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COMPUTER SIMULATION OF HYDRID FILL IN CROSSFLOW MECHANICAL-INDUCED-DRAFT COOLING TOWERS

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ABSTRACT

A computer model was developed to simulate the operation of evaporative cooling towers. Special consideration was given in the development of this computer model to simulate hybrid fills for evaluating alternatives to improving the cooling capacity of existing towers. Results from this computer simulation are presented which predict the effect on overall cooling tower performance of this hybrid fill. The effect of increasing the heat transfer potential is contrasted with the increased resistance to airflow offered by the film fill. To verify the computer model, results were compared to field measurements from two mechanical-induced-draft cooling towers at the Browns Ferry Nuclear Plant--one with splash-bar fill and one modified by adding diagonal wedges of film fill.

INTRODUCTION

Evaporative cooling towers are used to reject heat to the atmosphere from thermal systems such as steam power plants. In an evaporative cooling tower, the water acts as both the heat transporting medium and the source of evaporative mass. Evaporation occurs as hot water comes in direct contact with colder air. This evaporative process is effective even when the air is initially saturated with water vapor because the water-vapor-bearing capacity of air increases as it is warmed by the hot water. Because the latent heat capacity of water at atmospheric pressure is three orders of magnitude larger than the specific heat, evaporation of even a small fraction of the water produces significant cooling.

In a mechanical-induced-draft cooling tower, the air is drawn through the tower by means of a fan located downstream of the air/water interaction zone. In this region several transport processes occur including evaporation, which involves the transfer of both mass and energy; convective heat transfer, which involves the transfer of energy; and fluid flow, which involves the transfer of momentum. Because the desired effect of the cooling tower is the transfer of energy from the water to the air, energy transfer is the process of primary importance. The processes of mass and momentum transfer are also significant because they are intimately coupled to the heat transfer. Thus any attempt to numerically model evaporative cooling towers should include all three processes.

In the air/water interaction zone of an evaporative cooling tower, the object is to transfer the maximum amount of energy from the water to the air. Two key factors in this transfer of energy are interfacial area and contact time between air and water. The purpose of fill material is to increase the contact time and interfacial area in an evaporative cooling tower. The effect of the fill is to retard the falling of the water thereby increasing the contact time as well as to break up the waterflow into fine droplets or thin sheets, which increases the interfacial area. There are two major classifications of fill commonly used in large-scale evaporative cooling towers: splash-bar and film. Splash-bar fills emphasize separating the waterflow into droplets and forcing it to cascade. Splash-bar fills range in fabrication from redwood slats to perforated PVC troughs. Film fills emphasize breaking up the waterflow into thin sheets and are typically fabricated from asbestos-cement or PVC sheets oriented vertically within the interaction zone. Due to the vertical orientation of the sheets in film fill it is predominantly used in counterflow arrangements. There are some fills currently manufactured which are neither splash-bars nor sheets but a three-dimensional lattice structure. This third category of fills which has both splash-bar and film characteristics is commonly lumped into the category of film fills. Thus the reader should be aware that not all film fills are of the sheet variety.

In evaporative cooling, activity is defined as the product of the interfacial area and the contact time. Splash-bar fills typically provide less activity than film fills. However, film fills typically offer greater resistance to airflow than splash-bar fills. The intermediate type fills such as the three-dimensional lattice are an attempt to combine the lower resistance to airflow found in splash-bar fill with the greater activity associated with sheet film fill. Another means of incorporating the desirable features of the splash-bar and film fills is to use both types of fill in the same cooling tower. This combination is referred to as a hybrid fill.

Hybrid fills can be used to upgrade the performance of existing cooling towers. Total replacement of splash-bar fill in an existing cooling tower with film fill in an attempt to upgrade performance may be financially as well as mechanically infeasible. In addition to the consideration of salvaging some of the investment in the original fill, there is the concern of structural strength and fan sizing. Because film fill is more effective than splash-bars in retarding the water as it falls, the existing cooling tower structure may not be able to support the weight of an entire zone of water-laden film fill. Because film fill typically offers greater resistance to airflow, the fan system as originally sized may no longer be adequate. Thus there is a clear motivation in such cases to consider a hybrid fill.

Another motivation for the consideration of hybrid fills is the optimization of such factors as cooling load; water pumping power cost, which is related to the height of the fill; fill cost; structural cost; and fan power costs. An important factor to consider in the design of a hybrid fill is that the heat and mass transfer driving potentials are not uniform in a crossflow cooling tower. The heat transfer driving potential is the difference between the water and dry-bulb temperatures. The mass transfer driving potential is the difference between the concentration of the evaporating species at the source (the water) and in the receiving species (the air). The water is hotter at the inlet than the exit and the air is cooler and drier at the inlet than the exit. Thus, there is the potential for an optimum hybrid design based on the concept of locating the high activity film fill in the region of lowest energy transfer potential and locating the less resistant-to-airflow splash-bar fill in the region of highest energy transfer potential. As mentioned previously, the heat, mass, and momentum transfers are coupled; therefore, altering the fill structure will affect the airflow, which in turn affects the heat and mass transfers. As a result of the coupling of the transfers, the determination of an optimum hybrid is a formidable task. The logical approach to the task of designing an optimum hybrid is the development of a computer simulation which will account for the coupling of the heat, mass, and momentum transfers and rapidly evaluate alternative designs.

COMPUTER SIMULATION OF EVAPORATIVE COOLING TOWERS WITH HYBRID FILL

A computer simulation of any process is essentially the development of a computational algorithm which models the phenomena involved in the process. In the case of an evaporative cooling tower, this involves the determination of empirical relationships for the heat transfer, mass transfer, and pressure drop. This information is obtained via laboratory studies (Lowe and Christie) where experimental controls and detailed measurements can be obtained as well as data collection and correlation (Kelly, CTI, and Majumdar and Singhal). Any applicable governing principles must also be considered in the development of a computer simulation. In this case the governing principles are the conservation of mass, energy, and momentum.

These transfer relationships and governing equations representing the phenomena must be solved by analytical or numerical methods. In this case the latter is chosen because nonlinearities and coupling of the phenomena render analytical methods intractable. Application of the transfer relationships and governing principles by means of numerical methods begins with discretization of the cooling tower int
components consisting of inlet air straighteners, ho
water distribution system, fill, excess moistur
separators, plenum, and fan. These components are the
further divided into computational cells. It i
necessary in the use of numerical methods to divide th
region of interest into smaller regions so that th
finite resolution of the computations will approximat
the infinite resolution of mathematical analysis. Th
selection of computational cells and the application o
mathematical relationships to those cells is beyond th
scope of this paper. The specifics of the compute
simulation used in the present study are given b
Benton. A brief description of the governi
equations, modeling assumptions, and numerical schem
may be found in the appendix.

The computer simulation of hybrid fills involve
difficulties not encountered in the simulation
uniform fills. One such difficulty is that the resolu
tion of the location of different fill types is
greater than the resolution of the computational cel
within the fill. The shape of the hybrid fill is al
limited by the shape of the computational cells.
the present computer simulation, the computation
cells within the fill are rectangular, havi
dimensions of approximately one foot (0.3 meter) on
side (Benton). There are 225 computational cel
within the fill, which is assumed to have later
symmetry. Each cell may be assigned a different ty
of fill. Computer simulation of hybrid fills where t
adjacent computational cells contain two differe
types of fill which have significantly different hea
mass, and momentum transfer characteristics prese
another difficulty. This situation is analogous to
discontinuous medium, and special consideration
given to cases such as these in the present comput
simulation (as detailed by Benton). To verify
computer simulation for hybrid fills it is necessary
obtain field measurement on two full-scale cool
towers which are identical except for the introduct
of the hybrid fill.

VERIFICATION OF COMPUTER SIMULATION

To verify the computer simulation, it is necess
to demonstrate internal or local consistency wit
each individual computational cell. This is assured
the present simulation by the similarity betwee
single computational cell and the experimen
apparatus used to determine the empirical relationsh
for heat transfer, mass transfer, and pressure dr
The criteria for the consistency of the experimen
data and the accuracy of the empirical relationsh
used are discussed by Lowe and Christie, CTI,
Majumdar and Singhal. The configuration of the t
cell used to obtain these relationships varies from
investigator to another, which introduces s
uncertainty. The expense of obtaining such data
substantial and much is proprietary. There is lit
opportunity to compare the consistency of data ta
with the same fill in different experimental apparat

The demonstration of global consistency is
necessary in the verification of the computer sim
tion. First, global checks are made for s
consistency and are used to determine the converg
of the numerical algorithm. These global checks
total mass transfer, total heat transfer, and pres
balance. Second, a comparison is made between comp
and measured water temperatures for full-scale coo
towers.

The mechanical-induced-draft crossflow coo
towers at the TVA Browns Ferry Nuclear Plant (B
provide an ideal verification opportunity f

computer simulation of hybrid fills. The plant, which is located in northern Alabama, has three 1100 MWe generating units and six banks of cooling towers, each with 16 cells. The cooling towers were originally fitted with splash-bar fill. To improve the performance of the towers, diagonal wedges of film fill were added to one bank of towers and both towers were tested. The towers are identical except for the film fill wedges. The test data as well as a description of the test conditions and procedure for the tower with hybrid fill and the tower with splash-bars only are given by Gidley. A description of the towers and the modifications are also found in Gidley. The actual location of the film fill is illustrated in Figure 1 (this figure is drawn to correct scale as indicated). The approximate location of the film fill in the tower used in the computer simulation is indicated by "F" in Figure 2. Other data were also used to verify the present computer simulation (Benton). The empirical relationships for heat transfer, mass transfer, and pressure drop were taken from Majumdar and Singhal without modification. A comparison of the measured and computed exit (cold) water temperatures is given in Figure 3. In this figure exact agreement between measured and computed temperatures would be indicated if all the data points lay directly on the solid line. Note that this is a comparison and not a correlation. There is no curve-fitting in this analysis.

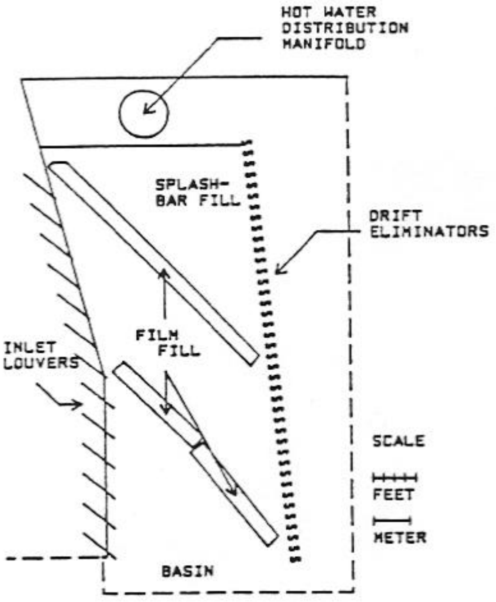

Fig. 1 Location of Film Fill in BFNP Hybrid Tower

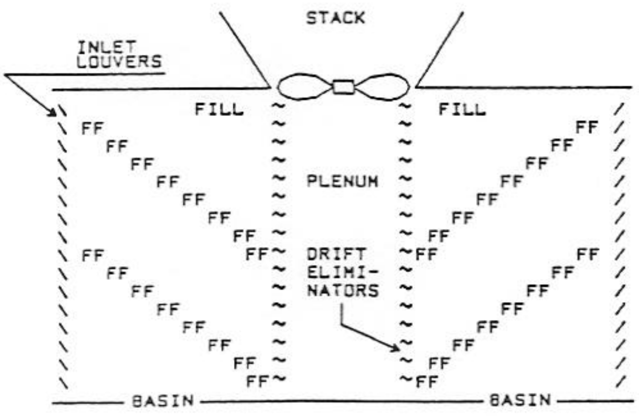

Fig. 2 Approximate Location of Film Fill in BFNP Hybrid Tower Used in Computer Model

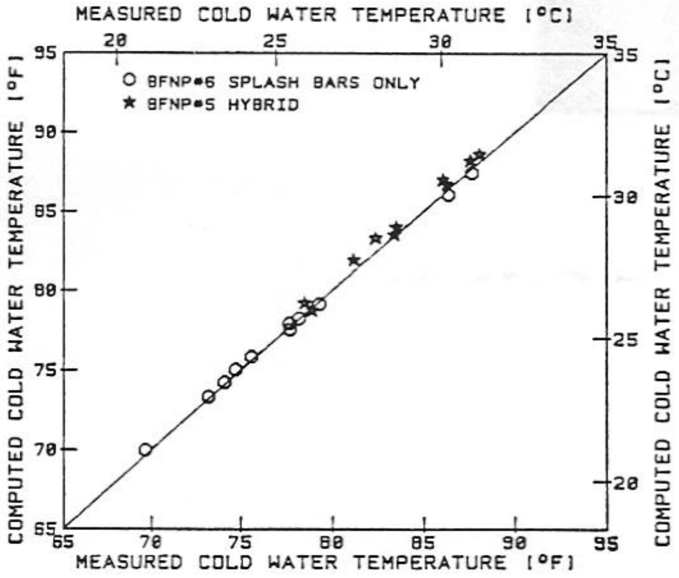

Fig. 3 Comparison of Measured and Computed Cold Water Temperature

EVALUATING THE PERFORMANCE OF COOLING TOWERS WITH HYBRID FILLS USING COMPUTER SIMULATION

Simulation of the hybrid fill in the BFNP cooling towers is an example of how the present computer model can be used to evaluate the performance of evaporative cooling towers with uniform or hybrid fills and to examine alternative designs for improving performance. The location of the film fill in a hybrid arrangement influences the performance of the tower because the heat, mass, and momentum transfers are coupled. To determine the total effect of the hybridization on cooling tower performance it is necessary to simulate the operation of the tower over an entire range of conditions and compare the heat rejection performance. This comparison is limited to the design conditions for the BFNP towers: a constant water loading of 17,188 gpm (1.08 m^3/s), a constant fan power input of 170 hp (127 kW), relative humidity of 75 percent, and a constant range of 31.7°F (17.6°C). The range of a cooling tower is defined as the difference between the average inlet water temperature and the average exit water temperature and is directly proportional to the energy transferred from the water to the air. The towers evaluated include all splash-bar fill (the original BFNP towers), splash-bar fill with two downward sloping diagonal sections of film fill (modified hybrid BFNP tower as shown in Figure 2), splash-bar fill with two staggered upward sloping diagonal sections of film fill (Figure 4), splash-bar fill with five cascaded upward sloping diagonal sections of film fill (Figure 5), and all film fill. The dimensions of the towers in each of these five cases are identical and are indicated by the scale in Figure 1.

The quantity typically selected to illustrate the heat rejection performance of an evaporative cooling tower is the average exit (cold) water temperature.

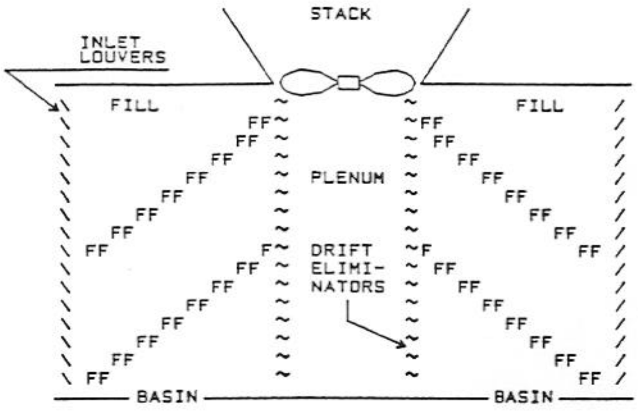

Fig. 4 Hypothetical Hybrid With Two Downward Sloping Diagonal Wedges of Film Fill

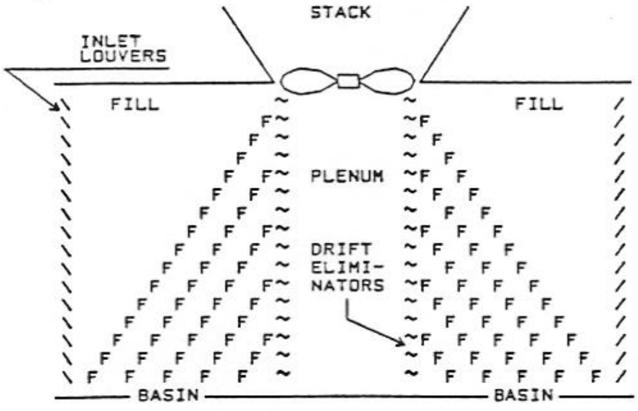

Fig. 5 Hypothetical Hybrid With Five Downward Sloping Diagonal Wedges of Film Fill

The computed cold water temperatures for the five cases listed previously are illustrated in Figure 6 for a range of wet-bulb temperature. A lower cold water temperature at a given wet-bulb indicates better cooling tower performance. The bottom curve in Figure 6 indicates the best performance and the top curve indicates the poorest performance. Figure 6 shows that the only hybrid investigated that is consistently superior (under these conditions) to the original splash-bars is the two staggered upward sloping diagonals (Figure 4). The greatest improvement in performance of the four alternatives is obtained with the five cascaded upward sloping diagonals (Figure 5). However, for the latter there is a slight loss in performance at high wet-bulbs. The case of "all film fill" consistently resulted in the poorest performance of those investigated.

DISCUSSION

The decrease in performance in cases with the addition of film fill, as indicated by a higher cold water temperature in Figure 6, may be explained in light of the coupling of the heat, mass, and momentum transfers. Because of the increased resistance to airflow offered by the film fill, the net activity within the fill zone may be reduced, resulting in less heat and mass transfer. The potential effects of hybrid fill on the airflow are a reduction in the mass flowrate and avoidance. The introduction of any high airflow-resistant fill will result in a reduction in the total airflow, assuming that the delivered fan power remains constant. Avoidance is a more serious design problem because the air will tend to avoid the regions of higher resistance unless there is no other available path. Selecting the location of the film fill within a hybrid must be based on a coupled thermodynamic and hydrodynamic model such as the present computer simulation.

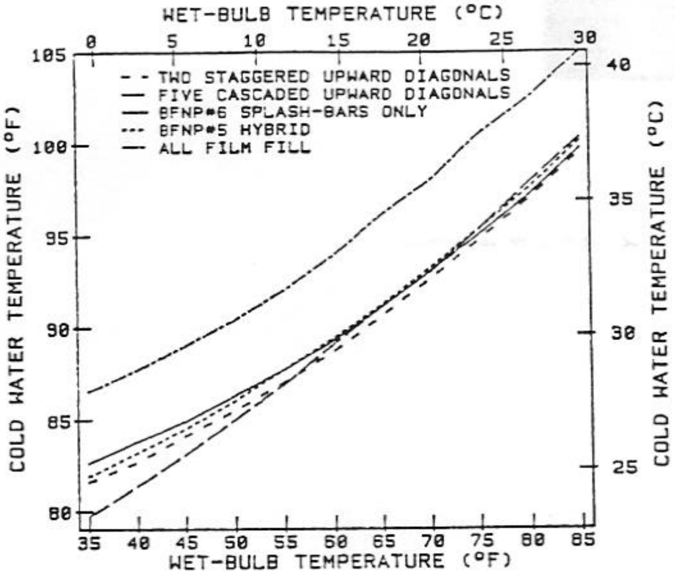

Fig. 6 Computed Cold Water Temperature For Five Fill Arrangements

The computed total airflows corresponding to the cases illustrated in Figure 6 are shown in Figure 7. As expected, the airflow for the hybrids is always less than the "splash-bars only" case. The "all film fill" shows a substantial reduction in airflow. As illustrated in Figure 6, a reduction in airflow does not necessarily indicate a reduction in performance because all of the hybrids produced lower cold water temperatures than the "splash-bars only" at moderate wet-bulbs. Figure 6 shows that the performance of most of the hybrids is less than the performance of the "splash-bars only" at high wet-bulbs. Figure 7 shows a corresponding reduction in airflow at high wet-bulbs. This reduction in airflow along with the coupled reduction in performance of the hybrids is a result of the fact that the mass flowrate of air for a constant fan power is proportional to the density to the two-thirds power, which is inversely proportional to the absolute temperature. Thus, for a constant fan power the mass flowrate of air is inversely proportional to the absolute temperature to the two-thirds power.

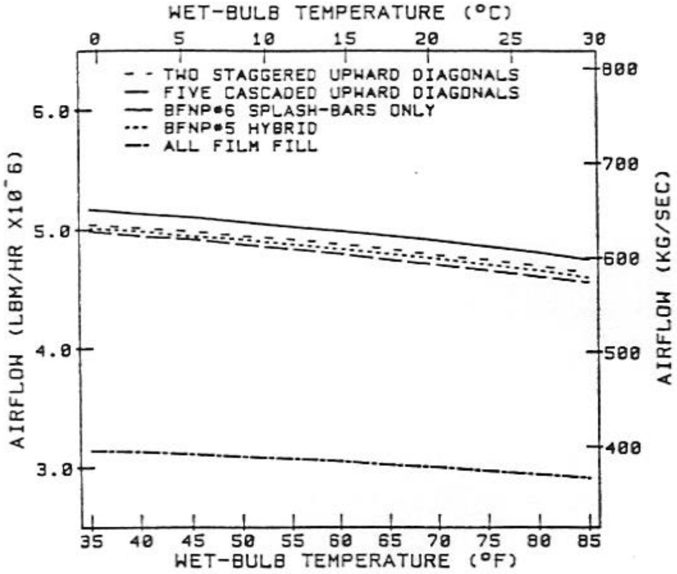

Fig. 7 Computed Airflow For Five Fill Arrangements

Because of this reduction in airflow due to the increased resistance of film fill, film fill must be used sparingly in a hybrid to obtain positive results. To alleviate the problem of avoidance, the film fill within a hybrid must be strategically located. Both thermodynamics and hydrodynamics must be considered in the strategic design of hybrid fills. The thermodynamic parameters considered are the local heat and mass transfer driving potentials (i.e., the local temperature and mass concentration differences, respectively). The relative local heat and mass transfer potentials are shown in Figures 8 and 9, respectively, for a wet-bulb of 55°F (12.8°C), "splash-bars only," water loading of 17,188 gpm (1.08 m^3/s), fan power input of 170 hp (127 kW), relative humidity of 75 percent, and range of 31.7°F (17.6°C). In Figures 8 and 9, a "9" indicates the highest potential and a "1" indicates the lowest potential.

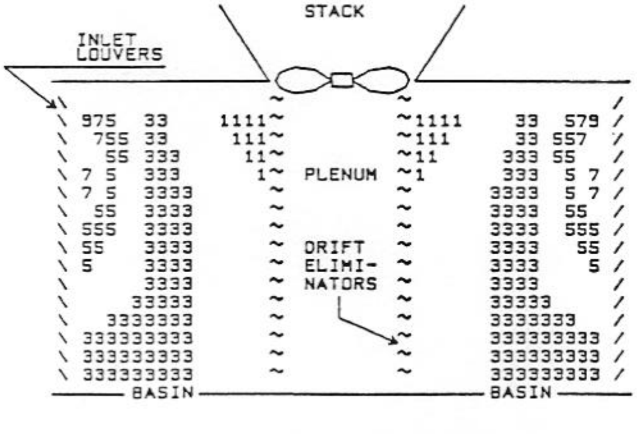

Fig. 8 Computed Distribution of Relative Mass Transfer Driving Potential

It can be seen from these figures that the highes potential is in the upper, outside corner of the fil and the lowest is toward the center, particularly nea the bottom.

It would be tempting to locate the film fill i the regions indicated in Figures 8 and 9 by "1" and ou to the edge of the "3"s. This selection, however ignores the hydrodynamic considerations. If too muc film fill is located in the bottom of the tower, th air will avoid it. If too much film fill is located a the top near the "1"s the airflow will be reduced i the region designated by the "9"s. Furthermore, if th film fill is oriented in a vertical column, only part of the water will pass through it. These thermo dynamic and hydrodynamic considerations lead to th hybrids illustrated in Figures 1, 2, 4, and 5. Th hybrid shown in Figure 4 provides the best performanc over the entire range of wet-bulbs shown in Figure 6 The hybrid in Figure 5 provides the best performanc for wet-bulbs below 55°F (12.8°C). Both were obtaine by trial and error from 24 designs inspired by Figure 8 and 9. If different splash-bars and film fill wer considered, the optimum location of the film fill coul change.

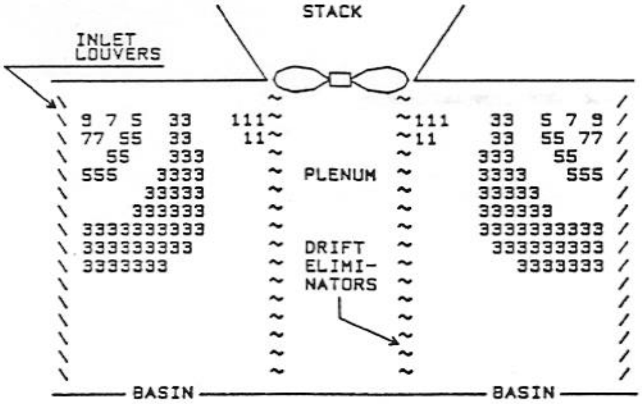

Fig. 9 Computed Distribution of Relative Heat Transfer Driving Potential

CONCLUSIONS

The present computer simulation is a coupled mode for heat, mass, and momentum transfer. Other tha specific geometry, the simulation requires empirica relationships for heat transfer, mass transfer, ar pressure drop for the fill, some of which are readil available from experimental studies (e.g. Lowe ar Christie). The simulation is consistent with globa checks of the conservation equations and agrees wel with field data for full-scale towers (e.g., Figure and Benton). The present computer simulation als agrees well when used for hybrid fills as demonstrate using the field data taken at the BFNP towers. Tr present computer simulation can be used to evaluat hybrid fill designs and to determine an optimum hybri for a particular application.

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APPENDIX

GOVERNING EQUATIONS SOLVED IN THE COMPUTER MODEL

1. Conservation of mass for the dry air (the net increase of dry air within a computational cell is zero).
2. Conservation of mass for the water vapor (the net increase in water vapor leaving a computational cell equals the evaporation rate within the cell).
3. Conservation of momentum (Bernoulli's equation with headloss is used).
4. Conservation of energy for the moist air (the net increase in the enthalpy flux of the moist air leaving a cell equals the sensible plus evaporative heat transfers within the cell).
5. Conservation of energy for the water (the net gain in energy of the moist air within a cell equals the net loss of energy of the water).

ASSUMPTIONS MADE IN THE COMPUTER MODEL

1. Steady-state, steady-flow.
2. Lateral symmetry.
3. Wet-bulb temperature is equivalent to the adiabatic saturation temperature.
4. The water flows vertically downward.
5. The airflow may be described by Bernoulli's equation with headloss.

NUMERICAL SCHEME USED IN THE COMPUTER MODEL

1. The cooling tower is broken down into computational cells, each cell is treated as a separate thermodynamic control volume.
2. The grid consists of cell boundary nodes (no central nodes are used).
3. The governing equations are applied to each cell in integral form.
4. The heat and mass transfer within each cell is evaluated using implict values to assure maximum numerical stability.
5. The Gauss-Seidel method (current-update, point-by-point successive substitution) is used to solve the resulting set of nonlinear simultaneous equations.