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Experimental Study of Bank Aerodynamics
of Atmospheric Spray Cooling Systems

by

William Wang
Robert W. Porter

December 1977

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EXPERIMENTAL STUDY OF BANK AERODYNAMICS
OF ATMOSPHERIC SPRAY COOLING SYSTEMS

by

William Wang
Research Assistant

Robert W. Porter
Associate Professor of Mechanical Engineering

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ABSTRACT

Atmospheric spray cooling systems are alternatives to cooling ponds and cooling towers for rejecting condenser heat of steam-electric power plants. These systems may also be employed in connection with secondary wastewater treatment for a beneficial use of waste heat. The wastewater may be introduced for evaporative and blow-down make up although heavier loading is also possible. Aerobic biological processes are thermally accelerated, and the sprays provide the necessary increased oxygen through their natural aeration.

The present study concerns the flow of the atmospheric wind over the confining banks of the system. Of particular interest were the effects of bank height and geometry on the profiles of wind velocity and turbulent diffusivity incident to the sprays and the possibility of flow separation over the sprays which may substantially degrade thermal performance. The literature of flow over similar geometries is reviewed. A wind-tunnel study was performed on a scale reduced 90:1 wherein both 1:3 and right-angle banks of two bank heights were analyzed. The full-scale equivalent bank heights were 2.3 m (7.5 ft) and 6.8 m (22 ft). Measurements were also taken with sprays modeled with wire mesh of equivalent aerodynamic blockage. The atmospheric boundary layer was approximately simulated through the use of a counter wall jet, screens and artificial aerodynamic surface roughness. The resultant profiles of wind velocity, Reynolds turbulent stress and turbulence kinetic energy are presented and compared. The Reynolds stress and turbulence kinetic energy are indicative of the level of turbulent diffusivity, important in atmospheric dispersion of heat and humidity. Field measurements were also taken of mean wind velocity for three bank geometries at Commonwealth Edison Company's Quad-Cities Nuclear Station (Cordova, Illinois). However, these data were more limited and less controlled than the wind-tunnel results. The 1:3 slope bank cases resulted in no apparent flow separation although the velocity and turbulent stress were reduced near the base of the banks, especially for the higher bank case. In the case of the right-angle banks, flow separation occurred extending downwind approximately 1.5 bank heights. It is suggested that the spacing from the base of the bank to the first row of modules be greater than 1.5 bank heights.

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviation	Term
U	Mean Longitudinal Velocity
u	Longitudinal Velocity
u'	Fluctuation of Longitudinal Velocity
$\overline{u'^2}$	Squared RMS Longitudinal Velocity Fluctuation
V	Mean Lateral Velocity
v	Lateral Velocity
v'	Fluctuation of Lateral Velocity
$\overline{v'^2}$	Squared RMS Lateral Velocity Fluctuation
W	Mean Vertical Velocity
w	Vertical Velocity
w'	Fluctuation of Vertical Velocity
$\overline{w'^2}$	Squared RMS Vertical Velocity Fluctuation
x	Longitudinal Distance
y	Lateral Distance from Centerline
z	Vertical Distance from Floor

CHAPTER I

INTRODUCTION

A. Basic Problem

In some steam electric power plants, open atmospheric spray cooling systems are used to reduce the temperature of hot circulating water discharged from condensers. The hot water flows in a canal where arrays of modules spray water into the air above for cooling purposes (Fig. 1). Fixed-manifold spray ponds are also employed. In either case, effective cooling depends on convection and diffusion offered by the atmospheric wind. That is, heat and mass transfer from the sprays is gained by the atmospheric boundary-layer wind. The ability of the atmosphere to disperse heat and humidity will determine the local driving potential for combined sensible-evaporative cooling, the wet-bulb temperature. In the worse case, it may be envisioned that the atmospheric wind would separate over the top of the spray field. In any case, it is important to have a knowledge of the effect of bank geometry on both the approach wind and the interference of upwind sprays on downwind sprays.

Measurements of mean velocities at a number of locations were made in the field at Commonwealth Edison Company's Quad-Cities Nuclear Station (Illinois) for several canal bank heights and wind directions. In addition, much more detailed information and consistency were obtained in a wind tunnel where the approach wind was well defined and controlled. The objective of the study included definition of the effect of bank

APPROACH
BOUNDARY LAYER

Figure 1. Cross Section of Typical Canal with Wind in Cross Flow

height and spray blockage on basic flow patterns, including guidelines on the possible onset of flow separation over the sprays, as a function of geometry. In addition it was desired to identify "flow modules" or well defined segments, which might be more amenable to analysis than the entire complex system.

B. Literature Survey

In modeling the atmospheric wind, Cermak (1971) found the so-called Richardson number, a measure of atmospheric stability, to be important in the lower or "surface" layer of the atmospheric boundary layer. Instability occurs due to surface heating or induced buoyancy. Assuming fully turbulent flow over a plane with uniform surface roughness, quantities including friction velocity, friction temperature and a certain "Monin-Obukhov" length may be used as characteristic dimensional parameters. To simplify the problem, the present study was limited to neutral stability where the "Monin-Obukhov" length is infinite and the only relevant parameter is friction velocity. In stable and unstable atmospheres, diffusivity is decreased and increased, respectively. The mean velocity profiles are also altered about the neutral case.

The surface layer, which extends approximately up to 30 m height, is analogous to the equilibrium constant-stress layer of a turbulent boundary layer. Extensive experiments have been made to confirm the neutrally stable logarithmic mean velocity profile as well as

constant Reynolds stress (Haugen, Kaimal and Bradley, 1971). Sutton (1953) prepared a table of the roughness length usually encountered in the atmosphere. Considering the turbulent energy equation, production and dissipation terms are found to balance each other during equilibrium conditions (Lumley and Panofsky, 1964). Successful wind-tunnel simulations for the surface layer under neutral and unstable conditions were accomplished by Mery, Schon and Solal (1974) using injection-jet techniques.

The atmospheric boundary layer can also be analyzed numerically based on certain closure models (Wyngaard, Cote and Rao, 1974) which define turbulent diffusivity. The air flow over the canal including sprays might be represented as a discontinuity of surface roughness. Elliot (1958) used the horizontal momentum integral equation assuming that the downstream mean velocity profile becomes logarithmic with its own characteristic friction velocity immediately behind the discontinuity. The immediate adjustment of the friction velocity was moreover confirmed experimentally. Schlichting (1968) and Taylor (1969) used the horizontal momentum and continuity equations with a mixing-length closure model for the Reynolds stress and found self-preservation of Reynolds stress distribution. Recognizing the importance of turbulence modeling, Peterson (1969) added a third equation, namely the turbulent energy equation, with a

equilibrium closure model and found a characteristic inflection point in the mean velocity profile. Later Peterson (1972) studied the relative importance of various terms in the equations with a more detailed analysis. He also observed from his numerical analysis that at least in the upper portion of a transition layer, the production and dissipation terms did not balance and the diffusion term became of the same order of magnitude as the convection term and was not negligible. Adding the pressure term, which was neglected in all the analyses mentioned above, Shir (1972) did a more complete analysis using vorticity, continuity and turbulent energy equations with essentially the same closure model. He also found an inflection point in the mean velocity profile. A more sophisticated model was developed by Rao, Wynaard and Cote (1974) who used 7 equations for 7 unknowns ($\overline{u'w'}$, $\overline{u'^2}$, $\overline{v'^2}$, $\overline{w'^2}$, U , W and ϵ where ϵ is a dissipation factor) with a closure model by Lumley and Nouri (1974). They found that $\frac{\overline{u'w'}}{q}$, where q is turbulence energy, was not constant in the transition layer. They also observed an inflection point in the mean velocity profile.

In the results of the theoretical work mentioned above and some experiments (Bradley, 1968), an internal boundary layer was found to exist originating from the roughness discontinuity and to grow as the $4/5$ power of distance downstream. Elliot (1958) found that its height increased and decreased according to instability and stability conditions, respectively. It was observed that the internal boundary layer must go to a thickness of 500 m before it was in complete equilibrium with the high-altitude geostrophic wind (Munn, 1966). Peterson (1969), Shir (1972), and Rao, Wynaad and Cote (1974) all found that the wind shear differed from the equilibrium value.

In addition to the model of a step change in the roughness height to characterize the surface roughness change, different roughness configurations were also used for experimental and theoretical analysis. Peterson, Kristensen and Su (1976) in observing air flow from a bay onto land noticed an acceleration caused by the slope of the bank coupled with a slowing down by the greater roughness of the land. A similar analysis was done numerically (Britte and Frost, 1976) for air flow over a single step up and indicated an overshoot in the

velocity profile near the ground as the air passed over the step. Also it was found that smaller roughness lengths contributed to delayed reattachment of the flow because of larger acceleration. Sato, Onda and Saito (1974) found reverse flow and indications of vortex shedding in their modeling of air flow over a hill.

C. Summary of Approach

Laboratory Experiments. In order to simulate the atmospheric surface layer, an abnormally thick boundary layer is needed in the wind tunnel. A combination of inlet screens, roughness (Gartshore and DeCroos, 1976) and a counter-jet (Nagib and Tan-atichat, 1974) was used.

For scaling purposes, a boundary layer was generated with a reference velocity at a scaled-down height matched to that of full-scale height in the atmosphere. For comparable non-dimensional velocity profiles, this approach is equivalent to matching the turbulent stress τ

and the friction velocity $\sqrt{\tau/\rho}$ because the turbulent diffusivity and velocity gradient should compensate. The velocity at a reference height was chosen because of its prior measurement in the field. Models resembling sprays were placed between model banks inside the wind tunnel. The models were scaled down 90:1 to approximately 5 cm size, as were the canal banks. Spray models were constructed with wire mesh of 20% porosity which approximates the blockage of actual full-scale sprays (see Appendix) based on mean drop size (about 4 cm), spray height (about 5 m), spray diameter (about 13 m) and flow rate (about 10^4 l/min). The wind tunnel was about 43.2 x 43.2 cm in cross section. The modification of the simulated approach atmospheric boundary layer was studied as it proceeded over the upwind bank and through the sprays. Actually, emphasis was given to the simpler case of no sprays where a variety of bank heights and slopes were utilized. Hot-film anemometry, including measurement of mean velocity, turbulence intensity and Reynolds stress, was used.

Assuming an atmospheric "surface layer" of 30 m, which when scaled down 90:1 reduces to 33 cm (13.1 in), the flow in the wind tunnel should ideally have constant Reynolds stress ($\overline{u'w'}$) up to 33 cm (13.1 in) height. However because of limitations of the facility, this goal was not fully accomplished. A lesser goal would be to simulate the constant stress layer over a characteristic height of

the order of the height of the model used in the tunnel. The height of approximately constant Reynolds stress was found to be about 6 cm (2.5 in) which corresponds to 5.4 m full scale in the atmosphere. The two models tested here had heights of 2.5 cm (1 in) and 7.6 cm (3 in) which correspond to 2.3 m (7.5 ft) and 6.9 m (22.6 ft) full scale, respectively. Thus, while the mean velocity profiles were simulated over somewhat greater heights than either of these, the Reynolds stress profiles were deficient particularly for the higher bank case. The reason for the deficiency in Reynolds stress profile is related to the lack of "equilibrium" of the boundary layer generated by artificial means. In this regard, the present facility does not represent nearly as high a degree of simulation as, for example, achieved by Nagib and Tan-atichat (1974) in a larger closed-cycle facility. Thus due caution should be exercised in interpreting the results. Nevertheless, the experiment should give a better understanding of what may be expected as one varies the bank height and shape in the atmospheric shear layer, as compared with the meager information previously available.

Field Experiments. Measure of mean velocity were made in the field for several bank heights and wind directions. Cup anemometers were used to measure wind speed, and wind direction was found from bivanes with a rheostat element. Measurements at an upwind location 2 m

over ground level and at one or more positions on the banks were made. Data were also taken directly within the spray field in other experiments. However, it was not possible to make measurements in the wind tunnel directly corresponding to these particular locations because of interference of the mesh model with traversing. Nevertheless, wind tunnel measurements were taken above the sprays and downwind.

Care must be taken in interpreting the field experimental results because of uncontrollable factors involved. Gusts and complex bank geometry are two reasons which prevented reliable and comparable results. As a consequence, for example, large deviation of the results was obtained after data reduction. Therefore only qualitative comparison could be made in this respect. The large scatter in the field data is characteristic of what is obtained in atmospheric experiments especially where terrain is not uniform and the surface layer is not in equilibrium. Indeed, while the wind tunnel does not represent an accurate simulation of the atmospheric wind, it is relatively reproducible and allows a comparison of different geometries under more controlled conditions. Further, it was not practical to utilize hot-wire anemometry instrumentation in the field. Therefore, only mean wind speed and direction were measured in that case while Reynolds stress and turbulence energy were

determined in the laboratory.

CHAPTER II

LABORATORY EXPERIMENT

A. Description of Wind Tunnel

A centrifugal blower was used to drive with induced draft an open-cycle wind tunnel 43.2 cm x 43.2 cm in cross section (Fig. 2). A butterfly valve between the tunnel and blower controlled the flow rate. Starting from the open end, a counter jet and then an array of flow resistances were used to obtain the profile intended. The counter jet was a 5.08-cm (2-in) diameter cylinder with 3.18-mm (0.125-in) diameter holes spaced 1.27 cm (0.5 in) apart and aligned along the side. The counter jet could be rotated about its axis which was positioned just upstream of the inlet plane. Thus, the air jet stream could be adjusted for various momentum defect of the lower air stream drawn into the wind tunnel. The flow resistances consisted of sheets of air-conditioner filters placed one behind the other normal to the air flow at the inlet plane. Different heights of the sheets across the section resulted in a profile of drag across the inlet stream which in turn allowed further control of the initial velocity profile.

Downstream of the inlet plane there was a 30.4-cm (1-ft) long plywood section with soda straws acting as honeycomb in order to damp large-scale turbulence.

Figure 2. Views of Wind Tunnel

Artificial two-dimensional roughness of 9.52-mm (0.375-in) height, placed 7.62 cm (3 in) apart, was used to maintain the boundary layer throughout the tunnel. Following a 1.22 m (4 ft) long plywood approach-flow section for flow stabilization, the air entered a 2.13 m (7 ft) long clear-plexiglass test section of 9.52-mm (0.375-in) wall thickness. The plywood approach-flow section and the plexiglass test section were provided with a false floor about 7.62 cm (3 in) above the bottom surface. The canal-section model formed a depression into the false floor as described later. However, the tunnel was initially operated with a uniform flat floor in order to establish the existence of equilibrium of the approach boundary layer. Finally, the test section exhausted into a second soda-straw honeycomb followed with a nozzle leading to the butterfly valve and blower.

The ceiling of the test section consisted of 15.2 cm (0.5 ft) and 30.4 cm (1 ft) long plexiglass panels at either end and a 1.68 m (5.5 ft) long x 91.4 cm (3 ft) extra-wide plexiglass panel in between, which could be slid laterally for traversing. Longitudinally along the movable top there was a 1.3 m (53 in) long and 1.11 cm (0.438 in) wide slot along which tracks for the traversing mechanism were placed and through which the hot-film probe support was inserted. A 3.35 m (11 ft) long x 2.54 cm (1 in) wide steel strap with a

hole of diameter slightly larger than that of the probe support was placed over the long slot to close the opening and to reduce air leakage. The traversing system permitted three-dimensional mobility. By sliding the plexiglass top, a probe could be moved laterally from wall to wall. The traversing track mechanism allowed covering the 1.35 m long test length from end to end. A height about equal to that of the test section could be traversed manually with the probe clamped in place for measurements.

B. Instrumentation

An 'x'-type hot film probe fed orthogonal velocity signals to each of two Thermo-System Inc. Heat Flux System Anemometers (Model 1000A, Serial No. 025,026). A Thermo-System Inc. Heat Flux System Sum and Difference Meter (Model 1015) was used to add or subtract the signals and to provide either a DC or AC output (Fig. 3). The latter was fed into a Hewlett Packard RMS Voltmeter (Model 3400A) to obtain the root mean square of the signal. Then an integrator with a 10-s time constant integrated the signal. A Vidar Integrating Digital Voltmeter (Model 500) was used to provide the final reading. For mean signal measurement, the DC output from the sum and difference meter was connected directly to the integrator. Calibration of the hot-film

Figure 3. Schematic of Experiment Instrumentation

probe was done by means of a separate confined-flow measurement. A Brooks Instrument Co. Inc. Rotometer (Model 6-1110-24-MFB) was used to measure air flow rate through a cylinder with 9.52-mm (0.375-in) diameter opening at both ends. The probe was placed just inside the downstream opening, and readings on the digital voltmeter were calibrated against the average flow velocity through the opening as implied by the rotometer. A mathematical analysis of the measured signals is provided in the appendix. As a result of data processing, the mean velocity, the turbulent energy and Reynolds stress are determined.

C. Models

To simulate a maximum anticipated bank height above water level (about 7 m), the canal-section model had a 7.62 cm (3 in) high bank which fell below the false floor (Fig. 2). There were two 1:3 slope sections between which a 68.6 cm (27 in) long plexiglass sheet was placed to simulate the collecting water surface. More shallow bank heights could be simulated by using a raised collecting surface floor. Right-angle banks of variable height were also employed.

Spray models were made of wire mesh with 20% porosity which approximated the blockage of actual full-scale sprays (see Appendix).

The wire mesh were made into cones with a 12.7-cm (5-in) base diameter and then the top half of the cones were displaced downward to give an "umbrella" height of 5.08 cm (2 in). The models were placed between the slope sections in the wind tunnel. However, most of the measurements were taken without the sprays in order to determine the effect of bank geometry only.

As the bank height was 7.62 cm (3 in) above the wind-tunnel floor, the bottom 7.62 cm (3 in) of height at the two ends of the tunnel were blocked off. The straw-honeycomb sections were also blocked off. Therefore instead of the full 43.2-cm height, the effective cross section of the wind tunnel was 35.6 cm high.

As previously noted, from the plywood flow-developing section to the end of the test section, artificial two-dimensional roughness consisting of horizontal wood bars placed perpendicular to the air flow were glued along the floor. In order to simulate approximately the same friction velocity as full scale (about 0.3 m/s) with typical free-stream velocity obtainable in the wind tunnel (4.99 m/s), 7.62-cm (3-in) spacing between the 9.52 mm (0.375 in) high x 1.27 cm (0.5 in) wide roughness bars were required (Gartshore and DeCroos, 1976).

The boundary-layer velocity profile (Fig. 4) extended over a thickness of about 15 cm (6 in), corresponding to 14 m in the full scale atmosphere. The actual atmospheric

Figure 4. Typical Mean Velocity Profile

boundary-layer extends to so-called geostrophic heights of the order of 300 m. The Reynold stress ($\overline{u'w'}$) and turbulence energy $\frac{u'^2 + w'^2}{2}$ profiles are shown in Figures 5 and 6. These quantities should be constant in the lower "surface layer" which extends to about 30 m in the real atmosphere. The present simulation has only very approximately constant quantities and then only over a height of about 6 cm (2.5 in) which corresponds to a simulated height of 5.4 m in the atmosphere. Thus, caution should be made in evaluating the resultant flow patterns. However, the region close to the wall was considered most important, and the results obtained may be satisfactory when comparing data for the lower bank-height cases. Results for the higher bank cases are not strictly comparable with the lower height cases because the simulation was less valid. Neveththeless some trends can be identified, and the results for both high and low banks seem consistant as discussed later. The lack of complete simulation is due in part to the so-called macro and micro scales of turbulence not being correctly developed relative to full scale. Kulik (1976) found that in the present tunnel, before modification with the false floor which should have little effect, the scales were not in good agreement with those found in the atmosphere. As discussed in Chapter 1, the present facility does not have the degree of equilibrium required for accurate

Figure 5. Typical Reynolds Stress Profiles

Figure 6. Typical Turbulence Energy Profile

simulation of the mean flow together with the turbulence characteristics in the surface layer. The best that could be achieved in the present tunnel was an approximate simulation of mean profile, Reynolds stress and turbulence energy over a height of the order of the model characteristic height. This was considered an acceptable minimum requirement for present purposes.

D. Results

In the following, measured profiles of mean velocity U , Reynolds stress $-\overline{u'w'}$, and turbulence energy $(\overline{u'^2} + \overline{w'^2})/2$ are discussed and compared. Within the experimental accuracy, generally a few per cent, the profiles were found to be typically as shown in Figures 4-6 and quite invariant over the distance along the flow direction when the false floor was continued over the canal-section model. Evidently, much greater length of tunnel is needed to achieve Reynolds stress and turbulence energy equilibrium with the velocity profile as characterized by a height of constant latter quantities. It was also established that there was no significant variation across the width of the wind tunnel outside of the thin boundary layers on the vertical walls. Unless noted otherwise, all measurements presented refer to centerline values. It should be noted that with changes in models, the tunnel freestream varied slightly. However, this change was not great enough to affect the qualitative

discussion that follows. However, in the numerical comparison in the next chapter where field data are also considered, velocities are taken in ratio to a reference approach velocity (the upstream approach velocity at a height corresponding to 2 m full scale or 2.2 cm in the wind tunnel). While turbulence characteristics were not made in the field, a typical friction velocity $u_* = \sqrt{\tau_w/\rho} = \sqrt{u'w'}$ for the atmospheric surface layer is 0.3 m/s. In the present facility, the $u'w'$ of Figure 5 suggest a value of u_* about 0.44 m/s in the laboratory, which may be high. Since no turbulence measurements were made in the field, no further quantitative evaluation can be made in this regard.

Profiles for the following 5 cases are shown in Figures 7-11. Dashed lines in Figure 11 represent the wire mesh.

Table 1. Definition of 5 Experimental Cases

Case	Bank Geometry	Bank Height	Spray Model
1	1:3 slope	7.62 cm (3 in)	Absent
2	Right-angle	7.62 cm (3 in)	Absent
3	1:3 slope	2.54 cm (1 in)	Absent
4	Right-angle	2.54 cm (1 in)	Absent
5	1:3 slope	2.54 cm (1 in)	Present

For Cases 1 and 5, the original model was used. A horizontal sheet 99.1 cm (39 in) long was placed over the

Figure 7. Development of Profiles for Case 1

Figure 8. Development of Profiles for Case 2

Figure 9. Development of Profiles for Case 3

Figure 10. Development of Profiles for Case 4

Figure 11. Development of Profile for Case 5

model collecting surface for Case 3 in order to reduce the bank height. For Case 2, two right-angle bank sections were placed over both slope sections while using the original collecting surface, and an addition 68.6 cm (27 in) long sheet was placed elevated between the bank elements to raise the collecting surface for Case 4.

Case 5 includes the spray models added to Case 3. The bank height in both of these cases corresponds to 2.3 m (7.5 ft) full scale which is representative of bank heights in many applications. The 1:3 slope is also more representative than the right-angle step. Thus, Case 5 represents the most comprehensive and representative simulation. The 6 rows of spray modules of Case 5 were chosen to correspond to the largest systems now used in practice. However, the flow through multiple rows of sprays may be approximated by boundary-layer development where downstream influence is negligible (Chaturvedi and Porter, 1977). Thus, the situation where fewer rows of sprays are employed can be considered to a first approximation as being the flow encountered through the upwind number of rows of interest.

The widths of the canal-section models were matched in the following respects. The two high-bank cases (1 and 3) were of equal width at the water collecting surface. The lower bank-height cases (3, 4 and 5) were of equal width as measured across the top of the banks

in comparison with the respective cases of equal slope. Constraints on the length of the traversing mechanism prevented making measurements over the full downstream length of the 1:3 slope cases (1, 3 and 5). However, this region is less important in the present study than the approach-flow side.

Figures 7-11 show the overall characteristics of the flow. We shall refer to the upstream bank region in more detail later.

It may be observed that for the greater bank heights (Cases 1 and 2), mean velocity, Reynolds stress and turbulence energy profiles all have an inflection point which extends to nearly the same horizontal distance from the top of the bank during the course of flow development downwind. Thus, while the right-angle bank tends to separate, as shown in more detail below, recovery of the inflected profiles occur at approximately the same distance downwind. Where the first spray module is beyond this point, the effect of bank geometry on performance is expected to be of secondary importance. In the lower bank-height cases (3, 4 and 5), inflection of the velocity profiles is considerably less than the high-bank cases.

It is interesting to note that the spray-module models (Fig. 11) have considerable effect on the turbulence characteristics but lesser effect on the mean

flow as compared with the case without sprays (Fig. 9). The spray-model measurements were made down the centerline of the tunnel which was centered between two adjacent sprays. A comparison of Figures 9 and 11 suggests that the boundary-layer velocity is little altered in passing between the sprays but that turbulent diffusivity is increased due to the turbulence induced by blockage. It may be concluded that thermal performance would be greater than predicted by neglecting spray blockage because heat and humidity would disperse faster in the spray case.

It can be seen in Figure 11 for the spray case (5) that the non-uniform spray geometry results in a periodic-like structure of the turbulence parameters over distance, especially Reynolds stress. This may be due to repeated dispersion of turbulence of each spray-model encountered proceeding downwind. Analytical models such as those of Chaturvedi and Porter (1977) employ a uniform spray region and can not show such a structure. Apparent scatter in the experimental field data may be due to the nonuniformities.

We now consider the flow over the windward bank in more detail for Case 1-4 as illustrated in Figures 12-20. The objective was to characterize the effect of the banks on possible flow separation. We first discuss the 1:3 slope cases (1 and 3) and then the right-angle cases (2 and 4). The mean velocities for the 1:3 slope are

Figure 12. Mean Velocity Near the 1:3 Bank

Figure 13. Mean Velocity for High Bank (Continued)

Figure 14. Reynolds Stress Near the 1:3 Banks

Figure 15. Reynolds Stress for the High Bank (Continued)

Figure 16. Turbulence Energy Near the 1:3 Banks

Figure 17. Turbulence Energy Near the High 1:3 Bank (Continued)

Figure 18. Velocity Profiles Near the Right-Angle Banks

Figure 19. Reynolds Stress Near the Right-Angle Banks

Figure 20. Turbulence Energy Near the Right-Angle Banks

shown in Figures 12 and 13. At the same longitudinal distance from the top of the banks, the corresponding profiles are quite similar for both heights. However, the velocity continues to decrease for the high-bank case (Fig. 13), although there is no apparent separated flow. The Reynolds stress are compared in Figures 14 and 15, and it is seen that these profiles are also similar over the initial distances downwind measured from the top of the bank. In this case, the high-bank has a very low turbulent stress region at its base, suggesting dispersion would be considerably reduced therein. The turbulence energy profiles (Figs. 16 and 17) are quite similar.

The cases of the right-angle banks (2 and 4) are more dramatic. Indeed, these were selected to accentuate possible separation and indicate the potential of sensing the phenomena. The velocity profiles (Fig. 18) show a stagnant region at the base of the "backward facing step", especially for the high bank case. It should be noted that the "x-type" hot-film probe used can not actually sense a low-speed reverse flow due to its physical structure. However, the stagnant region likely includes some recirculation. The region appears to extend about 1.5 bank heights downstream in both height cases. It may be desirable to employ a criterion in system design wherein at least this distance is allowed up to the first

spray pattern. If a spray lies within the stagnant region, dispersion of heat and humidity would be appreciably reduced. Reynolds stress and turbulence energy are shown in Figures 19 and 20 for the right-angle cases. According to the analogy of heat, mass and momentum transfer, heat and humidity flux should be proportional to Reynolds stress.

It is sometimes assumed that the ratio of Reynolds stress to turbulence energy is constant. This ratio is illustrated in Figures 21-25. It appears that 0.5 would be an overall representative value (Figs. 21 and 22). However, there is considerable departure from this value in certain regions. Over the 1:3 slope, the ratio is reasonably maintained (Figs. 23 and 24). However, for the right-angle banks the ratio essentially vanishes near the base of step (Fig. 25). The characteristic horizontal distance in this regard is about 1 step height.

The above data and conclusions may be of value in formulating so-called "flow modules" wherein a complex flow field is analyzed in segments which are subsequently matched to describe the entire system. Summarizing the conclusions of the present section based on the wind-tunnel measurements:

1. The blockage of sprays does not greatly influence the mean wind profile but turbulence, characterized by Reynolds stress and turbulence energy, is increased. Neglect of spray blockage would

Figure 21. Ratio of Reynolds Stress to Turbulence Energy (1:3 Slope)

Figure 22. Ratio of Reynolds Stress to Turbulence Energy (Right-Angle Bank)

Figure 23. Ratio of Reynolds Stress to Turbulence Energy
Near the 1:3 Bank

Figure 24. Ratio of Reynolds Stress to Turbulence Energy Near the 1:3 High Bank (Continued)

Figure 25. Ratio of Reynolds Stress to Turbulence Energy Near the Right-Angle Bank

therefore provide conservative (low) dispersion of heat and humidity.

2. No appreciable alteration of the approach boundary-layer flow occurs over the low-bank case, which corresponds to 2.2 m (7.5 ft) full scale, with 1:3 slope. An increase in bank height leads to reduced wind velocity and turbulence at the base of the bank. For a right-angle bank, a stagnant region is contained within about 1.5 bank heights in the horizontal direction.
3. The ratio of Reynolds stress to turbulence energy is approximately 0.5 except in the "core" of the stagnant region (within about 1 bank height horizontally) wherein it effectively vanishes.

We will defer conclusions regarding spray-system design criteria until Chapter IV wherein both laboratory and field experiments are compared.

CHAPTER III

FIELD EXPERIMENT

A. Summary of Instrumentation

Wind direction and components of wind run were measured in the field experiments. Average wind speed was determined by the difference in wind run over a time interval. Horizontal wind run was determined by Gill cup-type photo-chopper anemometers which generated 10 counts/revolution corresponding to 1.00 m (3.28 ft) of wind run. A 2-2000 pulse divider module, which divided by 2, 4, 10, 20, 40, 100, 200, 400, 1000 or 2000, provided the necessary sensitivity and resolution. The instruments were calibrated in the IIT Environmental Wind Tunnel from 0.3 to 8.9 m/s ± 0.3 m/s (0.6 to 20 mph ± 0.6 mph). Counts were recorded on event channels of field strip-chart recorders which had a typical chart speed set at 1 cm/min with the pulse divider set for about 10 counts/cm on the chart. Wind direction in the horizontal plane was sampled by using a Gill bivane which had a potentiometer range of 1000 ohms and which corresponded to a range of 360 degrees. The output voltage signal from the bivane potentiometer was fed to an analog channel of a strip-chart recorder with a recorded accuracy within ± 5 degrees.

A Gill helical propeller-type anemometer with photo-chopper (15 counts/revolution with 0.29 m (0.96 ft) run of wind) drove a pulse divider module with a 64-count adder

and reset feature for analog recording. This instrument is typically accurate within ± 0.09 m/s (0.2 mph) over the range 0.07-8.9 m/s (0.2-20 mph). The device was originally intended to measure vertical velocity but this was found to be too small to measure in practice for the present experiments. Instead, the anemometer was oriented parallel with the canal bank but perpendicular to the canal in order to determine that component of velocity.

B. Geometry

Field data were taken at three locations of different bank heights: 1.5 m (5 ft), 3.4 m (11 ft) and 5.8 m (19 ft). The overall slopes of rise to run of the banks at these locations were 1:3, 1:2.5 and 1:5, respectively. The geometry of the banks and the location of the instruments used are shown in Figure 26. Ambient horizontal wind speed and direction were determined substantially upwind at a 2-m elevation. Starting with the low bank of 1.5-m (5-ft) height (Case A), the cup and propeller anemometers were placed essentially together 0.3 m (1 ft) vertically above a "shelf" on the bank and were even with the approach ground level. For the intermediate 3.4-m (11-ft) bank height (Case B), the anemometers were placed nearly together 1 m (3 ft) vertically above the ground near the middle of the bank slope. Three locations were chosen for the high 5.8-m (19-ft) bank height (Case C). One (Case C-1) was 7.6 m (25 ft), another (Case C-2) was 17 m (56 ft) and the last one (Case C-3)

Figure 26. Location of Field Measurements

was 20 m (64 ft) from the canal. They were all placed 2 m vertically above the sloping bank. Thus, all velocities were at 2-m local elevation except Cases A and B which were below that elevation. All average wind speeds were in the range of 2-4 m/s (5-10 mph). However, gusts of the order of $\pm 50\%$ were typical.

C. Results

Three-minute averages were computed from the wind-run data in order to eliminate the principal contribution of wind gusts. A diagrammatic representation of the velocity components plotted here are given in Figure 27. The results for each of the cases were again averaged, and the data are plotted in Figures 28-30 together with the standard deviation of the data. Averages of the combined cases are also shown.

For the ratio of local horizontal velocity normal to the canal to the upstream horizontal velocity normal to the canal (V_1/V_{1u}), an average value of 0.588 was obtained (Fig. 28). The data for C-3 corresponds to a near-parallel flow and is not meaningful for this normal component. The low-height-measurement case (A) appears to be in the range of the other data. An average value of 0.683 was found for the velocity parallel to the bank but normal to the canal in ratio to ambient horizontal normal velocity (V_3/V_{1u}). Because the horizontal velocity is one component of the velocity parallel to the bank, a higher ratio (0.683) should be and was obtained.

Figure 27. Velocity Components

Figure 28. Field Experimental Velocity Ratio-Horizontal and Normal Component

Figure 29. Ratio of Velocities - Parallel to Ground and Normal to Canal

Figure 30. Ratio of Velocities - Parallel to Canal

The ratio of horizontal velocities parallel to the canal are shown in Figure 30. It was anticipated that this ratio would be nearly unity as suggested by two-dimensional aerodynamic theory wherein the "sweep" velocity component perpendicular to the plane of two dimensionality is unaffected by the object in question. In the present case, the canal was not exactly two dimensional and there may have been appreciable effects of flow variation along the channel. In any case, the parallel component was reduced below ambient on the average.

It is apparent that the wind-velocity components over the canal banks are reduced below corresponding ambient components in all cases. Considering the component normal to the canal, which is of particular significance in providing air-vapor circulation, about 0.68 of the freestream component occurred parallel to the bank on the average. However, scatter in the data were in the range of $\pm 50\%$ of this value. This scatter may have been due to imperfect correlation of data due to both spatial and temporal variation of the "ambient" condition. Therefore, the conclusions drawn above should strictly only be interpreted qualitatively. Nevertheless, a comparison between field measurements and laboratory measurements is of considerable interest. Such a comparison is made in the next chapter although qualified by the scatter in the field data.

CHAPTER IV

DISCUSSION

A. Comparison of Laboratory and Field Data

When compared to the wind-tunnel study, mean velocity measurements in the field experiments agree qualitatively. The component of horizontal mean velocity across the canal bank was reduced in all cases. Because it was not attempted to model exactly the canal configuration of the field experiment, no precise comparisons can be made. Nevertheless, it is possible to select the laboratory simulation closest to the field experiment in question and to compare velocity ratios at corresponding locations. The comparison is summarized in Table 2.

The field cases listed in Table 2 are defined in Figure 26 and explained in more detail in Chapter III. The "location" noted in Table 2 corresponds to that of the base of the anemometer tripod as a fraction up the total bank height. The "slope" is the overall value corresponding to total rise to run ratio. However, it can be seen in Figure 26 that the actual bank geometry is made up of several intersecting slopes. The "bank height" is also the overall value. "Local measurement height" is that above ground level from the base of the anemometer tripod to the sensor. Quantity V_1/V_{1_m} is the ratio of local horizontal velocity normal to the canal to the corresponding reference ambient value. Ambient velocity

Table 2. Comparison of Laboratory and Wind Tunnel Results

Case	Location*	Field Experiments**				Lab. Experiments			
		Slope	Bank Ht. (m)	Local Meas. Ht. (m)	$V_1/V_{1\infty}$	Slope	Bank Ht. [†] (m)	Local Meas. Ht. [†] (m)	$V_1/V_{1\infty}$
A	58	1:3	2	0.3	0.50	1:3	2	0.3	0.30
B	50	1:2.5	4	1.0	0.45	1:3	2	1.0	0.53
C 1	24	1:5	6	2.0	0.50	1:3	7	2.0	0.18
C 2	58	1:5	6	2.0	0.80	1:3	7	2.0	0.35
C 3	68	1:5	6	2.0	3.75	1:3	7	2.0	0.42

*At per cent of height of rise (base of anemometer tripod).

**See Figure 26.

†Full-scale equivalent.

was taken at 2-m elevation.

In the case of the laboratory experiments, the nearest full-scale equivalent height is noted. The velocities were taken from Figures 7 and 9, using interpolation in order to determine velocities at the desired location. It can be seen that the laboratory equivalent bank height for Case B is only about 1/2 the field case. Similarly, the laboratory slope for Case C is 1:3 rather than 1:5 as in the field experiment. The effect of the difference between approach reference wind speeds in the field and wind tunnel is compensated by using velocity ratios relative to respective ambient values.

Because of the large standard deviations of the field data (Fig. 28), the laboratory and field experiments are in uncertain agreement for Cases A and B. However, much lower velocity ratios were found in the laboratory for Case C. It should be noted that the field data for Case C-3 is probably in error since the velocity ratio should not exceed unity. As discussed in Chapter III, there is a practical difficulty in performing both spatial and temporal correlations of the field data with the instrumentation employed. Further, the bank geometry was not exactly simulated. However, while the laboratory bank height was effectively higher, the slope was lower than the field case which tends to compensate the alteration of velocity profile. We must therefore attribute most of the

discrepancy to field experimental error. Indeed, ability to more accurately control conditions and to finely resolve spatial variation points out the advantage of wind tunnel measurements of the present type.

B. Summary of Conclusions

In examining the mean velocity, Reynolds stress and turbulent energy profiles, there seems to be a stagnant region immediately downstream of the banks, particularly for a right-angle step change (Figs. 18-20). In a study of high-speed flow, over a similar backward facing step change, a separation region was observed where reverse flow occurred (Chang, 1970). However, the hot-film probe used in this wind-tunnel measurement could not detect reverse flow; thus, no comparison could be made in this respect.

The similarity of the flow developments near the top of the right-angle banks suggests that this flow behaves like a separated free shear layer, which possesses an inflection point in the mean velocity profile (Schlichting, 1968). As the flow further develops, the ground at the base of the bank starts to interfere with the flow structure. At a large enough distance downstream, the flow behaves essentially as a wall boundary layer. There is also similarity in flows near the top of the sloping banks independent of height.

The assumption of a constant $\overline{u'w'}/((\overline{u'^2} + \overline{w'^2})/2)$ ratio seemed to be reasonably well justified by the laboratory experiment except in the stagnant region (Figs. 21 and 22). The stagnant region was particularly pronounced for the right-angle banks and extended downstream about 1.5 bank heights. A more limited stagnant region occurred at the base of the 1:3 sloping bank of equivalent full scale height of 7 m (20 ft). With the spray model placed between the canal banks, the flow suffered some retardation along the sprays (Fig. 11), but the principal effect seemed to be an increase in turbulence.

The onset of separation seemed to be dependent on the geometry of the bank. For the 1:3 slope bank (Figs. 12-17), only a relatively small stagnant region appeared to exist. However, for the more abrupt right-angle bank (Figs. 18-20), a very prominent stagnant region was evident. Because the present instrumentation can not resolve a low-speed reverse flow, the stagnant regions are suggestive of separated flow. Indeed, for the right-angle case such separated flow is expected.

Also an increase in sharpness of the bank and/or an increase in bank height leads to not only a decrease in velocity but a decrease in turbulence near the base of the bank as well. Reduction in velocity and turbulent diffusion may increase local heating and humidification

of the spray region and thereby reduce spray performance. Nevertheless, if one allows 1.5 bank heights downwind of the base of the bank before encountering the first spray pattern, interference of the bank on spray performance can probably be largely eliminated even for the higher, more abrupt banks.

C. Recommendations for Future Study

For efficient heat transfer, flow in the region between the canal banks should not be inhibited before encountering the sprays. Further the highest level of turbulence is desirable to encourage diffusion of heat and humidity. One possibility is to increase approach-flow aerodynamic surface roughness continuously far upstream of the sprays. Roughness just on the bank is unfavorable as it may aid separation, which would increase local heating and humidification build up and reduce spray performance. However, an increase in roughness upstream would increase turbulence of the approach flow. This would decrease wind velocity near the ground for given geostrophic wind but would tend to increase turbulent diffusivity. This effect could be conveniently studied in the wind tunnel because the free stream is only weakly dependent on the surface roughness, being dominated by the inlet and outlet flow control sections.

Another factor of possible interest in future studies

is the effect of the intermediate shelf that typically is found part-way down the bank (Fig. 26). It may also be desirable to study the effect of approach wind angle to the canal in the laboratory. No particular correlation was observed in the field experiments, probably due to scatter in the data. While normal wind velocity is important for convection, the full wind speed determines ambient turbulent diffusivity.

Other possibilities for study include the use of a "boundary-layer fence" upstream of the canal. This "shelterbelt" would lead to local flow separation. However re-attachment may be such to favor smooth non-separated flow over the bank. The main question to be answered would be how to design such a fence (height and position upstream) for a variety of atmospheric-stability-dependent velocity and turbulent diffusivity profiles and wind angles to the canal.

Finally, the wind tunnel should be upgraded in order to simulate both velocity and turbulence parameters to a greater height relative to the model. This may be done in part by moving the counter jet from the inlet into the confined section of the tunnel. The tunnel should also be lengthened.

Another factor is the dispersion of heat and humidity downstream in the environment. The present study concerned the so-called "near field" while previous studies concerned

the "far field" (Weinstein, Porter, Chaturvedi, Kulik and Paganessi, 1977) and did not consider the detailed geometry of the source. Modifications to the wind-tunnel facility in progress should permit simultaneous study of the near and far fields, especially as yet uncertain and undefined region where they overlap.

Finally, the present study has suggested some possible flow modules which may be studied experimentally and analytically by themselves. The modules include: the flow over a sudden change in wall angle for the case of a sloping bank, flow over a backward facing step for a right-angle bank, and flow through porous media with distributed non-uniform blockage. The major difficulty is that the present approach flow is a rather thick shear layer rather than a plug or thin boundary-layer flow as usually assumed by most investigators.

APPENDIX A

HOT FILM ANEMOMETRY

The "x-type" probe is illustrated in Figure 31. In the derivation below, lateral mean and fluctuating velocity are assumed zero in the y direction. Ordinarily in two-dimensional flow of the present type, these components are relatively small. Assuming King's law, the relationship between the power required to maintain constant film temperature and the convection velocity are as follow

$$P = A + BV_n^{1/2}$$

where V_n is the velocity normal to the film. As the two films in the "x"-type probe are orthogonal to each other, the normal velocity for the two films (1 and 2) would be respectively

$$V_{n1} = u \sin \theta_1 + w \cos \theta_1$$

$$V_{n2} = u \sin \theta_2 - w \cos \theta_2$$

where θ is the angle formed by either film to the mean flow vector (In our case, $\theta_1 = \theta_2$).

Using average and fluctuating quantities for total power based on $u = U + u'$ and $w = W + w'$

$$P_1 = \bar{P}_1 + P_1' = A_1 + B_1 (U \sin \theta)^{1/2}.$$

$$\left[1 + \frac{W \cot \theta}{U} + \frac{w' \cot \theta}{U} + \frac{u'}{U} \right]^{1/2}$$

Figure 31. Schematic Diagrams of X-Type Probe

$$P_2 = \bar{P}_2 + P_2' = A_2 + B_2 (U \sin \theta)^{1/2} \cdot \\ \left[1 - \frac{W \cot \theta}{U} - \frac{w' \cot \theta}{U} + \frac{u'}{U} \right]^{1/2}$$

Expanding the function under the square root term

$$\bar{P}_1 + P_1' = A_1 + B_1 (U \sin \theta)^{1/2} \cdot \\ \left[1 + \frac{W \cot \theta}{2U} + \frac{w' \cot \theta}{2U} + \frac{u'}{2U} \right] \quad (A-1)$$

$$\bar{P}_2 + P_2' = A_2 + B_2 (U \sin \theta)^{1/2} \cdot \\ \left[1 - \frac{W \cot \theta}{2U} - \frac{w' \cot \theta}{2U} + \frac{u'}{2U} \right] \quad (A-2)$$

Taking the time average of the equation A-1 and A-2 yields:

$$\bar{P}_1 = A_1 + B_1 (U \sin \theta)^{1/2} \left[1 + \frac{W \cot \theta}{2U} \right] \quad (A-3)$$

$$\bar{P}_2 = A_2 + B_2 (U \sin \theta)^{1/2} \left[1 - \frac{W \cot \theta}{2U} \right] \quad (A-4)$$

By A-3 and A-4

$$U = \frac{1}{4 \sin \theta} \left[\frac{\bar{P}_1 - A_1}{B_1} + \frac{\bar{P}_2 - A_2}{B_2} \right]^2 \quad (A-5)$$

$$\frac{W}{U} = \frac{2 \left[\frac{\bar{P}_1 - A_1}{B_1} - \frac{\bar{P}_2 - A_2}{B_2} \right]}{\cot \theta \left[\frac{\bar{P}_1 - A_1}{B_1} + \frac{\bar{P}_2 - A_2}{B_2} \right]} \quad (A-6)$$

Subtracting Eqs. A-3 and A-4 from A-1 and A-2 respectively,

$$P_1' = B_1 (U \sin \theta)^{1/2} \left[\frac{w' \cot \theta}{2U} + \frac{u'}{2U} \right]$$

$$P_2' = B_2 (U \sin \theta)^{1/2} \left[\frac{-w' \cot \theta}{2U} + \frac{u'}{2U} \right]$$

Taking the square and then time average of the equations

$$\overline{P_1'^2} = B_1^2 U \sin \theta \left[\frac{\overline{w'^2} \cot^2 \theta}{4U^2} + \frac{2\overline{u'w'} \cot \theta}{4U^2} + \frac{\overline{u'^2}}{4U^2} \right]$$

$$\overline{P_2'^2} = B_2^2 U \sin \theta \left[\frac{\overline{w'^2} \cot^2 \theta}{4U^2} - \frac{2\overline{u'w'} \cot \theta}{4U^2} + \frac{\overline{u'^2}}{4U^2} \right]$$

Rearranging

$$\frac{\overline{u'w'}}{U^2} = \frac{4 \left(\frac{\overline{P_1'^2}}{B_1^2} - \frac{\overline{P_2'^2}}{B_2^2} \right)}{\cot \theta \left[\frac{\overline{P_1} - A_1}{B_1} + \frac{\overline{P_2} - A_2}{B_2} \right]^2} \quad (\text{A-7})$$

$$\frac{\overline{u'^2} + \overline{w'^2} \cot^2 \theta}{U^2} = \frac{8 \left(\frac{\overline{P_1'^2}}{B_1^2} + \frac{\overline{P_2'^2}}{B_2^2} \right)}{\left[\frac{\overline{P_1} - A_1}{B_1} + \frac{\overline{P_2} - A_2}{B_2} \right]^2} \quad (\text{A-8})$$

For our case, $\theta = 45^\circ$, thus the equations A-5, 6, 7 and 8 reduce to

$$U = \frac{1}{2\sqrt{2}} \left(\frac{\bar{P}_1 - A_1}{B_1} + \frac{\bar{P}_2 - A_2}{B_2} \right)^2 \quad (\text{A-9})$$

$$W = \frac{1}{\sqrt{2}} \left[\frac{\bar{P}_1 - A_1}{B_1} - \frac{\bar{P}_2 - A_2}{B_1} \right] \left[\frac{\bar{P}_1 - A_1}{B_1} + \frac{\bar{P}_2 + A_2}{B_1} \right] \quad (\text{A-10})$$

$$\overline{U'W'} = \frac{1}{2} \left[\frac{\overline{P_1^2}}{B_1^2} - \frac{\overline{P_2^2}}{B_2^2} \right] \left[\frac{\bar{P}_1 - A_1}{B_1} + \frac{\bar{P}_2 - A_2}{B_2} \right]^2 \quad (\text{A-11})$$

$$\overline{U'^2} + \overline{W'^2} = \frac{1}{2} \left[\frac{\overline{P_1^2}}{B_1^2} + \frac{\overline{P_2^2}}{B_2^2} \right] \left[\frac{\bar{P}_1 - A_1}{B_1} + \frac{\bar{P}_2 - A_2}{B_2} \right]^2 \quad (\text{A-12})$$

The P_1 and P_2 required for data reduction were obtained from two anemometer channels which had voltage outputs proportional to the respective power required to maintain constant temperature of the hot films. The two signals were fed to a sum and difference meter which offered convenient switching from one signal to the other during measurement. The output was then fed to a RMS voltmeter, integrator, and then to a digital voltmeter for RMS fluctuation measurements $(\overline{P_1'^2}, \overline{P_2'^2})$, or directly to the integrator and digital voltmeter for mean value measurements $(\overline{P_1}, \overline{P_2})$.

APPENDIX B

ANALYSIS OF SPRAY BLOCKAGE

Figure 32. Sketch of Spray Pattern

The objective is to estimate the frontal-area blockage ratio of the layer of water drops in Figure 32. This ratio includes the accumulated frontal areas proceeding normal through the spray layer per unit normal area of the spray layer. Wire mesh of the same blockage ratio (porosity) is to be used to simulate the sprays.

In order to estimate the ratio, the following principal assumptions are made:

1. Drops are uniformly distributed in the spray layer.
2. The spray is confined in a volume between concentric cones of twice the spray height.

The center region of the spray is imagined to be formed by depressing the apex of the cones to the plane of the base of the cones. The following parameters are used in the resultant numerical calculation (Chaturvedi and Porter, 1977)

spray height	$h = 5 \text{ m}$
single spray flow rate	$Q = 0.167 \text{ m}^3/\text{s} \quad (10^4 \text{ liters/min})$
outer spray base diameter	$b_o = 13 \text{ m}$
Sauter mean drop diameter*	$D_s = 0.01 \text{ m}$

The frontal-area ratio for an average spray layer thickness $\delta/2$ where δ is the base spray layer thickness is

$$r = \frac{\delta}{2} \int_0^{\infty} n_D'''(D) \frac{\pi D^2}{4} dD$$

$$\equiv \frac{\delta}{2} n''' \pi D_A^2/4 \quad (\text{B-1})$$

where $n'''(D)$ is the number of drops per unit volume over the size range D to $D + dD$ per dD , n''' is the total number of drops per unit volume and D_A is the area averaged drop size. The total volume of water in the air is given by

*An intermediate value between those representative of fixed manifolded spray ponds and floating spray modules as given in Chaturvedi and Porter (1977).

$$\begin{aligned}
 Qt &= v_e \int_0^{\infty} n_D'''(D) \frac{\pi D^3}{6} dD \\
 &\equiv v_e n''' \frac{\pi D_v^3}{6}
 \end{aligned}
 \tag{B-2}$$

where t is time of flight, D_v is volume averaged drop size and v_e is the total volume of the spray layer.

The Sauter mean diameter is

$$D_s \equiv D_v^3 / D_A^2 \tag{B-3}$$

while the time of flight is estimated as the free-flight value

$$t = \sqrt{8h/g} \tag{B-4}$$

where $g = 9.8 \text{ m/s}^2$. The total spray volume is that bounded by the assumed cones

$$\begin{aligned}
 v_e &= \frac{2\pi h}{12} (b_o^2 - (b_o - 2\delta)^2) \\
 &\approx \frac{2}{3} \pi h b_o \delta
 \end{aligned}
 \tag{B-5}$$

Combining (B-1), (B-2) and (B-3)

$$r = \frac{3\delta Q t}{4 D_s v_e} \tag{B-6}$$

Using (B-4) and (B-5), the spray thickness δ cancels out

$$r = \frac{9}{4\pi} \sqrt{\frac{2}{gh}} \frac{Q}{D_s b_o} \quad (B-7)$$

$$= 0.186 \pm 20\%$$

using the assumed parameters.

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