I²SL International Institute for Sustainable Laboratories®

Best Practices Guide

# Designing and Operating Sustainable Laboratory Exhaust Systems

AUGUST 2021

## Introduction

This guide provides general guidance on the design and operation of laboratory exhaust systems to avoid adverse re-entrainment of the effluent at critical surrounding locations. 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.

Studies have shown a direct relationship between indoor air quality and the health and productivity of building occupants (Fisk, 2000; Yates, 2001; Kats, 2003). Historically, the study and protection of indoor air quality has focused on emission sources emanating from within the building. For example, to ensure that laboratory users are not exposed to toxic chemicals, ANSI/AIHA/ASSP Standard Z9.5 (American National Sandards Institute, 2012) provides "as manufactured" and "as installed" concentration limits, as measured at the manikin during an ASHRAE 110 fume hood containment test (ASHRAE, 2016). 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.

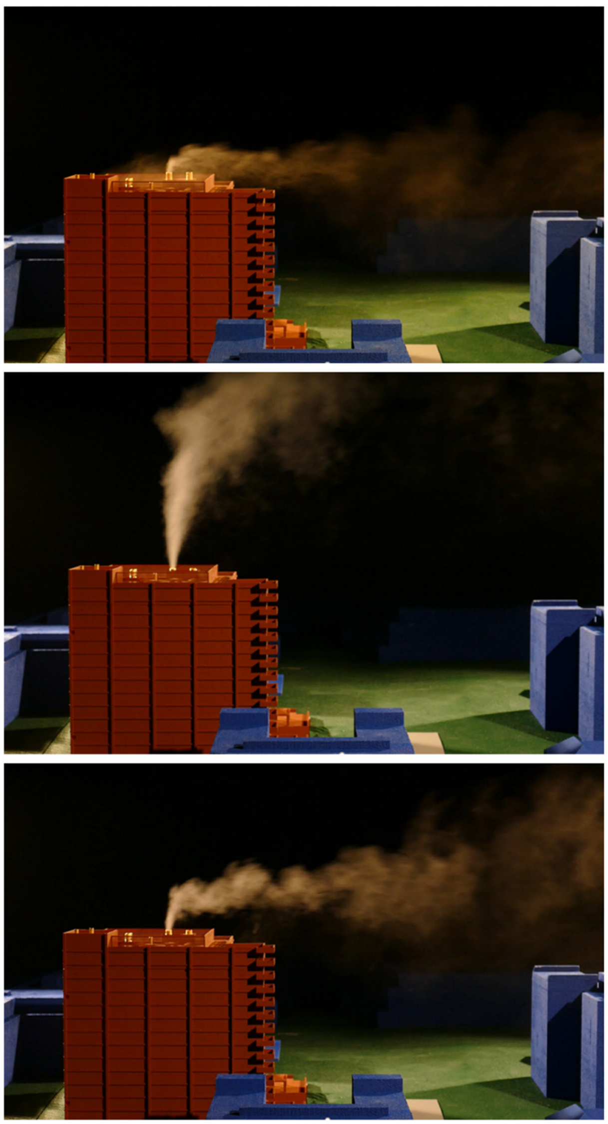
If the exhaust sources and air intakes are not properly designed, it is quite possible that higher concentrations of the emitted chemical(s) may be present at nearby air intakes than at the front of the fume hood, where the chemical was initially released. Furthermore, if a toxin is released within a fume hood, the worker can take corrective action by closing the sash and leaving the immediate area; thus, reducing exposure to the chemical vapors. Conversely, the presence of the toxic or odorous fumes at an 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 re-entry, 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. (2002) give a technical description of various aspects of exhaust and intake design. Some of the challenges of specifying a good stack design mentioned in their 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 (page 2) illustrates the impact that plume rise has on the dispersion of laboratory exhaust. The first photo shows a situation where there is inadequate plume rise and the exhaust is trapped on the roof of the lab, potentially creating adverse air quality at nearby air intakes. The second photo shows an example where the plume is jettisoned out of the top of the stack at a high exit velocity and/or volume flow rate. This results in low levels of re-entrainment but at the cost of high energy consumption. In the third photo, the plume rise, and thus the fan energy, has been optimized to produce an exhaust system that is both safe and energy efficient.

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 (the product of exit velocity and volume flow rate) is limited by capital and energy costs, noise, and vibration.



**Insufficient Plume Rise**
**High Levels of Re-entrainment**
**Potentially Unsafe**

**Excessive Plume Rise**
**Low Levels of Re-entrainment**
**Energy Intensive**

**Optimized Plume Rise**
**Low Levels of Re-entrainment**
**Reduced Energy Consumption**

*Figure 1. Photographs of wind tunnel simulations showing plumes exiting fume hood exhaust stacks. In looking at the photograph, we should ask: Are the concentrations at nearby air intakes safe? Only a detailed dispersion modeling analysis will provide the answer. Source for all images: CPP Inc.*

Furthermore, local jurisdictions are beginning to develop energy codes that limit the energy consumption of these systems, complicating the design and operation of these exhaust systems (California Energy Commission, 2019).

Modern laboratories are often designed with variable air volume (VAV) HVAC systems to minimize the supply air requirements during off hours or when the fume hoods are not being used at their peak design capacity (Bell, 2008; Varley, 2020). Conversely, the exhaust fans are typically designed to operate in a constant volume mode with the difference between the supply and the exhaust airflow requirements made up through bypass dampers on the exhaust manifold. While this type of system may optimize the energy consumption of the supply ventilation and conditioning, it ignores the potential energy savings that can be attributed to reducing the volume flow rate through the exhaust system.

A laboratory exhaust system may account for up to 40% of the ventilation system's energy consumption and about 30% of the laboratory building's total electrical energy consumption (International Institute for Sustainable Laboratories, 2020; Kaushansky & Maine, 2002). By appropriately applying VAV technology to the exhaust system, the system can still serve its intended purpose to adequately disperse all airborne contaminants while consuming significantly less energy.

Several organizations have published standards for, or recommendations regarding, laboratory exhaust stack design, as summarized in the box below.

### General Design Guidelines or Standards

1. Maintain a minimum stack height of 10 ft (3 m) to protect rooftop workers (American National Standards Institute, 2012; British Standards Institute, 2019). Note that the 10 ft (3 m) minimum height is specifically NOT defined to be sufficient to avoid adverse re-entrainment into nearby air intakes.
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 (ASHRAE, 2019).
3. Do not locate air intakes within the same architectural screen enclosure as contaminated exhaust outlets (ASHRAE, 2019).
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 (ASHRAE, 2019).
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 effect (ASHRAE, 2019). However, the addition of entrained air through an exhaust stack does not increase plume rise, and thus, does not reduce downwind concentrations.
6. In a scenario where separate exhaust systems are mandated by the International Mechanical Code*, or other authorities, group separate stacks together in a tight cluster (i.e., the stacks should be nearly touching) to take advantage of the increased plume rise from the resulting combined vertical momentum (ASHRAE, 2019). Note that all the exhausts must operate continuously at a similar discharge velocity to take full advantage of the combined momentum, and all stacks in the cluster should terminate at the same height. If all of the exhausts are not operating at the same time, such as in an n+1 redundant system, the clustered placement of stacks may be detrimental to their performance.

*continued on page 4*

## General Design Guidelines or Standards, Cont.

7. Maintain an adequate exit velocity to avoid stack-tip downwash. The American National Standards Institute/ American Industrial Hygiene Association standard for laboratory ventilation, Z9.5-2012 (American National Standards Institute, 2012) suggests that the minimum exit velocity from an exhaust stack should be at least 3,000 fpm. However, Appendix 3 of the standard states that the "3,000 fpm exit velocity should not be assumed to be safe." If the exhaust system has the potential to include any toxic emissions, dispersion modeling should be conducted to confirm the minimum safe exit velocity and volume flow rate. The resulting minimum operating conditions will be both system- and site-specific. No single exit velocity can be assumed to be safe under all operating and site conditions.
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 and may greatly increase downwind concentrations. 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 46 of the ASHRAE Handbook–HVAC Applications (ASHRAE, 2019).
10. The use of architectural screens to hide rooftop equipment can adversely impact the performance of the exhaust system. An ASHRAE-funded research study (Petersen et al., 1999) 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).
11. Avoid a direct line of sight between exhaust stacks and air intakes. An ASHRAE research project (Petersen et al., 2004) 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.

** The International Mechanical Code defines "hazardous" exhaust systems as being 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 (International Code Council, 2021).*

## Conducting an Air Quality Assessment for Laboratory Exhaust Systems

The topics discussed in the boxes on page 3 and above provide the design team with general recommendations on the design and placement of laboratory exhaust systems and air intakes. If followed, in part or in whole, these prescriptive measures will improve the performance of the laboratory exhaust system. However, none of these will guarantee that downwind concentrations will be limited to values that are below health limits and odor thresholds. Nor will implementing these design recommendations on their own meet the requirements in Standard Z9.5, Appendix 3, which states that "Necessary measures must be taken to protect the laboratory building and adjacent buildings from re-ingestion of toxic laboratory chemical hood exhaust back into a building air supply system" (American National Standards Institute, 2012).

The acceptable performance of a laboratory exhaust system that may contain toxic or odorous emissions can only be defined by conducting a quantitative air quality assessment.

A properly conducted air quality assessment should address the following questions:

1. What types of toxic or odorous emissions are anticipated for the exhaust system?
2. What is the maximum predicted emission rate for each of the chemicals of concern?
3. What are the allowable exposure limits for each of the chemicals of concern?
4. What is the measured/predicted maximum concentration at critical locations?
5. Is the maximum measured/predicted maximum concentration greater than the allowable exposure limits?

## Exhaust Design Criteria

The first three questions above can be addressed by developing acceptable design criteria for each type of emission source.

### Emission Sources

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, vivaria, loading docks, traffic, cooling towers, and boilers. Each source needs its own air quality design criteria. An air quality "acceptability question" can be written:

Is $C_{max} < C_{health} /_{odor}$?

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 (Equation 1).

When a source has the potential to emit a large number of pollutants, multiple 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*:

Is $(C/m)_{max} < (C/m)_{health} /_{odor}$?

The left side of Equation 2 above, $(C/m)_{max}$, 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 much higher emission rate.

### Exposure Limits

Recommended health limits, $C_{health}$, are based on the ANSI/AIHA Standard Z9.5-2012, (American National Standards Institute, 2012), 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 ACGIH, the Occupational Safety and Health Administration (OSHA), and the National Institute of Occupational Safety and Health (NIOSH), as listed by ACGIH (ACGIH, 2020a; ACGIH, 2020b). The American Industrial Hygiene Association (AIHA) can also furnish odor thresholds, $C_{odor}$, (AIHA, 2013).

Published health limits from ACGIH, NIOSH, and AIHA are recommended limits and tend to be more conservative (lower) than limits published by OSHA, which are enforceable.

## Emission Rates

For laboratories, 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.

Initially, a worst-case emission event within a fume hood can be based on a 1-liter spill of a liquid chemical. A 1-liter spill is used because guidance from the U.S. EPA Workbook of Screening Techniques (Environmental Protection Agency, 1992) is that a liquid will spread out to a thickness of roughly 1 mm. Therefore, a spill quantity of 1 liter will cover a surface are of roughly 1 $m^2$ (approximately the size of the basin within a 6-foot fume hood). The emission rate from this spill is calculated based on the evaporation equation from the EPA (Environmental Protection Agency, 1992). The calculation (Equation 3) is shown below.

$$m = 6.94 \, x \, 10^{-4} \, ( 1 + 0.0043 \, [ \, T - 273.15 \, ]^{2} ) \, U_r^{\,0.75} \, A \, M \, \frac{V_p}{V_{pk}}$$

Where:

$M$ = Mass emission rate, g/s

$T$ = Temperature of the liquid, (default 293 K)

$U_r$ = Air velocity over the surface of the spill (default value is 0.5 m/sec)

$A$ = Surface area of the spill ($m^2$)

$M$ = Molecular weight of the chemical (g/mole)

$V_p$ = Vapor pressure of liquid at temperature, T

$V_{pk}$ = Vapor pressure of hydrazine at temperature, T

The parameters within this equation that can be readily adjusted to reduce the emission rate are the surface area of the spill (*A*), and the air velocity over the spill ($U_r$). To avoid overly conservative emission rate estimates, these parameters should be reviewed in the context of the selected fume hood and laboratory practices if possible (e.g., are chemicals only to be handled in smaller-volume containers?).

In this context, spill volume is directly linked to the assumed spill depth. For example, if a 1-liter spill is expected to cover the entire available surface area in a fume hood, any increases in the spill volume will only create a thicker spill. Since the depth of the pool is not part of the emission equations, spills in excess of 1 liter will have the same emission rate. However, spill quantities that are less than 1 liter will have reduced emission rates proportional to the reduction in the spill volume (i.e., a spill of 500 ml will have half of the emission rate of a 1-liter spill).

The worst-case emission rate from a gaseous chemical is estimated to correlate with fully opening the valve on a lecture bottle. Tests have shown that it takes roughly one minute to fully evacuate the contents of a lecture bottle. Thus, the mass emission rate is simply the mass of the gaseous contents within the lecture bottle divided by 60 seconds per minute. Placing a restrictor valve in the supply line will reduce gaseous emission rates. The small orifices can be specified to only allow a set emission rate, based on the supply pressure and the molecular weight of the gas.

A chemical inventory is often not available, particularly for new laboratories. Even with existing laboratories, chemical usage may change over time. Therefore, it is often difficult to develop acceptable design criteria based on a specific set of chemicals. When this occurs, other guidance can be used to develop an acceptance criterion for the laboratory fume hood exhaust.

For teaching laboratories or other laboratories that are not likely to use extensive quantities of hazardous or odorous chemicals, one method is to limit the maximum downwind concentrations from the exhaust stack to be no greater than the maximum allowable concentration at the front of the fume hood as measured with an ASHRAE 110 containment test (ASHRAE, 2016), using the ANSI/AIHA Z9.5 “as installed” criterion (American National Standards Institute, 2012). This test allows a concentration of up to 0.10 ppm of a 4 L/min emission within the fume hood to be present within the breathing zone in front of the fume hood. This corresponds to a normalized concentration design criterion of 1,500 µg/m$^3$ per g/s.

Research-based laboratories often involve the potential to use greater quantities of hazardous or odorous chemicals. Therefore, it is reasonable to apply a more restrictive criterion for the allowable downwind concentrations. ASHRAE recommends a maximum downwind normalized concentration of 400 µg/m$^3$ per g/s (ASHRAE, 2019). This provides a factor of safety of just less than four between the concentrations present at the front of the fume hood and the allowable concentrations downwind of the exhaust stack. As long as fume hood users apply safe practices to protect their own safety by limiting the quantities of chemicals used within the hood, the maximum concentrations present at nearby air intakes and other sensitive receptor locations will remain well below the established health limits and odor thresholds.

Table 1 provides examples of design criteria for laboratory fume hood exhausts as well as other emission sources that might be associated with a laboratory facility. However, it is prudent to understand the details of a given assessment, including source-specific emission parameters and sensitivity to re-entrainment, to determine appropriate design criteria that satisfy the objectives of the project.

## Table 1: Examples of Normalized Concentration Design Criteria

| Source Type | Design Criteria Type | Design Criteria ($\mu g/m^3$) / (g/s) | Basis for Design Criteria |
|---|---|---|---|
| Research laboratory fume hood | Health | 400† | ASHRAE (2019) example criterion for a spill in a fume hood |
| | Odor | 400† | |
| Teaching laboratory fume hood | Health | 1,500# | Equivalent to the ANSI/AIHA Z9.5 (ANSI/AIHA, 2012) "as installed" criteria for allowable concentrations at the front of the fume hood during an ASHRAE 100 containment test (ASHRAE, 2016) |
| | Odor | 1,500# | |
| 30,000 cubic feet per minute (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 level for kitchen exhaust |
| 400 horsepower (hp) diesel truck | Health | 156,522 | Health limit associated for $NO_X$ emissions |
| | Odor | 5,293† | 1:2,000 odor dilution threshold for diesel exhaust |
| 250 kilowatt (kW) diesel generator | Health | 2,367 | Health limit associated for $NO_X$ emissions |
| | Odor | 492‡ | 1:2,000 odor dilution threshold for diesel exhaust |
| 2,000 kW diesel generator | Health | 296 | Health limit associated for $NO_X$ 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 for $NO_X$ emissions |
| | Odor | 23,576 | Odor threshold associated with nitric oxide |
| 100 hp boiler (4.5 MMBtu), gas-fired (20 ppm $NO_x$) | Health | 132,278 | Health limit associated for $NO_X$ emissions |
| | Odor | 192,122 | Odor threshold associated with nitric oxide |
| 500 hp boiler (21 MMBtu), oil-fired | Health | 4,613 | Health limit associated for $NO_X$ emissions |
| | Odor | 5,052 | Odor threshold associated with nitric oxide |
| 500 hp boiler (21 MMBtu), gas-fired (20 ppm $NO_x$) | Health | 28,345 | Health limit associated for $NO_X$ emissions |
| | Odor | 41,169 | Odor threshold associated with nitric oxide |

*†This criterion is more restrictive than the 0.05 ppm criterion stated in ANSI/AIHA Standard Z9.5 (American National Standards Institute, 2012) for the maximum concentration present at the face of the fume hood in an "as manufactured" configuration, which corresponds to a normalized concentration of approximately 750 $\mu g/m^3$ per g/s.*

*# This criterion is equivalent to the 0.10 ppm criterion stated in ANSI/AIHA Standard Z9.5 (American National Standards Institute, 2012) for the maximum concentration present at the face of the fume hood in an "as installed" configuration, which corresponds to a normalized concentration of approximately 1500 $\mu g/m^3$ per g/s. This less restrictive criterion can be applied where chemical usage is known and not expected to change significantly over time and administrative controls are in place for those chemicals with a normalized health limit less than 1,500 µg/m3 per g/s associated with either a 1-liter spill within the fume hood or a one-minute release from a lecture bottle.*

*‡ Normalized concentration design criteria based on dilution standards depend on the volume flow rate through the exhaust stack.*

## Dispersion Modeling Methods

Concentration predictions (*C/m*) at sensitive locations can be accomplished with varying degrees of accuracy using three different types of studies:

- A full-scale *field* testing program.
- A reduced-scale *physical* dispersion modeling assessment.
- A *numerical* dispersion modeling assessment.

### Field Testing

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 impossible to obtain data for future building configurations. Furthermore, there is currently no established guidance on the proper method to conduct a field-testing assessment for evaluating the performance of a laboratory exhaust system.

### Reduced-Scale Physical Dispersion Modeling

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 (Environmental Protection Agency, 1981a). A wind-tunnel modeling study is like a full-scale field study, except that it may be 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 the tracer gas are then measured at receptor locations of interest and converted to full-scale concentration values. Next, these values are compared with the appropriate design criteria to evaluate the acceptability of the exhaust design. ASHRAE (ASHRAE, 2019) and the EPA (Environmental Protection Agency, 1981a) 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 (see the box on page 24 for some relevant questions). Factors such as past experience and staff technical qualifications are extremely important. Any wind tunnel used for these reduced-scale physical dispersion model assessments should be specifically designed to accurately model the flow characteristics of the atmospheric boundary layer. This includes vertical mean velocity and turbulence intensity profiles that are appropriate for the site. In addition, the turbulent eddies within the flow should be generated with a method that produces a turbulent energy spectrum that matches the atmosphere.

The EPA provides a guideline for properly conducting a reduced-scale dispersion modeling assessment in an atmospheric boundary layer wind tunnel (Environmental Protection Agency, 1981a). Furthermore, the EPA Guideline for Fluid Modeling to Determine Good Engineering Practice Stack Height (Environmental Protection Agency, 1981b) requires various atmospheric dispersion comparability (ADC) wind-tunnel measurements to verify the ability of the wind tunnel to accurately simulate plume trajectories. A properly commissioned wind tunnel used for dispersion modeling should have ADC results available for review.

## Numerical Dispersion Modeling

Numerical 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 (ASHRAE, 2019). While the geometric method provides valuable information associated with the optimum placement of exhaust stacks to minimize the potential for adverse re-entrainment, it 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 (ASHRAE, 2019) will tend to give conservative results for an isolated building or one that is the same height as, 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 model is 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 vivaria and atriums, as well as in external aerodynamics for the aerospace industry. Aerospace CFD turbulence models, however, are ill-suited for modeling the atmospheric turbulence in complex building environments because of the differing geometric scales and the absence of large-scale turbulence features.

Background information on the use of CFD for dispersion modeling can be found in the ASHRAE Handbook on HVAC Applications (ASHRAE, 2019). Chapter 46 includes discussions on the various 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 method, can lead to “large, and sometimes very large, discrepancies in comparison with wind tunnel and full-scale measurements.”

LES (large eddy simulations) have a greater potential to provide accurate results. However, LES require significantly greater expertise, and the computational time and cost can be prohibitive.

Based on the current state of the art, steady-state CFD RANS models *should not* be used when modeling exhaust plumes resulting from laboratory pollutant sources. Current research indicates that CFD models can both over- and under-predict concentration levels by orders of magnitude, leading to potentially unsafe designs. If a CFD study is conducted for such an application to provide an early indication of plume behavior, the results should not be used in the final design or operation. Rather, these results should be validated with either a full-scale field or wind-tunnel assessment.

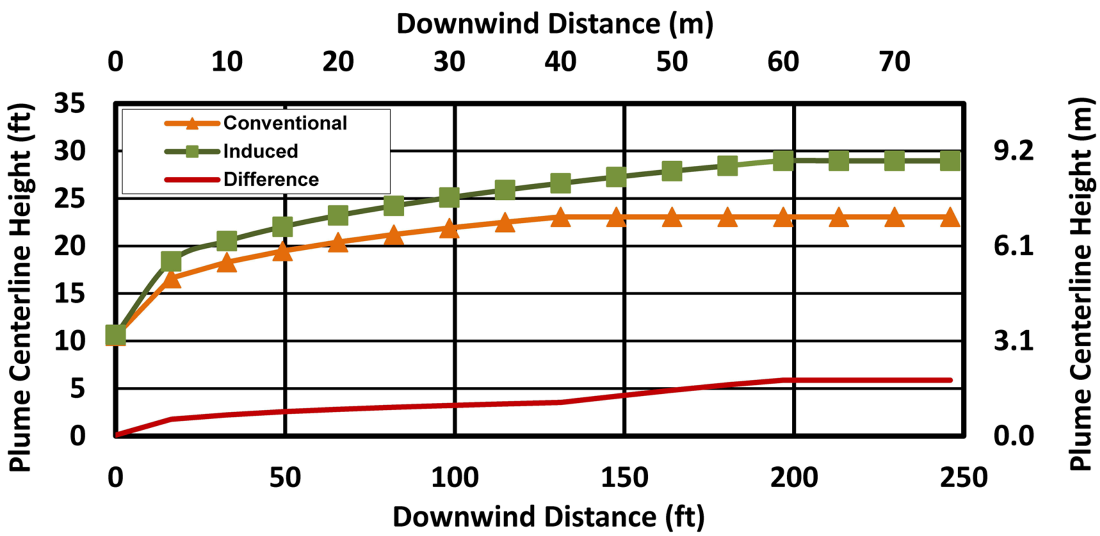
## Effective Stack Height and Induced-Flow Fans

Induced-flow 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 with 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 HVAC Applications Handbook.

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 HVAC Applications Handbook (ASHRAE, 2019). The "new" equations, 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 (Briggs, 1984).

A better method of comparing two different exhaust systems is to specify the effective increase in the plume height vs. 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 vs. downwind distance for an induced-air exhaust stack and a conventional exhaust fan system at a 20 mph (9 m/s) 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-flow 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.




| Exhaust Parameters | | | | |
|---|---|---|---|---|
| | Conventional | | Induced-Air | |
| **Stack Height (ft, m)** | 10.2 | 3.1 | 10.2 | 3.1 |
| **Stack Diameter (in.,m)** | 30.3 | 0.8 | 45.0 | 1.1 |
| **Discharge Flow Rate (cfm, $m^3/s$** | 15,000 | 7.1 | 32,466 | 15.3 |
| **Exit Velocity (fpm, m/s)** | 3,000 | 15.2 | 2,940 | 14.9 |
| **Wind Speed (mph, m/s)** | 20.0 | 8.9 | 20.0 | 8.9 |
| **Fan Power (bhp, bkW)** | 14.5 | 10.8 | 17.9 | 13.3 |

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

## Enhanced Dilution from Induced-Flow Fan

In addition to promoting the "effective stack height" for induced-flow fans, as discussed above, manufacturers of these fans often call out the additional dilution that occurs due to the added airflow into the exhaust stream due to entrainment. But does this additional dilution exiting the top of the stack actually impact the downwind concentrations?

Conventional wisdom might indicate that if you have twice the dilution (reduced concentrations by a factor of two) exiting the top of the wind band, then downwind concentrations of the plume must also be reduced by a factor of two. Unfortunately, it does not work this way.

The average concentration within the plume of the emitted chemicals is defined by the volume of the plume, $Vol_{plume}$, and the chemicals mass emission rate, $m$. Where:

(Equation 4) $Vol_{plume} = \pi \sigma_y \sigma_z U_s$

(Equation 5) $C = m/Vol_{plume}$

Both the lateral, $\sigma_y$, and vertical, $\sigma_z$, spread of the plume are a function of the turbulence in the airflow and are not dependent of the volume flow rate out of the top of the stack. (The initial diameter of the stack, $d_e$, can slightly increase the size of the plume, but this impact is quickly diminished as the plume travels downwind and becomes significantly larger than the diameter of the stack.) Therefore, the volume flow rate out of the top of the stack has no impact on either of these parameters.

In the example, illustrated in Figure 3, the height and width of the plume has grown to 10 m and the wind speed, $U_s$, is 5 m/s (approximately 10 mph). Therefore, the one-second cross section of the plume has a volume of 1,570 $m^3/s$, giving an average concentration of chemical A of 0.0013 $g/m^3$ (or 1,300 $\mu g/m^3$). Note that this concentration is only dependent on the mass of the chemical emission (g/s) and the volume of the plume. Therefore, the only impact that the induced flow has on the concentration flow field is limited to conditions right at the top of the stack. As the plume travels downwind this additional volume flow rate is "absorbed" by the approaching wind as potential

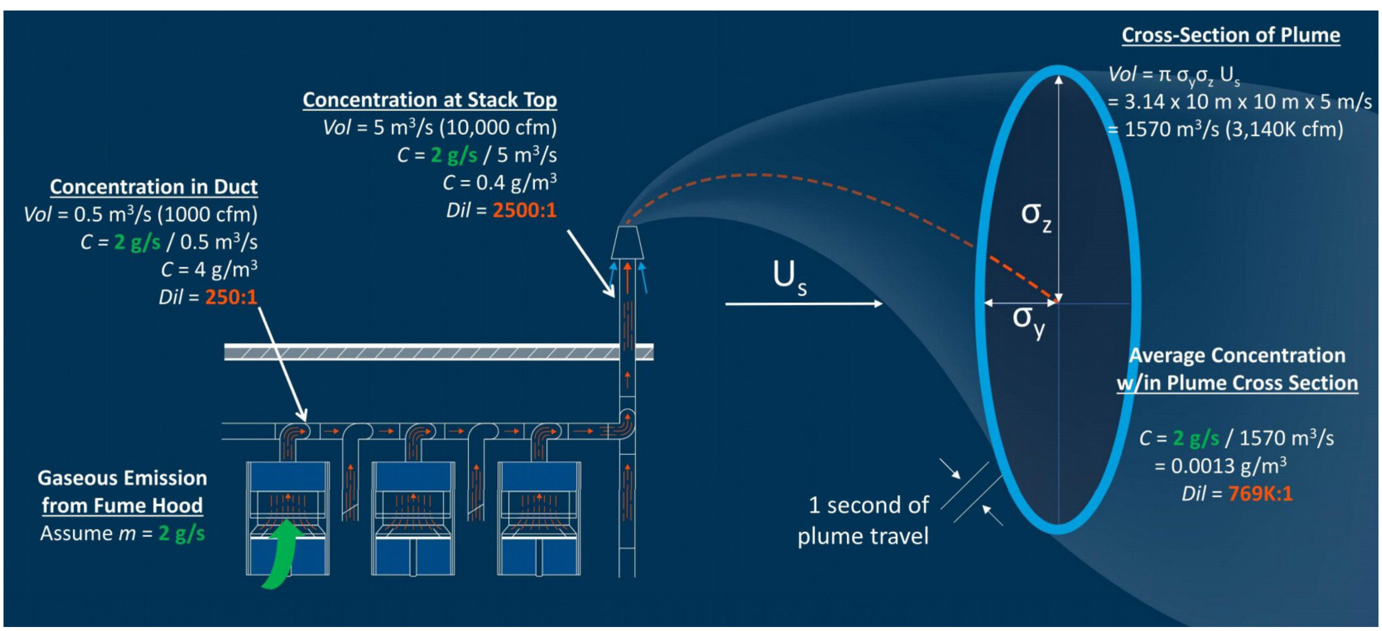



*Figure 3. Example of concentration distributions downwind of an induced-flow fan, illustrating that the induced flow has no impact on downwind concentrations.*

energy in the exhaust plume is converted to kinetic energy.

The height of the plume above a receptor location of interest is important since the concentration distribution of the emitted plume is not constant across its cross-section, but rather follows a Gaussian (normal) distribution where plume concentrations are at their maximum at the centerline of the plume. As a result, the amount of plume rise can have a significant impact on the concentrations at a given downwind location.

Induced-flow fans typically have higher plume rise than conventional (non-induced flow) fans, as discussed above, due to the increased momentum out of the top of the stack. This additional momentum is a result of the increased nozzle velocity, which can be as high as 5,000 to 7,000 fpm (compared with a conventional fan, which may operate closer to 3,000 fpm). The wind band does not add any momentum to the flow because it is a passive device. The induced air brought in under the wind band therefore has no impact on the size, shape, or height of the downwind plume, and, thus, does not decrease the concentrations (or increase the dilution) of the plume that are impacting a downwind location of interest.

## 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 (ASHRAE, 2019). 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 consumption issues 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 (ASHRAE, 2021a). 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 (ASHRAE, 2021b).

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.

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 (ASHRAE, 2019). 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 (ASHRAE, 2021b). Note that the ASHRAE-provided wind speed must be adjusted from the anemometer location to the stack top (ASHRAE, 2019).

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 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, which will be discussed in greater detail below. Many of these devices, such as an iris or damper blades, do not properly condition the flow as it exits the stack. This may reduce 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-Efficient Design and Operation

Several factors affect exhaust system energy consumption, including:

- 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.
- The environment surrounding the laboratory, involving the presence of nearby structures, air intakes, and other critical receptor locations.
- 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 minimum exit velocities, 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 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 4 (page 15) 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 5,000 cfm should be approximately 22 feet tall to achieve the design criterion at a receptor 160 feet downwind. Conversely, five stacks operating at 1,000 cfm would need to be nearly 38 feet tall to provide the same air quality at the same receptor location. (For more on manifolding lab exhaust, see Leibowitz & Williams, 2021.)

Figure 5 (page 15) 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-flow 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 5, consider the following example. A building exhaust system requires 30,000 cfm at a static pressure of 4 in. water column (w.g.) to adequately ventilate the building.

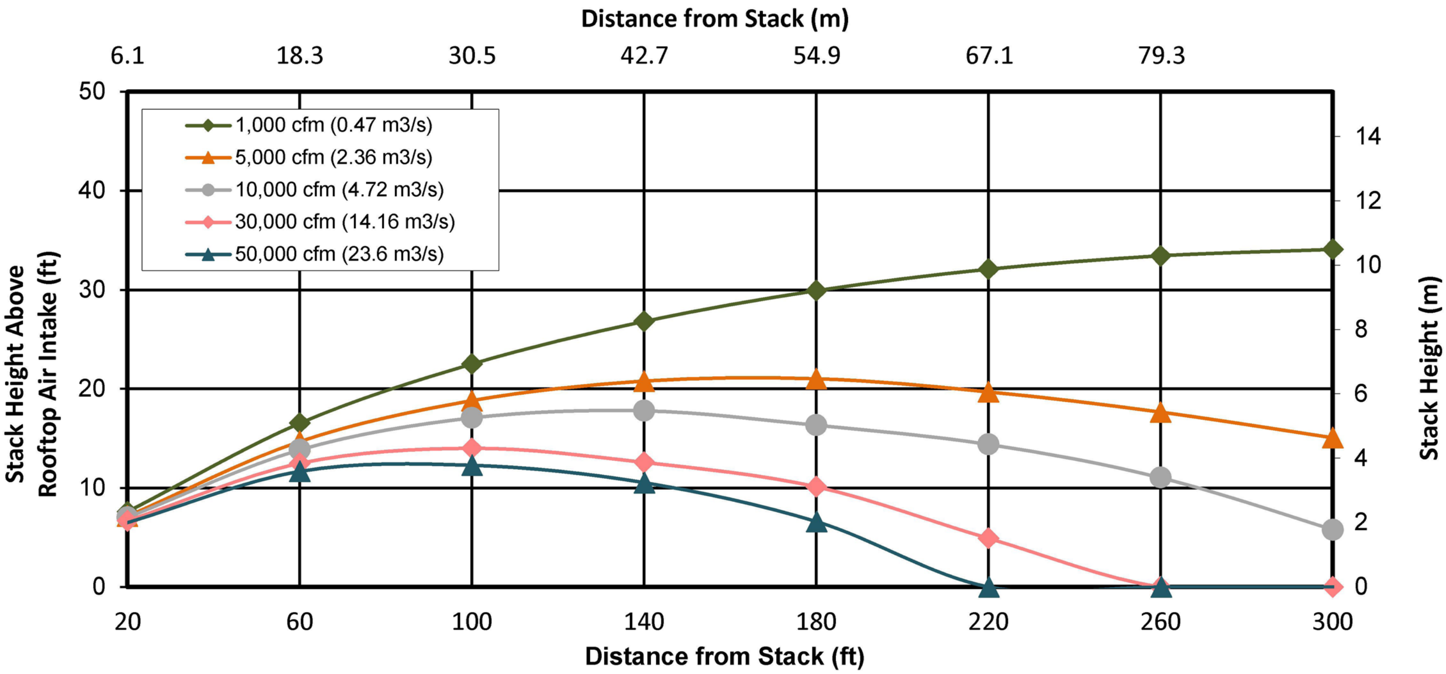



*Figure 4. Stack height above top of intake required to meet a specified design criterion for various exhaust volume flow rates at a range of downwind distances. (Design criterion = 400 µg/m³ per g/s; $V_e$ =3,000 fpm [15.2 m/s].)*

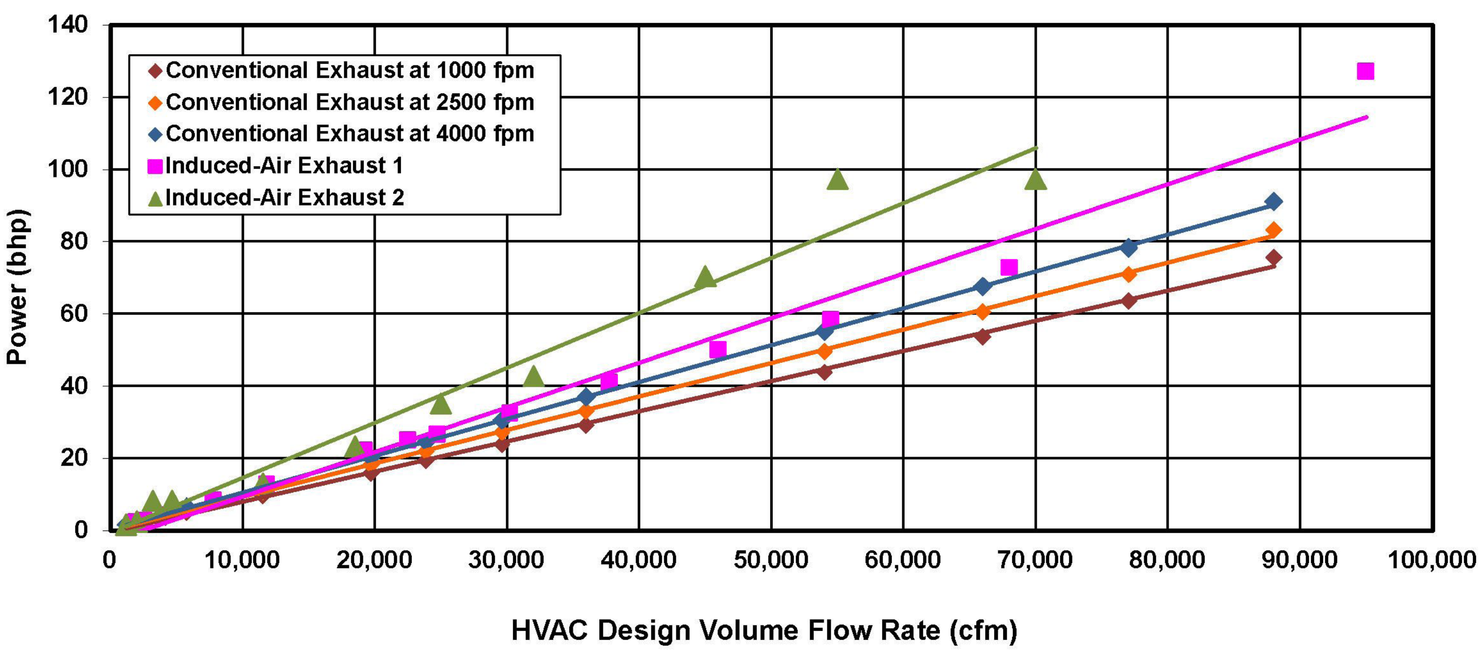



*Figure 5. Required fan power vs. HVAC design exhaust volume flow rate (at 4-in. w.g.).*

An assessment of the exhaust plume shows that a 10-foot-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 bhp (brake horsepower). An equivalent induced-flow 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-Exit-Diameter Nozzle Designs

One method that may be considered to reduce energy consumption in a laboratory exhaust system is to implement a variable nozzle exit diameter. Several manufacturers provide these types of devices, which can either be integrated into the exhaust stack or added to the top of the stack.

The rationale for implementing a variable-diameter exit nozzle is ability to maintain a constant exit velocity (typically defined as 3,000 fpm, per ANSI/AIHA Standard Z9.5) as the volume flow rate decreases. However, as discussed above, this philosophy is flawed at its core. The critical parameter for defining the performance of a laboratory exhaust system is the plume rise at critical downwind locations. Maintaining a constant exit velocity does not maintain a constant plume rise. A 30,000-cfm exhaust fan operating at 3,000 fpm provides significantly more plume rise than a 1,000-cfm exhaust fan also operating at 3,000 fpm. In the first case, the 3,000 fpm may be overly aggressive, and a lower exit velocity may be acceptable. In the second case, an exit velocity of 3,000 fpm may be insufficient for a fan only operating at 1,000 cfm.

Furthermore, reducing the nozzle diameter to maintain a constant exit velocity may actually consume more energy than using a fixed-diameter stack. When the nozzle size is reduced, the velocity pressure that must be overcome by the fan increases. Therefore, as the volume flow rate decreases, the fan energy required to maintain the constant exit velocity is greater than the fan energy required for a fixed-diameter system where the exit velocity changes proportionally with volume flow rate.

Figure 6 (page 17) shows an example of this. The plot shows two fan curves (volume flow rate vs. fan power). The first, blue, is for a constant-diameter nozzle stack where the exit velocity decreases in proportion with the decrease in the volume flow rate. The second curve (red dot) shows the fan curve for a variable-nozzle exhaust stack where the exit velocity remains constant as the volume flow rate decreases.

Note that the two curves meet at the far right, where both fans are operating at a volume flow rate 28,000 cfm and an exit velocity of 3,000 fpm. But, as the volume flow rate decreases (moves to the left), the fan power requirements for the variable-nozzle fan are greater, by an increasing amount, than for the fixed-nozzle design. This is entirely due to the additional static pressure drop across the exhaust fan due to the higher exit velocity through the nozzle. (This assumes a smooth transition in the nozzle diameter. Using either an iris or a louver to increase the exit velocity will result in additional pressure loss, which will need to be overcome by the fan).

Since the variable-nozzle design has a higher exit velocity at the same volume flow rate, it will provide greater plume rise than the fixed nozzle. If the dispersion analysis indicates that the fixed-nozzle design can safely operate at 19,000 cfm (2,000 fpm exit velocity), the plot shows that the associated fan power is roughly 9 bhp.

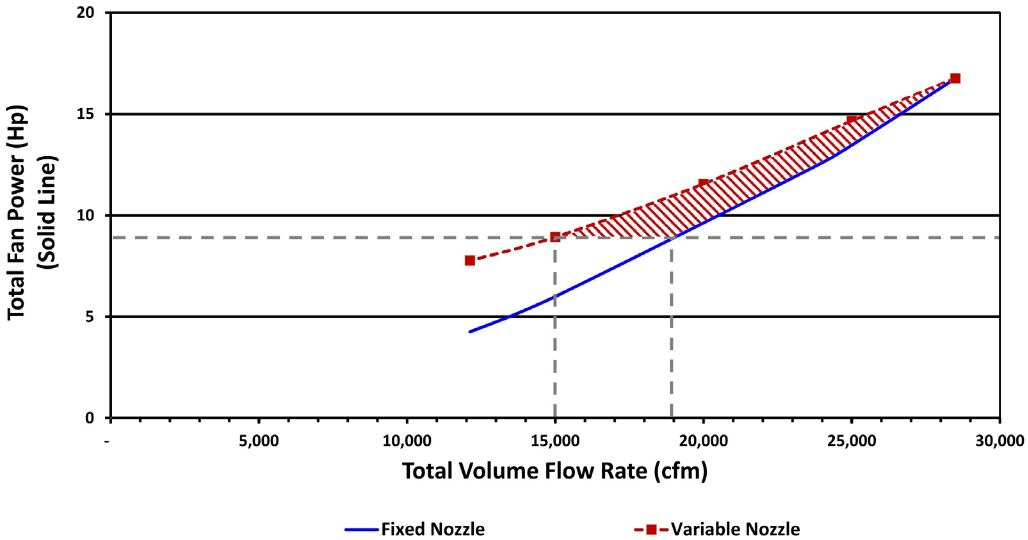



*Figure 6. Fan curves of volume flow rate vs. fan power for a fixed-nozzle stack and a variable-nozzle stack that maintains a constant exit velocity.*

Since plume rise is a function of the vertical momentum, which is provided through fan power, two systems providing the same fan power should result in similar plume rise when everything but the exit diameter is the same. Therefore, from the plot above, the variable nozzle should be able to operate safely down to a lower volume flow rate (15,000 cfm). But, when the fan is operating between 19,000 cfm and 28,000 cfm, the fixed nozzle is operating more efficiently. Then between 15,000 cfm and 19,000 cfm, bypass air could be added to the fixed-nozzle design, and it would still operate at a lower fan power until both fans are operating at 9 bhp. At this point, the fixed nozzle is operating at 19,000 cfm and 2,000 fpm while the variable nozzle is operating at 15,000 cfm and 3,000 fpm.

Only at the two extremes of the fan curves are the two fans operating at the same fan power. Everywhere in between, the fixed nozzle is consuming less energy (area shown by the red hatch in Figure 6). Thus, the addition of the variable nozzle makes the system less efficient, adds cost to the system, complicates the control strategy, and potentially increases long-term maintenance of the exhaust fan.

## Variable Air Volume Exhaust Control Strategies

Designing a laboratory to use a VAV exhaust control strategy 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. However, just as arbitrarily reducing the supply airflow may adversely affect air quality within the laboratory environment, converting an exhaust system to VAV control 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 control 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 an atmospheric 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: Simple Turndown VAV

In a simple turndown VAV system, the exhaust flow is based on the greater of two values: the minimum air quality setpoint and the building's ventilation demand. The minimum air quality setpoint is defined as the minimum volume flow rate/exit velocity/stack height needed to provide acceptable air quality at all sensitive receptor locations as defined in the dispersion modeling assessment (i.e., the maximum downwind concentrations are at or below the applicable design criterion established for the exhaust system).

During the assessment, when a simple turndown 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 ventilation demand volume flow rate from the laboratory will be roughly half of the maximum design value. This minimum load is often associated with nighttime turndown or minimum fume hood utilization.

For new systems, simple turndown is often achievable if exhaust dispersion and re-entrainment are considered early in design, so the location of exhaust stacks and air intakes can be optimized (unless there are significant design constraints specific to the project). From a controls standpoint, this is likely the simplest system to employ, particularly when retrofitting an existing laboratory (Figure 7, page 19). Simplification may also reduce construction and maintenance costs, while providing a very stable system that minimizes the annual energy consumption from the laboratory exhaust system.

For existing systems and/or retrofit designs, it may be necessary to increase the stack height for the system to operate safely at the minimum volume flow rate. In many scenarios, modest stack height increases (on the order of an additional 5 to 10 feet) may be sufficient, but this should be evaluated in the context of the building design and local site and meteorological context.

### Strategy 2: Wind-Responsive VAV With Anemometer

If the simple turndown VAV control system does not lower the minimum volume flow rate setpoint to, or below, the building ventilation demand, further optimization is available through knowledge of the current wind conditions at the stack, made possible by using an on-site anemometer.

Recall that the simple turndown VAV setpoint assumed the worst-case wind condition—which may be a relatively low-frequency event. In a wind-responsive control 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 direction and speed (Figure 8, page 20). When the wind conditions are at anything but worst-case, the exhaust system may be turned down to more closely match the building demand. Essentially, the air quality minimum setpoint is specified for each wind direction/speed combination. This usually results in air quality setpoints well below building demand for many

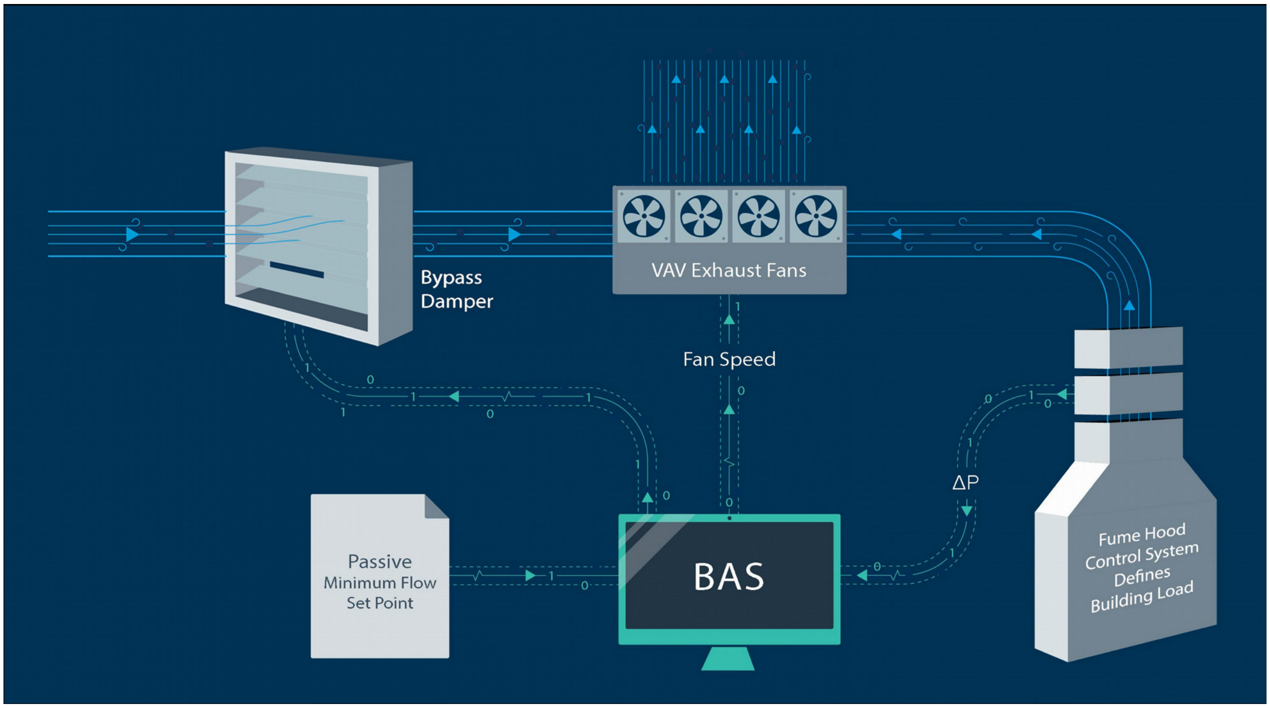



*Figure 7. Simple turndown VAV control strategy flow diagram.*

wind conditions, allowing the entire ventilation system to operate at optimum efficiency.

This strategy requires physical exhaust dispersion modeling in a wind tunnel since most numerical models do not provide off-axis concentration predictions. Minimum air quality setpoints 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.

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 (page 21) presents a lookup table of the air quality setpoint as a percentage of design flow. Note that the air quality setpoint for most directions is essentially 0 (no minimum setpoint, so the exhaust flow can be set to match the building demand without the need for any bypass air), although a few conditions require 80% of the design flow.

Care must also be taken in locating the anemometer associated with a wind-responsive VAV system. The anemometer should be positioned such that it is not located within the aerodynamic influence of nearby buildings or rooftop structures, as this may result in erroneous wind direction and speed measurements.

## Strategy 3: Chemical-Monitored VAV

An alternative to monitoring the local wind conditions is to monitor the contents of the exhaust stream (Cochran & Sharp, 2008; Cochran, 2020). A monitored exhaust system uses similar controls

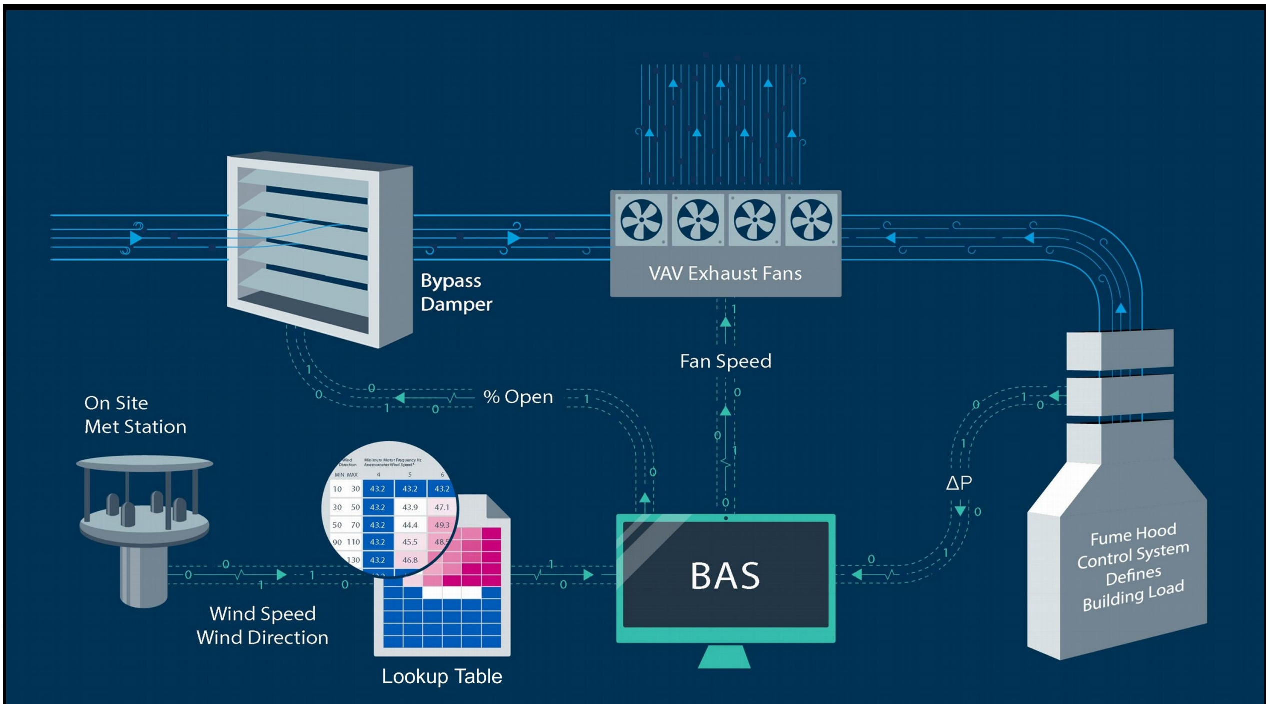



*Figure 8. Wind-responsive VAV control strategy flow diagram.*

as those used for demand controlled ventilation (DCV) within the laboratory room. Air samples are collected from within the exhaust manifold and routed to a sensor suite. 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.

The associated reduction in the plume rise may result in an increase in the concentration of the exhaust that is present at nearby air intakes. But, since the quantity of potential contaminants within the exhaust should be reduced, the overall concentration of the contaminants at the air intakes, in a properly designed system, should remain within acceptable health and odor levels.

Note that unless all potential contaminants can actually be measured at concentration levels well below their health limit and/or odor threshold, it cannot be assumed that the exhaust stream is actually "clean" of all contaminants.

The sensor suite may include detectors to measure carbon dioxide, particulates, carbon monoxide, and total volatile organic compounds (TVOC). The TVOC measurements are often used for detecting potential contaminants within the exhaust manifold using a photo ionization detector (PID).

The PID uses UV light to break down the VOCs within the air sample into positive (+) and negative (-) ions. The PID then measures the charge of the ionized gas to determine the concentrations of TVOCs in the exhaust manifold air sample. As such, it will only detect organic (carbon-containing) chemicals. The PID will not detect the presence of inorganic chemicals. Furthermore, since the PID is only measuring the ionization potential, it does not provide any indication of what chemical is creating the contamination or even the concentration of the chemical that is being emitted. Since each chemical has a different response factor, it is possible that a small release of a non-toxic (or low-toxicity) chemical with a high response factor (the ratio of

## Table 2: Air Quality Setpoint as a Percentage of Design Flow

| Wind Direction (degrees) | | Anemometer Wind Speed (m/s) / Minimum Volume Rate (% of Full Load) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Min | Max | <1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 18 | 21 |
| **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 |

the measured TVOC concentration to the actual chemical concentration) could swamp the signal from a highly toxic chemical with a low response factor.

The design of a monitored exhaust system requires the following parameters to be defined based on potential chemical usage.

- Concentration trigger level (ppm): The measured TVOC concentration level at which the air is considered to be contaminated.
- Allowable downwind concentration design criterion when the monitored concentrations are below the contaminated trigger level.
- Allowable downwind concentration design criterion when the monitored concentrations are above the contaminated trigger level.

Once these three variables are defined, then dispersion modeling can be used to define the minimum volume flow rate through the exhaust fans that meets the applicable design criterion when the contaminants are above and below the trigger levels.

The implementation of a monitored exhaust system requires knowledge of, and administrative controls for, potential chemical emissions. This doesn't mean that inorganic chemicals or highly toxic or odorous organic chemicals cannot be used in the areas served by these systems. However, their usage

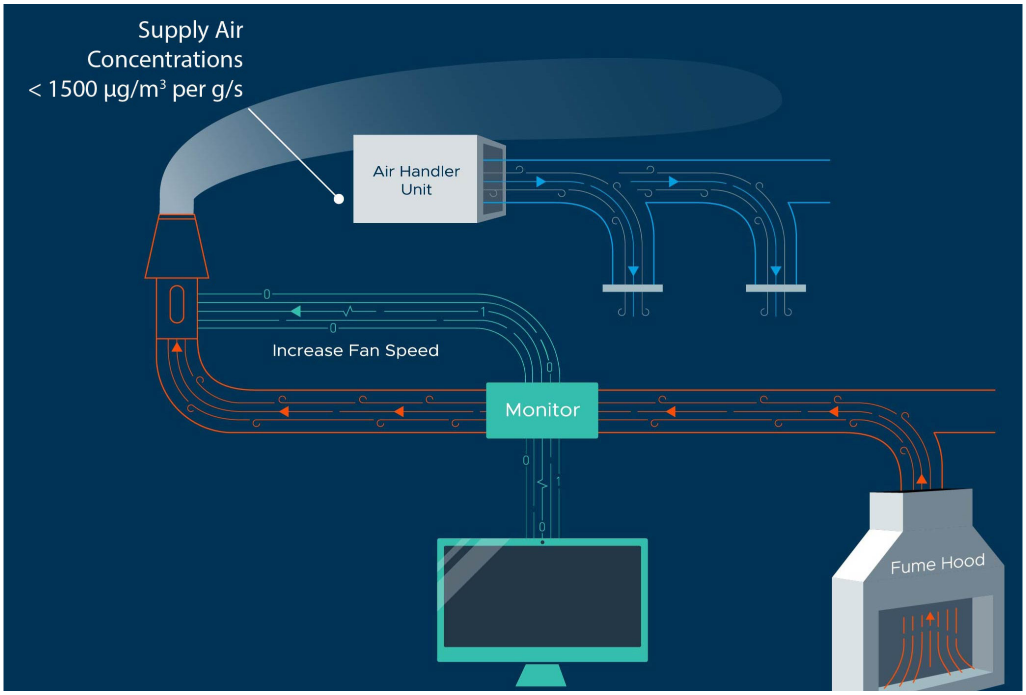



*Figure 9. Lower plume rise and higher intake concentrations are allowable when measured concentrations within the exhaust stream are below the monitored threshold value. (Note this does not necessarily mean the exhaust stream is "clean" of any contaminants, just that they are not detectable.)*

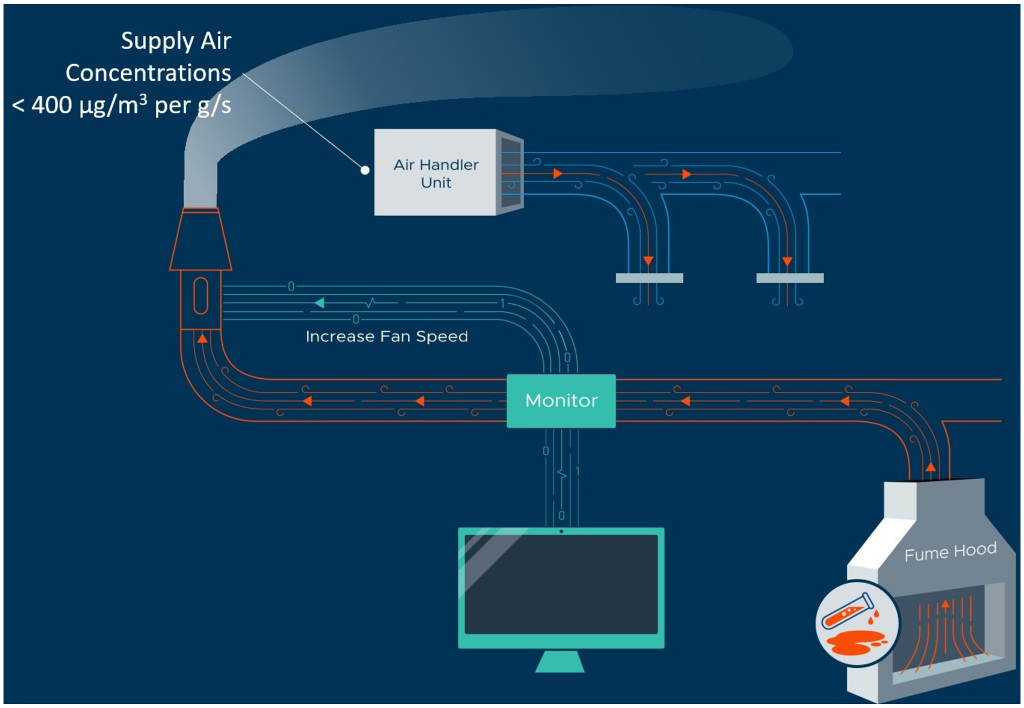



*Figure 10. When chemical concentrations in the exhaust stream are above the monitored threshold value, the exhaust volume flow rate is increased, creating greater plume rise and reducing downwind intake concentrations.*

will need to be administratively controlled to make sure that downwind concentrations remain below acceptable levels when the fans are operating at their minimum flow rate.

A critical part of any implementation of a monitored exhaust system should therefore include an inventory of allowable chemical usage. The emission rates of any chemicals that cannot be detected by the sensor suite should be limited to quantities that limit downwind concentrations to values below their health limit or odor threshold when the system is operating at the minimum volume flow rates when the contaminant trigger level is not exceeded. Similarly, chemicals that can be detected, but not at levels that would exceed the trigger value before exceeding their health limits and/or odor threshold downwind, should also be limited to make sure that downwind concentrations remain below their health limits and/or odor threshold when the contaminant trigger is not exceeded.

Figures 9 and 10 (page 22) provide an example where a design criterion of 1,500 mg/m$^3$ per g/s is applied as the maximum allowable downwind concentration when contaminants are below the trigger level and 400 mg/m$^3$ per g/s is applied as the design criterion when a contaminant is detected. As described above in the discussion of design criterion, the 1,500 mg/m$^3$ per g/s corresponds to the maximum allowable concentration at the manikin at the front of the fume hood defined by the ANSI Standard Z9.5 for the “as installed” configuration (ANSI/AIHA, 2012) during the ASHRAE Standard 110 containment test (ASHRAE, 2016). 400 mg/m$^3$ per g/s is the ASHRAE-recommended criterion for fume hood exhaust (ASHRAE, 2019); this limits the maximum downwind concentration to no more than roughly 25% of the concentrations at the front of the fume hood.

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) (Cochran & Sharp, 2008). This means that a typical monitored exhaust VAV control system may be able to operate at the lower volume flow rate setpoint more than 99% of the time, resulting in significant energy savings.

## Summary and Conclusions

An accurate assessment of exhaust dispersion can be used to produce exhaust/intake designs optimized for safety, comfort, and energy consumption. No matter what type of exhaust system is used, the most 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-flow 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 control 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 and proper reaction to any error codes.

## Key Questions for Exhaust/Intake Design

**Questions for the project team:**

- Where is the optimum placement of the exhaust stacks and air intakes?
- Can an exhaust manifold be utilized?
- Are induced-flow exhaust systems required, or will conventional, lower energy exhaust systems suffice?
- Is the site sufficiently complex to warrant a detailed wind tunnel modeling evaluation, or is a numerical dispersion assessment sufficient?
- Do laboratory exhausts have a high enough volume flow and exit velocity to disperse effectively?
- What type of control strategy is most appropriate based on stack height limitations, critical wind conditions, and potential chemical usage?

**Questions to ask when selecting a dispersion modeling consultant:**

- Does the method used predict concentrations or dilution at building air intakes and other sensitive locations?
- If conducting physical dispersion modeling, has an atmospheric dispersion comparability (ADC) assessment been conducted to properly commission the wind tunnel?
- If using CFD, is a transient solution being used, and, if so, will the results be validated with either a wind tunnel study or field assessment? (Steady-state CFD simulations should not be used for the final design.)
- Are allowable chemical emission rates included in the analysis?
- Does your method account for all wind conditions expected at the site?

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