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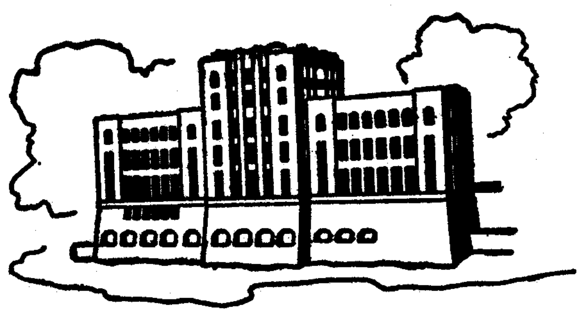

IIHR Report No. 160
Iowa Institute of Hydraulic Research
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ABSTRACT

An extended model investigation was conducted in a laboratory flume to determine downwind temperature distributions and the recirculation and interference characteristics of buoyant jets (forced plumes) issuing from 1/150-scale models of Marley Class 600 Double-Flow and from Marley round mechanical draft cooling towers. The dynamic scaling was based on equality of the densimetric Froude number $\mathbf{F}_D$ ($\mathbf{F}_D = V_j/\sqrt{(\Delta\rho_o/\rho_a)gD}$, where V_j is the jet velocity, D the stack diameter, g the gravitational constant, ρ_a the ambient fluid density, and $\Delta\rho_o$ the density difference between the jet effluent and its surrounding fluid), and the velocity ratio K ($K = V_j/V_a$, where V_a is the velocity of the cross-flow) in model and prototype. Plumes of positive (lighter effluent) and negative (heavier effluent) buoyancy were obtained by supplying heated and cooled, respectively, water through the model tower stacks. In the investigation $\mathbf{F}_D$ ranged from 2 to 7 and K from 0.4 to 12. Downwind temperature profiles and recirculation ratios for single towers and tower groups were determined, from temperature measurements made with thermistor temperature probes, for different tower orientations with respect to the approach flow. Various tower lengths, stack heights, and stack spacings were tested in order to quantify the recirculation ratio and to delineate temperature contours in the plumes as functions of $\mathbf{F}_D$, K, and tower geometry. It was found that recirculation generally increases with decreasing $\mathbf{F}_D$ for negative buoyancy plumes and with increasing $\mathbf{F}_D$ for positive buoyancy plumes. With increasing K the recirculation ratio generally decreases for positive buoyancy plumes; for negative buoyancy plumes recirculation first decreases then increases with K. Increasing stack height and stack spacing both reduce recirculation. The plume configuration is slightly sensitive to $\mathbf{F}_D$ in the range investigated, and is strongly affected by K. Round towers have significantly lower recirculation ratios than rectangular ones. The recirculation ratio for a two-tower system, with the second tower downwind from the first, is relatively insensitive to $\mathbf{F}_D$, but decreases markedly with increasing K.

ACKNOWLEDGEMENTS

Presented herein are representative results obtained in a laboratory investigation of cooling tower plumes which was initiated in 1968 and has continued to the present time (April 1974). The first eight authors were associated with one or another phase of the study. The investigation has been conducted under the administrative and technical guidance of Mr. Homer Fordyce of The Marley Company, and under the direction of J.F. Kennedy.

This report is essentially the same as a paper of the same title to be included in the Proceedings of Cooling Tower Environment - 1974, a three-day conference held at the University of Maryland in March, 1974. The present version has been prepared and issued in the Institute's Technical Report Series for use in responding to requests for copies of the Symposium paper, and for distribution by The Marley Company.

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LIST OF SYMBOLS

Symbol	Definition	Dimensions
D	Stack diameter	L
$\mathbb{F}_D$	$V_j/\sqrt{gD\lvert\Delta\rho_o/\rho_a\rvert}$	
H	Stack height, above far deck	L
K	V_j/V_a	
L	Spacing between axes of parallel, rectilinear towers	L
N	Number of cells in one tower	
$\mathbb{R}$	V_jD/ν	
S	Center-to-center stack spacing	L
T	Temperature	°C or °F
T_a	Ambient temperature	°C or °F
T_j	Jet temperature	°C or °F
ΔT	$T - T_a$	°C or °F
ΔT_o	$T_j - T_a$	°C or °F
V_a	Cross-flow velocity	L/T
V_j	Jet velocity	L/T
x, y, z	spatial components	L
ν	Kinematic viscosity	L^2/T
ρ_a	Density of ambient fluid	M/L^3
ρ_j	Density of jet fluid	M/L^3
$\Delta\rho_o$	$\rho_a - \rho_j$	M/L^3
θ	Angular orientation of tower relative to ambient flow	Degrees

PLUME RECIRCULATION AND INTERFERENCE IN MECHANICAL DRAFT COOLING TOWERS

I. INTRODUCTORY REMARKS

The aerodynamic functioning of a mechanical draft cooling tower and a mammalian nose are, in certain respects, quite similar. Each uses a common reservoir (the surrounding atmosphere) for both the source of fresh air and the sink for exhaled air. Moreover, the efficient operation of both depends on certain nonlinear features of fluid motion, which result in the velocity fields of jet flows from and sink flows to an orifice being radically different. In the case of the nose, the exhaled flow leaves the body as jets which discharge more or less along the nostril axes, outward from the body, rapidly mixing with the receiving air. The inhaled flow, on the other hand, approaches the nostrils as flow to a sink, a nearly irrotational motion, and hence the inhaled air comes from all around the nostrils. If these two fluid motions were fully reversible, with the flow fields during inhalation and exhalation differing only by the velocity directions being reversed, one would have to synchronize his breathing rhythm with a side-to-side motion of his head, or suffer asphyxiation in his own breath!

Figure 1 depicts schematically a cross section of a rectilinear mechanical draft cooling tower in a cross-wind. As is the case with noses, cooling towers of this type also rely on the differences between jet and sink flows for effective functioning. The buoyant jets, or forced plumes, leave the stacks with moderately high velocities (typically 25 to 35 fps; Kennedy, 1972), and the stack effluent is transported away from the tower as the plume transfers its momentum to and becomes diluted by the surrounding air. The flows toward the louvers and intake faces are of the sink type, with the ingested air being withdrawn from all around the tower. Therefore, in the absence of a cross-flow to deflect the plumes, relatively little of the discharged air is withdrawn back into the tower. When cross-winds are present, however, the plumes are deflected or "bent over", and their trajectories are shifted closer to one of the intake faces and significantly more of the tower effluent is brought back into the tower. This is the

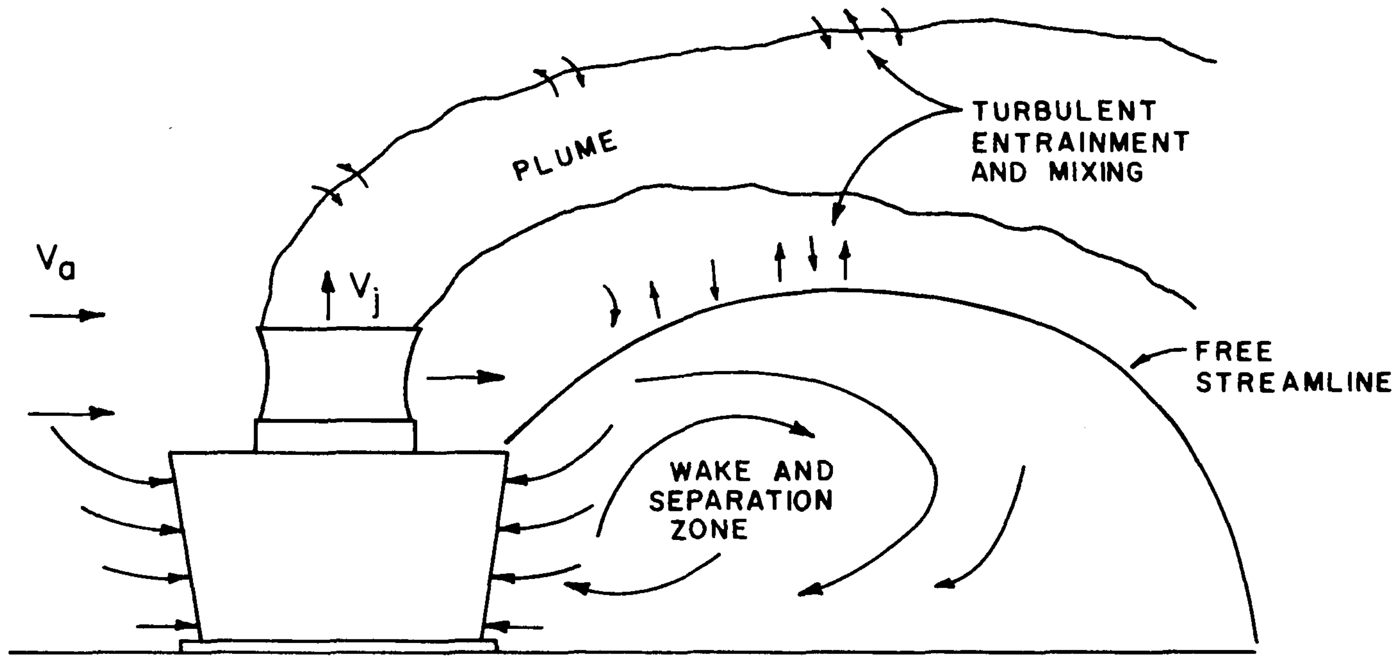


Fig. 1 Schematic depiction of a mechanical draft cooling tower in a cross-flow, illustrating phenomenon of recirculation.

phenomenon known as recirculation. It is aggravated, as will be discussed later, by the wake and large captive eddy that form on the lee side of the towers. The boundary region of the wake (the vicinity of the free streamline) is characterized by intense turbulent exchange or mixing, which is very effective in entraining plume fluid into the wake, from where it is recirculated through the tower. Note also that the wake is generally a region of low pressure (due to the high velocities and corresponding low pressures at the separation points on the structure and along the free stream lines or stream surfaces), which results in further deflection of the plumes toward the tower intake face; the deflection of a jet or forced plume by a wake is known as downwash (Briggs, 1969).

When one tower is located downwind of another, as shown in figure 2, some of the effluent from the upwind tower may be drawn into the intakes of the downwind tower. The concentration of effluent fluid may become particularly high in the captive eddy which forms and persists between the towers, which increases the recirculation of the upwind tower. The ingestion by one tower of the effluent from another is known as interference. The downwind tower generally will experience both interference and recirculation; the combined effect also is referred to as recirculation.

In wet cooling towers, evaporation generally accounts for 75 percent or more of the heat transfer (Kennedy, 1972). Because the air leaving the stacks is saturated or nearly so, its heat-transfer capacity is exhausted, and hence any stack effluent that is ingested by a tower is almost completely ineffective in cooling the circulating water. Now for a fixed plant load, the rate of heat rejection through the circulating cooling water is nearly constant (the variation being due just to changes in generating unit efficiency), and hence so also is the range for a specified condenser water discharge. When effluent is ingested by a tower, the effective wet bulb temperature for the tower will be increased and both the cold water and hot water temperatures will rise, so that the approach required to achieve the imposed heat-transfer load will be attained. The increase in the cold water temperature raises the turbine back-pressure and thereby reduces turbine efficiency. Viewed another way, a fraction of the cooling tower capacity roughly equal to the fraction of stack effluent in the ingested air is rendered inactive, and the effective size of the tower is reduced. Thus recirculation and interference directly affect plant efficiency and maximum electrical output, and it is, therefore, of considerable practical importance in power plant design to have quantitative data on recirculation and interference.

In 1968 the Marley Company engaged the Iowa Institute of Hydraulic Research to conduct small-scale model studies on various types of mechanical draft, wet cooling towers, with the goal of obtaining data or recirculation and interference for use in the sizing and siting of cooling towers. The program has been supported by Marley on a continuing basis, and with more than 250 tests having been completed by the end of 1973. Presented herein are a description of the experimental apparatus and technique used in these tests, and a summary and interpretation of some of the principal results. Further details and tests results are repeated in an Iowa Institute of Hydraulic Research Limited Distribution Report (Chan, Hsu, Lin, Hsu, Huang, and Kennedy).

II. DIMENSIONAL ANALYSIS AND MODELLING CONSIDERATIONS

All velocities will be denoted by V_i, densities by ρ_i, and temperatures by T_i; thus, V_a,ρ_a, and T_a are, respectively, the velocity, density, and temperature of the ambient flow, while V_j, ρ_j, and T_j represent the velocity, density, and temperature of the fluid discharged from the stacks. When the density difference $\Delta\rho_o = \rho_a - \rho_j$ is negative (i.e., when the density of the efflux is greater than that of the ambient fluid, which occurs when $\Delta T_o = T_a - T_j$ is positive), the buoyancy force acts downward and the jet is said to have negative buoyancy. In like manner, when $\Delta\rho_o$ is positive we speak of a positive buoyancy plume.

The parameter of primary concern in this investigation is the spatial distribution of the concentration of stack effluent or, equivalently (if heat conduction and change of phase in the fluid are disregarded), of the relative temperature ratio, $\Delta T/\Delta T_o$, where ΔT is the difference between the temperature T at any point in the flow field and that of the ambient flow, T_a. This ratio will be in general a function of the flow variables and the geometry of the system. We may therefore write

$$\frac{\Delta T}{\Delta T_o} = f(x, y, z, g, V_j, V_a, \rho_a, \nu, \Delta\rho_o, \theta, N, L, H, S, D) \qquad (1)$$

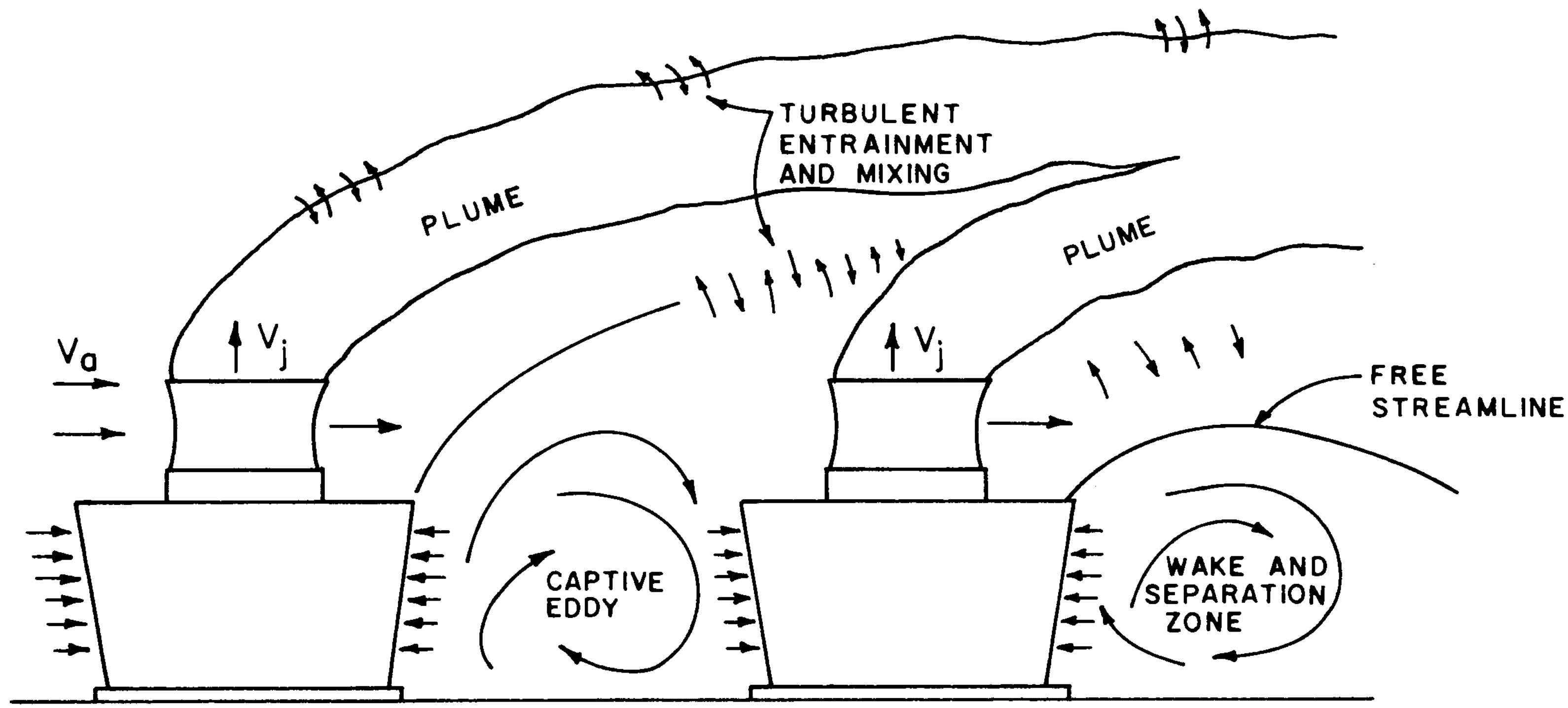


Fig. 2 A two-tower array in a cross-flow, illustrating recirculation and interference.

where x, y, and z denote Cartesian coordinates in the longitudinal, lateral and vertical directions, respectively; g is the gravitational acceleration; ν is the kinematic viscosity of the ambient fluid or jet; and θ, N, L, H, S, and D are parameters which describe the geometry and orientation of the cooling tower: θ is the angle at which the axis of a rectilinear tower is oriented with respect to the ambient flow, N is the number of cells in the tower, L is the length of the tower, and H, S, and D are, respectively, the stack height, spacing and diameter. Note that for the fluid used in the model study (water), $T = T(\rho)$ and is practically independent of pressure. Therefore T_a and T_o determine $\Delta\rho_o$. Dimensional considerations permit us to rewrite (1) as

$$\frac{\Delta T}{\Delta T_o} = f\left(\frac{x}{D}, \frac{y}{D}, \frac{z}{D}, \frac{V_j}{\sqrt{gD}}, \frac{V_j D}{\nu}, \frac{V_j}{V_a}, \frac{\Delta\rho_o}{\rho_a}, \theta, N, \frac{L}{D}, \frac{H}{D}, \frac{S}{D}\right). \tag{2}$$

The theory of nonhomogeneous flow (Yih, 1965) allows $\Delta\rho_o/\rho_a$ to be incorporated into the Froude number, $V_j/\sqrt{gD}$, with the result

$$\frac{\Delta T}{\Delta T_o} = f\left(\frac{x}{D}, \frac{y}{D}, \frac{z}{D}, \mathbb{F}_D, \mathbb{R}, K, \theta, N, \frac{L}{D}, \frac{H}{D}, \frac{S}{D}\right), \tag{3}$$

where

$$\mathbb{F}_D = \frac{V_j}{\sqrt{gD(|\Delta\rho_o/\rho_a|)}}, \qquad \mathbb{R} = \frac{V_j D}{\nu}, \qquad \text{and } K = \frac{V_j}{V_a}.$$

The quantity $\mathbb{F}_D$ is the densimetric Froude number and represents the ratio of the inertial forces to the gravitational forces; $\mathbb{R}$ is the Reynolds number and is equal to the ratio of inertial to viscous forces; and K is the ratio of the stack efflux velocity to the velocity of the ambient flow (i.e., the wind velocity). Therefore, when $\mathbb{F}_D$ is small the gravitational forces are large compared to inertial ones, and vice versa; similarly, when $\mathbb{R}$ is large the effects of viscosity are negligible.

In the present study it was assumed that the effects of molecular viscosity are negligible, and therefore that $\mathbb{R}$ may be deleted from (3). Further, it was assumed that the mixing between stack efflux and ambient fluid is purely kinematic; i.e., it is determined by the velocity field and that there is no change of phase (e.g., no condensation of water vapor or freezing of water droplets). These assumptions imply that the dilution of the stack effluent results from turbulent mixing and advection, and that the Reynolds number is sufficiently high that the turbulent mixing characteristics are Reynolds-number independent. Note that gravity is significant to the mixing process because of its effect on the flow pattern and hence on the advection, plume trajectory and configuration, recirculation, etc. Hence (3) may be written

$$\frac{\Delta T}{\Delta T_o} = f\left(\frac{x}{D}, \frac{y}{D}, \frac{z}{D}, \mathbb{F}_D, K, \theta, N, \frac{L}{D}, \frac{H}{D}, \frac{S}{D}\right). \qquad (4)$$

Equation 4 states that the model simulates the mixing properties in the prototype when model and prototype are geometrically and dynamically similar. Dynamical similarity is insured when the model Froude number, $\mathbb{F}_D$, and velocity ratio, K, are made equal to the corresponding quantities in the prototype.

Equating the Froude numbers for model and prototype yields

$$V_r = \sqrt{(|\Delta\rho_o/\rho_a|)_r D_r} \qquad (5)$$

where the subscript r denotes the ratio between any two corresponding quantities in the model and the prototype. Limitations of laboratory facilities generally impose certain restrictions on each of the three ratios appearing in (5). In a laboratory the model could, of course, be studied either in air or water, but using reasonable values of D_r (say 1/150) and $(\Delta\rho_o/\rho_a)_r$ for both water and air, it is easily shown that the model has to operate at quite low velocities. For instance, if the value of $(\Delta\rho_o/\rho_a)$ in the model and prototype are 0.001165 and 0.03798, respectively, and D_r = 1/150 is chosen, then V_r = 1/70. Thus, to simulate a stack efflux velocity of 30 fps in the prototype the model must operate with an efflux velocity of 0.429 fps; experiments at such low velocities are best carried out using water as the working fluid. Water offers the additional advantage that the required density differences are more easily produced (by heating or cooling) and concentrations of stack effluent can be easily measured (with temperature sensors).

Table 1 summarizes the results of a study of the frequency of occurrence of different values of $\mathbb{F}_D$, based on data furnished by The Marley Company on operating conditions and corresponding values of $\mathbb{F}_D$ for prototype Class 600 cooling towers. The value of $\mathbb{F}_D$ is, of course, dependent upon

Table 1

Occurrence Frequency of F_D for Various Ambient Conditions

(Marley Class 600 cooling tower; data provided by The Marley Company)

	Ambient Conditions			
Temperature	78°F WB (wet bulb)			
Relative Humidity	100%*		25%**	
F_D	No. of Events	%	No. of Events	%
2	0	0	0	0
2 - 2.5	19	9.8	0	0
2.5 - 3	53	27.4	7	4.8
3 - 3.5	45	23.2	24	16.5
3.5 - 4	30	15.5	20	13.7
4 - 4.5	20	10.3	19	13.0
4.5 - 5	13	6.7	15	10.2
5 - 5.5	8	4.1	10	6.8
5.5 - 6	4	2.0	8	5.5
6 - 7	2	1.0	11	7.6
7 - 10	0	0	14	9.6
10 - 20	0	0	10	6.8
20 and up	0	0	8	5.5
Total	194	100%	146	100%

* All positive buoyancy

** Some negative buoyancy

the temperature and relative humidity of the ambient air. From the frequency of occurrences it is clear that for most prototype situations, $2 \leq \mathbf{F}_D \leq 7$; accordingly, in the model tests reported herein $\mathbf{F}_D$ was limited to this range. The velocity ratio, K, was varied from 0.4 to 12.

III. APPARATUS AND PROCEDURE

The experiments for this investigation were conducted in a free-surface flume 2.5 ft wide, 3 ft deep, and 22.5 ft long. Figure 3 shows a schematic diagram of the experimental setup used, which consisted of five principal parts: the stack efflux supply system (I); the ambient flow supply system (II); the cooling tower model(s) (III); the intake water withdrawal system (IV); and the instrumentation system (V). Figures 12 and 14 present photos of model towers installed in the flume.

The desired temperature of the stack effluent was obtained by mixing heated or cooled water with water withdrawn from the constant-head tank, which is part of the laboratory's circulating supply system. The hot water used for the experiments with positive buoyancy plumes was supplied through four 75,000 BTU per hr gas fired water heaters; the cold water used for negative-buoyancy-plume experiments was obtained from the city water system during winter months when tap water was colder than that in the laboratory system. The mixed water travelled approximately 100 in. through a 1-in. diameter pipe before entering a 6 in. by 19 in. cylindrical stilling tank, from which it passed through valves and calibrated orifice meters to the model cooling tower stacks. The discharge from each stack of the tower was valve controlled and metered. The temperature of the stack efflux was measured in the mixing manifold by means of a thermometer having a discrimination of 0.05°C.

The modeled ambient flow was also supplied from the laboratory constant-head tank. The water discharge through the flume was controlled by a valve, measured with an in-line orifice meter, and the water depth and velocity in the working section adjusted by means of a tilting gate at the downstream end of the flume. The water depth in the flume was usually maintained at approximately five-times the cooling tower height, so that the free-surface effects were negligible for most flow conditions. The towers

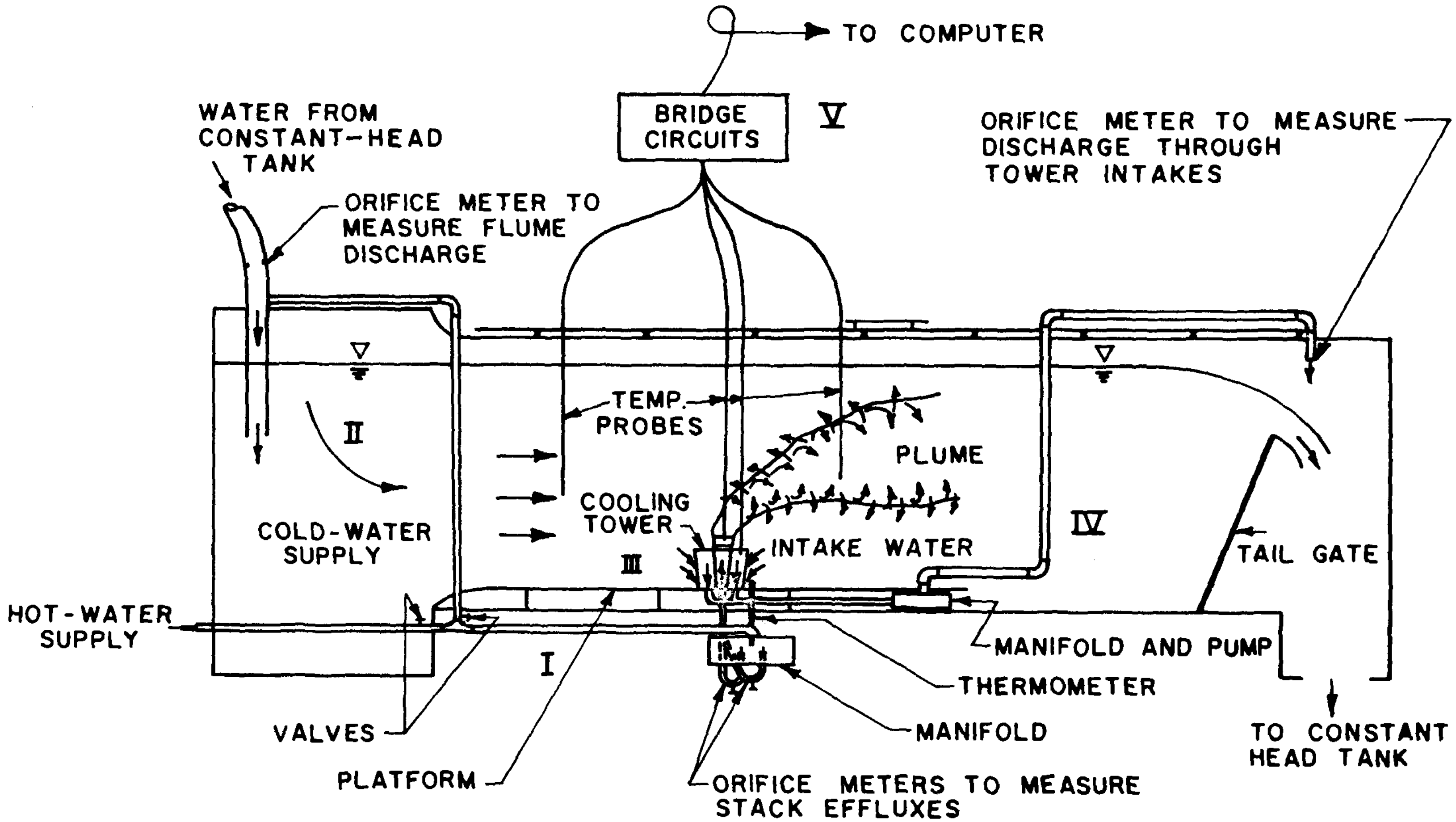


Fig. 3 Experimental set up used in cooling tower model study.

were positioned on a platform which formed a smooth transition for the oncoming ambient flow, as shown in figure 3. The model was located 7.5 ft downstream from the flume inlet and 15 ft upstream from the tail gate. The platform was elevated 6 in. above the flume floor and extended 5 ft downstream from the model. Flow visualization experiments indicated that the boundary layer on the platform was approximately 0.5 in. thick near the model, and that the flow distribution across the test section was uniform and had relatively low background turbulence intensity. The towers could be rotated and oriented in any desired direction relative to the approach flow. A thermistor probe mounted in the flume upstream from the model was used to measure the ambient flow temperature.

Most of the experiments were conducted on Marley Class 600 towers. The results are, however, applicable to other towers of comparable design and dimensions. The model towers had a model-to-prototype length-scale ratio of 1/150. Figure 4 depicts the details of model design for a (2-32-18) unit, which designates a two-cell tower with 18-ft high stacks on 32-ft centers. Note that the stack height (1.44 in.) and spacing (2.56 in.) shown in the figure correspond to this stack configuration; for towers with other stack heights and spacings, model units with corresponding dimensions were used. Each cooling tower cell had one stack-effluent inlet and four intake ports (two each on the upstream and downstream sides of the tower). Diffuser vanes were mounted in the approaches to the stacks to produce smooth transitions and prevent separation. The intake ports, through which the water withdrawn through the intake faces of the tower was pumped, were located on the bottom of the suction chambers. A layer of rubber insulation was provided between the suction chamber and the transition cone to reduce the heat transfer from the stack effluent through the walls of the stack approaches to the suction chambers. To achieve uniform withdrawal through both the upstream and downstream sides of the tower, perforated plates and louvers were mounted on the intake faces.

The water withdrawn through the intake faces of the towers was pumped through the intake ports into tubes underneath the platform and discharged through a 2-in. pipe at the downstream end of the flume. In the prototype the air is drawn into the cells by fans and discharged through the stacks; therefore, by the continuity principle, the air flow rate through the stacks must be equal to that through the intake faces of the tower.

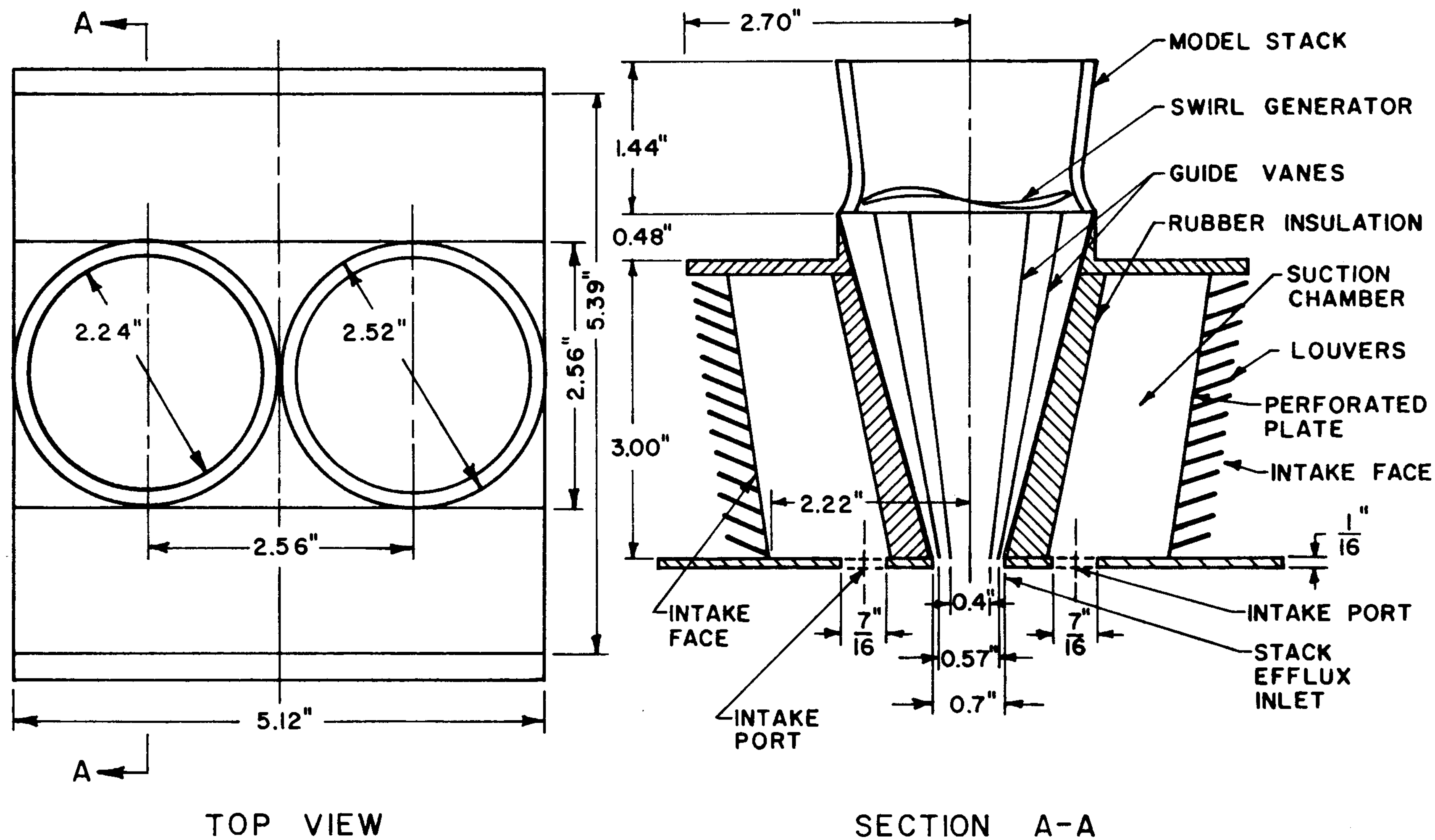


Fig. 4 Details of a 1/150-scale (2-32-18) tower.

Accordingly, in the model the total discharge through intake ports was measured by means of an orifice meter and was adjusted to be equal to the total stack effluent discharge.

From the foregoing description it is clear that four principal adjustments had to be made before beginning each experiment: the temperature and discharge of the stack efflux; the discharge of the approach flow (as well as the depth and velocity in the flume); and the intake-water discharge. The first two of these obviously are interrelated because $\mathbf{F}_D$ is determined by the temperature difference between the stack efflux and the approach flow and jet velocity. In addition, the temperature and discharge of the stack efflux were also affected by the temperature and discharge of hot or cold water as well as by the temperature and discharge of water supplied from the constant head tank. Consequently, constant monitoring and adjustment were required until the desired value of $\mathbf{F}_D$ was obtained. The discharge of the approach flow was determined by the required K, the ratio of jet velocity to that of the approach flow. Finally the discharge of water withdrawn through tower intake faces and intake ports was adjusted to be equal to that through the stacks. The temperatures and discharges were checked at frequent intervals and adjusted as needed to maintain the desired conditions.

The temperature measuring system, as it finally evolved, consisted of 14 probes fabricated from thermistors made of a semi-conductor with negative temperature-resistance coefficient of about 0.04/°C; this is approximately ten times larger than that of normal conductor metals. One probe was positioned upstream from the tower and used to measure T_a; a second was placed in a stack and measured T_j; and the other twelve were inserted through small, fitted holes in the model tower fan decks and positioned in the intake ports (see figure 3) to measure the temperature of the water ingested by the model tower, or were placed at various positions in the downstream flow field to measure temperatures from which the plume configurations were determined. The probes were mounted on a specially designed carriage and could be shifted easily from one position to another. Each probe was interfaced through its own bridge circuit with the Institute's IBM 1800 Data Acquisition and Control System. The sensors were calibrated at about fifteen temperatures between 22°C and 34°C, and the calibration relations so obtained were quantified by a least-squares fit to a second-order polynomial and stored in computer memory. The calibrations were checked from time to time and invariably found to be quite stable. The outputs from the thermistor bridges for each position setting of the probes were fed directly to the computer, which averaged the voltage output over a period of 60 seconds or longer and then printed out for each probe the average voltage, the corresponding temperature calculated from the probe's calibration curve, and the normalized temperature difference, $\Delta T/\Delta T_o$. The temperature measurements were judged to be accurate to ± 0.05°C. The corresponding accuracy in the normalized temperature difference and effluent concentration is about three percent.

At any point, the concentration of stack effluent was assumed to be equal to $\Delta T/\Delta T_o$, in keeping with the concept of kinematical mixing described above. The recirculation ratio, defined as the fraction of stack effluent in the ingested fluid, was taken as the average of the values of $\Delta T/\Delta T_o$ measured in the intake ports.

IV. FLOW PATTERNS AROUND COOLING TOWERS

Flow visualization and other special tests were performed with the model towers to elucidate the behavior and characteristics of the forced plumes, the cross-flows, the intake flows withdrawn from the surrounding fluid, and the interaction of these. The following description is based on observation made during these experiments and on the mechanics of forced plumes.

The stack efflux ejected upward from a cooling tower represents a momentum flux, and also a flux of buoyancy due to the temperature and humidity differences and accompanying density difference between the effluent and the surrounding fluid. Depending upon whether the stack effluent is more or less dense than the receiving fluid, a negative or positive buoyancy-force will be exerted on the plume; negative buoyancy will decelerate the upward motion, while positive buoyancy will reinforce it. The combination of momentum and buoyancy forces acting on a forced plume cause it to behave somewhat differently from a simple jet (momentum only) or a simple plume (buoyancy only). A negative buoyancy plume cannot penetrate beyond a maximum ceiling level, as a result of the downward acceleration the fluid receives from the negative buoyancy force. Positive buoyancy plumes, on the other hand, can continue to rise indefinitely in a homogeneous atmosphere. For even the case of a simple buoyant plume discharged into otherwise quiescent, unbounded surroundings, the turbulent mixing process is so complex that only approximate analytical models have been developed to date to describe their behavior (Briggs, 1969; Chan and Kennedy, 1972; Keffer and Baines, 1963; Schiller and Nakayama, 1973).

When another factor--a cross-flow--is introduced, it goes without saying that the flow field is complicated further. Consider first a round jet discharged perpendicularly into a uniform cross-flow with the same density as the jet. One realizes immediately that the jet will be deflected and inclined toward the downwind direction (see figures 5, 6, and 7), that the jet width will increase in the streamwise direction, and that the jet velocity will decay along the jet trajectory. In addition, it has been revealed in experimental studies that the inclined jet tends to be "rolled up" to form a pair of counter-rotating vortices, which give the plume kidney-shaped cross sections except very near the origin (Keffer and Baines, 1963). The "rolling-up" process is the result of differences in fluid entrainment rate and pressure around the jet periphery. Specifically, the cross-flow velocity around the plume produces higher tangential velocities at the sides of the plume and a return flow is generated in the vicinity of the plume center-plane, to set up the pair of eddies. These eddies are very effective in entraining fluid from the plume wake into the plume. In the region near the jet or plume origin, the turbulent mixing process dominates the entrainment of surrounding fluid; however, farther along the jet, the "rolling-up" process together with the cross-flow generally dominate the mixing of the jet with the surrounding fluid (Chan and Kennedy, 1972). For a better understanding of a jet in cross-wind, plane jets must also be considered. For a round jet, the cross-flow can reach practically every part of the jet boundary; however, a plane jet acts as a "porous curtain", and will block the cross-flow in such a way that a relatively large separation region occurs behind the jets. This region of separation is quite similar to that behind an obstacle in a stream.

The discussion of the two preceding paragraphs leads to the conclusion that when considering and investigating plume trajectories and the phenomenon of recirculation of forced plumes from cooling towers, the

$\mathbb{F}_D = 2$

$K = 4$

$\theta = 90°$

$\mathbb{F}_D = 2$

$K = 2$

$\theta = 90°$

$\mathbb{F}_D = 2$

$K = 1.02$

$\theta = 90°$

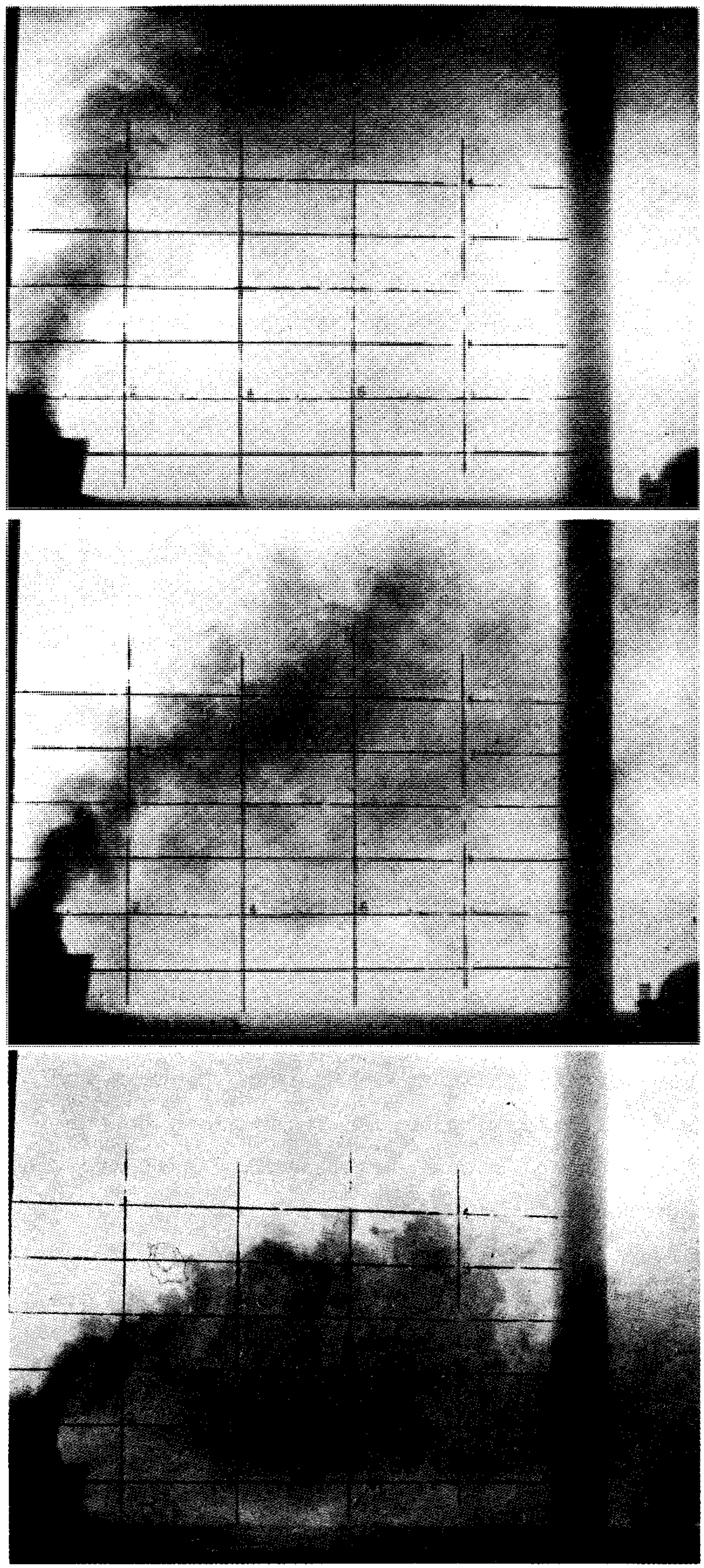
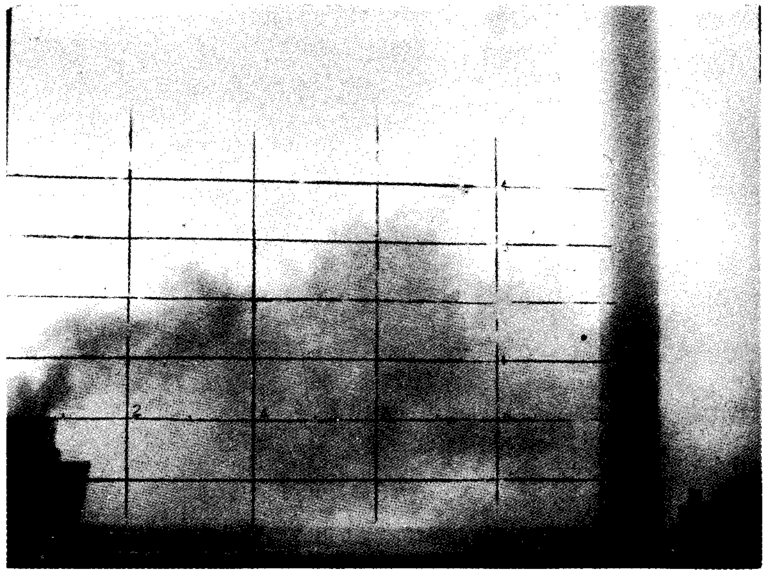


Fig. 5 Photos of positive buoyancy plumes from a (6-32-18) cooling tower in a cross-flow illustrating effects of ambient velocity. $\mathbb{F}_D = 2$; $\theta = 90°$; $K = 4$, 2, and 1.02. Grid spacing = 2D horizontally; = 1D vertically.

$\mathbb{F}_D = \infty$

$K = 1.02$

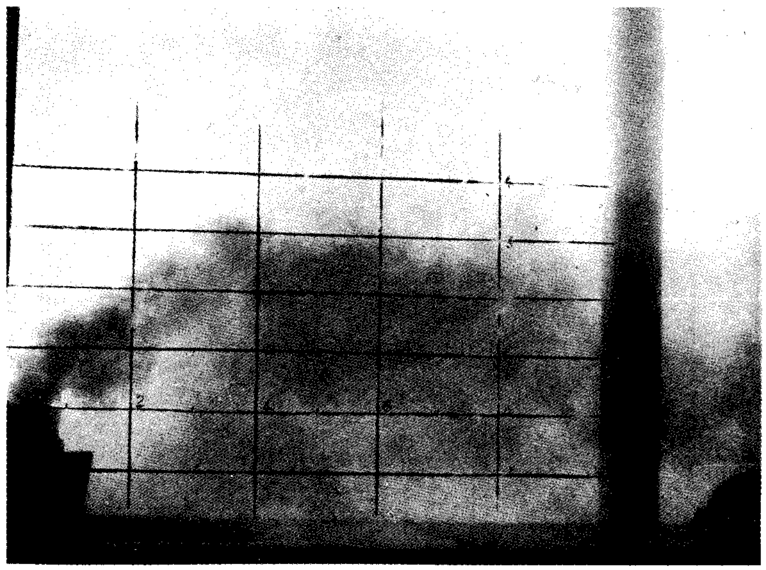
$\theta = 90°$



$\mathbb{F}_D = 4$

$K = 1.02$

$\theta = 90°$



$\mathbb{F}_D = 2$

$K = 1.02$

$\theta = 90°$

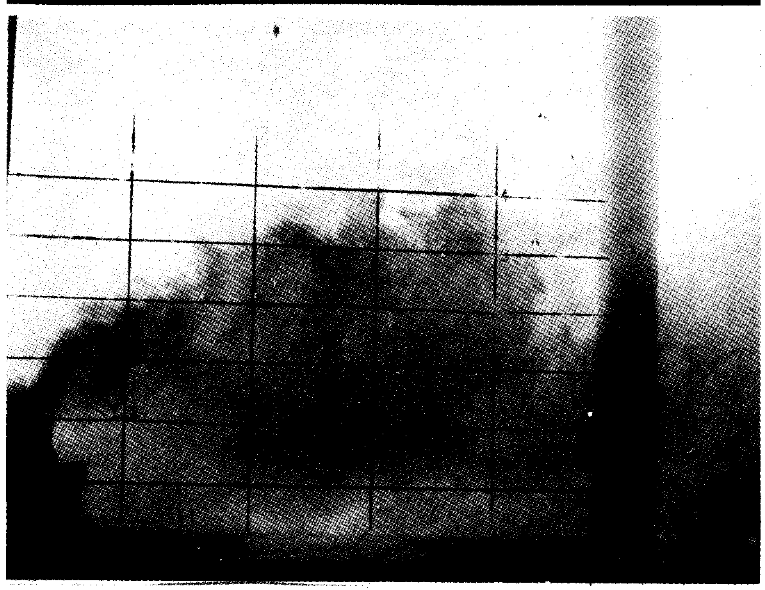
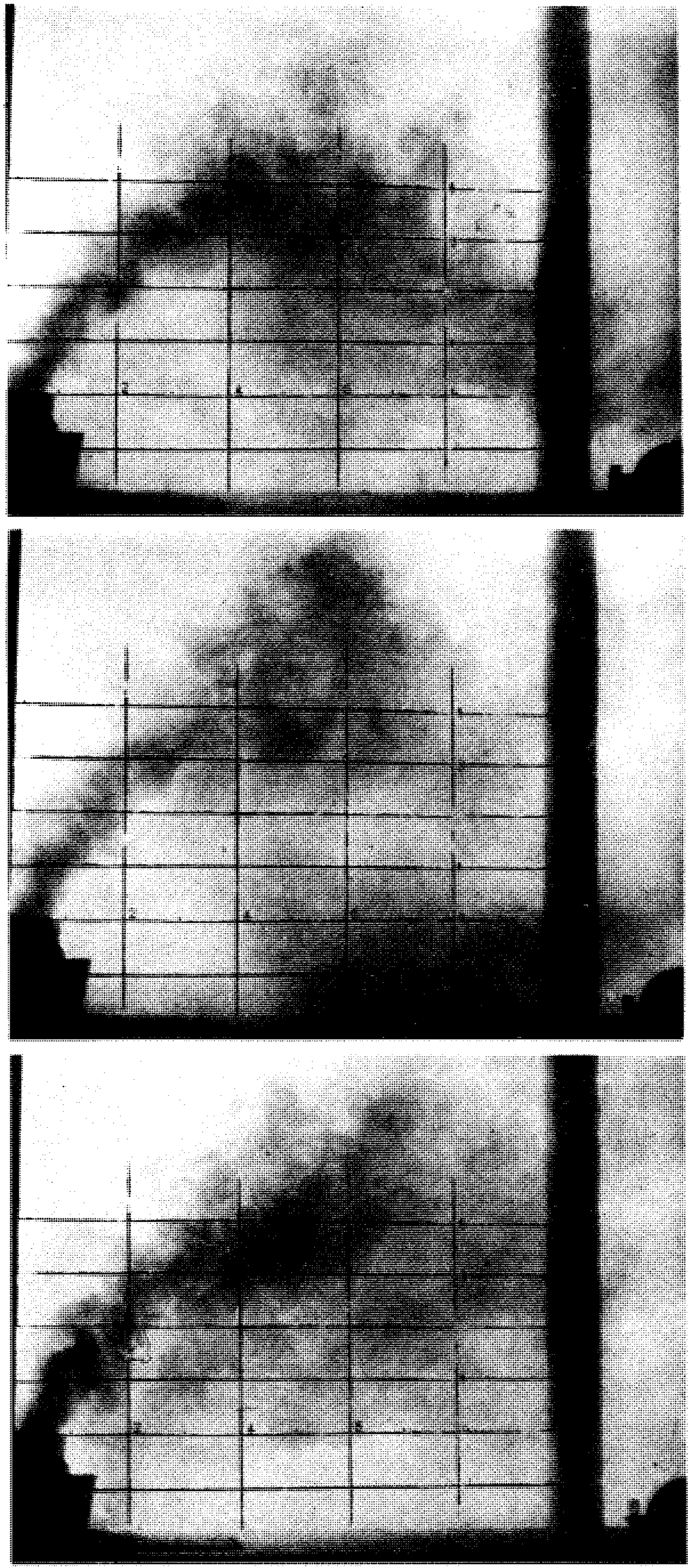


Fig. 6 Photos of positive buoyancy plumes from a (6-32-18) cooling tower in a cross-flow illustrating effects of Froude number. $K = 1.02$; $\theta = 90°$; $\mathbb{F}_D = \infty$, 4 and 2. Grid spacing = 2D horizontally; = 1D vertically.



$\mathbb{F}_D = \infty$
K = 2
θ = 90°

$\mathbb{F}_D$ = 4
K = 2
θ = 90°

$\mathbb{F}_D$ = 2
K = 2
θ = 90°

Fig. 7 Photos of positive buoyancy plumes from a (6-32-18) cooling tower in a cross-flow illustrating effects of Froude number. K = 2; θ = 90°; $\mathbb{F}_D = \infty$, 4, 2. Grid spacing = 2D horizontally; = 1D vertically.

parameters K (the ratio of the jet velocity V_j to wind velocity V_a) and $\mathbb{F}_D$ (the densimetric Froude number) must both be taken into account. The significance of K is indicated by the fact that it represented the square-root of the ratio of the momentum flux per unit area of the jet to the momentum flux (again per unit area) of the ambient flow. The quantity $\mathbb{F}_D$ is the ratio of momentum flux to buoyancy flux, hence the smaller $\mathbb{F}_D$ is, the stronger buoyancy force will be relative to the inertial force, and vice versa.

In addition to the parameters K and $\mathbb{F}_D$, one has to consider also the aerodynamic effects on the flow resulting from the presence of the tower itself, nearby buildings, and topographical features. The separation zone downwind from a tower is produced by the tower structure and by the jets. In the case of a multiple-cell tower, the forced plumes from each cell merge together and form a "plane" plume of limited lateral extent. The geometry of the separation zone is, of course, strongly influenced by the orientation of the tower relative to the approach wind. As will be discussed later, the occurrence of separation strongly affects the recirculation phenomenon, since the separation region serves as a well mixed "reservoir" from which fluid is withdrawn into the downwind intake face. Stack effluent is continuously drawn into this separation zone by the large captive eddy that dominates the wake and by turbulent mixing generated by the plume and by the tower wake, but this stack effluent is diluted by ambient flow passing through the jets, through the spaces between stacks, and around the ends of the tower. Some experiments were conducted to elucidate how this "reservoir" behaves. Dye was introduced into the stack efflux so the plumes and mixing could be observed. Potassium permaganate crystals were also dropped into the flow to study velocity patterns in specific regions. As expected, the velocity in the separation region was found to be quite low. Photographs of a (6-32-18) model taken during the experimental program are shown in figures 5, 6, and 7. Figure 5 demonstrates the effects of K on the jet flow patterns when $\mathbb{F}_D$ is fixed, and figures 6 and 7 show how the plume configuration varies with $\mathbb{F}_D$ for fixed K. The effect of K on the plume trajectory is very strong; $\mathbb{F}_D$ plays a smaller but still readily discernible role in determining the plume geometry. The influence of the fluid withdrawn through the intake face of the tower on the "reservoir" formed by the wake was also investigated by the flow visualization. It was found that the jet flow pattern and the separation zone are practically unaffected by withdrawal; i.e., their dimensions are not altered significantly when withdrawal is stopped. This is to be expected since the jets have far-reaching effects while the distributed "sink" disturbances represented by fluid withdrawal are of a potential flow type and hence decay very rapidly with distance from the sink. Moreover, the velocity of the fluid withdrawn through the intake faces is quite low in comparison with V_j.

A feature of the separation zone generated jointly by the structure and the jets is a pair of vortices rotating about nearly vertical axes near the lateral edges of the lee side of the tower and extending into the merged plumes. The visualization experiments revealed that ambient fluid flowing around the tower ends is entrained by these vortices, and has a significant effect in diluting (i.e., reducing the temperature) of the fluid taken in through the downwind face of the tower from the separation "reservoir".

In summary, a list of the factors influencing the flow pattern and therefore the downwind temperature profiles, recirculation, and interference in mechanical draft cooling towers is as follows:

(i) The ratio of jet velocity to the velocity of the ambient flow, K.
(ii) The densimetric Froude number, $\mathbf{F}_D$.
(iii) End effects, and the length-height ratio of the tower.
(iv) The separation zone due to the jets and tower structure.
(v) Stack height and spacing.
(vi) Orientation of tower with respect to ambient flow.
(vii) Environmental effects, such as surrounding topography, buildings, etc.

Some of these effects are considered in more detail in the following sections.

V. DOWNWIND TEMPERATURE (EFFLUX CONCENTRATION) PROFILES

Figure 8 presents a typical distribution of normalized temperature (which equals the stack effluent concentration, as discussed above) for positive buoyancy plumes issuing from a (6-32-18) model tower. The numbers shown by each measurement point are the experimentally determined values of $\Delta T/\Delta T_o$. Note that this case is also included in figure 6. For the conditions

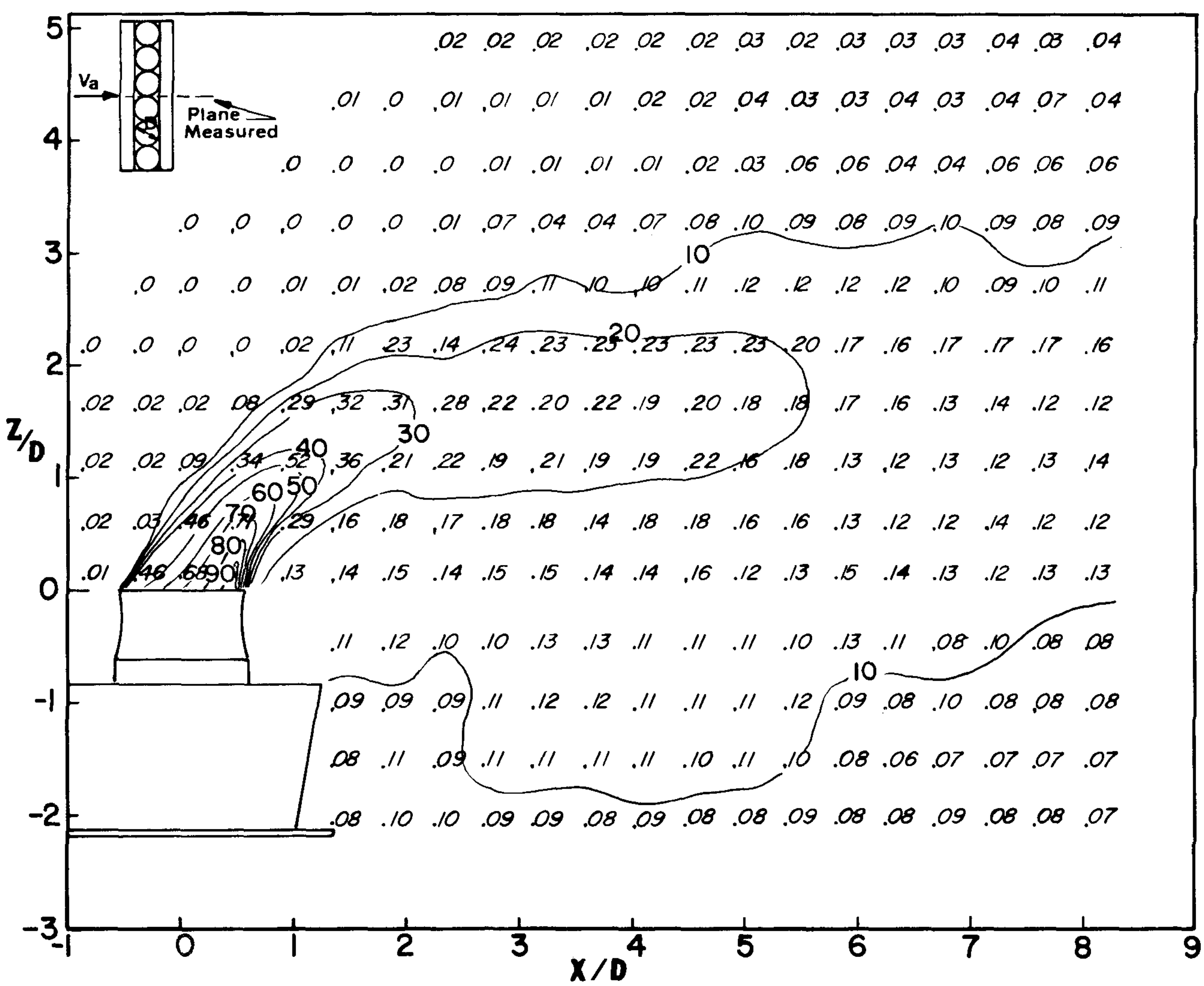


Fig. 8 Downwind temperature distribution for positive buoyancy plumes from a (6-32-18) tower with $\mathbb{F}_D = 4$, $K = 1.02$, and $\theta = 90°$.

shown, the plume trajectory, defined as the locus of points of maximum temperature along verticals, approaches asymptotically a maximum elevation or penetration of $z/D = 2$, approximately, where z is the vertical distance above the top of the stacks. At $x = 5D$, the vertical rise of the plume is virtually complete, although the plume continues to diffuse vertically as it is advected downstream. The asymptotic penetration is, of course, strongly dependent on K, and to a lesser extent on $\mathbf{F}_D$. It is seen that the plume is rapidly diluted along its trajectory as it leaves the stacks. Of particular importance in figure 8 is the occurrence region just downstream from the tower in which $\Delta T/\Delta T_o$ is practically constant. This is the well-mixed wake "reservoir" discussed earlier, into which stack effluent is entrained from the plume until an equilibrium concentration is reached, and from which fluid is withdrawn into the downstream intake face of the tower. This wake and its entrainment of plume fluid are, as noted above, of central importance to the phenomenon of recirculation.

Figure 9 shows the downwind temperature distribution for a (2-32-18) tower and a negative buoyancy plume. Comparison of figures 8 and 9, in both of which $K = 1.02$, shows that the negative buoyancy reduces the maximum penetration of the plume, for the reasons discussed in the preceding section. The shorter length of the (2-32-18) tower compared to the (6-32-18) unit of figure 1 is responsible for the more rapid dilution of the plume and lower effluent concentration in the tower wake. That is, a larger fraction of the plume periphery is exposed to the ambient fluid, with which it becomes diluted, and a larger percentage of the ingested fluid originates from around the ends of the tower (instead of over the tower, between the stacks and through the plume), where the effluent concentration is practically zero. In figures 8 and 9 it is seen that near the plume origin the upwind side of the plume is diluted more rapidly than the downwind side, as a consequence of the direct entrainment of the impinging cross-flow fluid.

VI. RECIRCULATION

The recirculation ratio, R, for a single tower is defined as the fraction of stack effluent in the fluid withdrawn into the downwind intake face of the tower. From the experimental results, R was calculated as

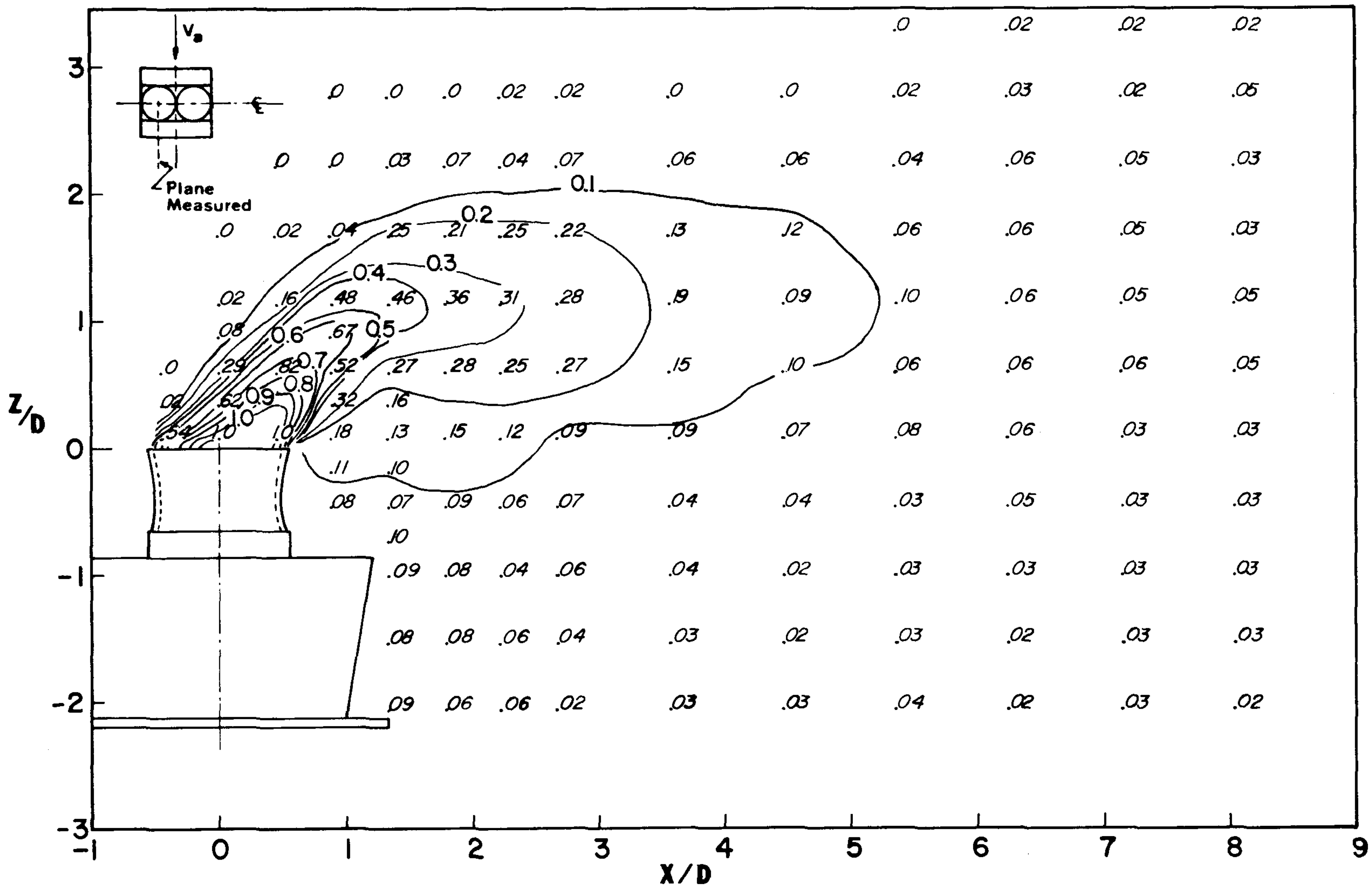


Fig. 9 Downwind temperature distribution for negative buoyancy plumes from a (2-32-18) tower with $\mathbb{F}_D = 7.06$, K = 1.02, and θ = 90°.

$$R = \frac{\bar{T}_w - T_a}{T_j - T_a} = \frac{\overline{\Delta T}_w}{\Delta T_o} \qquad (6)$$

where $\bar{T}_w$ is the average of the temperatures measured in the individual intake ports (see figure 4) and $\overline{\Delta T}_w = \bar{T}_w - T_a$. Calculation of R from (6) assumes that heat transfer by conduction is negligible, and that turbulent exchange of heat and fluid occur at comparable rates. These assumptions appear to be fully justified for the near field of cooling tower plumes, where the turbulent exchange is very intense and dominates the exchange of both heat and matter. If model and prototype are geometrically, kinematically, and dynamically similar, then the experimentally determined values of R may be applied directly to full-scale cooling towers. It was verified that for single rectilinear towers there is no recirculation through the upwind face.

Experiments were conducted for various flow conditions to investigate the effects on R of K, $\mathbb{F}_D$, length-height ratio of tower (or number of cells), stack height and spacing, tower orientation, and tower shape. The results are as follows.

A. The Effects of K. Consider first the case in which the densimetric Froude number, $\mathbb{F}_D$, is held fixed and the tower axis is orientated at $\theta = 90°$ with respect to the approach flow. At low values of K (i.e., when the ambient flow is large compared to the jet velocity) the plume is sharply deflected and stack effluent is entrained and advected away by the oncoming flow. In this case the near-field plume is shifted relatively close to the downwind tower intake face. At large values of K, on the other hand, the ambient flow velocities are relatively small, the plume is not so strongly deflected by the cross-flow, as the photographs in figure 5 clearly illustrate, and hence even the smallest distance between the plume from the intake face is relatively large. Therefore, for positive buoyancy plumes, the recirculation ratio is practically a monotonically decreasing function of K for $K > 1$, as is illustrated by the test results presented in figure 10 for a (6-32-18) unit. In the limiting case $K \to \infty$, which corresponds to a windless condition, the recirculation ratio approaches zero. With decreasing K the jet is deflected progressively nearer the intake face and R increases. However, as K decreases the dilution of the jets in the region just above and downstream from the stacks increases, and hence the temperature in the plume just above the tower wake decreases also. This can lead to a

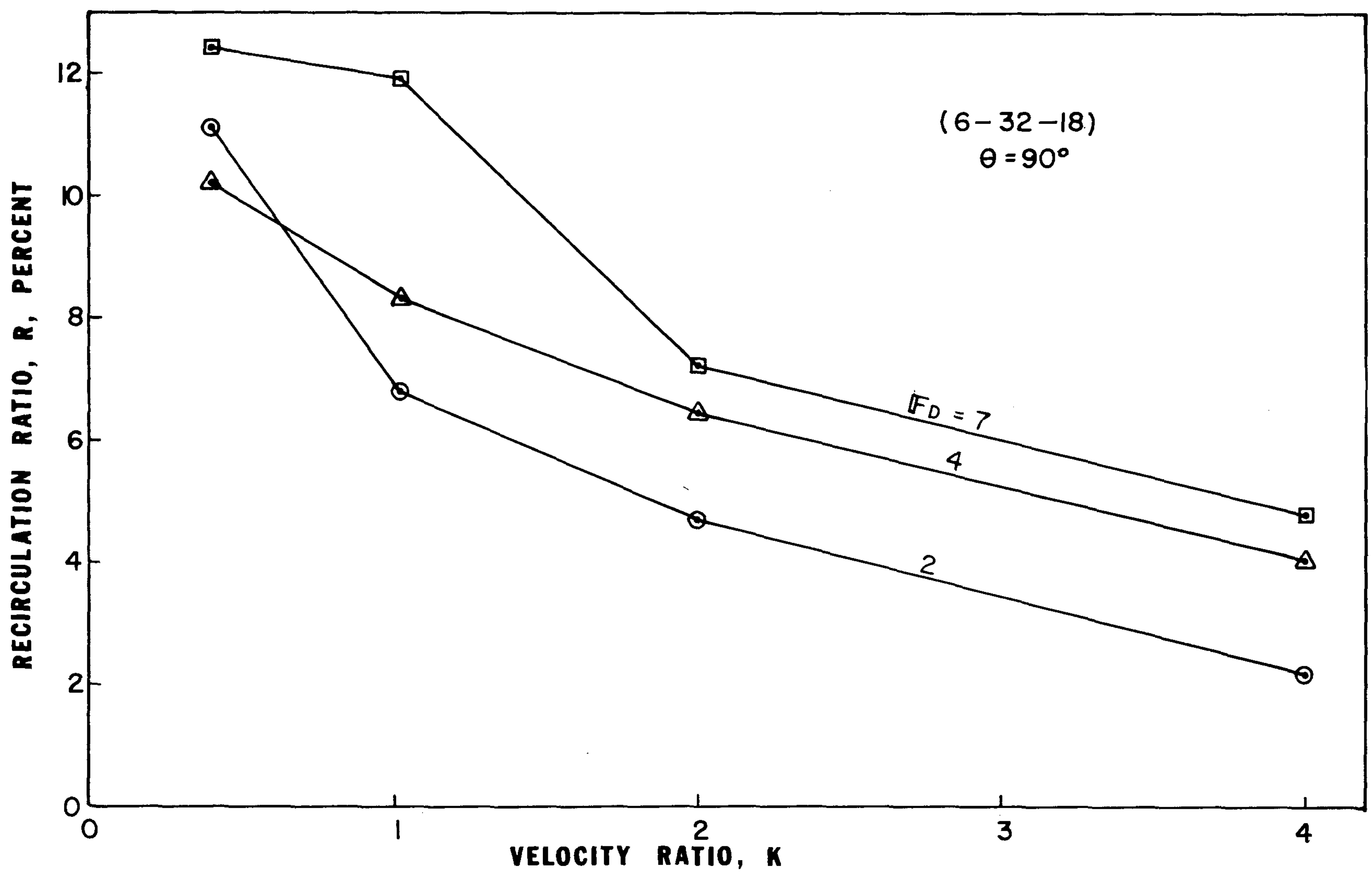


Fig. 10 Variation of R with K and $\mathbf{F}_D$ for a (6-32-18) tower with positive buoyancy plumes and θ = 90°.

reduction of R with still further decreases in K at values of K less than about 0.4 to 1.0. This was found to be the situation with a (6-40-18) tower, for example. In the case of the (6-32-18) tower (figure 10), on the other hand, R decreases monotonically with increasing K. This suggests that the occurrence of maxima in R for some tower geometries with larger stack spacings is due to the additional diluting fluid that passes through the wider spaces between the stacks. The results of a detailed study of spacing effect on the recirculation is presented below.

In the case of negative buoyancy plumes the variation of R with K for fixed $\mathbb{F}_D$ and $\theta = 90°$ was found to be somewhat different. As $K \to \infty$ (no wind condition) R attains some moderately large limiting value due to the settling of the plume over the tower. With decreasing K, R decreases because the stack discharge is advected downwind and diluted by the cross-flow. A minimum value of R is reached at a value of K of about 2 for a (6-32-18) unit at $\theta = 90°$; at smaller values R increases with decreasing K because the plume is bent over by the cross-flow and stack-effluent is entrained more effectively into the tower wake, resulting in larger temperatures in the "reservoir" from which the downwind intake face withdraws fluid. As $K \to 0$, an asymptotic value of R = 14 percent, approximately, was found for the aforementioned tower and orientation.

<u>B. The Effects of $\mathbb{F}_D$</u>. Consider now the situation in which K is fixed but the Froude number, $\mathbb{F}_D$, is varied. For fixed values of D and V_j, this corresponds to variation of the density of the jet effluent. An increase in $\mathbb{F}_D$ corresponds to a decrease in the magnitude of the buoyant (gravitational) force relative to inertial forces. It is seen in figure 10 for positive buoyancy plumes that at all values of K (with the possible exception of K = 0.4 in figure 10), the recirculation ratio decreases as $\mathbb{F}_D$ is decreased. This is a result of the larger upward buoyant force which corresponds to the smaller values of $\mathbb{F}_D$ acting to carry the jet upwards and hence farther away from the intake face and thereby decreasing the recirculation. It is reasonable to expect that R approaches an asymptotic limit, probably not greatly in excess of the values of R for $\mathbb{F}_D = 7$, as $\mathbb{F}_D$ tends to infinity (i.e., as the jet density approaches that of the surrounding flow) with K held fixed. In the case of negative buoyancy plumes, R was found, as expected, to increase as $\mathbb{F}_D$ is decreased.

C. End Effects. For a multiple-stack tower the plumes from each cell rapidly merge together and form a "plane" plume of limited lateral extent. However, because of the finite length of the towers, the separation region behind the tower is three-dimensional. The flow visualization experiments revealed that this three-dimensionality is dominated by a pair of end vortices with nearly vertical axes. One such vortex occurs at each end of a tower oriented broadside ($\theta = 90°$, or nearly so) to the oncoming wind. These vortices, which are the captive eddies produced by separation of the ambient cross-flow from the ends of the tower structure, are very effective in entraining ambient fluid into the tower wake and reducing the effluent concentration at the intake face. Some special experiments were carried out to obtain an indication of how much fluid is entrained around the tower ends and its effect in reducing recirculation. Four sets of experiments, with $\mathbf{F}_D = 4$, K = 1 and 2, and $\theta = 90°$, were conducted for the (6-32-18) and (6-40-18) units. For each condition two tests, one for three-dimensional flow and the other for two-dimensional flow, were made. To achieve two-dimensionality, two parallel pressed-wood sheets with spacing equal to the tower length were mounted in the flume, one against each end of the tower, in order to divide the channel into three parallel passages. The flow around the tower was then two-dimensional (except locally near the stacks) and no flow could enter the downwind intake face from around the tower ends. The recirculation ratios measured in these tests are tabulated in table 2; the experiments with stack partitions summarized in this table are considered in the following subsections. For comparison, the recirculation ratios for models (6-40-36) and (6-32-36) are also given to show the effect of stack height (which also will be discussed below) on the recirculation phenomenon.

In order to appreciate more fully the end effects on recirculation, compare 3-D and 2-D (w/o part.) for model (6-32-18) in table 2; the recirculation ratios for 3-D are about 50 percent lower than those for 2-D (w/o part.). Considering model (6-40-18), it is seen that the 3-D flow has a recirculation ratio about 25 percent lower than 2-D (w/o part.). Apparently the (6-32-18) tower entrains more ambient fluid around the tower ends than the (6-40-18) tower does. This is not surprising, since the (6-40-18) unit has a larger stack-spacing, and the ambient flow can pass through the spaces between the stacks more readily and contribute to the dilution of the wake fluid. The results for two-dimensional flows also give an upper

Table 2

Comparison of Recirculation Ratios for Two-Dimensional (2-D) and Three-Dimensional (3-D) Flows

UNIT		(6-32-18)		(6-32-36)		(6-40-18)			(6-40-36)	
Flow Condition		3-D	2-D	3-D	2-D	3-D	2-D		3-D	2-D
		w/o part.*	w/o part.*	w/o part.*	w/o part.*	w/o part.*	with part.**	w/o part.*	w/o part.*	w/o part.*
$F_D = 4$	K = 1	0.083	0.16	0.088	0.15	0.10	0.16	0.13	0.043	0.079
	K = 2	0.065	0.12	0.049	0.083	0.077	0.14	0.11	0.030	0.050

* without partitions between stacks

** with partitions between stacks

asymptotic limit of recirculation ratio as the number of tower cells increases, or as the length-height ratio of the tower becomes very large.

D. The Effects of Stack Height and Spacing. To appreciate the effects of stack height on the recirculation ratio, R, it is useful to compare the recirculation ratios for a given set of flow conditions for models (6-32-18) and (6-32-36), and for (6-40-18) and (6-40-36), given in table 2. It is seen that lower stack heights produce larger values of R, as would be expected; the larger distance between the point of discharge and the tower fan deck reduces the entrainment of stack effluent into the tower wake. When comparing two models with the same stack height but having different spacings, it appears that the (6-32-18) unit is superior to model (6-40-18)--an apparent contradiction. It is believed that this anomaly is a consequence of the greater length of model (6-40-18), and the resultant interference of the flume walls with the flow around the tower ends. This consideration probably also explains why increasing stack height is more effective in reducing R for the (6-40-18, 36) than for (6-32-18, 36) units; proportionately more of the diluting fluid passes over the tower and between the stacks in the former case. For the shorter unit, on the other hand, flow around the tower ends supplies more of the ingested fluid. In order to clarify further the effect of stack spacing on recirculation, another set of special experiments was conducted for a two-dimensional flow. Model (6-40-18) was used and partitions having the same height as the stacks were mounted between adjacent stacks so that the flow through these openings was blocked. When one compares 2-D (w/o part.) and 2-D (w part.) for model (6-40-18), the former has a recirculation ratio about 20 percent lower than that of the latter; i.e., larger stack spacing does reduce the recirculation ratio. However, the exact magnitude of the reduction cannot be determined from these tests, because of the aforementioned effects of the flume walls.

Another interesting feature can be seen in the results presented for 2-D (w/o part.) recirculation ratios for models (6-32-18) and (6-40-18) for different values of K. It is seen that the increased stack spacing is more effective in reducing R when K is smaller; this is a consequence of the larger V_a delivering more ambient fluid through the spaces between the stacks. For K = 2, increased stack spacing is seen to achieve little in reducing R. To isolate the effects of stack height from those of spacing, one may compare 2-D (w/o part.) for model (6-32-18) with 2-D (w/o part.) for model (6-32-36); it is seen that increased stack height has the effect of reducing the recirculation ratio by some 10 to 15 percent in this case. When comparing 2-D (w/o part.) for (6-40-18) and 2-D (w/o part.) for (6-40-36), the effect of stack height in reducing R is seen to be much greater. At higher values of K, increased stack height is generally more effective in reducing recirculation.

E. The Effects of Tower Orientation. Only positive buoyancy plumes will be considered here. The variation of R with K and $\mathbf{F}_D$ for $\theta = 90°$ is illustrated in figure 10, and an explanation for the observed form of the variation was given above. The variation of R with θ for fixed K and $\mathbf{F}_D$ is much more complex, as can be seen in figure 11 for a (6-32-18) model tower with $\mathbf{F}_D = 2$. In this figure it is seen that for $K \gtrsim 2$, the maximum R occurs at $\theta \sim 90°$, while with decreasing K below $K \sim 2$, the θ at which R is a maximum shifts to progressively lower values. For $\theta = 0$, R was found always to be quite small for positive buoyancy plumes. For negative buoyancy plumes at $\theta \sim 0$, however, R can be fairly large.

The effect of θ on R results from the complex interaction of the plumes and the tower wake. At small values of K and θ, the plume tends to be "draped" over the tower, with the jets originating from the upstream stacks being in rather close proximity with the downwind intake face over much of the length of the tower. This effect is particularly significant when the buoyant rise is small (large values of $\mathbf{F}_D$). Additionally, at very small θ the increased flow into the wake zone from around the upstream end of the tower does not compensate for the reduction at the downstream end, with the result that dilution of the wake zone by flow around the tower ends is reduced.

F. The Effects of Tower Shape. The foregoing description and discussion have stressed repeatedly the importance of plume deflection and wake entrainment of stack effluent to the recirculation phenomenon. Accordingly, it is of interest to explore the possibility of finding a tower shape that produces a plume which is deflected less abruptly by the cross-flow and which has a smaller fraction of its intake surface exposed to the wake and separation zone. The first goal requires a plume with a larger diameter (or larger ratio of cross-sectional area to periphery area per unit length of plume). A cooling tower with circular plan form with the fans and stacks

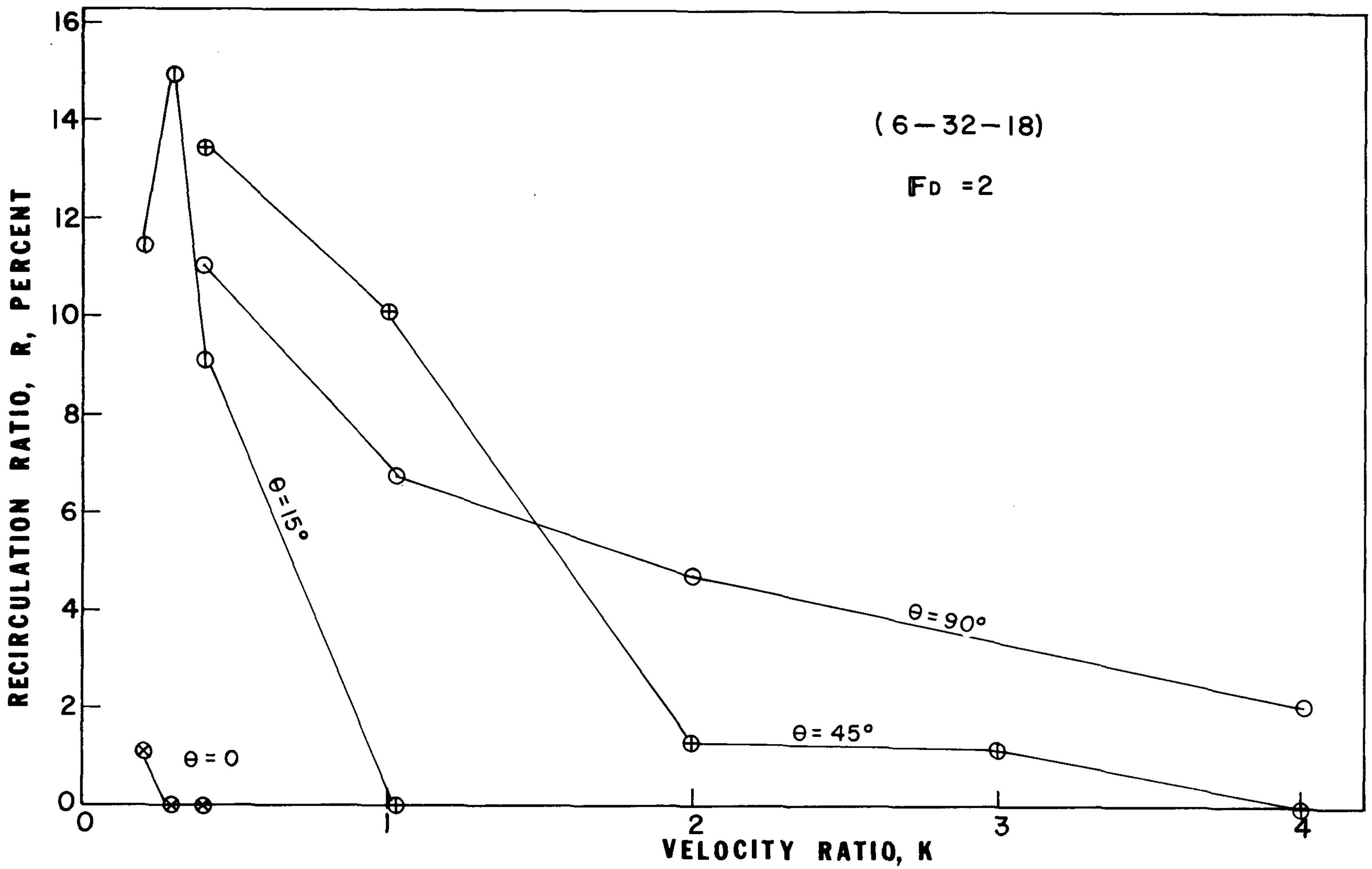


Fig. 11 Variation of R with K and θ for a (6-32-18) tower with $\mathbb{F}_D = 2$; positive buoyancy.

grouped near the center would appear to have these characteristics. The grouped stacks produce plumes which rapidly merge to form a single, large plume, and the fraction of the intake area exposed to the wake is much smaller than in the case of a rectangular tower, because flow separation from the tower sides occurs relatively far back on the tower. A seven-cell model tower of this type is shown in figure 12. The results of the recirculation tests on this model [designated (C7-18-36)] are summarized in figure 13. The recirculation ratios for this tower are seen to be much smaller than those of a rectilinear tower, given in figure 10. However, it must be recalled that R for the rectilinear tower is based on the intake through only one face, so that in making a comparison with the circular tower the values of R for the rectangular units must be divided by two. The reduction in R for the circular tower was determined in the experiments to be due to the factors noted above: the larger, more "coherent" plume is not deflected as close to the tower intake, and the lateral extent of the wake is greatly reduced.

G. Environmental Effects. In general the flow patterns around cooling towers are strongly affected by the physical surroundings, such as terrain, buildings, and weather. In particular, the atmosphere is generally stratified either stably or unstably, neutral stratification being rare. It should be emphasized here that the present laboratory investigation was carried out with homogeneous ambient fluid, which corresponds to neutral stratification. Fortunately, considering the scale of motion in the prototype, stratification effect and even compressibility effects may be neglected in the immediate vicinity of the tower, where attention was focused in this investigation.

VII. INTERFERENCE

The phenomenon of interference was described and discussed in the introductory section. A series of experiments was conducted using 2-(6-32-18) units with $\theta = 90°$, a spacing of one-half tower length (L/2), and one end of the models positioned against one wall of the flume, as shown in figure 14. This represented 2-(12-32-18) towers, because of the center-plane symmetry of the flow. The recirculation ratio of upwind and downwind towers were

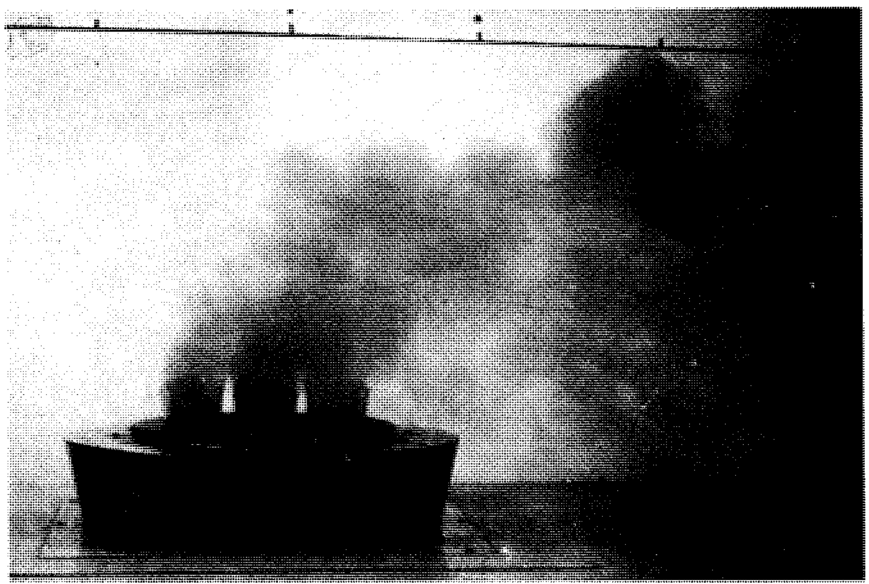


Fig. 12 Dyed plume produced by a (C7-36-18) tower with $\mathbf{F}_D = 4$, K = 1.0; positive buoyancy.

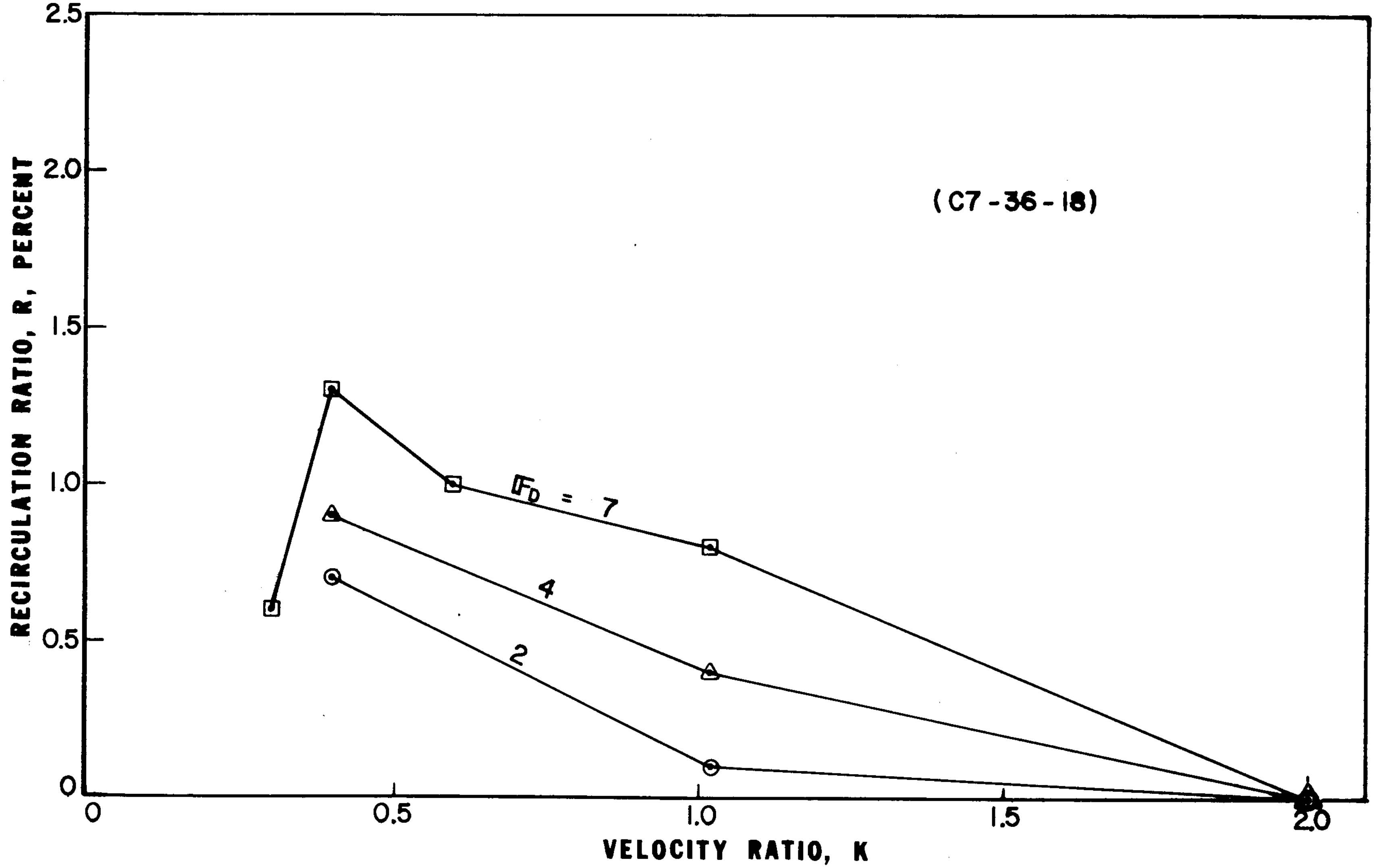


Fig. 13 Variation of R with K and F_D for a (C7-36-18) tower; positive buoyancy.

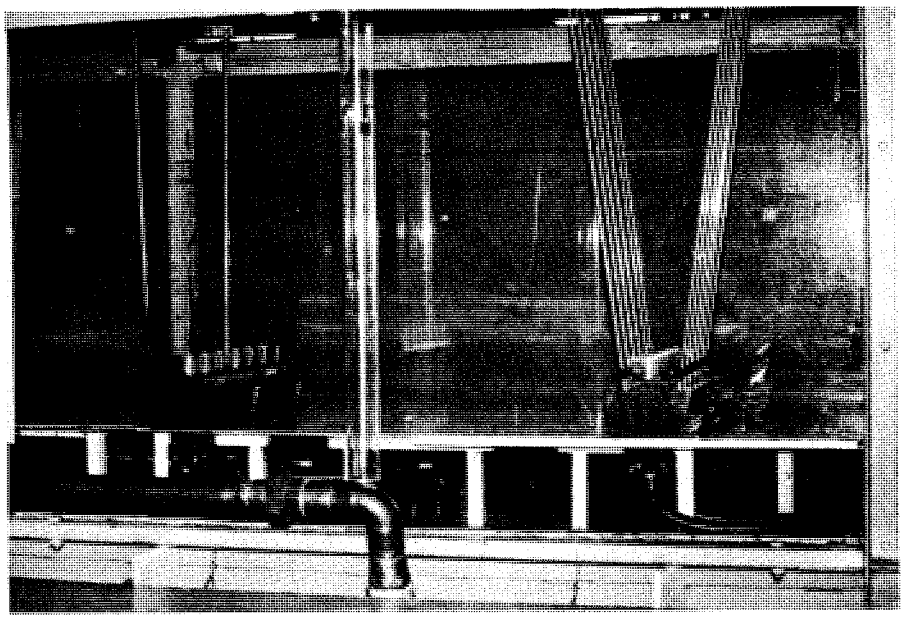


Fig. 14 Photograph of model cooling towers used in interference studies.

measured for several tower spacings; the results are summarized in figures 15 and 16. Note that for the upstream tower, R includes only the downwind face, while for the downwind tower the reported values include both faces. Therefore, the effective value of R for the two-tower system would equal one-half of R for the downwind tower plus one-fourth of R for the upwind one.

A comparison of the values of R given in figures 15 and 16 with those presented in figure 10 for a single (6-32-18) tower shows that the presence of a second tower significantly increases R for the upwind and especially for the downwind tower. At a spacing of a full tower length, R for both the upwind and downwind towers was significantly reduced below the values for a spacing of (L/2). As in the case of single tower, the plume deflection and accompanying entrainment of stack effluent into the wake were found to be responsible for much of the recirculation. The plumes from the two towers merged just downstream from the second tower to form a single plume. The plume issuing from the downstream unit was somewhat sheltered by the upstream tower and plume, and as a result was less sharply deflected.

VIII. SUMMARY AND CONCLUSIONS

The principal conclusions derived from the present laboratory investigation may be summarized as follows:

a. Cooling towers generally operate under conditions such that both momentum and buoyancy forces are important in governing the behavior of the forced plumes issuing from their stacks. Hence the limiting theories, which consider only momentum or buoyancy, are inadequate.

b. Flow around a cooling tower is strongly three-dimensional and the end vortices generated by the tower structure are very effective in diluting the jet effluent withdrawn into the downwind intake face of the tower from the separation zone in the wake generated by the tower and plumes.

c. The fluid in the separation zone downwind from the tower is well mixed and the concentration of stack effluent (i.e., the temperature) in this zone is more or less uniformly distributed. Hence the separation region acts as a relatively quiescent "reservoir", from which the fluid is withdrawn through the downwind suction face; the temperature in this region

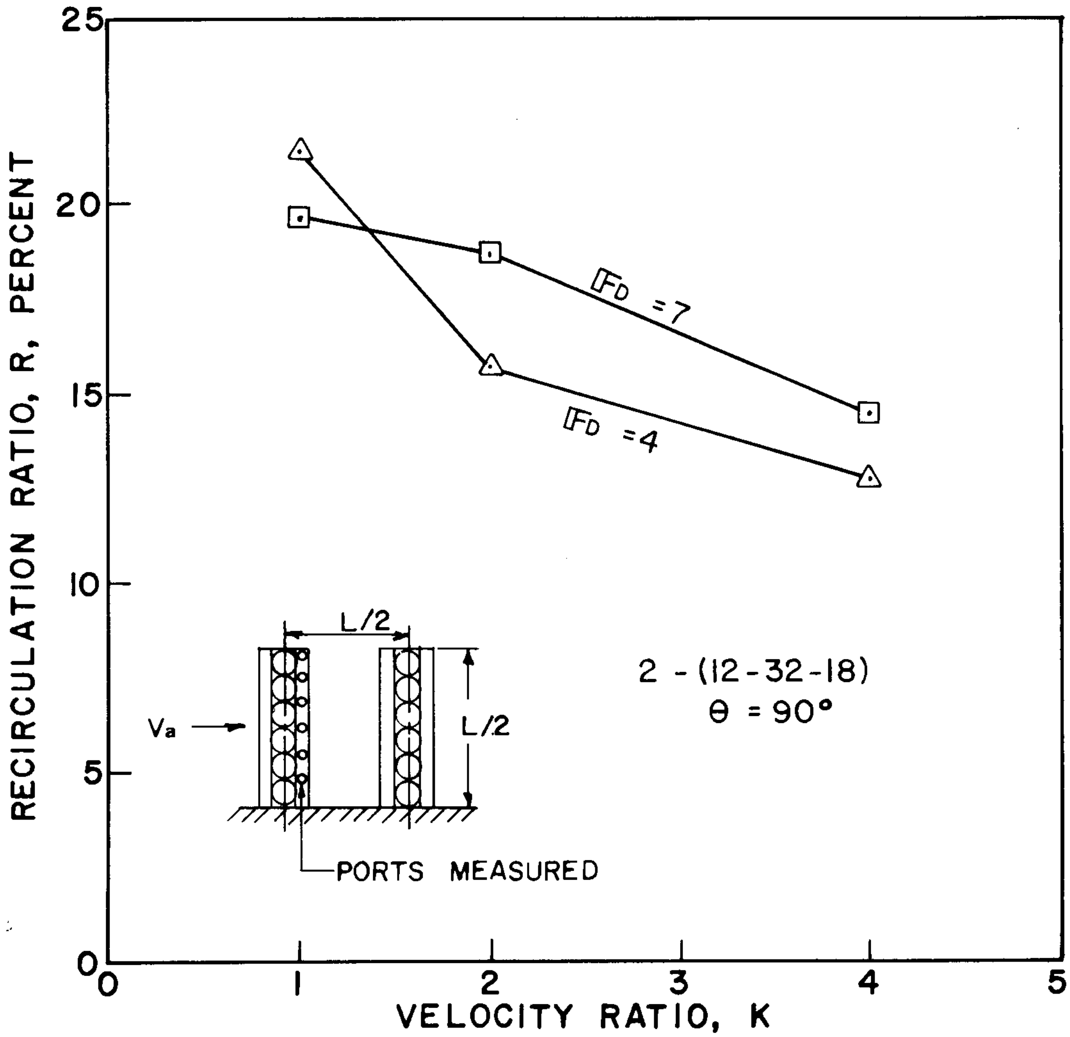


Fig. 15 Variation of R with K and $\mathbb{F}_D$ for upwind tower of a two-tower system. Positive buoyancy, 2-(6-32-18) towers, θ = 90°, spacing L/2.

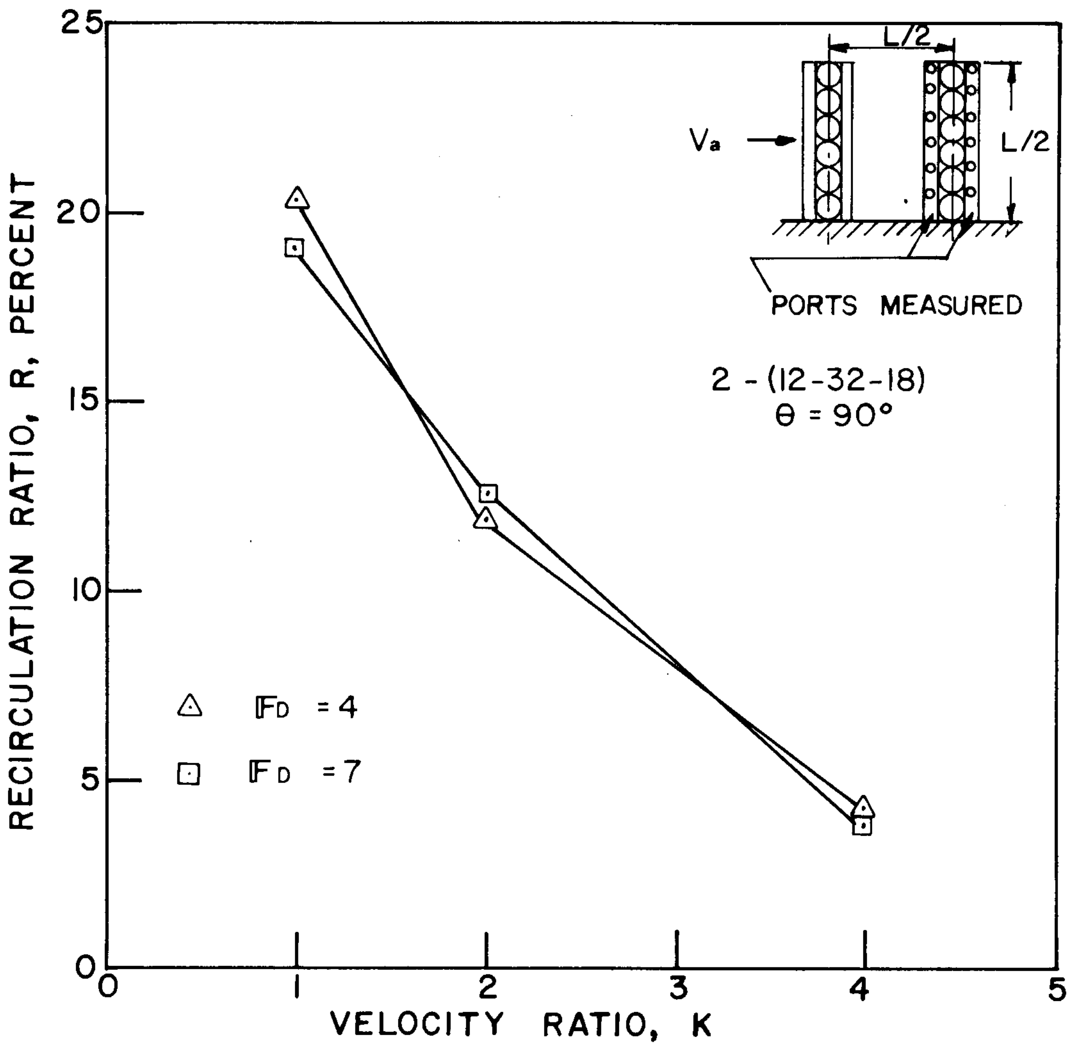


Fig. 16 Variation of R with K and $\mathbf{F}_D$ for downwind tower of a two-tower system. Positive buoyancy, 2(6-32-18) towers, θ = 90°, spacing L/2.

gives a good indication of recirculation ratio.

d. The variation of R with K for fixed $\mathbf{F}_D$ is complex. For negative buoyancy plumes and $\theta = 90°$, as K increases R first decreases, reaches a minimum, and then again increases and approaches an asymptotic value as $K \to \infty$. For positive buoyancy plumes, R generally decreases with increasing K, although in some cases of small K, R increases slightly with K.

e. Increasing stack height and stack spacing both reduce R. The relative effectiveness of one compared to the other depends on the length of the tower and the values of K and $\mathbf{F}_D$ under consideration.

f. The trajectory and spreading of the plumes, and hence also the recirculation ratio, are affected far more strongly by variations in K than by those in $\mathbf{F}_D$ (i.e., the cross-wind affects R more than does the density difference between the jet and the surrounding fluid).

g. As the wind direction changes, the interaction between the plume and the wake downwind of the tower will vary considerably. The value of θ at which maximum recirculation ratio occurs for a given $\mathbf{F}_D$ appears generally to decrease as K decreases.

h. Increasing the length-height ratio or the number of cells in a tower will cause an increase in recirculation ratio, a result of less ambient fluid being entrained around the tower ends. Accordingly, as the tower length is increased, the ambient fluid passing over the top of the tower, between the stacks, becomes more important, and the benefits to be derived from increasing stack height and/or spacing becomes greater.

i. The recirculation characteristics of circular towers are significantly better than those of rectilinear ones. The improvement results from the larger, merged plume of the circular tower being deflected less abruptly than that of a rectilinear unit, and from the reduced size of the wake of a circular tower.

j. For $\theta \sim 90°$, the presence of a second rectilinear tower positioned one-half tower-length downwind from the first markedly increases the fraction of stack effluent in the downwind intake of the upwind tower and in both intakes of the downwind unit. The captive eddy which forms between the units when a cross-wind is present to deflect the plumes entrains relatively large amounts of stack effluent. The resulting high concentrations of effluent in the region between the towers is primarily responsible for the large recirculation ratios which result for this tower array.

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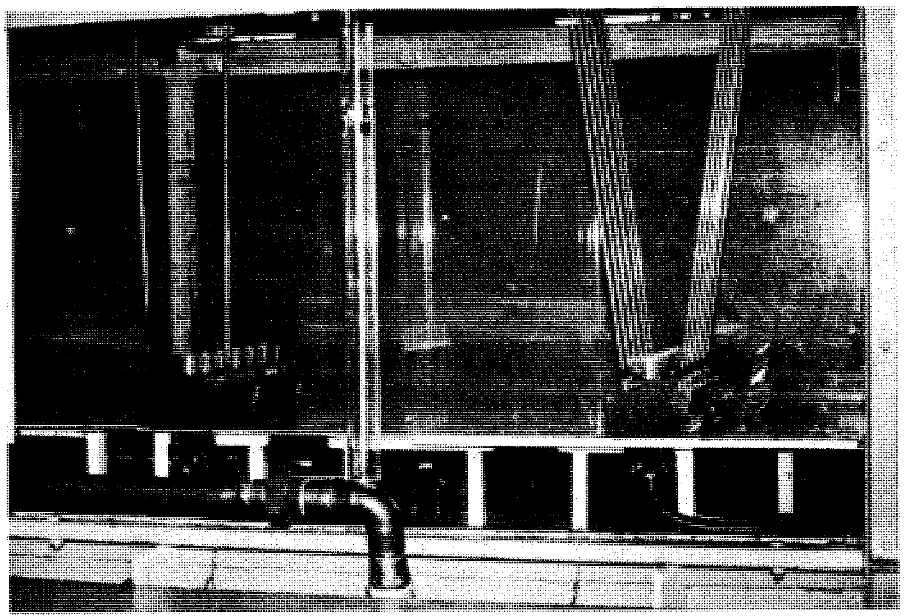

Fig. 14 Photograph of model cooling towers used in interference studies.

measured for several tower spacings; the results are summarized in figures 15 and 16. Note that for the upstream tower, R includes only the downwind face, while for the downwind tower the reported values include both faces. Therefore, the effective value of R for the two-tower system would equal one-half of R for the downwind tower plus one-fourth of R for the upwind one.

A comparison of the values of R given in figures 15 and 16 with those presented in figure 10 for a single (6-32-18) tower shows that the presence of a second tower significantly increases R for the upwind and especially for the downwind tower. At a spacing of a full tower length, R for both the upwind and downwind towers was significantly reduced below the values for a spacing of (L/2). As in the case of single tower, the plume deflection and accompanying entrainment of stack effluent into the wake were found to be responsible for much of the recirculation. The plumes from the two towers merged just downstream from the second tower to form a single plume. The plume issuing from the downstream unit was somewhat sheltered by the upstream tower and plume, and as a result was less sharply deflected.

VIII. SUMMARY AND CONCLUSIONS

The principal conclusions derived from the present laboratory investigation may be summarized as follows:

a. Cooling towers generally operate under conditions such that both momentum and buoyancy forces are important in governing the behavior of the forced plumes issuing from their stacks. Hence the limiting theories, which consider only momentum or buoyancy, are inadequate.

b. Flow around a cooling tower is strongly three-dimensional and the end vortices generated by the tower structure are very effective in diluting the jet effluent withdrawn into the downwind intake face of the tower from the separation zone in the wake generated by the tower and plumes.

c. The fluid in the separation zone downwind from the tower is well mixed and the concentration of stack effluent (i.e., the temperature) in this zone is more or less uniformly distributed. Hence the separation region acts as a relatively quiescent "reservoir", from which the fluid is withdrawn through the downwind suction face; the temperature in this region