Laboratories for the 21st Century: Best Practices

MODELING EXHAUST DISPERSION FOR SPECIFYING ACCEPTABLE EXHAUST/INTAKE DESIGNS

Introduction

This guide provides general information on specifying acceptable exhaust and intake designs. It also offers various quantitative approaches (dispersion modeling) that can be used to determine expected concentration (or dilution) levels resulting from exhaust system emissions. The guide, one in a series on best practices for laboratories, was produced by *Laboratories for the 21st Century* ("Labs 21"), a joint program of the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Energy (DOE). Geared toward architects, engineers, and facility managers, the guides contain information about technologies and practices to use in designing, constructing, and operating safe, sustainable, high-performance laboratories.

Studies have shown a direct relationship between indoor air quality and the health and productivity of building occupants.(1,2,3) Historically, the study and protection of indoor air quality has focused on emission sources emanating from within the building. For example, to ensure that the worker is not exposed to toxic chemicals, "as manufactured" and "as installed" containment specifications are required for fume hoods. But emissions from external sources, which may be re-ingested into the building through closed circuiting between the building's exhaust stacks and air intakes, are an often overlooked aspect of indoor air quality.

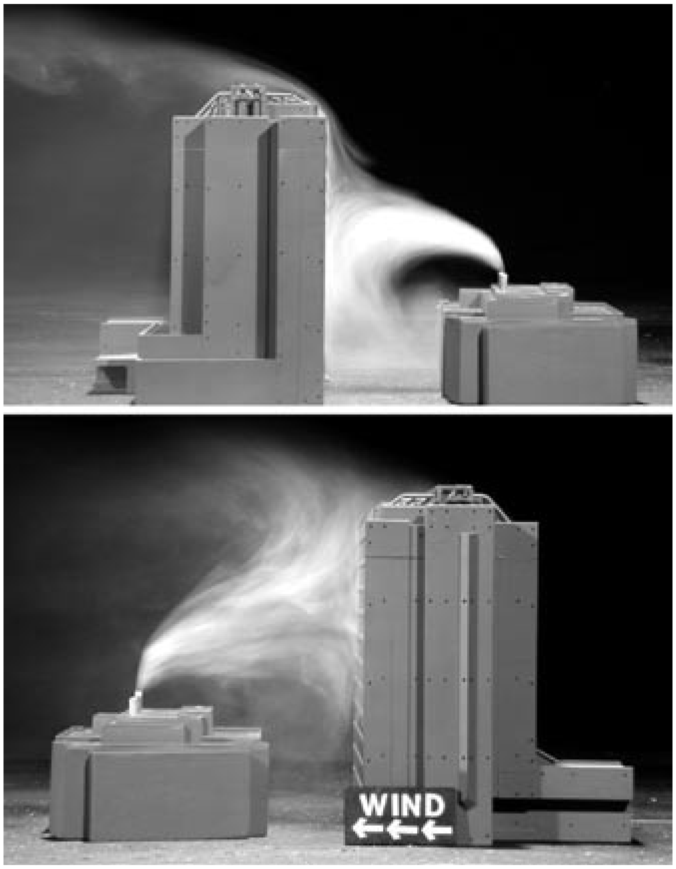

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Figure 1. Photographs of wind tunnel simulations showing fumes exiting fume hood exhaust stacks. In looking at the photograph, we should ask: Are the air intakes safer than a worker at the fume hood? Only a detailed dispersion modeling analysis will provide the answer.

EPA United States
Environmental
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Energy Efficiency and Renewable Energy
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If the exhaust sources and air intakes are not properly designed, higher concentrations of emitted chemicals may be present at the air intakes than at the front of the fume hood, where the chemical was initially released. Furthermore, if a toxin spills within the fume hood, the worker can take corrective action by closing the sash and leaving the immediate area, reducing his or her exposure to the released chemical vapors. Conversely, the presence of the toxic fumes at the air intake, which can distribute the chemical vapors throughout the building, typically cannot be easily mitigated. The only option may be to evacuate the entire building, which results in an immediate loss of productivity and a long-term reduction in occupant satisfaction with the working conditions.

Dispersion modeling calculates the amount of fume reentry, or the concentration levels expected at building air intakes and ensures a "good" exhaust and intake design. This includes mechanically driven air intakes, naturally ventilated intakes such as operable windows and entrances, and leakage through porous walls.

Petersen et al.(4) gives a technical description of various aspects of exhaust and intake design. Some of the challenges of specifying a good stack design mentioned in that article include the existing building environment, aesthetics, building design issues, chemical utilization, source types, and local meteorology and topography. For example, if a new laboratory building is being designed that is shorter than the neighboring buildings, it will be difficult to design a stack so that the exhaust does not affect those buildings. Figure 1 illustrates the effect of a taller downwind or upwind building. The figure shows how the plume hits the face of the taller building when it is downwind and how, when it is upwind, the wake cavity region of the taller building traps the exhaust from the shorter building. In either case the plume has an impact on the face of the taller building.

Typically, laboratory stack design must strike a balance between working within various constraints and obtaining adequate air quality at surrounding sensitive locations (such as air intakes, plazas, and operable windows). The lowest possible stack height is often desired for aesthetics, while exit momentum (exit velocity and volume flow rate) is limited by capital and energy costs, noise, and vibration.

Exhaust and Intake Design Issues

Qualitative Information on Acceptable Exhaust Designs

Several organizations have published standards for or recommendations on laboratory exhaust stack design, as summarized in the sidebar.

General Design Guidelines or Standards

1. Maintain a minimum stack height of 10 ft (3 m) to protect rooftop workers.(5)


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2. Locate intakes away from sources of outdoor contamination such as fume hood exhaust, automobile traffic, kitchen exhaust, streets, cooling towers, emergency generators, and plumbing vents.(6)
3. Do not locate air intakes within the same architectural screen enclosure as contaminated exhaust outlets.(6)


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4. Avoid locating intakes near vehicle loading zones. Canopies over loading docks do not prevent hot vehicle exhaust from rising to intakes above the canopy.(6)


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5. Combine several exhaust streams internally to dilute intermittent bursts of contamination from a single source and to produce an exhaust with greater plume rise. Additional air volume may be added to the exhaust at the fan to achieve the same end.(6) Note that the most recent version of the International Mechanical Code(7) states that "hazardous* exhaust systems shall be independent of other types of exhaust systems." This may preclude manifolding laboratory fume hood and laboratory room exhaust with general building exhaust. The 2004/2005 proposed changes exclude research laboratories from this requirement.


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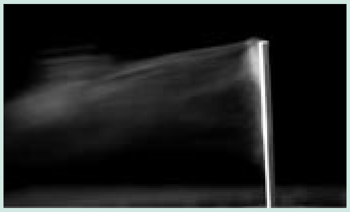
6. Group separate stacks together (where separate exhaust systems are mandated) in a tight cluster to take advantage of the increased plume rise from the resulting combined vertical momentum.(6) Note that all the exhausts must operate continuously to take full advantage of the combined momentum. If not all of the exhausts are operating at the

* Hazardous exhaust systems are designed to capture and control hazardous emissions generated from product handling or processes and convey them to the outdoors. Hazardous emissions include flammable vapors, gases, fumes, mists, or dusts, along with volatile or airborne materials that pose a health hazard, such as toxic or corrosive materials.(7)

same time, however, such as in an n+1 redundant system, the tight placement of stacks may be detrimental to their performance.

7. Maintain an adequate exit velocity to avoid stack-tip downwash. The American National Standards Institute (ANSI)/American Industrial Hygiene Association (AIHA) standard for laboratory ventilation, Z9.5-2003,(8) suggests that the minimum exit velocity from an exhaust stack should be at least 3000 fpm. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE)(6) recommends a minimum exit velocity of 2000 to 3000 fpm.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8. Apply emission controls where viable. This may include installing restrictive flow orifices on compressed gas cylinders, scrubber systems for chemical specific releases, low-NO_x (oxides of nitrogen) units for boilers and emergency generators, and oxidizing filters or catalytic converters for emergency generators.
9. Avoid rain caps or other devices that limit plume rise on exhaust stacks. Although widely used, conical rain caps are not necessarily effective at preventing rain from infiltrating the exhaust system because rain does not typically fall straight down. Alternate design options are presented in Chapter 44 of the *ASHRAE Handbook–HVAC Applications.*(6)


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10. Consider the effect of architectural screens. An ASHRAE-funded research study(9) found that screens can significantly increase concentrations on the roof and, in effect, reduce the effective stack height. A solid screen can decrease the effective stack height by as much as 80%. Alternatively, the effect of the screen can be minimized by installing a highly porous screen (>70% open).


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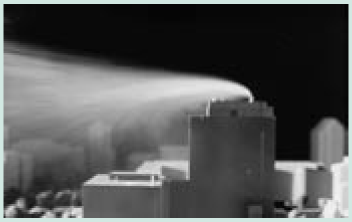
11. Avoid a direct line of sight between exhaust stacks and air intakes. An ASHRAE research project(10) demonstrated that there is a distinct reduction in air intake concentrations from rooftop exhaust stacks when air intake louvers are "hidden" on sidewalls rather than placed on the roof. Depending on the specific configuration, concentrations along the sidewall may be half to a full order of magnitude less than those present on the roof.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Exhaust Design Criteria

Laboratory design often considers fume hood stack emissions, but other pollutant sources may also be associated with the building. These could include emissions from emergency generators, kitchens, vivariums, loading docks, traffic, cooling towers, and boilers. Each source needs its own air quality design criteria. An air quality "acceptability question" can be written:

$$C_{max} < C_{health/odor}\,? \qquad (1)$$

where C_{max} is the maximum concentration expected at a sensitive location (air intakes, operable windows, pedestrian areas), C_{health} is the health limit concentration, and C_{odor} is the odor threshold concentration of any emitted chemical. When a source has the potential to emit a large number of pollutants, a variety of mass emission rates, health limits, and odor thresholds need to be examined. It then becomes operationally simpler to recast the acceptability question by normalizing (dividing) Equation 1 by the mass emission rate, m:

$$\left(\frac{C}{m}\right)_{max} < \left(\frac{C}{m}\right)_{health/odor}\,? \qquad (2)$$

The left side of the equation, $(C/m)_{max}$, is dependent only on external factors such as stack design, receptor location, and atmospheric conditions. The right side of the equation is related to the emissions and is defined as the ratio of the health limit, or odor threshold, to the emission rate. Therefore, a highly toxic chemical with a low emission rate may be of less concern than a less toxic chemical emitted at a very high emission rate. Three types of information are needed to develop normalized health limits and odor thresholds:

1. A list of the toxic or odorous substances that may be emitted
2. The health limits and odor thresholds for each emitted substance
3. The maximum potential emission rate for each substance.

Recommended health limits, C_{health}, are based on the ANSI/AIHA standard Z9.5-2003,(8) which specifies that air intake concentrations should be no greater than 20% of the acceptable indoor concentrations for routine emissions and 100% of acceptable indoor concentrations for accidental releases. Acceptable indoor concentrations are frequently taken to be the short-term exposure limits (STEL), which can be obtained from the American Conference of Governmental Industrial Hygienists (ACGIH), the Occupational Safety and Health Administration (OSHA), and the National Institute of Occupational Safety and Health (NIOSH), as listed in ACGIH.(11,12) ACGIH can also furnish odor thresholds, C_{odor}.(13)

Table 1. Typical Design Criteria

Source Type	Design Criteria		Basis for Design Criteria
	Type	$(\mu g/m^3)$ / (g/s)	
Laboratory fume hood	Health	400*	ASHRAE (2003) example criterion for a spill in a fume hood
	Odor	400*	ASHRAE (2003) example criterion for a spill in a fume hood
30,000-cfm vivarium	Health	N/A	Not applicable
	Odor	706†	1:100 recommended dilution for a vivarium
5,000-cfm kitchen hood exhaust	Health	N/A	Not applicable
	Odor	1,412†	1:300 recommended dilution for kitchen exhaust
400-hp diesel truck	Health	156,522	Health limit associated with NO_x emissions
	Odor	5,293†	1:2,000 odor dilution threshold for diesel exhaust
250-kW diesel generator	Health	2,367	Health limit associated with NO_x emissions
	Odor	492†	1:2,000 odor dilution threshold for diesel exhaust
2,000-kW diesel generator	Health	296	Health limit associated with NO_x emissions
	Odor	66†	1:2,000 odor dilution threshold for diesel exhaust
100-hp boiler (4.5 MMBtu) — oil-fired	Health	21,531	Health limit associated with NO_x emissions
	Odor	23,576	Odor threshold associated with NO
— gas-fired (20 ppm NO_x)	Health	132,278	Health limit associated with NO_x emissions
	Odor	192,122	Odor threshold associated with NO
500-hp boiler (21.0 MMBtu) — oil-fired	Health	4,613	Health limit associated with NO_x emissions
	Odor	5,052	Odor threshold associated with NO
— gas-fired (20 ppm NO_x)	Health	28,345	Health limit associated with NO_x emissions
	Odor	41,169	Odor threshold associated with NO

* This criterion is more restrictive than the 0.05 ppm criterion stated in Z9.5-2003(8) for the maximum concentration present at the face of the fume hood, which corresponds to a normalized concentration of approximately 750 $\mu g/m^3$ per gram per second. Less restrictive criteria may be applicable for exhausts with light chemical usage such as biological-safety cabinets.

† Normalized concentration design criteria that are based on dilution standards are dependent on the volume flow rate through the exhaust stack.

For laboratories, the emission rates are typically based on small-scale accidental releases, either from spilling a liquid or emptying a lecture bottle of compressed gas. For other sources, such as emergency generators, boilers, and vehicles, chemical emissions rates are often available from the manufacturer. Table 1 outlines typical design criteria for various sources.

Dispersion Modeling Methods

Concentration predictions (C/m) at sensitive locations can be accomplished with varying degrees of accuracy using three different types of studies: (1) a full-scale *field program*; (2) a reduced scale *wind-tunnel* study; or (3) a *mathematical modeling* study.

A full-scale field program, although it may yield the most accurate predictions of exhaust behavior, may be expensive and time consuming. If the nature of the study is to estimate maximum concentrations for several stacks at several locations, many years of data collection may be required before the maximum concentrations associated with the worst-case meteorological conditions are measured. In addition, it is not possible to obtain data for future building configurations.

Wind-tunnel modeling is often the preferred method for predicting maximum concentrations for stack designs and locations of interest, and is recommended because it gives the most accurate estimates of concentration levels in complex building environments.(6) A wind-tunnel modeling study is like a full-scale field study, except it is conducted before a project is built. Typically, a scale model of the building under evaluation, along with the surrounding buildings and terrain within a 1000-ft radius, is placed in an atmospheric boundary layer wind tunnel. A tracer gas is released from the exhaust sources of interest, and concentration levels of this gas are then measured at receptor locations of interest and converted to full-scale concentration values. Next, these values are compared against the appropriate design criteria to evaluate the acceptability of the exhaust design. ASHRAE(6) and the EPA(14) provide more information on scale-model simulation and testing methods.

Wind-tunnel studies are highly technical, so care should be taken when selecting a dispersion modeling consultant. Factors such as past experience and staff technical qualifications are extremely important.

Mathematical models can be divided into three categories: geometric, analytical, and computational fluid dynamic (CFD) models. The *geometric method*(6) defines an appropriate stack height based on the string distance between the exhaust stack and a nearby receptor location. This method is entirely inadequate for exhaust streams that contain toxic or odorous material because it does not yield estimated concentration values at air intakes or other sensitive locations. Hence, no information is provided for stack designs to avoid concentrations in excess of health or odor limits.

Analytical models assume a simplified building configuration and yield concentration estimates based on assumed concentration distributions (i.e., Gaussian). These models do not consider site-specific geometries that may substantially alter plume behavior; thus, concentration predictions are not as reliable. When properly applied, the analytical equations provided in the ASHRAE handbook on HVAC applications(6) will tend to give conservative results for an isolated building or one that is the same height or taller than the surrounding buildings and has air intakes on the roof. As such, the analytical model can be useful for screening out sources that are unlikely to be problematic, thus reducing the scope of more sophisticated modeling. Neither the geometric nor the analytical models are appropriate for complex building shapes or in locations where taller buildings are nearby.

The most common type of *computational fluid dynamics* resolves fluid transport problems by solving a subset of traditional Navier-Stokes equations at finite grid locations. CFD models are used successfully to model internal flow paths within areas such as vivariums and atriums, as well as in external aerodynamics for the aerospace industry. The aerospace CFD turbulence models, however, are ill suited for modeling the atmospheric turbulence in complex full-scale building environments because of the differing geometric scales. This is exemplified in the conclusions of Castro's recent evaluation of applying CFD to the built environment:

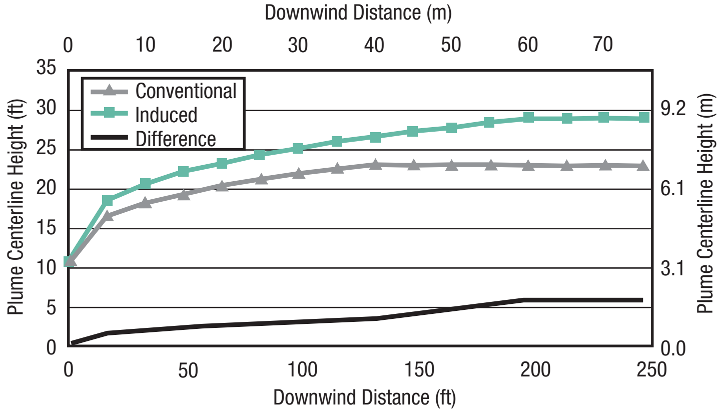
> "Despite considerable effort over the last two decades, there is no agreed modeling approach which will automatically yield accurate results for the surface pressure field on and/or the flow field around buildings in the wind…Only large eddy simulation (LES) techniques genuinely have the potential to yield adequate mean and fluctuating data, but these have yet to be fully developed for complex bluff body flows."(15)

Based on the current state of the art, CFD models should be used with extreme caution when modeling exhaust plumes resulting from laboratory pollutant sources. At this time, current research indicates that CFD models can both over- and underpredict concentration levels by orders of magnitude, leading to potentially unsafe designs. If a CFD study is conducted for such an application, supporting full-scale or wind-tunnel validation studies should be carried out.

Effective Stack Height and Induced-Air Fans

Induced-air fan manufacturers often quote an "effective stack height" for their exhaust fan systems. Many designers incorrectly interpret this value to be a physical stack height and compare it to the height requirement defined from a dispersion modeling study. The manufacturer's specified effective stack height is actually a prediction of the exhaust plume centerline's final height, based on a mathematical plume rise equation.(6) This final height typically occurs far downwind of the exhaust stack (on the order of 100 to 200 ft). A more general mathematical equation is available that predicts the height of the plume centerline as a function of downwind distance.(14) A better method of comparing two different exhaust systems is to specify the effective increase in the plume height versus downwind distance. The increase may not be as great as one might expect, as the following analysis points out.

Figure 2 shows the predicted plume centerline height versus downwind distance for an induced-air exhaust stack and a conventional exhaust fan system at a 20-mph stack height wind speed. The curves indicate that the difference in the plume height between the two exhaust systems is only 1 to 2 ft at 20 ft downwind with a maximum difference of 6 ft after both plumes have reached their final rise. Therefore, using an induced-air fan may reduce the



Exhaust Parameters				
	Conventional		Induced-Air	
Stack height (ft, m)	10.2	3.10	10.2	3.10
Stack diameter (in., m)	30.3	0.77	45.0	1.14
Discharge flow rate (cfm, m/s)	15,000	7.08	32,466	15.32
Exit velocity (fpm, m/s)	3,000	15.24	2,940	14.94
Wind speed (mph, m/s)	20	8.94	20	8.94
Fan power (bhp, bkW)	14.5	10.8	17.86	13.3

Figure 2. Plume centerline height for conventional and induced-air exhaust systems

necessary stack height by only a few feet, depending on the location of the nearby air intake locations. This analysis shows why the effective stack height specification is misleading.

Plume Rise and Exit Velocity

Adequate plume rise is important to ensure that the exhaust escapes the high turbulence and recirculation zones induced by a building's roof. Plume rise increases with increased exit momentum and decreases with increased wind speed.(14) Reducing the diameter to increase exit velocity will increase the exit momentum and thus the plume rise. There are limitations on how much the exit velocity can be increased before noise, vibration, and energy problems develop. Therefore, it is often preferable to increase the plume rise by augmenting the volume flow rate, possibly by bringing in additional air via a bypass damper at the base of the stack. Plume rise is adversely affected by atmospheric turbulence because the vertical momentum of the exhaust jet is more quickly diminished. In areas of high turbulence, then, the only method for obtaining an adequate plume centerline may be to increase the physical height of the stack.

If the ratio of exit velocity to approach wind speed is too low, the plume can be pulled downward into the wake of the stack structure, creating negative plume rise, a condition called stack-tip downwash. This downwash defeats some of the effect of a taller stack and can lead to high concentrations. The photo that accompanies Item 7 in the "General Design Guidelines or Standards" sidebar on page 3 of this guide shows an example of this phenomenon. A rule of thumb for avoiding stack-tip downwash is to make the exit velocity at least 1.5 times the wind speed at the top of the stack.(6) This stack top wind speed is commonly taken to be the 1% wind speed, which can be obtained from ASHRAE for various worldwide metropolitan areas.(16) Note that the ASHRAE-provided wind speed must be adjusted from the anemometer location to the stack top.(17)

Variable volume exhaust systems should be designed to maintain adequate exit velocity during turndown periods. The exit velocity should be sufficient to avoid stack-tip downwash at all times. A high exit velocity can be maintained either by having adjustable makeup air at the exhaust stack via a by-pass damper or by employing several stacks that can be brought on/off line in stages as flow requirements change. Products are also available that can change the geometry of the stack exit in an attempt to maintain a high exit velocity with variable volume flow rates. Many of these devices do not properly condition the flow as it exits the stack, which reduces the vertical momentum and ultimately the plume rise out of the stack. As an alternative, smart control systems can be used to set minimum exit velocity requirements based on the current wind conditions measured at a nearby anemometer.

Energy Issues

Several factors affect exhaust system energy consumption, including (1) the design and operation of the laboratory, specifically the relative location of exhaust sources and air intakes, the presence of nearby building elements such as screen walls and penthouses, the exhaust volume flow rates and exit velocities, and the chemical utilization within the fume hoods; (2) the environment surrounding the laboratory, involving the presence of nearby structures, air intakes, and other critical receptor locations; and (3) the local meteorology, specifically the distribution of local wind speeds and wind directions.

Chemical utilization is the basic criterion used to judge whether a specific exhaust/intake design is acceptable. An overly conservative judgment about the potential toxicity of an exhaust stream may result in a high-energy-use exhaust system as volume flow or exit velocity is increased unnecessarily. A more accurate assessment of the intended chemical use, with some consideration of the future program, will result in an exhaust system that yields acceptable air quality while consuming a minimum amount of energy.

Local wind speeds may be used to set exit velocity targets, as discussed previously. Exhaust momentum, however, is the true parameter governing exhaust plume rise and dispersion. In cases of high-volume flow-rate exhausts (i.e., 30,000 cfm or greater), studies have shown that exit velocities as low as 1000 fpm can produce acceptable plume rise and dispersion. Specific designs should be evaluated on a case-by-case basis, regardless of exhaust design parameters, to ensure that adequate air quality is maintained at all sensitive locations.

Figure 3 was developed using the laboratory fume hood criteria and the analytical models for dispersion described previously. The figure shows that as volume flow rate increases, shorter exhaust stacks can be used to meet the design criteria. The shorter stacks, however, are obtained at the cost of increased exhaust fan power. The figure also demonstrates the advantage of manifolding exhaust systems. For example, a single stack operating at 5000 cfm should be approximately 22 ft tall to achieve the design criterion at a receptor 160 ft downwind. Conversely, five stacks operating at 1000 cfm would need to be nearly 38 ft tall to provide the same air quality at the same receptor location.

Figure 4 shows how fan power may increase with exhaust flow rate for various system designs. The figure illustrates the relationships between the design volume flow rate, Q, and the fan power requirements for two

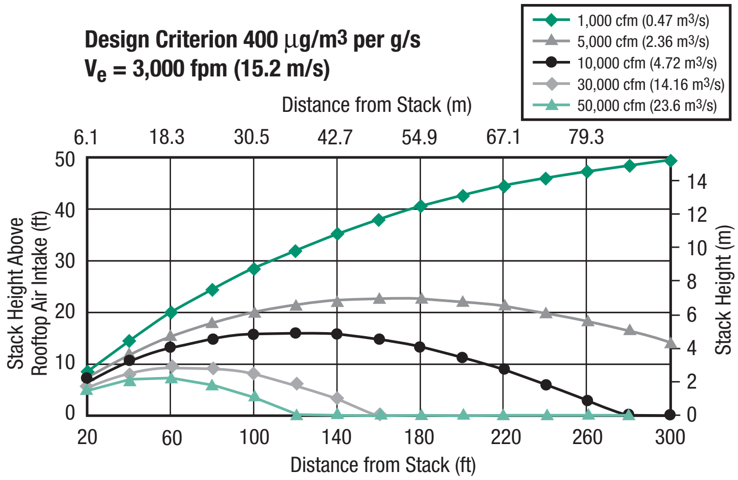


Figure 3. Stack height above top of intake required to meet a specified design criterion for various exhaust volume flow rates at a range of downwind distances

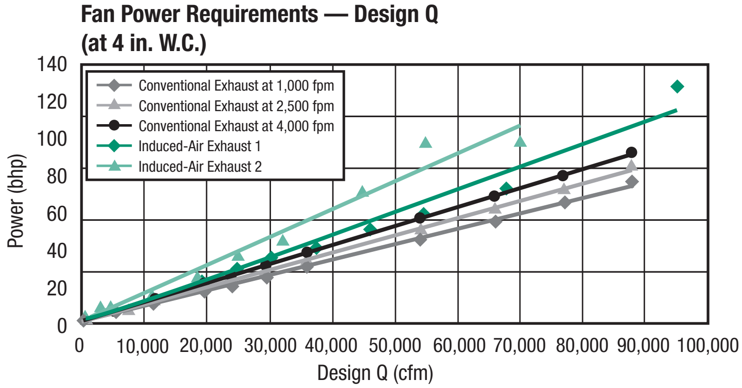


Figure 4. Required fan power versus design exhaust volume flow rate, Q

Key Questions for Exhaust/Intake Design

Questions for the project team

- Can an exhaust manifold be utilized?
- Are induced-air systems required or will conventional, lower energy systems suffice?
- Is the site sufficiently complex to warrant a detailed wind-tunnel modeling evaluation?
- Do the laboratory exhausts have a high enough volume flow and exit velocity to escape the building envelope?

Questions to ask when selecting a dispersion modeling consultant

- Does the method you are using predict concentrations or dilution at building air intakes?
- Is your technique validated or conservative?
- Do you utilize chemical emission rates in the analysis?
- Does your method account for all wind conditions expected at the site?

typical induced-air systems and for a conventional system at three different exit velocities. For the conventional exhaust systems, the figure shows the benefit of decreasing the exit velocity for a given design flow rate, always assuming that the specified system meets the design goals.

To better understand the data presented in Figure 4, consider the following example. A building exhaust system requires 30,000 cfm at a static pressure of 4 in. water column (W.C.) to adequately ventilate the building. An assessment of the exhaust plume shows that a 10-ft-tall, 30,000-cfm exhaust fan with a 2500-fpm exit velocity would meet the design criterion established for the exhaust stack. Figure 4 shows that a conventional exhaust system meeting these parameters requires fan power of approximately 27 bhp. An equivalent induced-air system requires between 32 and 42 bhp to exhaust the same 30,000 cfm from the building, an increase of 19% to 55%.

This discussion illustrates the importance of using dispersion modeling to evaluate exhaust performance—taking fan energy costs into consideration—to ensure that acceptable air quality is achieved.

Summary and Conclusions

An accurate assessment of exhaust dispersion can be used to produce exhaust/intake designs optimized for energy consumption. No matter what type of exhaust system is used, the important design parameters are physical stack height, volume flow rate, exit velocity, expected pollutant emission rates, and concentration levels at sensitive locations. Whether conventional or induced-air exhaust systems are used, the overall performance should be evaluated using the appropriate criterion that will ensure acceptable concentrations at sensitive locations.

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