Critical Review of Hydraulic Modeling on Atmospheric Heat Dissipation

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by
Y. Onishi
S. M. Brown

January 1977

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CRITICAL REVIEW OF HYDRAULIC MODELING ON ATMOSPHERIC HEAT DISSIPATION

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INTRODUCTION

Recently, a nuclear energy center concept has attracted national interest because of its possible advantages in licensing activities, safeguards, radioactive waste management, cost effectiveness and other factors. This center will consist of a large number of power plants and auxiliary fuel cycle facilities. Since the environmental impact of energy centers will concentrate in relatively small areas, cooling towers are expected to be widely used to reject waste heat generated by the power plants.

The amount of energy rejected by a nuclear energy center can be comparable to the amounts associated with significant and potentially severe atmospheric phenomena. Some of the potentially important meteorological effects of a nuclear energy center include: fogging and icing over a region, local heating and high humidity-induced problems, the solar radiation effects of visible plumes, drift and deposition of salts and pathogens, the scavenging of pollutants and radionuclides by cooling tower plumes, the triggering of local intense convective activity, the intensification of frontal rain storms and large storm systems moving over the energy center, and possible regional and global climatic changes. (1,2,3,4,5,6)

Another important aspect is interaction among cooling tower plumes. Since a nuclear energy center requires a large number of cooling towers, proper arrangement of these cooling towers at the site can be a critical design problem. Improper arrangement

can lead to recirculation of hot exhaust air into the intake of a cooling tower or be drawn into nearby cooling towers.⁽⁷⁾

Plume recirculation and interference increase the temperature of available ambient cooling air at the cooling tower inlet and cause an increase in the condenser temperature. This temperature rise in turn increases the turbine back-pressure and thereby reduces turbine-efficiency and the power plant's output of electricity.⁽⁸⁾

Consequently, it is important to investigate the plume dispersion process at a nuclear energy center prior to construction. These studies can be conducted by means of:

1. Actual field study for cases relevant to atmospheric heat dissipation of nuclear energy centers,
2. Mathematical modeling, and
3. Laboratory physical modeling.

These three methods must be integrated to solve this complex problem. Unfortunately, very little research has been conducted in this area. Full-scale field measurements of these phenomena are not practical because of prohibitive costs and because no sites have more than four cooling tower. Most of the available two-dimensional mathematical models cannot adequately predict multiple plume dispersion processes which are inherently a three-dimensional phenomenon.⁽⁸⁾ Although several three-dimensional numerical simulation models have been developed,^(9,10,11) their use is limited because of the high computer costs required to run these models.

A physical model study permits a valid and economical investigation for this complex problem under the neutral atmospheric condition and to a lesser extent under stable and unstable atmospheric conditions. The objectives of this study are:

1. To define the useful roles of hydraulic modeling in understanding and predicting atmospheric effects of heat dissipation systems,
2. To assess the state-of-the-art of hydraulic modeling of atmospheric phenomena,
3. To inventory potentially useful existing hydraulic modeling facilities both in the United States and abroad, and
4. To scope hydraulic model studies to assist the assessment of atmospheric effects of nuclear energy centers.

DIMENSIONAL ANALYSIS AND MODELING CRITERIA

In the following text, similarity criteria for modeling the atmospheric dispersion process in hydraulic laboratory facilities (hydraulic flumes, towing tanks, etc.) and wind tunnels will be derived through dimensional analysis.

To correctly simulate plume dispersion in a neutral or stratified atmosphere over a complex terrain, geometric, kinematic and dynamic similarities must be satisfied. For fixed cooling tower geometries and relative alignment, the spatial distribution of the temperature difference, ΔT , where ΔT is defined as the difference between the temperature T at any point in the flow field and that of the ambient flow, T_a , can be expressed by:

$$\Delta T = f[x, y, z, L, H(x,y,z), D, g, V_a, V_j, \rho_a,$$

$$\frac{\Delta \rho_a}{\Delta z}, \Delta \rho_o, v_a, v_j, \Delta T_o] \quad (1)$$

where

x, y, z = Cartesian coordinates in the longitudinal,
lateral and vertical directions, respectively

L = Characteristic length scale of the ambient
flow

$H(x, y, z)$ = Terrain profile

D = Cooling tower stack diameter

g = Gravitational acceleration

V_a, V_j = Velocities of the ambient flow and tower
discharge, respectively

ρ_a = Reference ambient fluid density

$\Delta\rho_a/\Delta Z$ = Vertical density gradient of ambient atmo-
spheric flow

$\Delta\rho_o$ = Density difference between the tower dis-
charge and the reference ambient fluid

ν_a, ν_j = Kinematic viscosity of the ambient fluid and
tower discharge, respectively

ΔT_o = Temperature difference between the tower
discharge and the ambient flow

Let L, ρ_a, V_a and ΔT be basic quantities to non-dimensionalize Equation 1. Dimensional analysis with the π theorem yields the following expressions from Equation 1:

$$\frac{\Delta T}{\Delta T_o} = f\left[\frac{x}{L}, \frac{y}{L}, \frac{z}{L}, H\left(\frac{x}{L}, \frac{y}{L}, \frac{z}{L}\right), \frac{D}{L}, \frac{V_j}{V_a}, \frac{V_a^2}{gL}, \frac{\Delta\rho_a L}{\Delta Z \rho_a}, \frac{\Delta\rho_o}{\rho_a}, \frac{V_a L}{\nu_a}, \frac{V_a L}{\nu_j}\right] \quad (2)$$

Equation 2 may be rewritten to the following more common expression by rearranging the right hand terms in Equation 2:

$$\frac{\Delta T}{\Delta T_o} = f \left[\frac{x}{D}, \frac{y}{D}, \frac{z}{D}, H \left(\frac{x}{D}, \frac{y}{D}, \frac{z}{D} \right), \frac{D}{L}, \frac{v_j}{v_a}, \frac{v_a^2}{gL}, \frac{v_a^2}{\frac{\Delta \rho_a g L^2}{\Delta z \rho_a}}, \frac{v_j^2}{\frac{\Delta \rho_o}{\rho_a} g D}, \frac{v_a L}{v_a}, \frac{v_j D}{v_j} \right] \quad (3)$$

or

$$\frac{\Delta T}{\Delta T_o} = f \left[\frac{x}{D}, \frac{y}{D}, \frac{z}{D}, H \left(\frac{x}{D}, \frac{y}{D}, \frac{z}{D} \right), \frac{D}{L}, K, F, F_a, F_j, R_a, R_j \right] \quad (4)$$

where

$$K = \frac{v_j}{v_a} : \quad \text{velocity ratio of the effluent to the ambient flow} \quad (5)$$

$$F = \frac{v_a}{\sqrt{gL}} : \quad \text{ambient Froude number} \quad (6)$$

$$F_a = \frac{v_a}{\sqrt{\frac{g}{\rho_a} \cdot \frac{\Delta \rho_a}{\Delta z} L^2}} : \quad \text{ambient internal Froude number} \quad (7)$$

$$F_j = \frac{v_j}{\sqrt{\frac{\Delta \rho_o}{\rho_a} g D}} : \quad \text{effluent densimetric Froude number} \quad (8)$$

$$R_a = \frac{v_a L}{v_a} : \quad \text{ambient Reynolds number} \quad (9)$$

$$R_j = \frac{v_j D}{v_j} : \quad \text{effluent Reynolds number} \quad (10)$$

The ambient Froude number, F , is the ratio of gravitational force due to the ambient density stratification to the inertia force of the ambient wind. This number is a special case (an extremely severe density stratification case) of a more general ambient internal

Froude number F_a , and the ambient Froude number, F , may be deleted from consideration. Hence the final expression of similarity criteria becomes:

$$\frac{\Delta T}{\Delta T_0} = f\left[\frac{x}{D}, \frac{y}{D}, \frac{z}{D}, H\left(\frac{x}{D}, \frac{y}{D}, \frac{z}{D}\right), \frac{D}{L}, K, F_a, F_j, R_a, R_j\right] \quad (11)$$

A similar line of argument can be used to derive the following functional relationship for a local velocity, V , at any point in the flow field:

$$\frac{V}{V_a} = f\left[\frac{x}{D}, \frac{y}{D}, \frac{z}{D}, H\left(\frac{x}{D}, \frac{y}{D}, \frac{z}{D}\right), \frac{D}{L}, K, F_a, F_j, R_a, R_j\right] \quad (12)$$

In Equations (11) and (12), geometric similarities are satisfied if x/D , y/D , z/D , $H(x/D, y/D, z/D)$ and D/L in a laboratory model have the same values as those in the prototype. When a value of K in a model is the same as that in the actual field case, kinematic similarity will be satisfied. Plume dispersion and velocity flow field are dynamically simulated when values of F_a , F_j , R_a , R_j in a scale model are equal to those of prototype. As described in Equations (11) and (12), five factors influence turbulent dispersion of the cooling tower plumes:

1. Momentum of effluent and ambient flows. The relative intensity of momentum of these flows is one of the dominant factors near the cooling tower stacks. K in Equation (5) corresponds to the square root of the ratio of the effluent flow momentum to the ambient flow momentum, provided the Boussinesq assumption is adopted (that is, the density difference between these two flows is important for consideration of the buoyancy force but not for the flow momentum).

2. Effluent buoyancy force due to the density difference between the discharge jet and the ambient flows, especially in the near field. The relative strength of the effluent momentum to the effluent buoyancy force is expressed by the effluent densimetric Froude number, F_j , as shown in Equation (8).
3. Atmospheric stratification which causes positive or negative buoyancy force due to density difference within the ambient atmosphere. It is well known that atmospheric stratification changes the plume dispersion process significantly.^(12,13,14) The relative strength of the atmospheric wind momentum to the atmospheric buoyancy force is expressed by the ambient internal Froude number, F_a , as shown in Equation (7). Atmospheric stratification not only has some effect on plume dispersion in the near field but is very important in the far field where the momentum and buoyancy force of the effluent no longer dominate.
4. Turbulent intensity of the effluent flow which is expressed by the effluent Reynolds number, R_j , in Equation (10). The plume turbulence is important to initial mixing in a near field but diminishes its significance in a far field.
5. Ambient flow characteristics (except density stratification which is described by F_a as discussed above). These atmospheric flow characteristics include background atmospheric turbulence, wakes behind cooling towers and topographical features, atmospheric turbulent boundary layers and wind shear stress. They are governed by the ambient

Reynolds number, Re , Equation (9). If the Reynolds number is sufficiently high and the atmospheric flow is turbulent, the above flow characteristics, except the small-scale turbulent eddies, may become independent of the Reynolds number. The background atmospheric turbulence is not important in the near field but is the dominant mechanism for dispersing the plume in the far field. An ambient Reynolds number in a model is usually several orders of magnitude less than a prototypic value. Plume dispersion due to small ambient turbulent eddies may not be correctly reproduced in the model without the aid of an appropriate artificial turbulent generator. This is an inherent limitation of all laboratory physical models.

To obtain similarity between the prototype and the model, the last five similarity criteria in the right hand sides of Equations (11) and (12), in addition to geometric similarity, must be satisfied. However, it is not possible to exactly satisfy all similarity conditions described in Equations (11) and (12); it is sufficient to satisfy the Reynolds number criteria, Re_a and Re_j , only to the extent that the ambient and jet flows in the model will be maintained as turbulent flows. (8,15,16)

For free convection flow cases such as convective planetary boundary layer flow caused by the ground surface heat, the effluent densimetric Froude number, Fr_j , is replaced by the Rayleigh number, Ra_{ay} , as a modeling criterion.⁽¹⁷⁾ The Rayleigh number is defined by:

$$Ra_{ay} = \frac{\beta g (T_w - T_a) L^3}{\nu \alpha} \quad (13)$$

where

T_w = temperature at a solid boundary of heat source

α = thermal diffusivity

β = thermal expansion coefficient

Common working fluids for laboratory physical modeling are air (wind tunnel tests) and water (hydraulic flume and towing tank tests). Most atmospheric dispersion studies have been conducted in wind tunnels. One advantage of using air as a model fluid is that the difference between humidity of plumes and ambient air can be directly simulated in a model, whereas it is more indirect (if possible at all) to simulate the humidity change in a hydraulic model. However, water has following superior characteristics as a model fluid as compared to air;

1. It is relatively easier, and requires smaller models to satisfy the densimetric Froude and Reynolds number criteria for the model.
2. Flow and temperature measurements are more easily conducted in water than in air.
3. Flow observation is more readily conducted in water.

For example:

Assume a dry cooling tower is emitting a heated plume into a neutrally stratified atmosphere.

Let:

$$\begin{aligned}D &= 20 \text{ ft} \\L &= 100 \text{ ft} \\T_a &= 70^\circ\text{F} \\T_j &= 100^\circ\text{F} \\V_a &= 10 \text{ fps} \\V_j &= 20 \text{ fps}\end{aligned}$$

where

T_a and T_j are temperatures of ambient air and the heated effluent. Similarity criteria for this case are F_j , K , R_a and R_j . Those values in prototype are:

$$F_j = 3.42$$

$$K = 2.0$$

$$R_a = 6.25 \times 10^6 \rightarrow \text{turbulent ambient flow}$$

$$R_j = 2.22 \times 10^6 \rightarrow \text{turbulent effluent flow}$$

Now three models will be constructed to simulate cooling tower plume dispersion; one in a hydraulic flume (Model 1) and the others in a wind tunnel (Models 2 and 3). Assume model fluid temperatures will be same as prototype values.

Model 1 (water)

Let the length scale ratio $L_r = 1/300$. The similarity criteria F_j and K lead to the following model conditions:

$$D = 0.0667 \text{ ft}$$

$$L = 0.333 \text{ ft}$$

$$T_a = 70^\circ\text{F}$$

$$T_j = 100^\circ\text{F}$$

$$V_a = 0.177 \text{ fps}$$

$$V_j = 0.354 \text{ fps.}$$

Consequently,

$$F_j = 3.42$$

$$K = 2.0$$

$$R_a = 5900 \rightarrow \text{turbulent ambient flow}$$

$$R_j = 3140 \rightarrow \text{turbulent effluent flow}$$

The ambient and effluent Reynolds numbers are large enough to produce a turbulent flow in the model and all similarity criteria are satisfied in this case. Hence Model 1 reproduces the prototype flow field correctly.

Model 2 (air)

Let $L_r = 1/300$. The modeling criteria, F_j and K , lead to:

$$\begin{aligned}
D &= 0.0667 \text{ ft} \\
L &= 0.333 \text{ ft} \\
T_a &= 70^\circ\text{F} \\
T_j &= 100^\circ\text{F} \\
V_a &= 0.578 \text{ fps} \\
V_j &= 1.16 \text{ fps.}
\end{aligned}$$

Consequently,

$$\begin{aligned}
F_j &= 3.42 \\
K &= 2.0 \\
R_a &= 1200 \rightarrow \text{laminar ambient flow} \\
R_j &= 428 \rightarrow \text{laminar effluent flow}
\end{aligned}$$

In this case R_a and R_j in the model are too small to ensure turbulent flows in the model. Hence Model 2, having laminar ambient and effluent flows, cannot simulate the prototype atmospheric dispersion.

Model 3 (air)

In order for Model 2 to have turbulent flows, the model length scale must be increased. Model 3 using air as a model working fluid corresponds to a case where effluent Reynolds number is same as that of Model 1. The length scale ratio in this case becomes:

$$L_r = 1/80$$

and

$$\begin{aligned}
D &= 0.250 \text{ ft} \\
L &= 1.250 \text{ ft} \\
T_a &= 70^\circ\text{F}
\end{aligned}$$

$$\begin{aligned}T_j &= 100^\circ\text{F} \\V_a &= 1.12 \text{ fps} \\V_j &= 2.24 \text{ fps.}\end{aligned}$$

Consequently,

$$\begin{aligned}P_j &= 3.42 \\K &= 2.0 \\R_a &= 8740 \rightarrow \text{turbulent ambient flow} \\R_j &= 3100 \rightarrow \text{turbulent effluent flow}\end{aligned}$$

These similarity criteria indicate that Model 3 ($L_r = 1/80$) can simulate the prototype flow field with approximately the same accuracy as that of Model 1 ($L_r = 1/300$).

The above example clearly illustrates that if water is used as a model fluid, it requires smaller models to simulate a prototype flow and temperature fields in models, as compared to models using air.

ROLES OF HYDRAULIC MODEL STUDY

Atmospheric effects of a heat dissipation system for a nuclear energy center must be investigated through a field study, mathematical modeling and laboratory physical modeling. Hydraulic models, which satisfy the similarity criteria previously described, correctly simulate prototypic flow and temperature field except in a far field. Full-scale field measurements of the thermal dispersion process at a power plant site or analogous heat dispersion phenomena (e.g., forest fire) are very expensive and time consuming. Moreover, since no sites have more than four cooling towers, it is not possible to obtain field data for a nuclear energy center to identify the effects of a large amount of heat emitted to the atmosphere and the behavior of multiple plumes

discharged from a large number of cooling towers located close to each other. Also, most of presently available numerical simulation models cannot adequately predict multiple plume dispersion processes, which is a true three-dimensional phenomenon.⁽¹⁸⁾

The simulation of the atmospheric effects of heat dissipation systems with physical models has shown great potential for solving problems that are presently difficult to solve mathematically or through a field study.^(8,15,17) Hydraulic model studies are best suited to investigate the following areas:

1. Near-field plume dispersion
  - a. general understanding of plume dispersion mechanics
  - b. multiple plume interaction
  - c. effects of nearby structures and local topography on plume dispersion
  - d. effects of atmospheric stratification on plume dispersion.
2. Study of air flow movement within a cooling tower
  - a. identify and understand important mechanics of internal air flow
  - b. effects of alignment of cooling tower components
  - c. effects of ambient wind
  - d. effects of cooling tower shape
  - e. effects of local topography.
3. Density stratified atmospheric flow phenomena
  - a. convective planetary boundary layer induced by heated land surface
  - b. atmospheric flows induced by forest fire or rejected heat from urban areas to determine the applicability of using forest fire plume data in predicting nuclear energy plume effects.

- c. Mixing of two atmospheric flows with different densities.
- 4. Physical model study to provide information necessary for planning a heat dissipation field study, such as identification of strategically important measuring locations.
- 5. Calibration and verification of mathematical models by conducting physical model studies for several different cases under controlled conditions, and use these experimental data and some field data to verify and select useful numerical models.

Although hydraulic models cannot take into account water condensation effects, they can significantly contribute to solve atmospheric pollutant transport (i.e., pollutant dispersion, diffusion and advection) in the above described areas.

STATE-OF-THE-ART OF HYDRAULIC MODELING

In the previous section, the useful roles of hydraulic models for studies of atmospheric dispersion of various pollutants were discussed. This section will assess the state-of-the-art of hydraulic modeling of atmospheric dispersion phenomena by examining existing facilities both in the United States and abroad, and outlining types of studies which have been performed. An inventory of potentially useful existing hydraulic model facilities will also be presented.

There are basically two types of laboratory hydraulic model facilities currently being used to model heat dissipation systems. The first is a hydraulic flume in which a pump recirculates water through a test section in the channel. The facility is operated in a manner similar to a wind tunnel, except the operating fluid

is water. The second type is a towing tank in which models are attached upside down to a movable carriage mounted on the tank side walls. Effluent plumes from cooling tower stacks are discharged downward into quiescent water by using negative buoyant plumes, while the model itself is towed the length of the test section simultaneously. Since the ambient water is stagnant, it is relatively easy to establish stably stratified atmospheric conditions. One shortcoming associated with the towing tank is that there is no background atmospheric turbulence except the one generated by the models. It should be noted that any hydraulic flume with a movable carriage can be used as a towing tank.

For convenience, the model facilities will be discussed by country and the pertinent information is presented in Table 1. W , h and L in Table 1 indicate the width, height and length of a model facility.

United States

Battelle, Pacific Northwest Laboratories

Battelle, Pacific Northwest Laboratories (PNL) has two hydraulic flumes for studies of the atmospheric effects of heat dissipation systems. Physical model studies of free surface flow phenomena have been performed in a 3.1 m wide, 0.5 m deep and 14.3 m long flume equipped with a motor driven carriage. The slope of the flume is adjustable. A 255 kW water heat exchanger provides heated effluents for plume dispersion studies. Remote sensing devices (e.g., infrared camera) installed on the carriage make it possible to observe and measure surface water temperature distributions. Thermistors, connected directly to a PDP 11/10 computer, are used to measure temperature profiles within the flow.

A deeper glass-walled hydraulic flume (1.2 m wide, 1.5 m deep and 13.4 m long) can also be used to model thermal dispersion phenomena. A 4-watt argon laser system provides the capability to measure flow velocities and concentrations of solid substances at

TABLE 1. List of Hydraulic Flume Modeling Facilities Being Used to Study Atmospheric Pollutant Dispersion

LOCATION	TYPE	TEST SECTION SIZE (w x h x l meters)	DISCHARGE (m ³ /sec)	TOWERING CARRIAGE SPEED RANGE (cm/sec)	DENSITY GRADIENT CONTROL	BOUNDARY LAYER THICKNESS, MAX (cm)	TYPES OF STUDIES PERFORMED	REFERENCE NUMBER	SPECIAL NOTES
BATTELLE PACIFIC NORTHWEST LABORATORIES (RICHLAND, WA, USA)	FREE SURFACE FLUME	3.1 x 0.9 x 14.3	0.28	---	HEATING DEVICES	28	DISPERSION, RECIRCULATION AND INTERFERENCE OF PLUMES FROM DRY COOLING TOWERS IN VARIOUS TOPOGRAPHIES.	8	1/600 SCALE RATIO HEATING CAPACITY 8.7x10 ⁵ BTU/hr LINKED TO PDP COMPUTER TO GET DATA ON-LINE REMOTE SENSING DEVICES FOR WATER TEMP. MEASUREMENT
	FREE SURFACE FLUME	1.2 x 1.5 x 13.4	0.28	---	HEATING DEVICES	28			HEATING CAPACITY 8.7x10 ⁵ BTU/hr LINKED TO PDP COMPUTER TO GET DATA ON-LINE LASER SYSTEM FOR VELOCITY MEASUREMENT
IOWA INSTITUTE OF HYDRAULIC RESEARCH (IOWA CITY, IA, USA)	FREE SURFACE FLUME	0.8 x 0.9 x 6.9	0.10	---	HEATING DEVICES	17	DETERMINE DOWNWIND TEMPERATURE DISTRIBUTION, RECIRCULATION AND INTERFERENCE OF BOUYANT JETS FROM MECHANICAL DRAFT COOLING TOWERS. MODEL STUDIES OF A COOLING TOWER AT THE JACK WATSON PLANT.	19, 20	1/150 AND 1/600 SCALE RATIOS HEATING CAPACITY 3x10 ⁵ BTU/hr LINKED TO IBM COMPUTER TO GET DATA ON-LINE HEATING AND COOLING CAPACITY 10 ⁶ BTU/hr LINKED TO IBM COMPUTER TO GET DATA ON-LINE
	FREE SURFACE FLUME	3.1 x 2.3 x 18.3	5.10	---	COOLING AND HEATING DEVICES	26			
UNIVERSITY OF UTAH (SALT LAKE CITY, UT, USA)	CLOSED RETURN WATER CHANNEL	0.5 x 0.6 x 9.2	0.50	---	none	13	STUDIES OF DETAILED FLOW PATTERNS AND DIFFUSION IN STREET CANYONS, BUILDING WAKES, AND COMPLEX TOPOGRAPHY.	21, 22, 30	TILTABLE FLUME
ENVIRONMENTAL PROTECTION AGENCY (RESEARCH TRIANGLE PARK, NC, USA)	FREE SURFACE FLUME- TOWING TANK	2.4 x 1.2 x 25.0	2.72	1-50	SALT WATER SOLUTION	32	STUDY DISPERSION UNDER STABLY STRATIFIED ATMOSPHERIC CONDITIONS, FLOW VISUALIZATION AND COMPLEX TERRAIN STUDIES.	23	DUAL -PURPOSE FLUME AND TOWING TANK. BROAD VARIETY OF ATMOSPHERIC STRATIFICATIONS.
FLOW RESEARCH, INC. (KENT, WA, USA)	TOWING TANK	1.2 x 0.9 x 18.3	---	5-61	SALT WATER SOLUTION	--	STUDY THE FLOW AND DIFFUSION OF POLLUTANTS IN COMPLEX TERRAIN.	14, 15, 24, 25, 30	MODEL TOWED THROUGH STILL WATER SCALE RATIO 1/2500 ARBITRARY VERTICAL DENSITY PROFILE POSSIBLE OIL LUBRICATED INSTRUMENT CARRIAGE TO MEASURE VELOCITY, TEMPERATURE AND SALINITY.
MASSACHUSETTS INSTITUTE OF TECHNOLOGY (CAMBRIDGE, MA, USA)	TOWING TANK	0.3 x 1.0 x 1.5	---	2-25	none	--	PLUME RISE STUDIES USING A DENSE JET OF SALTWATER INJECTED INTO A STILL TANK OF FRESHWATER.	26, 30	MODEL TOWED THROUGH STILL WATER
COLORADO STATE UNIVERSITY (FORT COLLINS, CO, USA)	WIND-WATER TUNNEL	0.6 x 0.8 x 13.4	---	---	none	--	STUDY PLUME DISPERSION OVER WIND GENERATED WATER WAVES.	27	OPTICAL MEASURING SYSTEM USED TO DETERMINE POLLUTANT CONCENTRATIONS.
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH (BOULDER, CO, USA)	PLEXIGLASS TANK	1.1 x 1.2 x 0.8	---	---	HEATING DEVICES	--	SIMULATE THE UNSTABLE PLANETARY BOUNDARY LAYER AND STUDY THE MOVEMENT OF POLLUTANTS FROM A POINT SOURCE.	17, 28	CONVECTIVE HEATING CREATED WITH A HEAT EXCHANGER IN THE BOTTOM OF THE TANK. OIL DROPLETS WERE INSERTED IN THE TANK AND THEIR MOTION PHOTOGRAPHED.
PRINCETON UNIVERSITY (PRINCETON, NJ, USA)	LUCITE TANK	0.5 x 0.5 x 0.5	---	---	SALT WATER SOLUTION	--	EXPERIMENTAL RESULTS OF A FORCED PLUME IN A STRATIFIED ATMOSPHERE COMPARED WITH MATHEMATICAL RESULTS.	29	PLUME PRODUCED BY FORCING FLUID THROUGH A NOZZLE AT THE FREE SURFACE.
METEOROLOGIE NATIONALE (PARIS, FRANCE)	FREE SURFACE FLUME	1.0 x 0.6 x 2.5	0.12	---	HEATING DEVICES	7	STUDIES CONCERNED WITH CHANNEL- ING POLLUTANTS THROUGH VALLEYS AND AROUND HILLS IN COMPLEX TERRAIN.	30, 31	SCALE RATIO 1/10,000 PROVISIONS FOR SHAPING UPSTREAM MEAN VELOCITY PROFILE TRANSPARENT SHEET OF PLASTIC USED TO SIMULATE INVERSIONS pH SENSITIVE DYE USED FOR POLLUTANT CONCENTRATION MEASUREMENTS.
SECURIPOL (FRANCE)	FREE SURFACE FLUME	3.0 x 1.0 x 18.0	---	---	HEATING DEVICES OR SALT WATER	--	SIMULATE PLUME DISPERSION IN COMPLEX TERRAIN.	30, 32	pH SENSITIVE DYE USED FOR POLLUTANT CONCENTRATION MEASUREMENTS. TWO TANDEM FLUME SECTIONS (3mx1mx5m AND 3mx1mx6m) WHICH CAN BE COMBINED.
SOGREAH (GRENOBLE, FRANCE)	TOWING TANK	0.8 x 0.7 x 4.0	---	2-40	SALT WATER SOLUTION	--	BUILDING DOWNWASH, PLUME RISE, AND COMPLEX TERRAIN IN URBAN AREAS.	30, 33, 34	SCALE RATIOS 1/1000 FOR BOUYANT PLUME STUDIES, 1/3900 FOR UNIFORM POLLUTANT SOURCE AND 1/25,000 FOR ALPINE-GRENOBLE REGION. INVERSIONS CREATED BY LAYER OF PURE WATER OVER SALT WATER.
CENTRAL RESEARCH INSTITUTE OF ELECTRIC POWER INDUSTRY (ABIKO, CHIBA, JAPAN)	FREE SURFACE FLUME	1.5 x 0.8 x 10.0	0.34	---	SALT WATER SOLUTION	19	STUDY DIFFUSION IN A STABLY STRATIFIED ATMOSPHERE	30, 35	CONTINUOUS FLOW AND DENSITY GRADIENT MAINTAINED ALCOHOL USED TO SIMULATE PLUME BOUYANCY

any location in the section. As in the wider flume, a data acquisition system is linked directly to a PDP 11/10 computer, as well as other large computer systems, for rapid handling, storage and analysis of data.

Density gradients can be created in the flow by the heat exchanger system. A broad variety of atmospheric conditions can be simulated with this system in either flume.

Onishi and Trent⁽⁸⁾ have used this facility to investigate recirculation and temperature distributions of plumes from two dry cooling towers at the Wyodak Power Plant in Wyoming. The length scale ratio for the study was 1/600. During this study, the effects of wind velocity, temperature of heated effluent, adjacent cooling towers and local topography were examined. Results of the study indicated that plume recirculation and dispersion were strongly influenced by local topography and nearby structures as well as by the ambient wind velocity and effluent exit temperature. The study also revealed that strong nonuniform distributions of air temperature occurred around cooling tower inlets within the tower.

During this same study, a two-dimensional numerical model (VECTRA) was used to calculate temperature distribution of the plumes from cooling towers and the flow patterns including wakes behind the towers, recirculation and interference. Comparison of the calculated and experimental results for these cooling tower cases revealed that the computer results showed a larger circulation pattern in the wakes of these two towers and more significant plume recirculation than those obtained by the experiments. This disagreement is due to the fact that the computer model is two-dimensional, whereas the hydraulic model revealed significant three-dimensional effects such as lateral withdrawal and entrainment of ambient flow, because of these cooling towers' short lengths as compared to widths. This was confirmed by the comparisons between computer and experimental results for two-dimensional heated jet cases. For these

cases, the agreement was excellent. This study clearly indicated the limitations of a two-dimensional code to solve three-dimensional phenomena of plume dispersion and the value of hydraulic model studies in computer model verification.

Iowa Institute of Hydraulic Research, University of Iowa

Extended model investigations to determine downwind temperature distributions, recirculation and interference of buoyant jets issuing from mechanical draft cooling towers have been performed at the University of Iowa.^(19,20) A hydraulic flume (0.8 m wide, 0.9 m deep and 6.9 m long) was used to measure downwind temperature profiles and recirculation ratios for various tower lengths, stack heights and stack spacings.

Researchers there⁽²⁰⁾ conducted plume recirculation studies for a round-shaped cooling tower by using models with several length scale ratios (from 1/600 to 1/150) and found that plume recirculation varied with the model scale for the same values of K and F_j . This implies the importance of R_a if the flow separation from a cooling tower, other structures or local topographic features depends on the ambient Reynolds number.

More recently, another hydraulic flume (3.1 m wide, 2.3 m deep and 18.3 m long) has been constructed at the University. This larger water channel is now being used to study the Jack Watson Plant cooling tower. In this flume, cooling and heating devices can be used to simulate negative and positive plume buoyancy as well as to create stratifications in the flow. To facilitate data collection and analysis, thermistors and other instruments are linked directly to an IBM 1801 computer.

University of Utah

Researchers at the University of Utah have also been studying atmospheric dispersion with small-scale models.^(21,22) Investigations of the detailed flow patterns and pollutant diffusion in

street canyons, building wakes and complex topography have been conducted. A small tiltable water channel (0.5 m wide, 0.6 m deep and 9.2 m long) has been the major laboratory facility used in these studies.

National Environmental Research Center, Environmental Protection Agency

The Fluid Modeling Facility operated by National Environmental Research Center, the Environmental Protection Agency (EPA) at Research Triangle Park, NC, is unique in that it can be operated both as a towing tank and hydraulic flume (2.4 m wide, 1.2 m deep and 25 m long). EPA's primary interest in modeling atmospheric diffusion processes has been to establish and to refine the National Ambient Air Quality Standards. Towing tank studies performed at this facility have generally involved the examination of plume dispersion under stably stratified atmospheric conditions. A saltwater filling system provides the capability of modeling any desired stratification, from elevated- or ground-based inversions to neutral conditions. In the hydraulic flume mode, the EPA facility can be used to determine the dispersion of pollutants over complex terrain and to perform various flow visualization studies.⁽²³⁾

Flow Research, Inc.

Investigators at Flow Research have been extensively using a towing tank to investigate the effects of atmospheric stability and terrain on plume dispersion under neutral and stably stratified atmospheric conditions.^(14,15,24,25) The dimensions of the towing tank are 1.2 m wide, 0.9 m deep and 18.3 m long. Inverted three-dimensional models are towed through the tank to simulate flow over complex terrain. Saltwater, supplied to the test section through a filling system, creates predetermined density profiles. Using shadow graph and dye visualization techniques, characteristics of plume dispersion can be observed and measured. Special features of the Flow Research towing tank include an oil-lubricated carriage

to mount devices for accurate measurements of turbulent velocity, temperature and salinity fluctuations and a direct on-line computer data acquisition and analysis system.

Towing tanks, as utilized by Flow Research investigators, are best used for the study of stably stratified conditions where salt-water is commonly used to produce density gradients. Model studies conducted in a towing tank can simulate ambient flow conditions produced by topography and ground structures as well as effluent flow conditions. However, they cannot produce any small-scale ambient background turbulent eddies. Also, development of an ambient flow and boundary layer and data sampling time may be fairly limited unless a considerably long model including local topography is used. This shortcoming may be somewhat reduced by artificially producing turbulence in the flow. This practice has been used by Flow Research investigators.

Massachusetts Institute of Technology

The Fluid Mechanics Laboratory at Massachusetts Institute of Technology has conducted several plume rise studies in a small towing tank (0.3 m wide, 1.0 m deep and 1.5 m long). Plume buoyancy was simulated by injecting a dense jet of saltwater into a still tank of fresh water. Overcamp and Hoult⁽²⁶⁾ have used this facility to study the effects of cold climates on precipitation from cooling tower waste heat discharges. Since this towing tank is so small, no fully developed ambient flow can be generated.

Colorado State University

In a unique combination of wind and water tunnels, (0.6 m wide, 0.8 m deep and 13.4 m long) investigators at Colorado State University have been studying the dispersion of air pollutants in a neutrally stable boundary layer over a wind-disturbed water surface. The experimental results obtained by Liu and Karaki⁽²⁷⁾ were compared with numerical solutions. In their apparatus, an atomizer

was used to generate particles to be transported and diffused over the free water surface by the wind tunnel. Water surface undulations, generated by a plunger type mechanical wave generator, provided additional dispersion to the particles. The concentrations of the particles were measured throughout the test section by a special optical system.

National Center for Atmospheric Research (NCAR)

In a large plexiglass tank (1.1 m wide, 1.2 m deep and 0.8 m long), Willis and Deardorff have examined the dispersion of pollutants due to convective lifting in the planetary boundary layers.^(17,28) Since the flow is free convection, the Rayleigh number, R_{ay} , was used instead of R_j and R_j as discussed before. By uniformly heating the bottom of the tank, an unstable temperature gradient is established in the simulated atmosphere.

Neutrally buoyant particles, composed of oil droplets dyed with white pigment, are released from the bottom and traced with streak photography. The facility is equipped with vertically aligned thermocouples and a horizontal resistance wire to determine profiles of mean temperature and heat flux. The NCAR laboratory model has been used to study the evolution of pollutant concentration distributions downwind from a simulated continuous point source. Although the model size was too small to obtain accurate test results, Willis and Deardorff have found that fairly good agreement exists between the model measurements and prototypic atmospheric observations.

Princeton University

Studies of the dispersion of a forced plume in a stratified atmosphere were performed at Princeton University.⁽²⁹⁾ The negative buoyant plume was injected into the stratified fluid through a nozzle at the free surface of a small lucite tank (0.5 m wide, 0.5 m deep and 0.5 m long). Stratifications in the

atmosphere were simulated with a layered saltwater solution. The investigators used the results from this study to verify mathematical modeling predictions. Even though this tank was very small, the experiments conducted were very useful for verifying the computer results.

France

Meteorologie Nationale

Most of the studies conducted by the French Meteorological Service are concerned with pollutant pathways through valleys and around hills.^(30, 31) Bouyant stack plumes are generally simulated by mixing alcohol with the effluent water in a hydraulic flume (1.0 m wide, 0.6 m deep and 2.5 m long). Researchers at this facility use adequate upstream topography to develop velocity profiles rather than shaping the flow at the entrance. Occasionally, a grid heating system is used to simulate a variety of atmospheric conditions. In the case of sharp atmospheric inversions, a transparent sheet of plastic is placed just above the model to restrict plume dispersion.

The most unique feature of this facility is the technique used to measure the concentration of effluent pollutants. The base of the water channel is coated with a pH sensitive dye. During the test procedure, a weak solution of hydrochloric acid is released from the stack. The dye changes color in response to the acid concentration, making it possible to observe and measure dispersion characteristics. To obtain three-dimensional concentration profiles a coarse wire mesh coated with the dye is placed at various sections in the channel.

Investigators at Meteorologie Nationale use an interesting approach to study atmospheric pollutant dispersion occurring over a large area. For a model with the length scale

of 1/10,000, ground roughness was exaggerated to generate artificial turbulence in the model. Then, as a verification of the model, the ambient flow velocity was adjusted so the measured pollutant concentrations in the experiment matched predicted concentrations on the ground level for a neutrally stratified ambient flow case. Although this approach provides useful information on pollutant dispersion in a large area by using a small model, the results should be regarded as qualitative rather than quantitative.

SECURIPOL

SECURIPOL has recently constructed a large hydraulic flume (3.0 m wide, 1.0 m deep and 18 m long) to study diffusion of pollutants over complex terrain.^(30, 32) The pH sensitive dye technique, similar to the one used by Meteorologie Nationale, is utilized to measure pollutant concentrations. Density gradients are produced by injecting either hot or salt water into the flow. The unique feature of this facility is that the water channel is composed of two tandem sections. These sections can be operated independently or combined into a single long flume.

Society of Grenoble for the Study and Application of Hydraulics (SOGREAH)

SOGREAH has performed a broad variety of physical modeling studies in their towing tank facilities (0.8 m wide, 0.7 m deep and 4 m long). Their investigations include extensive measurements of buoyant plumes in both neutral and stably stratified surroundings and the simulation of a uniform source of pollution which is at a higher temperature than the ambient atmosphere.^(30, 33) Recently, SOGREAH has constructed a model of the Alpine-Grenoble region.⁽³⁴⁾ The scale model (length scale ratio of 1/25,000) of the city of Grenoble and surrounding mountainous terrain was used to determine the best location for new industrial and housing projects. Atmospheric stratifications in this facility are

generated with salt water. To measure the dispersion of pollutants, SOGREAH uses conductivity meters.

A physical model cannot exactly simulate far field pollutant dispersion because of the difficulty in scaling down prototype atmospheric small-scale background turbulence. If atmospheric flow is controlled by large eddies, such as wakes and separation due to large topographical features, or is stably stratified, a physical model may tend to produce a more accurate prediction.

It is worth noting that a physical model, as demonstrated by SOGREAH and SECURIPOL, can provide qualitative but critically important information on far field pollutant dispersion for regional assessment of air pollution.

Japan

Central Research Institute of Electric Power Industry

A once-through water channel (1.5 m wide, 0.8 m deep and 10 m long) at this institute has been used to study diffusion in stably stratified atmospheres. Alcohol mixed with water is used to simulate plume bouyancy. Although limited information is available on this facility, reports ^(30, 35) indicate that researchers at the Institute have successfully used salt water to produce continuous density gradients in a moving ambient flow without inverting the model.

In addition to the hydraulic facilities described above, Electricite de France (France), Delft Hydraulic Laboratories (Netherlands) and Southampton University (Great Britain) have hydraulic facilities for modeling atmospheric pollutant dispersion. However, detailed descriptions of these facilities have not been received.

With the exception of the NCAR, Princeton University and Colorado State University Studies, the state-of-the-art in hydraulic modeling of atmospheric phenomena is dominated by both towing tank

and hydraulic flume facilities. Depending on the atmospheric conditions to be modeled, each of these hydraulic modeling facilities has distinct capabilities.

In general, towing tanks are best used for the study of stably stratified conditions where salt water can be used to create density gradients. Specially designed filling systems make it possible to model conditions from elevated or ground-based inversions to neutral conditions. A carriage, mounted on the side walls of a towing tank, provides the added capability of carrying data collection devices anywhere in the section. The major limitation of the towing tank facility is the simulation of background turbulence and velocity profiles found in the atmosphere. An excessively long towing tank would be required to generate a sufficient turbulent boundary layer with upwind terrain. Also short time limitation on data sampling is a major problem associated with towing tank studies.

Hydraulic flumes, on the other hand, have the advantage that turbulence and velocity profiles can be more easily produced in the moving fluid. Using sufficient roughness elements upstream of the model or adjusting the flow at the channel entrance makes this type of water flume desirable for many modeling situations. Complex terrain, plume recirculation and interference and various stack configurations and orientations can easily be modeled in hydraulic flumes for both steady and unsteady dispersion phenomena. Plume buoyancy is generally simulated by mixing alcohol with water or using heated water. Currently, grid heating systems are used to simulate density profiles in the fluid since salt water gradients are difficult to maintain. If the salt water technique developed by the Central Research Institute of Electric Power

Industry in Japan can maintain continuous profiles in the moving fluid, the experimental capabilities of the hydraulic flume will be greatly increased.

The previous discussion should indicate the diversity of hydraulic modeling facilities both in the United States and abroad. A broad range of techniques are available to gather data, including infrared photography, pH sensitive dye, thermistors and conductivity meters. Sophisticated data acquisition and analysis systems directly linked to computers have significantly improved the physical modeling process. Finally, there are a variety of flume sizes and configurations, as shown in Table 1, used for atmospheric dispersion studies.

Hydraulic models have been used successfully to analyze the atmospheric effects of heat dissipation systems for several decades and will continue to provide valuable experimental results in the future.

RECOMMENDED EXPERIMENTAL PROGRAMS

In this section, actual experimental programs using hydraulic model facilities (especially hydraulic flumes) for investigations of atmospheric heat dissipation systems of nuclear energy centers will be described. The following programs are recommended:

1. NEAR FIELD MULTIPLE PLUME DISPERSION ANALYSIS FOR NUCLEAR ENERGY CENTERS

Objectives

The objectives of this recommended study are:

1. to investigate interactions among plumes from a large number of cooling towers at energy centers through the use of physical model studies,

2. to evaluate the effects of adjacent towers on the performance of each cooling tower, and
3. based on the physical model test results, to investigate methodology for making a two-dimensional simulation model, such as the VECTRA code,⁽⁸⁾ applicable to multiple plume cases.

Recommendations will be made regarding the development of a three-dimensional simulation model, should such development prove necessary for multiple plume dispersion problems.

Justification

A recent cooling tower study⁽⁸⁾ reported that temperature distributions in the near field are strongly affected by adjacent cooling towers and local topography. Interaction among plumes from a large number of cooling towers at an energy center is extremely complex. Unfortunately, very little research has been conducted in this area.^(3,12,13) Full-scale field measurements of these effects are not practical because of prohibitive costs and because no sites have more than four towers.

A physical model study permits a valid and economical investigation for this complex problem under the neutral atmospheric condition and to a lesser extent under stable and unstable atmospheric conditions. Observations of this type are invaluable for developing and evaluating analytical and numerical models. Experimental results of such a near field study can be used as an input for far field numerical models to assess the impact of an energy center on meteorological conditions.

In order to eliminate the effects of flume side walls and water surface, it is necessary to use large and deep hydraulic flumes, such as the flumes at PNL, EPA and Iowa Institute of Hydraulic Research. For example, based on required similarity criteria, (densimetric Froude and Reynolds similarity criteria), the PNL

flume (1.2 m wide, 1.5 m deep and 13.4 m long) is equivalent to a wind tunnel approximately 4.5 m wide, 5.6 m deep and 50 m long. A large glass-walled hydraulic flume will permit observations of three-dimensional flows not possible with other facilities.

Work Plan

Laboratory experiments will be conducted in a glass-wall hydraulic flume. Physical models of cooling towers will be used to obtain temperature and velocity distributions in the near field and inside the cooling tower air intakes. Effluent plume conditions, the number of cooling towers, meteorological conditions and local topography will be varied to determine their effects on plume interaction. The laboratory test results will also be used to evaluate cooling tower performance for an energy center and to test the applicability of a two-dimensional hydrothermal model to multiple plume dispersion problems. Possible code modifications will be examined to adapt the two-dimensional model to plume dispersion analyses for an energy center. The applicability and limitations of two-dimensional analytical and numerical models to multiple plume dispersion problems will be discussed, and recommendations will be made concerning the development of three-dimensional codes for this problem.

2. COOLING TOWER SITING CRITERIA

Objectives

The objectives of this study are:

1. to analyze the effects of local topography, nearby structures, atmospheric stratifications, and cooling tower effluent source characteristics on plume dispersion and recirculation, and
2. to derive design criteria for selection of sizes, locations, spacing and orientation of cooling towers to optimize cooling tower performance and to minimize environmental impact.

Justification

Local topography and adjacent cooling towers and buildings, as well as ambient flow and effluent discharge parameters, are important factors in plume recirculation, interference and in plume rise.^(3,8,12,13,15) These factors can also result in a poor distribution of cooling tower inlet air temperature. Plume recirculation and nonuniform distribution of cooling tower inlet air temperature, caused by poor arrangement of cooling towers on a power plant site can reduce the cooling capacity of the towers. This would result in a reduction in turbine efficiency and related electrical output.^(7,19) Onishi and Trent⁽⁸⁾ reported that a dry cooling tower at the proposed Wyodak plant in Wyoming caused a 7% reduction in cooling capacity for a downwind dry cooling tower, and that this reduction could be two or three times greater for a wet cooling tower. Because little is known about these problems, effects on cooling tower performance are difficult to predict. Actual field measurements or model studies for each power plant are expensive and time consuming. Therefore, it is beneficial to conduct studies on recirculation and interference problems for various topographies and nearby structures, and to obtain general cooling tower siting criteria. The criteria developed in this recommended study will be used to determine cooling tower placement with respect to local terrain and nearby structures. These criteria will also be used to evaluate cooling tower efficiency and to assess environmental impact of site specific power plants.

Work Plan

The recommended study will be conducted experimentally and analytically to determine temperature and velocity distributions in the near field of the cooling tower and within the cooling tower air intake. The following conditions will be considered in this program:

1. Meteorological Conditions
  - Wind Speed and Direction
  - Atmospheric Stratification
2. Nearby Structures
  - Adjacent Cooling Towers
  - Adjacent Buildings
3. Terrain
  - Flat Ground
  - Various Simplified Topographies

3. STUDY ON COOLING TOWER INTERNAL AIR FLOWS

Objectives

The objectives of this work are to analyze experimentally and mathematically the internal air flow movement within a cooling tower in relation to cooling tower geometry, arrangement of cooling tower components, nearby cooling towers, and meteorological conditions (wind velocity and density stratification).

Justification

Recently, field observations and laboratory experiments for cooling towers revealed severe, nonuniform distributions of cooling tower inlet air flows (velocity and temperature) which cause nonuniform distributions of internal air flows within the cooling towers.⁽⁸⁾ These nonuniformities of flow and temperature not only reduce the cooling tower efficiency but may also cause severe icing problems during the winter. To obtain optimum sizing of cooling tower systems and arrangement of their components (resulting in optimum cooling tower performance), a functional relationship must be developed among the internal air flow movement, cooling tower size and shape, alignment of cooling tower components and external flow conditions including the ambient wind. Unfortunately, very little research has been conducted,^(36,37) and little information is available to improve and evaluate true

cooling tower performance. Consequently, investigating the air flow movement inside a cooling tower would be important. This information would also lead to optimum cooling tower geometry which has better aerodynamic characteristics.

Work Plan

Hydraulic model studies will be conducted in a large glass-wall water flume to simulate air movements within a dry cooling tower and in the vicinity of the tower. Heat exchangers will be simulated by installing heating coils in the model tower. An existing two-dimensional model such as the VECTRA code⁽⁸⁾ will be modified and applied to large wet and dry mechanical cooling towers to obtain velocity and temperature distributions. The results of these studies will identify cooling tower operational problems and will be used to improve performance. In addition, the results identify cooling tower plume source characteristics which are input data for all plume analyses. Recommendations will be made regarding the applicability of two-dimensional numerical models and the necessity of developing a three-dimensional simulation model.

4. STUDY ON HEAT CONVECTION FLOWS INDUCED BY MULTIPLE COOLING TOWER PLUMES, FOREST FIRE AND REJECTED URBAN HEAT

Objective

The objectives of this study are:

1. to analyze experimentally (by using a hydraulic model) and mathematically atmospheric heat convection flows induced by plumes emitted from a large number of cooling towers (or by cooling ponds) in a nuclear energy center,
2. to analyze experimentally and mathematically atmospheric heat convection flows induced by forest fire and rejected heat from a large urban area, and

3. to assess similarity among these cases and applicability of using forest fire and urban heat data in predicting atmospheric effects caused by nuclear energy center heat dissipation systems.

Justification

Possible meteorological effects of nuclear energy centers (e.g., intensification of rain storms, thunderstorms) are some of the important aspects to be evaluated. Although the impact of nuclear energy centers cannot be measured directly, a large number of data are available on forest fire and urban heat sources, and their implications on meteorological conditions. These data may be used to predict possible atmospheric effects of the center.

Work Plan

A deep hydraulic flume will be used to simulate heat convection flow. Temperature and velocity will be measured for these cases and their similarities analyzed. A two-dimensional code will also be used to provide additional information on these phenomena.

5. VERIFICATION OF NUMERICAL MODELS

Objectives

The objectives are:

1. to conduct hydraulic model plume studies for various cases under controlled conditions, and
2. to use these experimental results and some field data to verify and select useful numerical models.

Justification

Numerous mathematical models (ranging from simple empirical equations to sophisticated three-dimensional numerical models) are presently available to predict the plume dispersion. However, almost all of these models are not fully verified and presently there is confusion about the selection of these models to a particular

problem. The field data that are available, such as those at Paradise, Chalk Point, Gaston, Keystone and Watson power plants, do not cover a wide range of conditions and are limited in their accuracy. Hydraulic model results provide a wide range of excellent, controlled data to be used for verification of numerical data. If a mathematical model cannot properly simulate controlled laboratory experimental situations, it cannot simulate more complex field conditions. A physical model does not have to simulate an actual field case because the experimental conditions and results will be used for verification of mathematical models.

Work Plan

Hydraulic model studies will be conducted to produce a wide range of plume dispersion test results. The following conditions will be considered:

1. Meteorological Conditions
  - Wind Speed and Direction
  - Atmospheric Stratification
2. Cooling Tower Geometry and Size
  - Two-Dimensional Tower
  - Three-Dimensional Tower
3. Nearby Structures
  - Adjacent Cooling Towers
  - Adjacent Building
4. Terrain
  - Flat Ground
  - Various Complex Topographies

Various mathematical models will be tested against these experimental cases to select useful models.

In addition to these five programs, hydraulic models will be used to provide information for planning various field measurements.

This information will include the sensitivity range of measuring instruments to determine those needed for field studies. Sampling locations and times will also be selected.

CONCLUSIONS

A critical review of hydraulic modeling on atmospheric dispersion was made in this study. The main conclusions of the investigation are summarized as follows:

1. Modeling criteria derived by dimensional analysis for atmospheric plume dispersion are the velocity ratio of the effluent to the ambient flow, K (Equation 5) the ambient internal Froude number, F_a (Equation 7), the effluent densimetric Froude number, F_j (Equation 8), the ambient Reynolds number, R_a (Equation 9) and the effluent Reynolds number, R_j (Equation 10). If free heat convection flow is simulated, the Rayleigh number, R_{ay} (Equation 13) will replace F_j .
2. Hydraulic models correctly simulate the near field atmospheric dispersion process. Because of the difficulties in scaling down the atmospheric background small-scale turbulent eddies in a model, a physical model cannot exactly simulate far field pollutant dispersion phenomena. Nonetheless, a physical model can provide qualitative but critically important information on far field pollutant dispersion. Accuracy of the far field model results may increase if an ambient flow in a far field is controlled by large eddies such as those caused by wakes and flow separation which are associated with features of complex terrain (e.g., mountains and valleys).
3. The most common physical model facilities for plume dispersion are wind tunnels. However, water has better characteristics as a model fluid than air, because:

- a) it is relatively easier and requires smaller models to satisfy the densimetric Froude and Reynolds number criteria for the model, b) flow and temperature measurements are more easily conducted in water than in air, and c) flow observation is more readily conducted in water. A shortcoming of hydraulic models is the lack of ability to simulate water condensation mechanics.
4. Hydraulic model studies are commonly conducted by using a hydraulic flume or a towing tank. Towing tanks are best used for a study of stable stratified flow conditions. The major limitations of towing tank facilities is the simulation of turbulence and velocity profiles found in the atmosphere. Short time limitation on data sampling is also a problem associated with this type of facility. A hydraulic flume, on the other hand, has advantages concerning these aspects. Complex terrain, plume recirculation and interference, and various stack configurations and orientations can easily be modeled in a hydraulic flume for both steady and unsteady dispersion phenomena. However, it is more difficult to produce a stratified ambient flow in a hydraulic flume than in a towing tank.
5. Useful roles and recommended programs of hydraulic model studies on atmospheric heat dissipation of nuclear energy centers are: a) near field plume dispersion analyses to investigate multiple cooling tower plume dispersion and effects of local topography, nearby structures, atmospheric stratification on plume dispersion, b) a study of air flow movement within the cooling tower, c) a study on heat convection flows induced by multiple cooling tower plumes, forest fire and rejected urban heat, and d) verification of numerical models by using experimental results of hydraulic model studies.

Experimental programs outlined in the previous section are recommended to support the overall objectives of the Atmospheric Effects of a Nuclear Energy Center program.

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APPENDIX 1. LIST OF SYMBOLS

D	= Cooling tower stack diameter
F	= Ambient Froude number
F_a	= Ambient internal Froude number
F_j	= Effluent densimetric Froude number
g	= Gravitational acceleration
$H(x,y,z)$	= Terrain profile
h	= Height of hydraulic model facility
K	= Velocity ratio of the effluent to the ambient flow
L	= Characteristic length scale of the ambient flow
l	= Length of hydraulic model facility
L_r	= Length scale ratio (model/prototype)
Re_a	= Ambient Reynolds number
Re_{ay}	= Rayleigh number
Re_j	= Effluent Reynolds number
T	= Temperature at any point in the flow
ΔT	= Difference between the temperature at any point in the flow and the ambient temperature
T_a	= Temperature of the ambient flow
ΔT_o	= Temperature difference between the tower discharge and the ambient flow
T_w	= Temperature at a solid boundary heat source
V_a	= Velocity of the ambient flow
V_j	= Velocity of the tower discharge
w	= Width of hydraulic model facility
x,y,z	= Cartesian coordinates in the longitudinal, lateral and vertical directions, respectively
Δz	= Change in elevation
α	= Thermal diffusivity
β	= Thermal expansion coefficient
ν_a	= Kinematic viscosity of the ambient fluid
ν_j	= Kinematic viscosity of the tower discharge
ρ_a	= Reference ambient fluid density
$\Delta \rho_a$	= Change in ambient fluid density
$\Delta \rho_o$	= Density difference between the tower discharge and the reference ambient fluid

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