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. In addition, the guide describes methodologies that can be employed to operate laboratory exhaust systems in a safe and energy efficient manner by using variable air volume (VAV) technology. The guide, one in a series on best practices for laboratories, was produced by Laboratories for the 21st Century (Labs21), 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 show 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 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. However, 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.

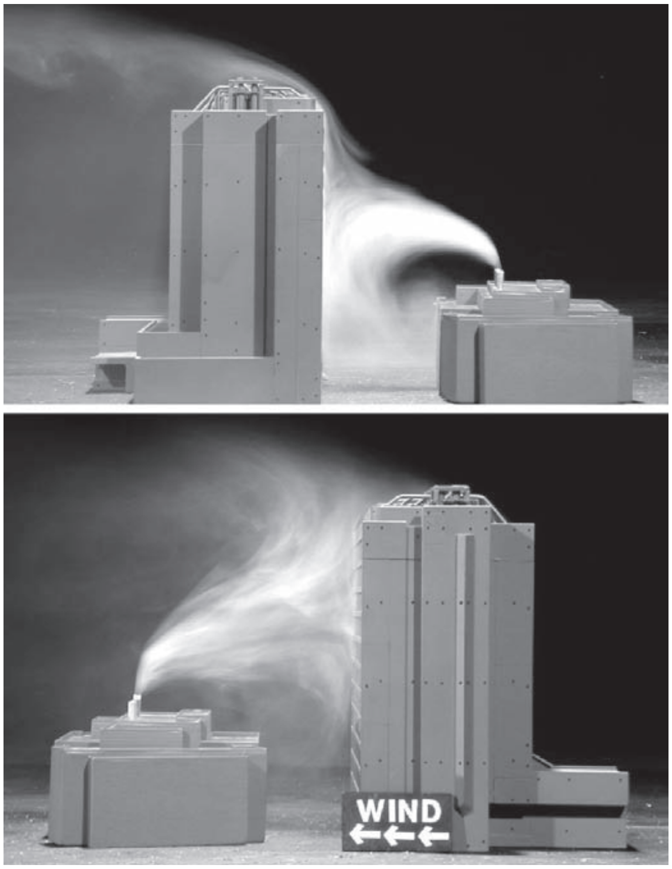

Figure 1. Photographs of wind tunnel simulations showing fumes exiting fume hood exhaust stacks. In looking at the photograph, one should ask: Are the air intakes safer than a worker at the fume hood? Only a detailed dispersion modeling analysis will provide the answer.

Photo from CPP, Inc., NREL/PIX 13813

EPA United States Environmental Protection Agency

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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 is spilled within the fume hood, the worker can take corrective action by closing the sash and leaving the immediate area; thus, 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 predicts the amount of fume reentry, or the concentration levels expected at critical receptor locations, with the goal of defining a "good" exhaust and intake design that limits concentrations below an established design criterion. Receptors considered in the assessment may include mechanically driven air intakes, naturally ventilated intakes like operable windows and entrances, leakage through porous walls, and outdoor areas with significant pedestrian traffic like plazas and major walkways.

Petersen et al. gives a technical description of various aspects of exhaust and intake design[4]. 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.

General Design Guidelines or Standards

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

Photo from CPP, Inc., NREL/PIX 13814

3. Do not locate air intakes within the same architectural screen enclosure as contaminated exhaust outlets.[6]
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]

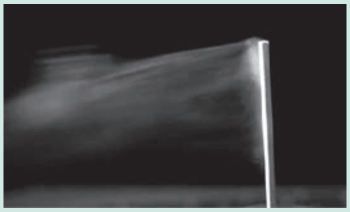
Photo from CPP, Inc., NREL/PIX 13815

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

Photo from CPP, Inc., NREL/PIX 13816

Photo from CPP, Inc., NREL/PIX 13817

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, Z9.5-2011,(9) suggests that the minimum exit velocity from an exhaust stack should be at least 3,000 fpm. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE)(6) recommends a minimum exit velocity of 2,000 to 3,000 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)

Photo from CPP, Inc., NREL/PIX 13819

10. Consider the effect of architectural screens. An ASHRAE-funded research study found that screens can significantly increase concentrations on the roof and reduce the effective stack height as a result[11]. 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 greater than 70% open).

Photo from CPP, Inc., NREL/PIX 13820

11. Avoid a direct line of sight between exhaust stacks and air intakes. An ASHRAE research project demonstrated 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[12]. 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.

Photo from CPP, Inc., NREL/PIX 13821

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.

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:

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

In this equation, 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) the equation above by the mass emission rate of each constituent of the exhaust, *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 of each emitted chemical. 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; and
3. The maximum potential emission rate for each substance.

Recommended health limits, C_{health}, are based on the ANSI/AIHA standard Z9.5-2011[9], which specifies that air intake concentrations should be no greater than 20% of the acceptable indoor concentrations for routine emissions

Table 1. Typical Design Criteria

Source Type	Design Criteria		Basis for Design Criteria
	Type	(μg/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 Z9.5-2011(9) for the maximum concentration present at the face of the fume hood, which corresponds to a normalized concentration of approximately 750 µg/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 based on dilution standards depend on the volume flow rate through the exhaust stack.

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[13,14]. ACGIH also furnishes odor thresholds, C_{odor}[15].

For laboratories, emission rates are typically based on small-scale accidental releases, either from spilling a liquid or evacuating 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[16]. 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 1,000-foot 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[10] and the EPA[16] 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 defines an appropriate stack height based on the string distance between the exhaust stack and a nearby receptor location[10]. 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.

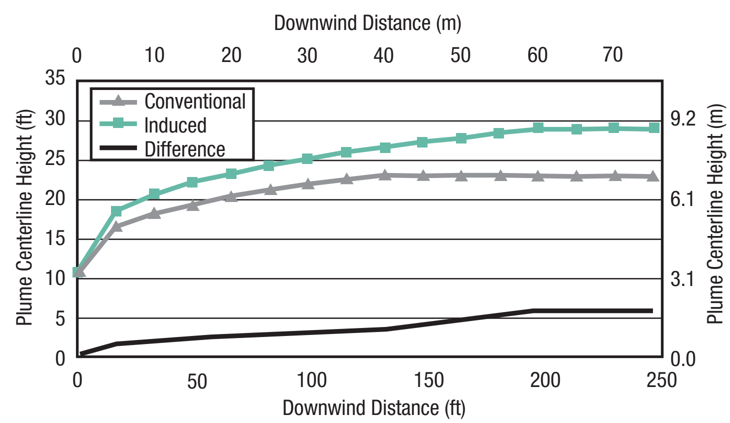
Analytical models assume a simplified building configuration and yield concentration estimates based on assumed concentration distributions (i.e., Gaussian). These models do not consider site-specific geometries that may substantially alter plume behavior; thus, concentration predictions are not as reliable. When properly applied, the analytical equations provided in the ASHRAE Handbook on HVAC Applications 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 [10]. 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 models resolve 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. Background information on the use of CFD for dispersion modeling can be found in ASHRAE Handbook on HVAC Applications[10]. The chapter includes discussions on the various solutions methods that can be used. The general conclusion is that RANS (Reynolds-Averaged Navier Stokes), which is the most commonly used and most cost and time effective, can lead to "large, and sometimes very large, discrepancies in comparison with wind tunnel and full-scale measurements." Furthermore, LES (Large Eddy Simulations) have a greater potential to provide accurate results. However, it requires significantly greater expertise and the computational time and cost can be prohibitive.

Whether using RANS or LES, CFD models should be used with extreme caution when modeling exhaust plumes resulting from laboratory pollutant sources. 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 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 from an outdated version of the ASHRAE Applications Handbook[18]. This final height typically occurs far downwind of the exhaust stack (approximately 100 to 200 feet) as predicted using the updated plume rise equations presented in the most recent ASHRAE Applications Handbook[10]. The "new" equa-



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

tions, which are actually a more precise version of the original Briggs plume rise equations, predict the height of the plume centerline as a function of downwind distance[19].

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 in Figure 2 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 plume height between the two exhaust systems is only 1 to 2 feet at 20 feet downwind with a maximum difference of 6 feet after both plumes have reached their final rise. Therefore, using an induced-air fan may reduce the 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 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[10]. Reducing the diameter to increase exit velocity increases 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, 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 to create 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. 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[17]. This stack top wind speed is commonly taken to be 1% wind speed, which can be obtained from ASHRAE for various worldwide metropolitan areas[21]. Note that ASHRAE-provided wind speed must be adjusted from the anemometer location to the stack top[21].

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 by having adjustable makeup air at the exhaust stack via a bypass damper or by employing several stacks that can be brought on/offline 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 the design and operation of the laboratory, specifically the exhaust volume flow rates and exit velocities and the chemical utilization within the fume hoods; the environment surrounding the laboratory, including the presence of nearby structures, air intakes, and other critical receptor locations; and the local meteorology.

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, results 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. However, exhaust momentum is the true parameter governing exhaust plume rise and dispersion. In cases of high-volume flow-rate exhausts (e.g., 30,000 cfm or greater), studies show that exit velocities as low as 1,000 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 shorter exhaust stacks can be used to meet the design criteria as volume flow rate increases. The shorter stacks, however, are obtained at the cost of increased exhaust fan power.

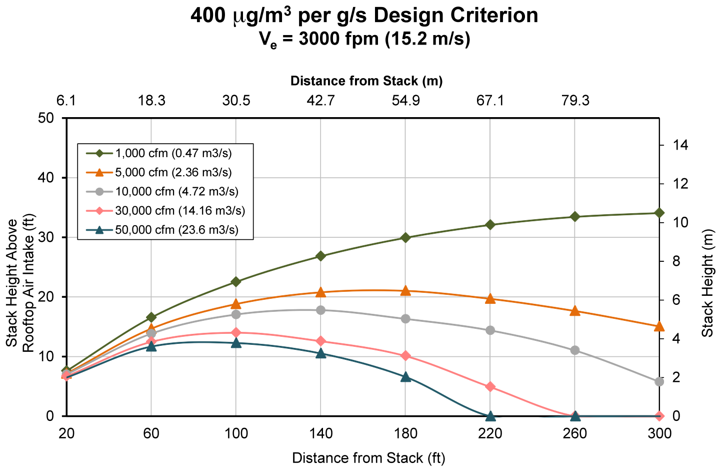


Figure 3. Stack height above top of intake required to meet a specified design criterion for various exhaust volume flow rates at a range of downwind distances

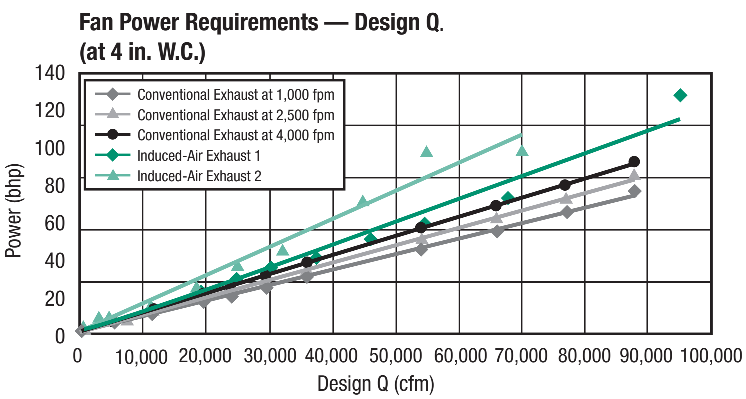


Figure 4. Required fan power versus design exhaust volume flow rate, Q

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?

The figure also demonstrates the advantage of manifolding exhaust systems. For example, a single stack operating at 5,000 cfm should be approximately 22 feet tall to achieve the design criterion at a receptor 180 feet downwind. Conversely, five stacks operating at 1,000 cfm would need to be nearly 30 feet 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 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.

Consider the following example to better understand data presented in Figure 4: A building exhaust system requires 30,000 cfm at a static pressure of 4-inch water column (W.C.) to adequately ventilate the building. An assessment of the exhaust plume shows that a 10-feet tall, 30,000 cfm exhaust fan with a 2,500 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 brake horsepower (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.

Variable Air Volume Exhaust

Designing a laboratory to utilize a VAV exhaust system allows the exhaust ventilation system to match, or nearly match, the supply ventilation airflow requirement of the building. This allows the designer to take full advantage of energy-saving opportunities associated with employing various strategies to minimize airflow requirements for the laboratory. However, just as arbitrarily reducing the supply airflow may adversely affect air quality within the laboratory environment, blindly converting an exhaust system to VAV without a clear understanding of how the system will perform can compromise air quality at nearby sensitive receptor locations (e.g., air intakes, operable windows, plazas, etc.). Therefore, before employing a VAV system, the potential range of operating conditions should be carefully evaluated through a detailed dispersion modeling study as described earlier in this guide. Since the nature of these assessments is to accurately determine the minimum volume flow requirements for the exhaust system, the preferred method is the use of physical modeling in a boundary-layer wind tunnel. Numerical methods can be used, but these will more often than not result in higher minimum volume flow rates when properly conducted and the resulting energy savings potential will be reduced.

Three different strategies that can be used for operating VAV laboratory exhaust systems are described below.

Strategy 1: Passive VAV

In a passive VAV system, the exhaust flow is based on the greater of two values: the minimum air quality set point and the building's ventilation demand. The minimum air quality set point is defined as the minimum flow / exit velocity / stack height needed to provide acceptable air quality at all sensitive receptor locations as defined in the dispersion modeling assessment. During the assessment, when a passive VAV system is to be employed, the stack design often focuses on the minimum potential volume flow rate for the laboratory building rather than the maximum value as evaluated for a constant volume exhaust system. In many cases, this minimum flow rate will be roughly half of the maximum value and is associated with nighttime turndown or minimum fume hood utilization. For a system to operate safely at 50% of full load, taller stack heights and / or the optimum placement of air intakes to minimize re-entrainment of the exhaust at these reduced flow rates are often required. Typically, 5 feet or 10 feet increases in stack height have been effective. From a controls standpoint, this is likely the simplest system to employ, particularly for retrofit of existing laboratories.

Strategy 2: Active VAV with Anemometer

If the passive VAV system does not lower the air quality exhaust set point equal to, or lower than, the building ventilation demand, further optimization is available through knowledge of the current wind conditions at the stack through use of an onsite anemometer. Recall that the passive VAV set point assumed the worst-case wind condition — a relatively low-frequency event.

In this strategy, a local anemometer is connected to the building automation system (BAS) and the minimum required exhaust flow rate is varied based on current wind conditions (direction and speed). When the wind conditions are anything but worst-case, the exhaust system may be turned down to more closely match the building demand. Essentially, the air quality minimum set point is specified for each wind direction / speed combination. This usually results in air quality set points well below building demand for many wind conditions, allowing the entire ventilation system to operate at optimum efficiency.

This strategy requires physical exhaust dispersion modeling in a wind tunnel as most numerical models do not provide off-axis concentration predictions. Minimum air quality set points as a function of wind direction (WD) and wind speed (WS) require concentration predictions at all sensitive locations (receptors) for all wind directions, wind speeds, stack heights, and exhaust flow parameters. Typically, initial testing is conducted to identify an acceptable stack height. Subsequent testing is conducted for all wind directions and speeds using a fixed stack diameter to produce concentrations for each stack / receptor combination for all combinations of wind direction, wind speed, and volume flow rate (Figure 6).

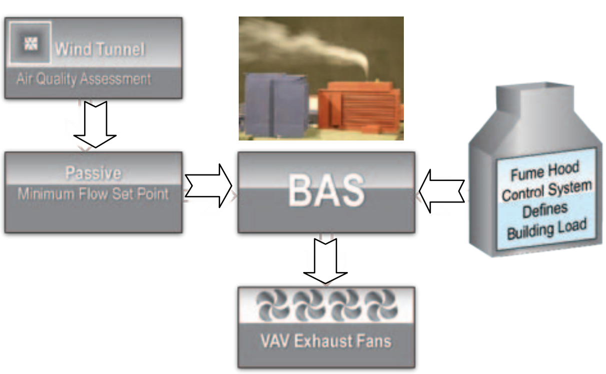


Figure 5. Passive VAV

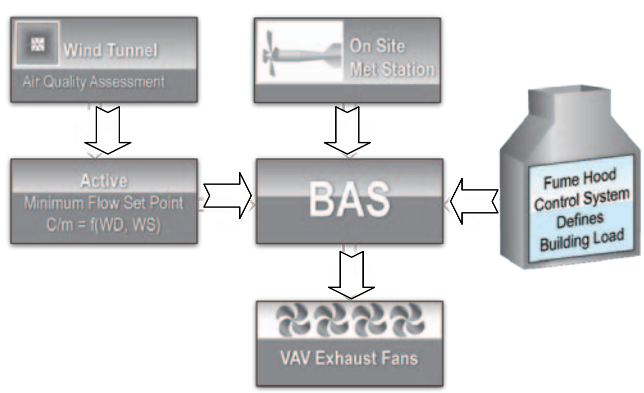


Figure 6. Active VAV with Anemometer

Table 2. Example of Minimum Fan Load Percentages versus Anemometer Reading (BAS Lookup Table)

Wind Direction (Deg)		Anemometer Wind Speed (m/s)														
Min	Max	<1	1	2	3	4	5	6	7	8	9	10	11	12	13	14
350	10	57	57	78	81	76	68	61	58	57	57	56	49	33	6	0
10	30	57	41	62	75	81	82	79	75	71	66	62	60	58	57	57
30	50	57	31	38	40	40	38	36	33	31	30	29	29	30	30	30
50	70	57	29	27	24	21	18	15	12	10	7	6	4	3	2	2
70	90	57	36	47	48	43	37	31	27	25	25	26	27	27	27	24
90	110	57	39	50	48	42	34	29	26	25	26	27	26	25	22	22
110	130	57	33	47	51	48	42	36	31	27	26	25	26	26	27	27
130	150	57	22	22	21	19	17	15	13	11	11	10	10	11	11	12
150	170	57	34	45	46	42	36	31	26	24	24	24	26	26	26	25
170	190	57	35	46	46	41	34	29	25	24	24	25	26	27	26	23
190	210	57	21	20	19	17	16	15	15	15	15	16	16	15	15	14
210	230	57	5	2	0	0	0	0	0	0	0	0	0	0	0	0
230	250	57	5	2	1	0	0	0	0	0	0	0	0	0	0	0
250	270	57	10	8	7	6	6	6	6	6	6	7	6	5	1	0
270	290	57	13	11	9	7	7	7	8	8	8	7	7	7	10	19
290	310	57	13	12	10	7	8	7	7	8	8	8	8	7	6	7
310	330	57	13	12	10	7	8	7	7	8	8	8	7	7	6	8
330	350	57	32	40	39	32	36	29	28	29	30	31	31	29	27	26

Similar data for all receptors is then compiled into either a single lookup table or a series of wind-direction-specific polynomial equations for the BAS. Table 2 presents a lookup table of the air quality set point as a percentage of design flow. Note that the air quality set point for most directions is essentially 0 (no minimum set point so the exhaust flow can be set to match the building demand without the need for any by-pass air), although a few conditions require 80% of the design flow.

Strategy 3 Active VAV with Chemical Monitor

An alternative to monitoring the local wind conditions is to monitor the contents of the exhaust stream[22]. When the monitor does not detect any adverse chemicals in the exhaust stream, the exhaust system is allowed to operate at a reduced volume flow rate. While there may be an increase in the plume concentrations at the nearby air intakes, air quality will not degrade since the exhaust plume is essentially "clean."

The usual assumption is that a contaminant is present in the exhaust stream, and the exhaust design is specified to achieve acceptable air quality through either mathematical or wind tunnel exhaust dispersion analysis. If a monitoring system were used, the "normal" mode would be to establish a minimum air quality exhaust set point that allows higher plume impact. Plume impact would still be limited, just to a less conservative criterion than otherwise allowed. If contaminants were detected in the exhaust stream, the exhaust flow would increase to achieve a more stringent criterion.

Figures 8 and 9 show 1,500 $\mu g/m^3$ per grams per second (g/s) as an example of the "normal" allowable impact and 400 $\mu g/m^3$ per g/s as the criterion when a contaminant is detected. To put the 1,500 $\mu g/m^3$ per g/s and 400 $\mu g/m^3$ per g/s into perspective, considerer the "as manufactured" and "as installed" chemical hood containment requirements outlined in Z9.5-20119 (i.e., a concentration at a manikin outside the chemical hood of 0.05 ppm or less for "as manufactured" and 0.10 ppm or less for "as installed" with a 4 liters per minute (L/m) accidental release in the hood as measured using the ANSI/ASHRAE 110-1995 test method). The "as manufactured" requirement is equivalent to a design criterion of 750 $\mu g/m^3$ per g/s and the "as installed" requirement is equivalent to a design criterion of 1,500 $\mu g/m^3$ per g/s. Hence, the criterion for a manikin (i.e., worker outside the chemical hood) is 1.9 to 3.8 times less restrictive than that for the air intake or other outdoor locations when applying the 400 $\mu g/m^3$ per g/s design criterion when chemicals are detected within the exhaust hood. Applying the 1,500 $\mu g/m^3$ per g/s when no contaminant is detected in the exhaust streams means that the exhaust system is still providing an equivalent level of protection to the nearby air intake that the fume hood is providing to the inhabitants of the laboratory.

Data collected at operating research laboratories with air quality monitors in the exhaust manifold indicate that emission events that would trigger the higher volume flow rate typically occur no more than one hour per month (12 hours per year; 0.1% of the time)[22]. This means that a typical system will be able to operate at the lower air quality set point more than 99% of the time, resulting in significant energy savings.

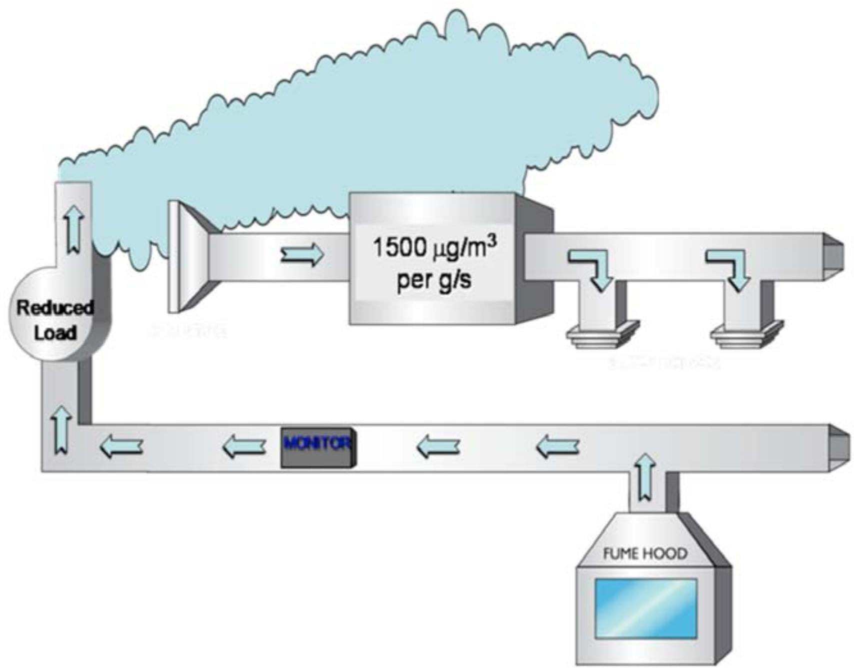


Figure 8. Higher intake concentrations are allowable when the exhaust stream is essentially "clean."

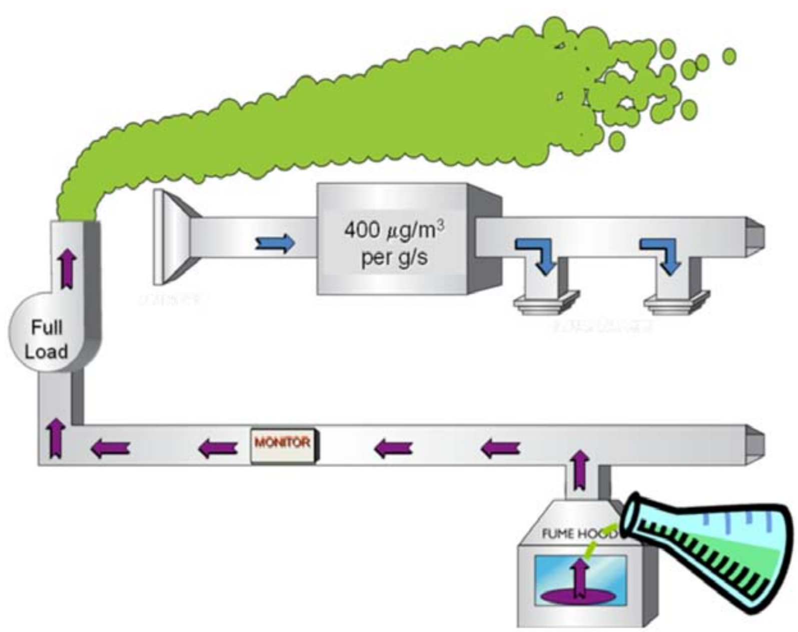


Figure 9. When chemical concentrations are detected in the exhaust stream, the exhaust volume flow rate is increased, reducing downwind intake concentrations.

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 ensures acceptable concentrations at sensitive locations. When employing a VAV heating, ventilation, and air conditioning (HVAC) supply system for the laboratory, the design team should strongly consider opportunities to include VAV laboratory exhaust systems as well to fully realize the energy savings potential of VAV. However, blindly applying VAV can be detrimental to the air quality at air intakes and other locations of concern if a dispersion modeling study is not conducted to define acceptable minimum volume flow rates. Any implementation of a VAV exhaust system should include a building automation system designed to handle the appropriate control logic. In addition, commissioning of the system should include the full range of operating conditions.

References

1. Fisk, W.J., "Review of Health and Productivity Gains from Better IEQ," *Proceedings of Healthy Buildings*, Vol. 4, pp. 23–34, 2000.

2. Yates, A., "Quantifying the Business Benefits of Sustainable Buildings (Draft)," Building Research Establishment, Ltd., Project Report 203995, 2001.

3. Kats, G., "The Costs and Financial Benefits of Green Buildings," California's Sustainable Building Task Force, Capital E, 2003.

4. Petersen, R.L., B.C. Cochran, and J.J. Carter, "Specifying Exhaust and Intake Systems," *ASHRAE Journal*, August 2002.

5. Bell, G.C., "Optimizing Laboratory Ventilation Rates," Laboratories for the 21st Century, U.S. Environmental Protection Agency, Office of Administration and Resources Management, September, 2008.

6. Weale, J., D. Sartor, L Eng, "Low-Pressure Drop HVAC Design for Laboratories," Laboratories for the 21st Century, U.S. Environmental Protection Agency, Office of Administration and Resources Management, February, 2005.

7. Labs21 Benchmarking Tool, http://ww.labs21century.gov/toolkit/benchmarking.htm, Laboratories for the 21st Century, U.S. Environmental Protection Agency, Office of Administration and Resources Management, online database.

8. Kaushansky, J. and G. Maine, "Laboratories for the 21st Century: Case Studies – Pharmacia Building Q, Skokie, Illinois," Laboratories for the 21st Century, U.S. Environmental Protection Agency, Office of Administration and Resources Management, December, 2002.

9. ANSI/AIHA, American National Standard for Laboratory Ventilation, Standard Z9.5-2011.

10. ASHRAE, ASHRAE Handbook-HVAC Applications, Chapter 44, Building Intake and Exhaust Design, 2011.

11. Petersen, R.L., J.J. Carter, and M.A. Ratcliff, "Influence of Architectural Screens on Roof-top Concentrations Due to Effluent from the Short Stacks," ASHRAE Transactions, Vol. 105, Part 1, 1999.

12. Petersen, R.L., J.J. Carter, and J.W. LeCompte, "Exhaust Contamination of Hidden vs. Visible Air Intakes," ASHRAE Transactions, Vol. 110, Part 1, 2004.

13. ACGIH, Guide to Occupational Exposure Values, 2010.

14. ACGIH, Threshold Limit Values for Chemical Substances and Physical Agents, 2010.

15. ACGIH, Odor Thresholds for Chemicals with Established Occupational Health Standards, 1989.

16. EPA, Guideline for Use of Fluid Modeling of Atmospheric Dispersion, April 1981.

17. ASHRAE, ASHRAE Handbook – Fundamentals, Chapter 24, Airflow Around Buildings, 2009.

18. ASHRAE, ASHRAE Handbook-HVAC Applications, Chapter 44, Building Intake and Exhaust Design, 2003.

19. Briggs, G.A., "Plume rise and buoyancy effects," Atmospheric Science and Power Production, D. Randerson, ed. U.S. Department of Energy DOE/TIC-27601, Washington, D.C., 1984.

20. ASHRAE, ASHRAE Handbook-Fundamentals, Chapter 14, Climatic Design Information, 2009.

21. ASHRAE, ASHRAE Handbook-Fundamentals, Chapter 24, Airflow Around Buildings, 2009.

22. Cochran, B. and G. Sharp, "Combining Dynamic Air Change Rate Sensing with VAV Exhaust Fan Control to Minimize HVAC Energy Consumption in Laboratories," Labs21 Conference Session VAV vs. CAV, San Jose, California, 2008.

Acknowledgments

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Energy Efficiency and Renewable Energy
www.eere.energy.gov

Prepared at the
National Renewable Energy Laboratory
A DOE national laboratory

DOE/GO-102011-3331
September 2011

Printed with a renewable-source ink on paper containing at least 50% wastepaper, including 10% post consumer waste.