

APPLICATIONS OF WIND TUNNEL MODELING FOR ASSESSING ODOR IMPACTS

Ron L. Petersen, Ph.D., CCM
CPP, Inc.
1415 Blue Spruce Drive
Fort Collins, CO 80524
rpetersen@cppwind.com

ABSTRACT

Wind tunnel modeling is a very useful tool to assess and mitigate odors from industrial, laboratory, sewage treatment, hospital, and landfill pollutant sources. As the EPA Fluid Modeling Guideline so aptly puts it: “A well-designed and carefully executed fluid modeling study will yield valid and useful information – information that can be applied to real environmental problems – with just as much and generally more credibility than any current mathematical models.” This paper discusses the validity of wind tunnel modeling and how these studies are conducted, and also presents three applications to assess and mitigate odor impacts. The first application deals with odorous engine exhaust from a natural gas pumping station. A resident was complaining of odors during certain operating and weather conditions. Wind tunnel modeling was conducted to provide the operator various alternatives to solve the problem. The alternatives ranged from taller stacks to installing induced air exhaust fans. The second application relates to the Puente Hills Landfill in Los Angeles. The primary purpose of this study was to determine how the changing landscape of the landfill (existing versus future contours) would affect levels of odors experienced by the nearby community. Wind tunnel testing confirmed that odors will decrease for the future configuration. The third application relates to odor impacts from laboratories and hospitals. Wind tunnel modeling was used to determine the optimum exhaust system such that odor impacts are minimized.

KEYWORDS

Dispersion modeling, wind tunnel modeling, odor mitigation, landfills, laboratory, hospital, engines

INTRODUCTION

For those who are unfamiliar with “wind tunnel” modeling of pollutant dispersion, a general description is first in order. The goal of wind tunnel modeling is to reproduce the important aspects of the atmospheric boundary layer and the resulting dispersion patterns of pollutants at a reduced scale.

The theoretical basis for wind tunnel modeling can be derived from the basic equations of motion in dimensionless notation. If the important dimensionless parameters and dimensionless boundary conditions are identical at two different scales (i.e., full scale and model scale), the solution to the equations will be identical. It should also be noted that these equations, if solved exactly, will yield a correct simulation. Unfortunately, an exact match of all dimensionless parameters is not physically possible. The challenge for the wind tunnel modeler is to find the appropriate dimensionless parameters and dimensionless boundary conditions such that an accurate simulation of pollutant dispersion is achieved.

Wind tunnel modeling has been found, and continues to be, a very useful tool to assess and mitigate odors from industrial, laboratory, sewage treatment, hospital, and landfill sources. As the EPA (Snyder,

1981) Fluid Modeling Guideline so aptly put it: “A well-designed and carefully executed fluid modeling study will yield valid and useful information – information that can be applied to real environmental problems – with just as much and generally more credibility than any current mathematical models.” While this reference is over 25 years old, significant improvements in the accuracy of numerical models for complex setting (i.e., complex terrain and building wakes) have not been made. For these situations, wind tunnel modeling can provide more accurate dispersion estimates.

This paper addresses the validity of wind tunnel modeling, discusses how wind tunnel modeling studies are conducted, and presents several applications to assess and mitigate odor impacts.

VALIDITY OF WIND TUNNEL MODELING

There are several reasons why wind tunnel modeling is a valid tool to evaluate atmospheric dispersion of odors. The first and most important reason is theoretical. A wind tunnel simulation is, in effect, a solution to the basic equations of motion. The basic equations are solved by simulating the flow at a reduced scale and then the desired quantity (i.e., odor dilution is measured). Solving the basic equations (i.e., the wind tunnel simulation) provides a steady-state solution with a complete record of the time varying velocity and concentration fields. It should be noted that the Gaussian dispersion model also predicts steady-state average concentrations. The wind tunnel model, in effect, can be described as an analog computer with near infinitesimal resolution and near infinite memory. More information on the theoretical aspects can be found in Snyder (1981) and Cermak (1975).

Another determining factor demonstrating the validity of wind tunnel modeling relates to dispersion comparability. With passage of the EPA “good engineering practice” (GEP) stack height regulation, wind-tunnel modeling has been required to determine the GEP stack height for many facilities. As part of a GEP stack height evaluation, the wind-tunnel modeler must perform what is referred to as an “atmospheric dispersion comparability test (EPA, 1985).” For this test, wind profiles and dispersion are measured in the wind tunnel without the presence of structures. A flat, uniform, grassland type roughness is simulated. These tests have demonstrated that wind tunnel velocity profiles match profile shapes observed in the atmosphere, and that the profiles fit similarity theory. The tests have also shown that the horizontal and vertical dispersion coefficients are consistent with the default dispersion coefficients used in the AERMOD/PRIME model (Cimorelli, et al., 2005) for urban and rural dispersion (Petersen, 1985). The horizontal and vertical dispersion coefficients are also consistent with similarity theory and consequently reflect the character of the underlying surface roughness.

Wind tunnel modeling is further validated by comparisons with field measurements, which showed a high degree of consistency and accuracy (Petersen, 1986; Weil et al., 1981; Meroney, 1986).

SETTING WIND TUNNEL OPERATING CONDITIONS

An accurate simulation of the boundary-layer winds and stack gas flow or source release conditions is an essential prerequisite to any wind tunnel study of diffusion. The similarity requirements can be obtained from dimensional arguments derived from the equations governing fluid motion. Based on the dimensional analysis and the requirements in the EPA fluid modeling guidelines (Snyder, 1981), the criteria that are frequently used for conducting wind-tunnel simulations of atmospheric dispersion are:

- match (equal in model and full scale) momentum ratio, M_o ;

$$M_o = \lambda \left(\frac{V_e}{U_H} \right)^2 \quad (1)$$

- match buoyancy ratio, B_o ;

$$B_o = \frac{gdV_e(\rho_a - \rho_s)}{\rho_a U_h^3} = \left(\frac{\rho_s}{\rho_a} \right) \left(\frac{(V_e/U_h)^3}{Fr_s^2} \right) \left(\frac{d}{z_r} \right) \quad (2)$$

where

$$Fr_s^2 = \frac{\rho_s V_e^2}{g(\rho_a - \rho_s)d} \quad (3)$$

- ensure a fully turbulent stack gas flow [stack Reynolds number ($Re_s = V_e d/\nu$) greater than 670 for buoyant plumes or 2,000 for turbulent jets (Arya and Lape, 1990), or in-stack trip]
- ensure a fully turbulent wake flow [terrain or building Reynolds number ($Re_b = U_H H_b/\nu$) greater than 11,000 or conduct Reynolds number independence tests]
- identical geometric proportions
- equivalent stability [Richardson number, $Ri = (g\Delta\theta H_b)/(T U_H^2)$, in model equal to that in full scale, equal to zero for neutral stratification]
- equality of dimensionless boundary and approach flow conditions

where:

V_e	=	stack gas exit velocity (m/s)
U_h	=	ambient velocity at building top (m/s)
d	=	stack diameter (m)
ρ_a	=	ambient air density (kg/m ³)
$\Delta\theta$	=	potential temperature difference between H_b and the ground (K)
T	=	mean temperature (K)
ρ_s	=	stack gas density (kg/m ³)
ν	=	viscosity (m ² /s)
H_b	=	typical building height (m)
λ	=	density ratio, ρ_s/ρ_a (-)
z_r	=	
Fr_s	=	

It is advantageous to conduct certain simulations at model scale Reynolds numbers less than 11,000. When this situation arises, Reynolds number independence tests are usually conducted.

For buoyant sources, the ideal modeling situation is to simultaneously match the stack exit Froude number, momentum ratio, and density ratio. Achieving such a match requires that the wind speed in the tunnel must be equal to the full-scale wind speed divided by the square root of the length scale. For

example, for a 1:180 length scale reduction, the wind speed ratio would be approximately 1:13, meaning the tunnel speeds would be 13 times lower than the full-scale wind speeds. Such a low tunnel speed would produce low Reynolds numbers and is operationally difficult to achieve. Hence, Froude number scaling is typically not used. Instead, for buoyant sources, the buoyancy ratio defined above is matched between model and full scale. Using this criterion, the exhaust density of the source can be distorted, which allows higher wind-tunnel speeds.

Even with distorting the density, there may still be situations in which the buoyancy ratio cannot be matched without lowering the wind tunnel speed below the value established for the critical building Reynolds number. When this conflict exists, the buoyancy ratio is distorted and the building Reynolds number criterion is not relaxed. Distorting the buoyancy ratio will result in lower plume rise, which in turn will result in higher predicted ground-level concentrations. Hence, the results of the study will be conservative.

Testing in complex building environments is typically performed under neutral stability ($Ri = 0$). Meroney (1990) cites a Colorado State University report that determined that the effect of atmospheric stability on dispersion within five building heights of a building complex is relatively small due to the dominance of mechanical turbulence generated within the building complex.

EXPERIMENTAL METHODS

Wind tunnel modeling of pollutant dispersion is conducted in a wind tunnel that is specifically configured to simulate the atmospheric boundary layer. Unlike an aerodynamic wind tunnel, which is designed to evaluate a body moving through relatively non-turbulent air, an atmospheric boundary-layer wind tunnel is designed to evaluate the flow of air over a stationary body immersed in the earth's atmospheric boundary layer. Two evenly spaced vertical spires and a trip immediately downwind of the flow tunnel entrance begin the development of the atmospheric boundary layer as shown in Figure 1 (top portion of figure). A long boundary layer development region between the spires and the site model is filled with roughness elements placed in a repeating roughness pattern that is experimentally set to develop the appropriate approach boundary layer wind profile and approach surface roughness length.

Figure 1 shows a typical wind tunnel setup for a power plant evaluation. Notice the roughness elements upwind of the model turntable area and the spires and trip at the entrance to the wind tunnel.

Figure 1. Typical wind tunnel setup for modeling power plant exhaust dispersion



Once the scale reduction factor has been defined, a physical model of the test buildings and/or terrain is constructed by applying the scale reduction factor to the full-scale dimensions in all three dimensions without distortion. The model should include all significant features that can impact the flow trajectories or the sources under evaluation.

Exhaust sources are simulated by installing stacks constructed of tubes (typically brass) at appropriate locations. If the internal flow Reynolds number is insufficient, trips should be installed within the stacks to ensure that the stack flow is fully turbulent upon exit.

Most receptor locations (concentration sampling points) can be evaluated by installing a point receptor at the specified location. One end of a sampling tube is installed at the receptor location. The other end of the tube is then connected to the inlet port of a concentration measuring device to determine the amount of tracer gas present at the receptor location.

After the desired atmospheric condition has been established in the wind tunnel, a mixture of inert gas and a tracer of predetermined concentration is released from an emission source at the required rate to simulate the prototype plume rise. For area type sources, an extremely low exhaust velocity is set so no plume rise is simulated. Typical tracer gases include ethane, methane, propane, carbon monoxide, and sulfur hexafluoride. The volume flow rate of the gas mixture is controlled and monitored by a precision mass flow controller to ensure an accurate simulation.

The collected air samples are analyzed in either real time or as a time averaged sample. In a real time application, the air sample is drawn directly into a concentration detector. The type of detector will depend upon the tracer gas used in the simulation. Either a flame ionization detector (FID) or photo ionization detector (PID) is commonly used for hydrocarbon (ethane, methane, propane, etc.) tracers. For a time averaged sample, the air sample is drawn into a collection chamber, such as a syringe or a Tedlar[®] bag. After a complete sample has been collected, the air within the collection chamber is fed

into a concentration detector. The advantage of a real time sampling system is that peak-to-mean concentrations can be obtained, which are often important for odor assessments.

Measured model concentrations are converted to full-scale normalized concentrations by equating the non-dimensional concentration, $K = CUL^2/m$, in both model and full scale, using an equation presented in the Guideline for Use of Fluid Modeling of Atmospheric Diffusion (Snyder, 1981). Typically, concentrations measured in the wind tunnel are averaged over a period long enough to represent a steady-state average concentration. In the full scale, a steady-state average concentration is usually assumed to correspond to a 15-minute to 1-hour average concentration due to the natural fluctuations in both wind speed and wind direction present within the atmosphere. Full-scale concentration estimates for averaging times less than 24 hours can be developed using the following power law relationship defined by Turner (1994):

$$\left(\frac{C}{m}\right)_s = \left(\frac{C}{m}\right)_k \times \left(\frac{t_k}{t_s}\right)^p \quad (4)$$

where:

- $(C/m)_s$ = normalized concentration estimate for averaging time t_s
- $(C/m)_k$ = normalized concentration estimate for averaging time t_k
- p = power law exponent between 0.17 and 0.20

For odor assessments, a peak concentration is frequently of interest. In this situation, a real time concentration analyzer is used and peak can be measured in the wind tunnel directly.

APPLICATIONS

Natural Gas Pumping Station

The first application deals with odorous engine exhaust from a natural gas pumping station. A resident complained of odors during certain operating and weather conditions. The operator of the station commissioned a wind tunnel modeling study to assess the existing situation and various methods to mitigate the odors. A 1:300 scale model of the terrain and pumping station was constructed and placed in a boundary-layer wind tunnel as shown in Figure 2. Tracer gases were released from the exhaust sources and exhaust dilution (normalized concentration) was measured in the nearby neighborhood. Figure 3 is a visualization of plume behavior and shows the plume impacting the nearby neighborhood. The visible plume is created by seeding a metered air stream with small white particles. Other studies had been conducted to determine the dilution needed to prevent odor complaints. Initial testing confirmed that odors may be occurring in the neighborhood. Next, various mitigation measures were evaluated, including: 1) increasing the stack height; 2) adding bypass air to the exhaust stream; and 3) constructing a new single stack off the roof that merges all three engine exhausts. The maximum normalized concentration for each case at the problem receptor locations is provided in Table 1. Using this information, the operator could choose from various alternatives to solve the odor problem.

Figure 2. 1:300 gas compressor station model installed in wind tunnel

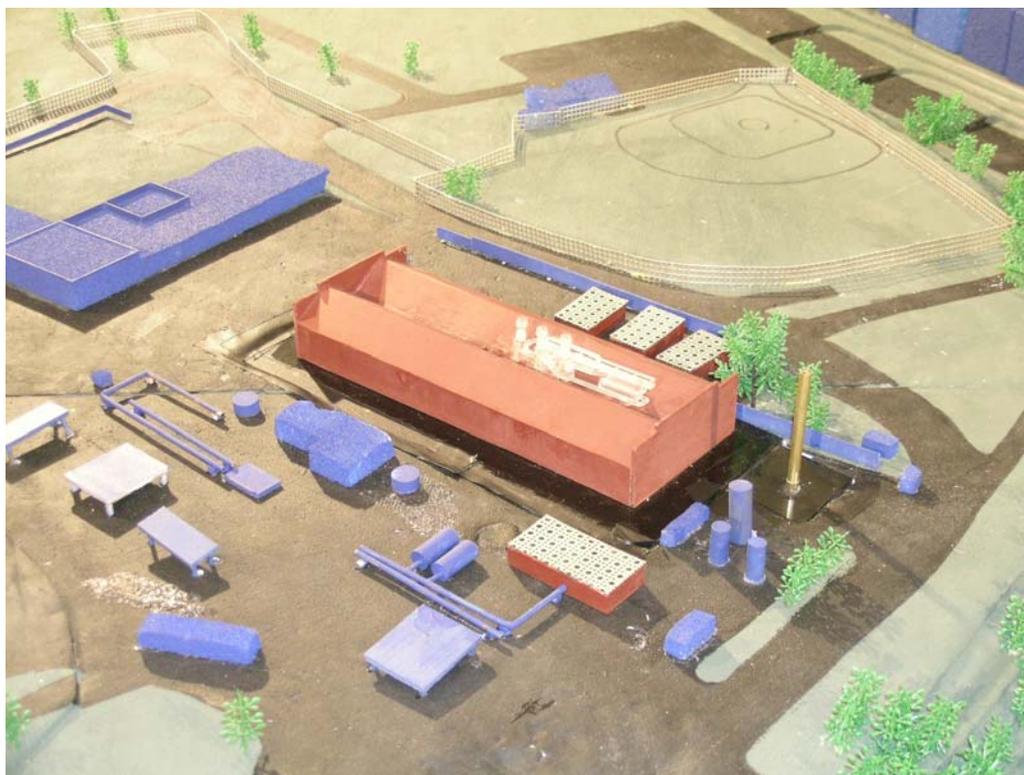
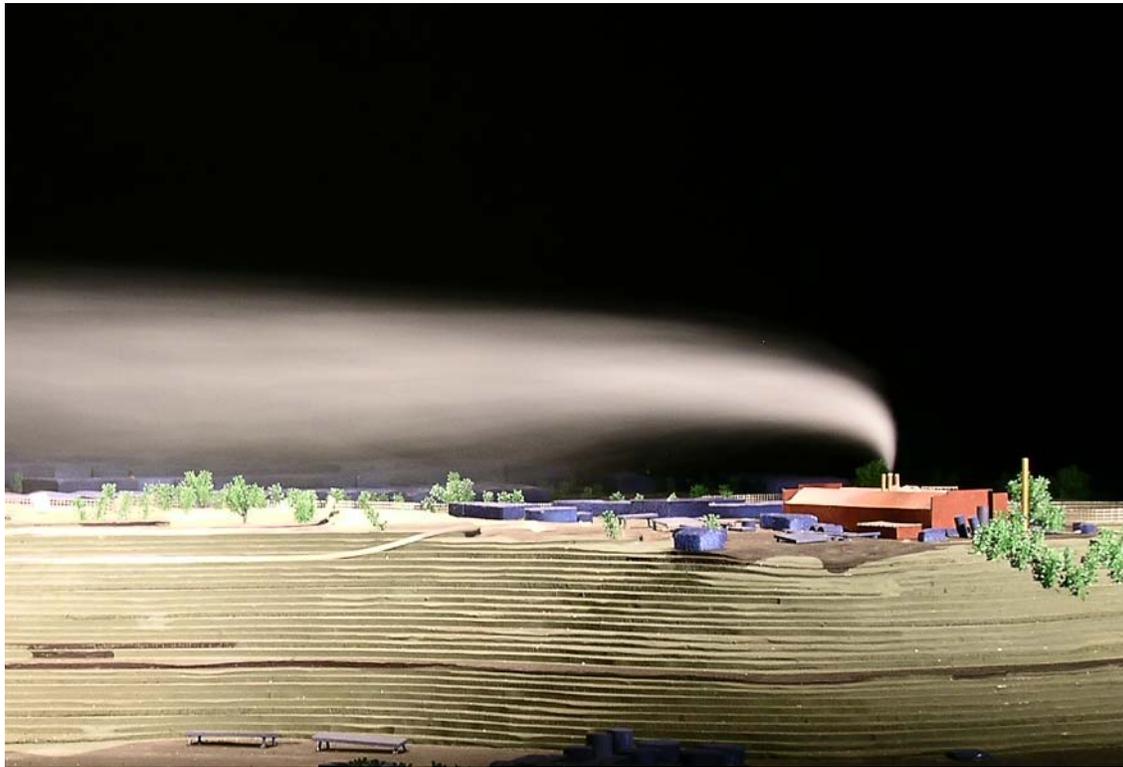


Table 1. Summary of Maximum Normalized Concentrations at Critical Receptor

Exhaust Scenario	Stack Height (ft above roof)	Exhaust Volume Flow (cfm/stack)	(C/Q)_{max} ug/m³ per g/s
Existing 3 Stacks	10.5	15,500	58
	20	15,500	52
Existing 3 Stacks with bypass air added	10.5	46,500	26
	20.0	46,500	11
New Stack Combined Exhaust	80	15,500	18
	100	15,500	15
	120	15,500	9

Figure 3. Visualization of exhaust plume impacting neighborhood



Landfill

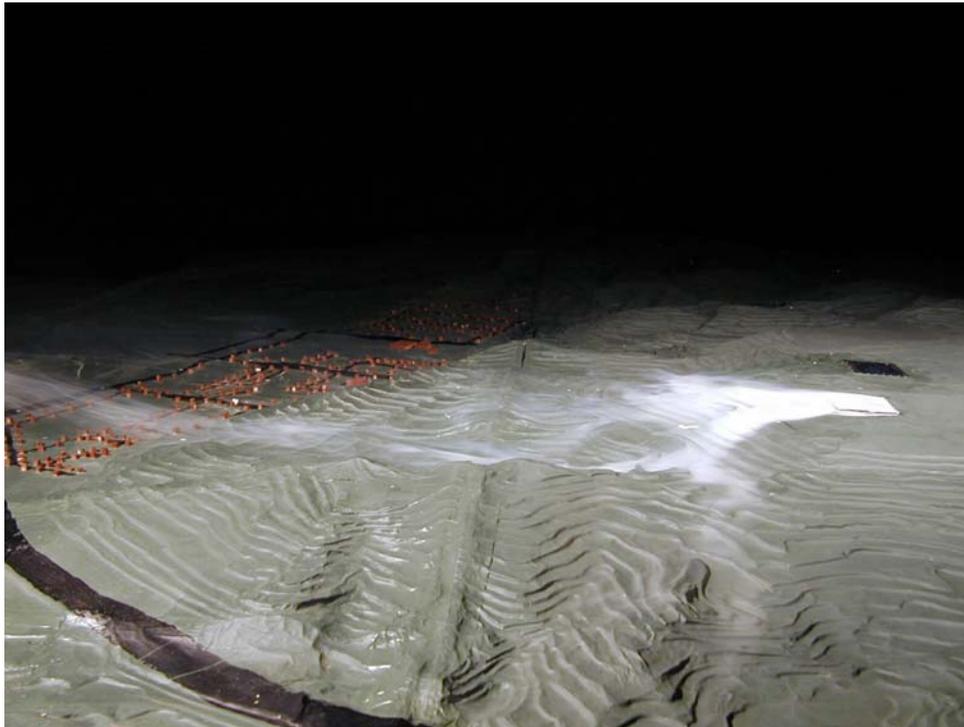
A second application relates to the Puente Hills Landfill in Los Angeles, California. The primary purpose of this study was to determine how the changing landscape of the landfill (existing versus future contours) would affect levels of odors experienced by the nearby community. Scale models (1:1200) of the existing and future landfill configuration were constructed and placed in the wind tunnel. Figure 4 is a photograph of the model installed in the wind tunnel. Tracer gases were released from an area source representing the existing and future landfill configuration. Figure 5 shows a visualization of the area source plume under a simulated stable nighttime condition. The figures show how the plume remains close to the ground, with little vertical mixing and flow into the nearby neighborhood.

The testing confirmed that odors will decrease for the future landfill configuration. Caponi and Larro (2003) provide a detailed description of this evaluation.

Figure 4. 1:1200 Scale Model of Puente Hills Landfill



Figure 5. Visualization of area source plume under stable stratification



Laboratories and Hospitals

Laboratories and hospital have many pollutant sources that can create odors at building air intakes or outdoor areas. These sources include emergency generators, animal rooms, fume hoods, and idling

vehicles. These sources are usually located in a complex building environment where standard numerical models cannot provide accurate concentration estimates. The existing building environment presents a challenge when building heights vary significantly. If a new laboratory or hospital shorter than surrounding buildings were being designed, it would be difficult to design a stack such that the exhaust would not impact neighboring buildings. The effect of a taller, downwind building is illustrated in Figure 6, which shows how the plume hits the face of the downwind building. In addition, when the taller building is upwind, as shown in Figure 7, the wake cavity region of the taller building may trap the exhaust from the shorter building. In this case, the plume once again impacts the face of the taller, upwind building. Hence, the frequency of adverse concentrations on the face of the taller building face is augmented.

Figure 6 - Plume impacting taller, downwind building

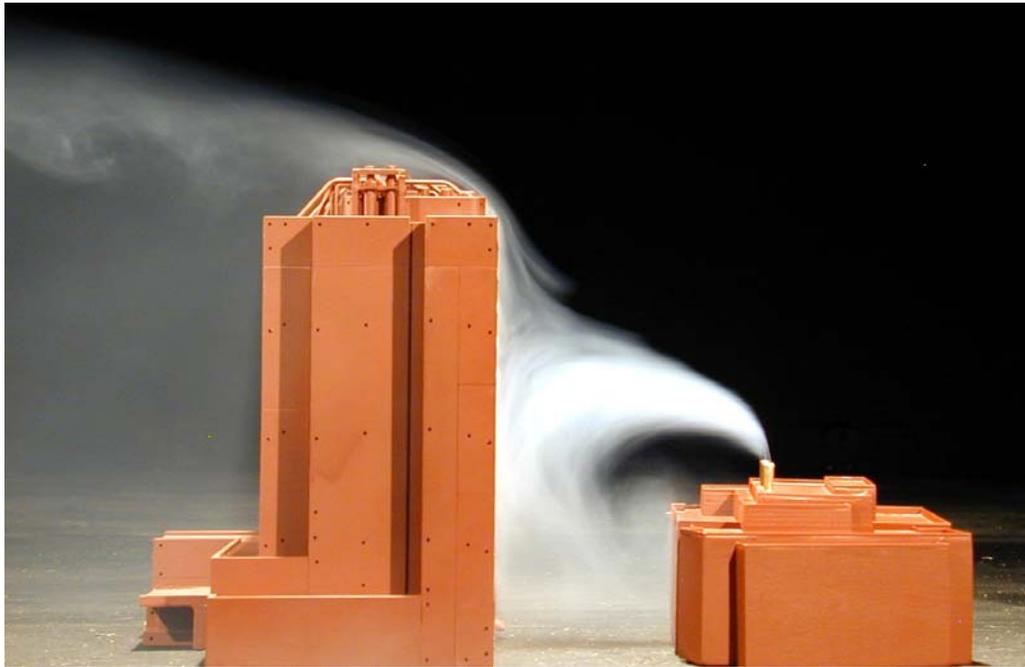


Figure 7 - Plume caught in taller, upwind building cavity.



Constraints are typically placed on laboratory and hospital stack design. The lowest possible stack height is desired for aesthetics and economy. The exit momentum (exit velocity and volume flow rate) is limited by capital and energy costs, noise, and vibration. The laboratory stack design then becomes a balance between these constraints and obtaining adequate air quality at surrounding receptors (air intakes, plazas, operable windows, etc.). If an exhaust stack is not properly designed, fumes from the exhaust may reenter the building or adjacent buildings, or impact pedestrians at unacceptable concentration levels. To avoid reentry, taller stacks, higher volume flows, and/or optimum locations on the roof may be necessary.

To determine the optimal exhaust design, predictions of the expected concentrations of pollutants in the exhaust stream at air intakes and other sensitive locations are needed to compare with health limits and odor thresholds. This near-field dispersion problem is ideally suited to wind tunnel modeling. More detailed information on this topic can be found in Petersen et al. (2002).

SUMMARY

This paper provides documentation on the validity of wind tunnel modeling and provides general information on wind tunnel modeling procedures and methods. Three applications of wind tunnel modeling are presented: 1) engine exhaust odors from a natural gas pumping station; 2) existing and future odors due to the Puente Hills Landfill in Los Angeles; and 3) odor impacts from laboratories and hospitals. For all three applications accurate concentration estimates were obtained at the locations of interest so that informed decisions could be made regarding odor mitigation.

REFERENCES

- Arya, S.P.S. and J.F. Lape, Jr. "A Comparative Study of the Different Criteria for the Physical Modeling of Buoyant Plume Rise in a Neutral Atmosphere," *Atmospheric Environment*, Vol. 24A, No. 2, pp. 289-295, 1990.
- Caponi, Frank and Terence Larro. "Use of Wind Tunnel Modeling to Assess Odor Impacts From a Municipal Solid Waste Landfill," A&WMA's 96th Annual Conference & Exhibition, Paper # 69392, San Diego, CA, June 22-26, 2003.
- Cimorelli, A.J.; S.G. Perry; A. Venkatram; J.C. Weil; R.J. Paine; R.B. Wilson; R.F. Lee; W.D. Peters; and R.W. Brode. "AERMOD: A Dispersion Model for Industrial Source Applications. Part I: General Model Formulation and Boundary Layer Characterization," *JAM*, 44, 682-693. American Meteorological Society, Boston, MA. (2005).
- Cermak, J.E. "Applications of Fluid Mechanics to Wind Engineering," A Freeman Scholar Lecture, *Journal of Fluids Engineering*, Vol. 97, p. 9, 1975.
- EPA. "Guideline for Determination of Good Engineering Practice Stack Height (Technical Support Document for the Stack Height Regulation)," US EPA Office of Air Quality, Planning and Standards, Research Triangle Park, North Carolina, EPA-450/4-80-023R, 1985.
- EPA. "Screening Procedures for Estimating the Air Quality Impact of Stationary Sources, Revised," EPA-454/R-92-109, 1992.
- Meroney, R.N. "Bluff body Aerodynamics Influence on Transport and Diffusion," *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 33, p. 21, 1990.
- Meroney, R.N. "Validation of Fluid Modeling Techniques for Assessing Hazards of Dense Gas Cloud Dispersion," submitted to *Journal of Hazardous Materials*, April 21, 1986.
- Petersen, R.L. "Wind Tunnel Investigation of the Effect of Platform-Type Structures on Dispersion of Effluents from Short Stacks," *JAPCA*, Vol. 36, No. 12, December 1986.
- Petersen, R.L. "Dispersion Comparability of the Wind Tunnel and Atmosphere for Adiabatic Boundary Layers with Uniform Roughness," Seventh Symposium on Turbulence and Diffusion, Boulder, Colorado, November 12-15, 1985.
- Petersen, R.L.; B.C. Cochran; and J.J. Carter. "Specifying Exhaust and Intake Systems," *ASHRAE Journal*, August 2002.
- Snyder, W.H. "Guideline for Fluid Modeling of Atmospheric Diffusion," EPA, Environmental Sciences Research Laboratory, Office of Research and Development, Research Triangle Park, North Carolina, Report No. EPA600/8-81-009, 1981.
- Weil, J.C.; S.C. Traugott; and D.K. Wong. "Stack Plume Interaction and Flow Characteristics for a Notched Ridge," Maryland Power Plant Siting Program, PPRP-61, August 1981.

Turner, D.B. "Workbook of Atmospheric Dispersion Estimates," Lewis Publishers, Boca Raton, Florida, 1994.