text{residence time}) = \left(\frac{\dot{m}_w}{\rho_w V_d}\right)\left(\frac{\partial z}{v_d}\right). \quad (12)$$

The total surface area of the drops belonging to a particular packet in an element can be calculated from the known number of these drops in the element.

For very small drops, or drops with terminal velocities very close to the velocity of the upward flowing air stream, the total surface area of the drops in an element may be very large, which may cause numerical instability in the calculation of the drop temperature. To cure this, the value of ∂z must be decreased by subdividing each element into even smaller steps. For each of the smaller steps, a stable value of ∂T_w can be found. In some cases where $t_{res} \to \infty$ (drops moving down very slowly), an excessive number of steps would be required to achieve a stable solution for T_{wo}. In these cases, the drop temperature approaches the adiabatic saturation temperature at the local air conditions and in the simulation model it is assumed that $T_{wo} = T_{sat}$.

Aerodynamic drop break-up. Large water drops accelerating in air become unstable due to the aerodynamic forces acting on each drop. The various criteria for aerodynamic drop break-up are discussed by Dreyer [13]. The splash pack simulation program uses the criterion specified by Wierzba [24] to determine whether a given drop is unstable. According to this criterion the drop will be unstable if the drop Weber number, $\rho_a v^2 d/\sigma$, is greater than 11. If a particular drop is found to be unstable, the drop is divided into two identical, smaller drops. Each smaller drop has 50% of the volume of the parent drop, the same temperature and the same velocity as the parent drop.

Drop–drop collisions. Drop–drop collisions occur in a splash pack due to the difference in velocity between different drops. The complete stochastic modelling of drop–drop collisions would require excessive computing time. A simplified algorithm to evaluate the probability of drop–drop collisions, proposed by Dreyer [13], is used in the splash pack simulation program. According to this model the number of collisions between drops in two packets (say A and B) can be calculated from the probability of collision between the drops. Consider a drop of diameter, d_A, falling at a given velocity, v_A, through a cloud of slower moving drops belonging to packet B. During a unit time, this drop sweeps out the following volume:

$$\dot{V} = \left(\frac{\pi}{4}\right)(d_A + d_B)^2 |v_A - v_B|. \quad (13)$$

Assuming that there are N_A drops in packet A and N_B drops in packet B per unit volume and assuming a collision efficiency of η_{coll}, the number of collisions occurring between these two packets per unit volume per unit time can be expressed as

$$\dot{N}_{coll} = \left(\frac{\pi}{4}\right)(d_A + d_B)^2 |v_A - v_B| \eta_{coll} N_A N_B. \quad (14)$$

Assuming a collision efficiency of unity, the number of collisions occurring between the two packets in an imaginary volume of thickness ∂z and frontal area of A_{fr} per second can then be expressed as

$$\dot{N}_{coll,A,B} = \dot{N}_{coll} A_{fr}\, \partial z. \quad (15)$$

For each pair of packets, the collision probabilities, $(\dot{N}_{coll,A,B}/\dot{N}_A)$ and $(\dot{N}_{coll,A,B}/\dot{N}_B)$, are calculated. To ensure that the drop collisions are evaluated correctly, the collision probabilities are calculated using the conditions (drop diameter, velocity and drop temperature) of the packets leaving the previous element. The packets resulting from the collisions are stored in temporary arrays. This means that the effect of collisions between packets A and B does not reduce the number of drops in packet A, which could influence the number of collisions between packets A and C, etc.

Upon collision, it is assumed that only coalescence or bouncing occurs. The simulation program employs the relation by Brazier-Smith *et al.* [25] to determine the coalescence efficiency. The number of colliding drops which coalesce after collision are removed from their parent packets and form a new packet. The diameter, velocity, temperature and mass flow rate of the drops in the new packet are determined from the laws of energy, momentum and mass conservation.

In actual collisions between liquid drops, it is expected that satellite drops would form. This has not been incorporated in the current mathematical model in order to prevent excessively large numbers of new packets from forming.

Handling of upward flowing drops. If the velocity of the upward flowing air stream is higher than the terminal velocity of a given drop, the drop will move upwards with the air stream. In a cooling tower most of these up-flowing drops will be intercepted by the drops falling through the packing or by the drift eliminators installed above the packing (in most cooling towers). Only very small drops will leave the cooling tower through the drift eliminator. The effect of this water loss on the performance of splash packing material is usually negligible due to the very small mass flow rate which these drops represent. This phenomenon is handled in one of three ways in the simulation program.

(1) The up-flowing drop mass is assumed to be lost, i.e. it is removed from the calculation.

(2) All the up-flowing drops originating in a given element are assumed to be caught by the falling drops in the element. The mass, momentum and temperature of these drops are redistributed among the falling drops according to the probability of collision between the up-flowing drops and the down-flowing drops.

(3) The up-flowing drops are assumed to collect on the drift eliminator which is usually installed above the packing in a counterflow cooling tower. These drops are assumed to cool to the local air wet-bulb temperature at the tower outlet and then drip down as large drops. In the simulation program it is assumed that these drops (at the air wet-bulb temperature at the air outlet side) can be included in determination of the average water outlet temperature. In actual fact, these large drops could undergo further cooling and/or splashing as they fall towards the pond below the packing, but attempting to include these effects in

the simulation would complicate matters significantly. This simplification is expected to be less important since the effect of drift loss on the thermal performance of the splash pack was found to be insignificant.

Pressure drop. The static pressure drop across the free fall zones (i.e. excluding the pressure drop across the splash grids) can be expressed as the sum of the drag forces experienced by all the drops divided by the air flow area, i.e.

$$\Delta p_{\text{drops}} = \frac{\sum_{i=1}^{N_{\text{elements}}} \sum_{j=1}^{N_{\text{packets}}} (F_{\text{drag},i,j})}{A_{\text{fr}}}. \quad (16)$$

Grid evaluation

Grids are placed in the fall path of the drops moving through a cooling tower to decrease the average drop size, redistribute the water (large drops, which are normally warmer due to their relative small surface area and short residence times, splash and form smaller splash drops which cool much more efficiently) and to reduce the average drop velocity in the cooling tower. The surface area of the grid can also have a noticeable effect on the overall performance of the packing, due to the cooling of the water film covering the grids. Upon drop impact on the surface of a grid, the drop may splash if the impact energy is high enough, or the drop may experience a cutting or splitting action if the impact is close to the edge of a slat. Only a fraction of the water which impacts a grid is lost due to splashing and/or cutting, while the rest drips from below the grid as relatively large drops. Dreyer [13] and Dreyer and Erens [26, 27] studied the various methods of drop formation and presented empirical correlations to describe their findings.

In the splash pack simulation, the imaginary elements in the packing are selected in such a way as to ensure that every grid (if any) falls on the boundary of an element. The following assumptions are made: (i) the incoming drops are assumed to travel in straight trajectories; (ii) the drop packets are evenly distributed over the entire flow area; and (iii) the drop impacts on the slats and the resulting crown formation are not influenced by neighbouring impacts.

Splashing. The total mass of water splashing from the surface of a slat when it is struck by an incoming drop is given, in terms of a splash fraction, by

$$m_{\text{s}} = \bar{f}_{\text{s}}\left(\rho_{\text{w}}\left(\frac{\pi d_{\text{i}}^3}{6}\right)\right). \quad (17)$$

Similarly, the total mass flow rate of water splashing from a slat when it is struck by the drops of a packet, say packet A, is given by

$$\dot{m}_{\text{s,A}} = \overline{f_{\text{s,A}}}(W + d_{\text{i,A}})L\dot{M}_{\text{w,A}}. \quad (18)$$

The mean splash fraction is dependent on the film thickness on the slat before the drop impact, the size of the incoming drop and the velocity of the incoming drop. Dreyer [13] and Dreyer and Erens [26] presented the following empirical correlations for the mean splash fraction for splashes on slats of $W = 2$, 5, 10 and 25 mm. Linear interpolation can be used to find splash fractions for other slat widths. The average splash fraction data for the 25 mm slat was correlated by an equation of the form

$$\bar{f}_{\text{s}} = 0.01\left(c_1 + \left(\frac{\delta}{d_{\text{i}}}\right)\left(c_2 + c_3\left(\frac{We}{We_{\text{ref}}}\right) + c_4\left(\frac{We}{We_{\text{ref}}}\right)^{0.4}\right)\right) \times \left(c_5 + c_6\left(\frac{We}{We_{\text{ref}}}\right)^{c_7}\right)\left(c_8 + c_9\left(\frac{\delta}{d_{\text{i}}}\right)^{c_{10}}\right) \quad (19)$$

and the average splash fractions for the 2, 5 and 10 mm wide slats were correlated by equations of the form

$$\bar{f}_{\text{s}} = 0.01\left(c_1 + c_2\left(\frac{\delta}{W}\right)\right)\left(c_3 + c_4\left(\left(\frac{We}{We_{\text{ref}}}\right) \times \left(\frac{d_{\text{i}}}{W}\right)^2\right)^{c_5}\right)\left(c_6 + c_7\left(\frac{d_{\text{i}}}{W}\right)^{c_8}\right) \quad (20)$$

where

$$We = \frac{\rho_{\text{w}} v^2 d_{\text{i}}}{\sigma}. \quad (21)$$

The reference Weber number is defined as the Weber number of the maximum stable drop size at terminal velocity at standard temperature and pressure, i.e.

$$We_{\text{ref}} = \frac{\rho_{\text{w}} v_{\text{T}}^2 d_{\text{m}}}{\sigma} \quad (22)$$

where

$$d_{\text{m}} = \sqrt{\frac{16\sigma}{g(\rho_{\text{w}} - \rho_{\text{a}})}}. \quad (23)$$

The constants in the above correlations are given in Table 1. Note that by using the mean splash fraction in the equations above, the mass of the drops splashing from a slat is independent of the impact position on the slat. These equations express the splash drop mass as the average mass leaving the slat for any drop impact position between $-(W+d_{\text{i}})/2$ and $(W+d_{\text{i}})/2$.

Dreyer [13] and Dreyer and Erens [26] found the splash drop sizes to be distributed according to the Rosin–Rammler distribution

$$R(d) = 1 - \exp\left(-(d/d_{\text{RR}})^{n_{\text{RR}}}\right) \quad (24)$$

where the Rosin–Rammler shape parameter is given by

Table 1. Constants in the correlations for the average splash fraction

Constant	25 mm slat, equation (19)	10 mm slat, equation (20)	5 mm slat, equation (20)	2 mm slat, equation (20)
c_1	−1.930	4.882	6.613	10.737
c_2	67.471	22.930	8.200	6.805
c_3	101.876	−2.301	−12.550	−12.996
c_4	−298.003	3.242	13.700	14.766
c_5	−62.009	5.327×10^{-2}	1.628×10^{-2}	3.578×10^{-2}
c_6	36.996	8.061	5.506×10^{-1}	1.210×10^{-1}
c_7	9.383×10^{-2}	2.598	12.551	15.575
c_8	4.466×10^{-1}	−2.977	−1.792	−2.148
c_9	−4.454	—	—	—
c_{10}	2.086	—	—	—
R^2	0.969	0.965	0.956	0.963

$$n_{RR} = \left(24.532-75.174\left(\frac{\delta}{d_i}\right)\left(\frac{We_i}{We_{ref}}\right)^{0.74}\right) \times\left(0.149+6.801\times10^{-4}\left(\frac{KE}{KE_{ref}}\right)^{-0.76}\right) \quad (25)$$

and the mass median drop size by

$$\left(\frac{d_{50}}{d_m}\right) = 3.08\times10^{-2} +\left(-0.163+4.560\times10^{-2}\left(\frac{\delta}{d_m}\right)^{-0.34}\right) \times\left(-0.804-0.619\left(\frac{We_i}{We_{ref}}\right)^{-0.27}\right) \times\left(-1.738+1.980\left(\frac{\delta}{d_i}\right)^{-0.17}\right) \quad (26)$$

where d_m, We and We_{ref} are defined above, and

$$KE_{ref} = 0.5\left(\frac{\rho_w \pi d_m^3}{6}\right)v_T^2. \quad (27)$$

Two models can be employed to determine the initial downward velocity and the initial temperature of the drops formed by splashing.

Model 1. The first model ignores the upward motion of the splash drops due to the splashing action. In this case the splash drops are assumed to start from zero velocity from the slat position, and the initial splash drop temperatures are calculated using the following mixing model

$$T_s = \phi T_f + (1-\phi)T_i. \quad (28)$$

The temperature of the film can be calculated iteratively from the equation above and the energy balance of the water striking the slat and leaving the slat, i.e.

$$\dot{m}_d T_f = \sum_j (\dot{M}_w L(W+d_{i,j})T_{i,j}) -\sum_j (\overline{f_{c,j}}\dot{M}_w L(W+d_{i,j})T_{i,j}) -\sum_j (\overline{f_{s,j}}\dot{M}_w L(W+d_{i,j})T_{s,j}). \quad (29)$$

Model 2. In the second model, the upward motion of the splash drops is taken into account when determining the initial splash drop velocity and temperature. The splash drop motion and the corresponding drop cooling can be calculated using the simplified analytical model described by Dreyer [13]. The initial drop velocity (for the splash drops falling downwards from the slat) is also determined from the analytical drop trajectory calculations. The initial temperature of the splash drops at the start of the upward splash drop motion can be determined from the mixing model proposed above. The initial upward velocity of the splash drops can be determined from the correlation given by Dreyer [13] and Dreyer and Erens [26].

Cutting. The average mass of water lost due to cutting for a given drop impact can expressed by

$$m_c = \overline{f_c}\left(\rho_w\left(\frac{\pi d_i^3}{6}\right)\right). \quad (30)$$

As before, the total mass flow rate of water in a packet, say packet A, which is lost over the edge of the slat due to cutting, is given by

$$\dot{m}_{c,A} = \overline{f_{c,A}}(W+d_{i,A})L\dot{M}_{w,A}. \quad (31)$$

For a drop impact near an edge, the mass of water which is not directly over the slat is given by

$$m_c = \rho_w\left(\frac{\pi h^2}{3}\left(\frac{3d_i}{2}-h\right)\right) \quad \text{where} \quad h = \left(\frac{2x-W}{2}\right)+\left(\frac{d_i}{2}\right) \quad (32)$$

for $W > d_i$ and $0 > h > d_i$. On a narrow slat, with

$W < d_i$, it is possible that a given drop is cut by both edges of the slat. Assuming that the mass of water lost due to cutting is equal to that not directly above the slat, Dreyer [13] and Dreyer and Erens [26] found that the mean cutting fraction can be expressed as

$$\overline{f_c} = \left(\frac{d_i}{W+d_i}\right) \tag{33}$$

for any combination of incoming drop size and slat width. From equations (31) and (33), it follows that

$$\dot{m}_{c,A} = d_{i,A} L \dot{M}_{w,A}. \tag{34}$$

If a drop of diameter d is cut into two equally sized drops, each of the two resulting drops will have a diameter of approximately $0.79d_i$. For any incoming drop, with $d_i < W$, by striking a slat close to the edge it can be shown that the mean drop size of the drop formed by the part of the incoming drop lost over the edge can also be calculated and expressed as $0.79d_i$. Assuming that a drop striking a thin edge, with $d_i > W$, will be cut into two parts, say parts A and B, the mass of each of the two parts can be calculated from equation (32) where b_A and b_B are given by

$$\overline{b_A} = b_A\left(\frac{1}{2}\left(\frac{W+d_i}{2}\right)\right) = \left(\left(\frac{3d_i}{4}\right)-\left(\frac{W}{4}\right)\right) \tag{35}$$

and

$$\overline{b_B} = b_B\left(\frac{1}{2}\left(\frac{d_i-W}{2}\right)\right) = \left(\left(\frac{d_i}{4}\right)-\left(\frac{W}{4}\right)\right). \tag{36}$$

Note that each impacting drop does not result in one drop formed by cutting, but that the total mass of drops of diameter, d_i, which are cut on impact with the grid, is redistributed as cut drops.

It is assumed that the new packets, containing drops formed by the cutting action, have initial velocities and initial temperatures equal to the velocity and temperature, respectively, of the packet from which they were formed.

Heat/mass transfer from grids. The water film flowing down over the surface of a slat is cooled by simultaneous heat and mass transfer to the air. The temperature of the water film dripping from below a slat, T_{fo}, can be calculated from

$$T_{fo} = T_{fi} - \left(\frac{KA_{slat}(i_{asw}-i_a)}{\dot{m}_d c_{pw}}\right). \tag{37}$$

The mass transfer coefficient can be determined from the analogy between heat and mass transfer and the convective heat transfer coefficient around a slat [see equation (11)]. The applicability of the correlation by Gnielinski [28], for the calculation of the convective heat transfer coefficient experienced around any type of slat, was confirmed experimentally by Dreyer [13] and Erens and Dreyer [29]. The correlation of Gnielinski is strictly valid only for determining the heat transfer coefficient around a single slat, but it is assumed that this correlation can be used to approximate the average heat transfer coefficient experienced around a bi-planar (two-dimensional) grid as well.

Dripping below grids. Once the splashing and cutting of all the packets striking a particular grid have been evaluated, the mass flow rate of the water dripping below the grid can be determined from the mass balance of water striking and leaving the grid, i.e.

$$\dot{m}_d = \sum_j (\dot{M}_w L(W+d_{i,j})) - \sum_j (\overline{f_{s,j}} \dot{M}_w L(W+d_{i,j})) - \sum_j (\overline{f_{c,j}} \dot{M}_w L(W+d_{i,j})). \tag{38}$$

The simulation program uses the models presented by Dreyer [13] and Dreyer and Erens [27] or Yung *et al.* [30] to describe the distribution of the dripping water mass flow rate into new packets. The temperature of the dripping drops can be obtained from the energy balance of the water flowing over the grid and the cooling of the water film on the surface of the grid, as described above. The drops which drip from below the grid obviously start from zero velocity.

Pressure drop. The static pressure drop across the grids in the packing can be expressed as

$$\Delta p_{grids} = N_{grids} K_{\Delta p}(0.5\rho_a v_a^2) \tag{39}$$

where the pressure loss coefficient, $K_{\Delta p}$, is calculated from an applicable empirical correlation.

The static pressure drop due to the splash drop motion above a grid can be calculated from the following relation:

$$\Delta p_{drops} = \frac{\sum_{j=1}^{N_{packets}} (F_{drag,j})}{A_{fr}}. \tag{40}$$

Note that in some cases the initial (upward) velocities of the splash drops could be larger than the air velocity which results in reduced pressure drop due to the fast moving drops dragging the air upwards.

Optimization

The packet concept works very well in the modelling of splash packing material, but the splashing action on the grids and the drop/drop collisions result in the formation of very large numbers of new packets. This creates two problems, i.e. excessive execution time and large amounts of computer memory storage space. The following algorithm is employed to reduce the overall number of packets.

After integration through an element, every packet is compared with every other packet to determine if the two packets are similar enough to be combined into a single packet. The two packets, say A and B, are combined into a single packet if all three of the following criteria are met: (i) the drops must belong to the same size class, or $d_A = d_B$; (ii) the drop velocities must be within a specified range from each other, or $|v_A - v_B| < v_{crit}$; and (iii) the drop temperatures must be similar, or $|T_A - T_B| < T_{crit}$.

The following critical values, viz. $v_{crit} = 0.25$ m s^{-1}

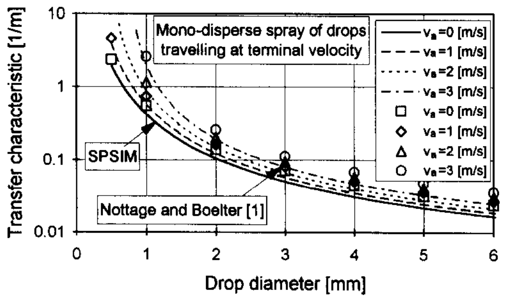

Fig. 4. Comparison between the transfer characteristics based on the model of Nottage and Boelter [1] and the predicted values obtained with SPSIM.

and $T_{crit} = 0.25$ K, have been found to reduce the number of packets significantly without over-simplifying the calculations.

If two packets are combined, the total water mass flow rate of the new packet is equal to the sum of the water mass flow rates of the two packets which are combined. The temperature and velocity of the drops represented by the new packet are determined from the energy and momentum conservation laws.

DISCUSSION

Monodisperse sprays

The transfer characteristics for monodisperse sprays of drops predicted by SPSIM are compared with those predicted by the model proposed by Lowe and Christie [12] [see equation (7)] in Fig. 4. The drops were assumed to be travelling at terminal velocity. The drop drag calculations in SPSIM were performed using the model accounting for drop deformation. The model by Lowe and Christie used the steady state 'dynamical function' data ('dynamical function' for drops falling at terminal velocity) tabulated by Nottage and Boelter [1].

There is good agreement between the trends predicted by these two methods. Generally, the transfer characteristics predicted by the model of Nottage and Boelter [1] fall slightly above that predicted by SPSIM.

Sensitivity analysis

The splash pack simulation program, SPSIM, was used to predict the performance of a typical splash pack. For the reference case, the splash pack geometry, the modelling options and the input parameters were set at fixed values. The sensitivity of the simulation program for the different parameters and options was then determined by changing these options one at a time. The following simulation program options were used as the reference case.

1. Layout: the fill was made up of 10 splash grids consisting of 9 mm wide slats spaced at 50 mm. The vertical spacing between the grids was taken to be 200 mm. It was assumed that there was a spray zone of 0.5 m above the top grid and a rain zone of 0.0 m below the packing. (Note that the packing height is 2 m measured downwards from the top grid, although the distance between the top and bottom grids is only 1.8 m.)
2. Input: water mass flux, $\dot{M}_w = 10\,000$ kg m^{-2} h^{-1} (2.78 kg m^{-2} s^{-1}).
   The air velocity was varied between 0.75 and 3 m s^{-1}.
3. Options: minimum/maximum drop sizes: 0 and 10 mm.
   Number of drop size classes: 30.
   Film thickness on the slats, δ: 0.5 mm.
   Mixing ratio, ϕ: 0.5.

The program was found to be insensitive to the following options and settings: (i) drop drag model; (ii) heat/mass transfer correlation used for heat/mass transfer from drops; (iii) crown splash angle (between 50 and 70°); (iv) mixing ratio (varying the mixing ratio, ϕ, between 0.4 and 0.6 resulted in changes in the predicted transfer characteristics of less than 0.1%); and (v) drop–drop collisions.

The program was found to be sensitive to: (i) the water film thicknesses on slats; (ii) the up splashing from slats; (iii) the cooling of the water film on surface of slats (in the reference case the area of the grids was significant, $a = 6.2$ m^2 m^{-3}); and (iv) the initial drop size distribution.

Figure 5 shows the variation in the predicted splash pack performance for different film thicknesses. The effect of three different fixed film thicknesses (i.e. $\delta = 0.4$, 0.5 and 0.6 mm) on the splash pack simulation is shown. A reduction in the film thickness results in a sharp increase in the predicted transfer characteristic. Such a reduction in the film thickness results in a corresponding increase in the predicted pressure drop across the packing. It can be concluded that the simulation program is very sensitive to film thickness.

The sensitivity of the simulation for the cooling of the splash drops during the splash drop motion above the level of the grids was investigated by comparing the reference case with a similar case which ignores the upward splash motion of the splash drops. It was found that the predicted transfer characteristics are

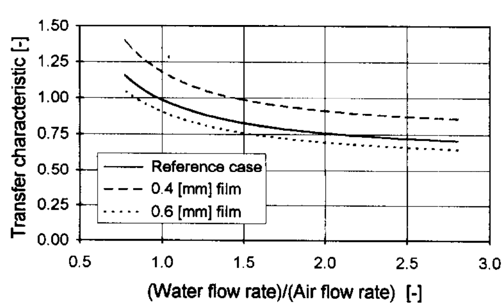

Fig. 5. Predicted transfer characteristics with different film thicknesses.

reduced by approximately 5% when the upward splash drop motion is ignored. The program execution time is halved when the upward drop splashing is ignored. Ignoring the upward splash drop motion has a negligible effect on the predicted pressure drop across the splash pack.

The cooling of the water films covering the surface of the slats is found to contribute significantly to the overall transfer. The predicted transfer characteristic, ignoring the cooling on the slats, is approximately 20% lower than that predicted with the cooling on the slats taken into account.

The effect of the initial (spray) drop distribution was investigated by comparing the reference case to the predictions obtained using the following three initial drop size distributions: (i) monodisperse initial drop distribution with $d = 7$ mm (note that the mass median diameter of the drops produced by the experimental water distribution system is 7 mm at $\dot{M}_w = 10\,000$ kg m^{-2} h^{-1}); (ii) Rosin–Rammler drop distribution with $d_{50} = 7$ mm and $n_{RR} = 3$; and (iii) Rosin–Rammler drop distribution with $d_{50} = 3.5$ mm and $n_{RR} = 3$. The results of these calculations are shown in Fig. 6. The predicted transfer characteristics with the monodisperse initial drop distribution are lower than that of the reference case. The case with a Rosin–Rammler initial drop distribution with $d_{50} = 7$ mm agrees very closely with the predictions of the reference case. The predicted transfer characteristics with the Rosin–Rammler initial drop distribution with $d_{50} = 3.5$ mm are higher than that of the reference case. It is obvious from this that the type of water distribution system can have a significant effect on the measured transfer characteristics in an experimental investigation of splash packing performance.

Comparison with experimental data

Dreyer [13] conducted a series of tests on 12 different types of splash pack to obtain transfer characteristic and pressure drop data for comparison purposes. The initial drop size distribution of the water distribution system was determined photographically.

The predicted and measured overall transfer characteristics for all 12 of the experimental splash

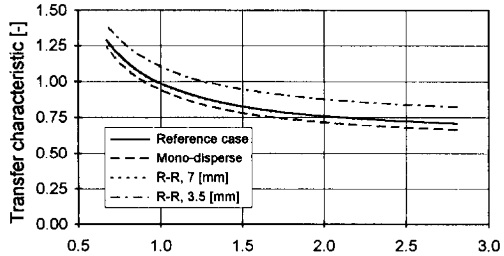

Fig. 6. Predicted transfer characteristics with different initial drop size distributions.

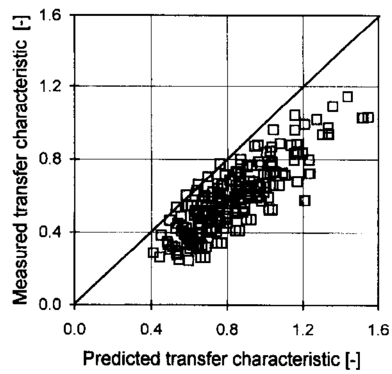

Fig. 7. Correlation between predicted and measured transfer characteristics.

packs are compared graphically in Fig. 7. Each packing was evaluated at three water flow rates, i.e. 5000, 10 000 and 15 000 kg m^{-2} h^{-1}, and six air flow rates between 0.75 and 3.25 m s^{-1}. The measured transfer characteristics were corrected by subtracting from it the empty tower transfer characteristic data for $z = 0$ m to account for heat and mass transfer occurring on the water distribution system and the water collecting troughs used in the experimental investigation. There is fair agreement between the predicted and the measured data although the predicted data is approximately 25% higher than the measured data. The over-prediction of the transfer characteristics can be attributed to one or more of the following:

(1) The corrected experimentally determined transfer characteristics are too low due to the over-estimation of the inlet/outlet correction applied to the measured data.

(2) The experimentally determined transfer characteristics are too low due to the influence of water bypassing the fill by flowing down the side walls of the fill test facility. According to Fabre and Legrand [31] the actual transfer characteristics of the fill can be between 20 and 50% higher than that based on the mean outlet water temperature and the total water flow leaving the test section.

(3) The possibility that the simulation program over-predicts the performance of the splash pack due to its inability to account for the interaction effects between neighbouring splash crowns (see discussion in Dreyer [13]).

Figure 8 shows the correlation between the predicted and measured pressure drop across the 12 splash packs which were tested. The predicted pressure drop data were generated for air flow rates between 0.75 and 2.75 m s^{-1} and water flow rates between 5000 and 15 000 kg m^{-2} s^{-1}. It can be seen that the pressure drop is over-predicted by approximately 25%. This over-prediction can be attributed to the simulation program over-predicting the number of splash drops due to its inability to account for interaction between neighbouring splash crowns. The over-prediction of the number of splash drops, which

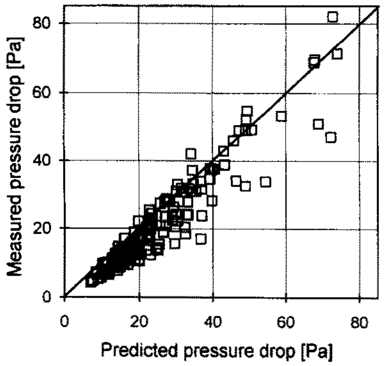

Fig. 8. Correlation between predicted and experimentally determined pressure drop.

are usually smaller than 2 mm, results in an over-prediction of the pressure drop across the splash pack since smaller drops contribute more to the pressure drop than larger drops. The over-prediction of the pressure drop seems to substantiate the possibility that the simulation program over-predicts the thermal performance of the splash pack.

It should be borne in mind that the simulation program does not account for the expected increased pressure drop across each grid due to the increased blockage resulting from the water films flowing down the sides of the slats. The water hanging below the slats is expected to reduce the pressure drop across each grid by streamlining the leading edge of each slat, but since this effect is not easy to quantify, it is not incorporated in the simulation program SPSIM.

Optimization

The simulation program, SPSIM, was used to calculate the transfer characteristics and pressure drop across typical splash packs. The effect of slat width on the performance of the splash pack was investigated by varying the slat widths between 2.5 and 25 mm while keeping the grid porosity, β, constant at 70, 80 or 90%. In all the cases the same simulation options as in the reference case of the sensitivity analysis were used. The effect of cutting becomes more important than splashing in the case of narrow slats ($W < 5$ mm) and since the simulation program uses a very simple model to describe the cutting phenomenon, care should be taken when using the simulation program to model splash packs with such narrow slats. The contribution of the film cooling on the slats tends to dominate the predicted performance of the splash packs with smaller slat widths and lower grid porosities. Figure 9 shows the predicted performance of the splash packs when the cooling of the films on the slats is neglected. The predicted pressure drop across the splash pack is shown in Fig. 10. As expected, the pressure drop across the grids with the higher porosities (more open area) is less than that across grids with lower porosities. The packing with the highest transfer characteristics also yields the highest pressure drop.

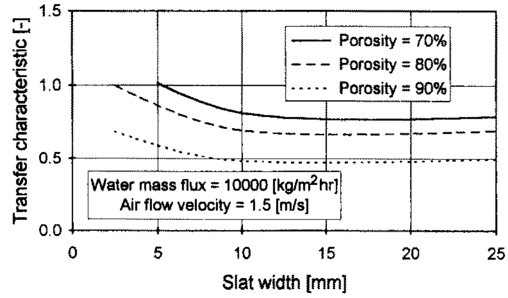

Fig. 9. Predicted transfer characteristic variation with slat width when cooling of the films covering the slats is *not* taken into account.

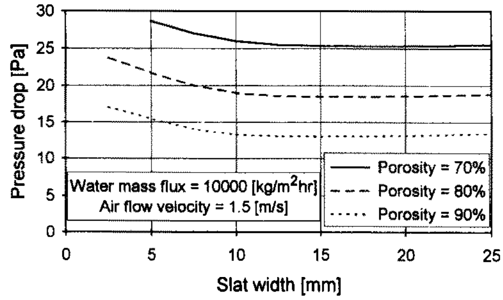

Fig. 10. Predicted pressure drop variation with slat width.

The packing efficiency, which is the ratio of the overall transfer characteristics to the pressure drop across the packing, can be used to compare the different packing materials on a common base. It can be seen from Fig. 11 that the packing thermal efficiency increases with decreasing slat width. The packing with 80% porosity shows the highest efficiencies for slat widths of less than 10 mm. The efficiencies of the splash packs evaluated here typically lie at approximately 0.035 Pa^{-1} when the cooling of the films on the slats is ignored. This corresponds to the efficiencies found in monodisperse spray towers with drop diameters between 1 and 2 mm.

The mass median drop diameter of the initial drop distribution is approximately 7 mm. This means that through the use of splash grids it was possible to obtain the same cooling from a very coarse spray of drops as one would obtain from a much finer spray in

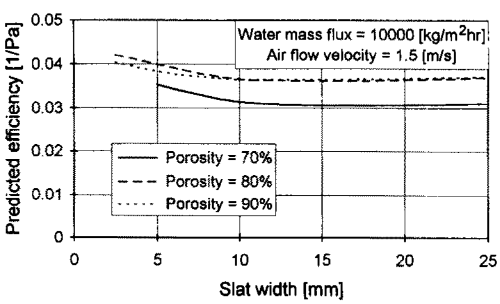

Fig. 11. Predicted packing efficiency variation with slat width when cooling of the films covering the slats is *not* taken into account.

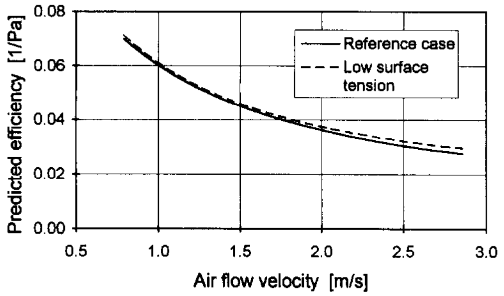

Fig. 12. Predicted splash pack efficiency with and without surface tension reducing additives.

an empty tower. The production of such a fine spray by a pressure nozzle would require a high water pressure, which in turn would require far more pumping power than would be required to generate a coarse spray such as that used in the splash pack simulation.

The performance of cooling tower splash pack could be enhanced by the reduction of the water surface tension with a chemical additive. Ryan [32] found that the addition of minute amounts of fluorochemical surfactants reduced the surface tension of water by up to 75%. The reduced surface tension results in smaller drops being formed through splashing and dripping, which in turn influences the thermal performance of the splash pack. Figure 12 shows the predicted performance of the reference splash pack (see the sensitivity analysis above) with and without a 50% reduction in the water surface tension. Both the predicted transfer characteristics and the pressure drop across the packing were increased by the reduction in water surface tension. The overall efficiency of the pack is slightly increased by the reduction in surface tension.

CONCLUSIONS

A mathematical model and a computer simulation program have been developed to predict the performance of counterflow cooling tower splash packing material. This program can be used to evaluate different splash pack designs without making use of empirical data from splash pack tests. The program uses empirical data relating to the grid characteristics, drop dynamics and drop formation by splashing, cutting and dripping. The use of the packet concept to group similar drops together works well in reducing the number of calculations and the amount of computer memory.

The counterflow cooling tower splash packing simulation program, SPSIM, was found to predict the correct trends in transfer characteristics and pressure drop with varying air and water flow rates. The predicted pressure drop data agreed well with the experimentally determined data for air and water flow rates in the ranges used in cooling towers. The actual transfer characteristic values were over-predicted by up to 25% at high water flow rates when the simulation program is compared with experimentally data obtained in a fill test facility with a 1.5×1.5 m^2 test section. In such a small test section, the effect of water bypassing the packing by flowing down the walls of the test tunnel is expected to yield low transfer characteristic data. Some uncertainty exists regarding the size of the correction made to correct the experimental transfer characteristic data for inlet and outlet effects. The simulation program can be used to compare different fill geometries and operating conditions, regardless of the fact that it may not predict the exact fill characteristics.

Through the use of the simulation program, some general guidelines regarding the optimum layout of cooling tower splash pack could be determined. It was found that the reduction of the surface tension of the circulating water results in increased cooling capacity and increased pressure drop across a splash pack due to reduced drop sizes. The overall improvement (ratio of transfer characteristics to total pressure drop across the packing) was found to be small even for a 50% reduction in water surface tension. The main limitations of the of current model are the following.

(1) The water film thickness covering the slats has to be specified. The thickness of the films on the slats cannot be determined analytically at this stage. The film thickness is expected to depend on the air flow rate, the water flow rate, the drop size distribution, the drop velocities, surface tension and grid geometry.

(2) The inability to predict the interaction effects between neighbouring splash crowns on the slats. These interactions are expected to influence the total mass of water splashing from the slats and/or the distribution of drops formed by splashing. At high water flow rates these interaction effects are expected to become more pronounced. The interaction effects could also be influenced by the air velocity through the packing material; at low air velocities the relative velocity between the drops and the slats increases, resulting in larger splash crowns being formed, which in turn implies more interaction between neighbouring splashes.

Suggestions for further work include the following:

1. Analytical determination of the film thicknesses on the upper surfaces of the slats.
2. The modelling of the interaction effects between splash crowns which are expected to influence the total mass of water splashing from the impact point and the distribution of the splash drop sizes.
3. The modelling of the splashing on the upper surface of the slats taking the varying film thicknesses and the wave action in the thin films covering the slats into account.
4. Determining the effect of the shape of the upper surfaces of the slats on the total volume of water leaving the surface of the slats due to splashing and the distribution of splash drops.
5. The analytical modelling or experimental deter-

mination of the size distribution of drops dripping below bi-planar grids.

6. The modelling of non-contact interaction effects in a poly-disperse spray of drops (with different velocities). These effects are expected to result in lower drop drag and a corresponding decrease in heat/mass transfer.

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