
Nathan Ho

Performance-Based Approach to Laboratory Exhaust Systems

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Laboratory facilities serve as a critical nexus for innovation and discovery, but they often come with the potential for high operational cost (HVAC energy consumption) and high risk (air quality performance). A prescriptive approach to designing laboratory exhaust stacks has been common. It will likely have a place in the future based on the need for broadly applicable minimum design criteria that can be enforced consistently through code adoption and inspectors. However, achieving superior energy performance and acceptable air quality requires a performance-based approach to laboratory exhaust stack design.

Examples of Prescriptive Design Criteria

A performance approach begins with an understanding of the origins and limitations of prescriptive design criteria. Local code and recognized industry standards often serve as the basis of prescriptive criteria a designer would use to design a laboratory exhaust stack. Let us examine the California Mechanical Code, California Energy Code and the American National Standards Institute/American Industrial Hygiene Association Standard for Laboratory Ventilation (ANSI/AIHA Z9.5) as examples.

2019 California Mechanical Code[1]

"502.2.2 Product Conveying Ducts. Ducts conveying explosive or flammable vapors, fumes or dusts shall terminate not less than 30 ft (9 m) from a property line, 10 ft (3 m) from openings into the building, 6 ft (2 m) from exterior walls or roofs, 30 ft (9 m) from combustible walls or openings into the building that are in the direction of the exhaust discharge and ***10 ft (3 m) above adjoining grade***. (Emphasis is the author's.)

Other product-conveying outlets shall terminate not less than 10 ft (3 m) from a property line, 3 ft (914 mm) from exterior walls or roofs, 10 ft (3 m) from openings into the building and ***10 ft (3 m) above adjoining grade***." (Emphasis is the author's.)

2019 California Energy Code[2]

"140.9 (c) Prescriptive Requirements for Covered Processes, Prescriptive Requirements for Laboratory and Factory Exhaust Systems.

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3. Fan System Power Consumption. All newly installed fan exhaust systems serving a laboratory or factory greater than 10,000 cfm (4719 L/s) shall meet subsection A and either B, C or D:

A. System shall meet all discharge requirements in ANSI Z9.5-2012." (Emphasis is the author's.)

ANSI/AIHA Z9.5-2012, Laboratory Ventilation[3]

"5.4.6 Exhaust Stack Discharge. In any event the discharge shall be a minimum of 10 ft (3 m) above adjacent roof lines and air intakes and in a vertical up direction.

Exhaust stack discharge velocity shall be at least ***3,000 ft per minute (fpm) (15.2 m/s)*** [emphasis is the author's] unless it can be demonstrated that a specific design meets the dilution criteria necessary to reduce the concentration of hazardous materials in the exhaust to safe levels at all potential receptors.

The air intake or exhaust grilles shall not be located within the architectural screen or mask unless it is demonstrated to be acceptable."

A relationship exists between codes and standards. Often, codes are mostly sections of existing industry standards with modifications made by the authority having jurisdiction. Therefore, to identify the design parameters to address with a performance approach to laboratory exhaust stack design, it is necessary to understand the context and limitations of the referenced standard. It is also essential to keep in mind that the prescriptive criteria for stack height and exit velocity have substantial disclaimers, such as the one in Appendix 3 of ANSI/AIHA Z9.5-2012.

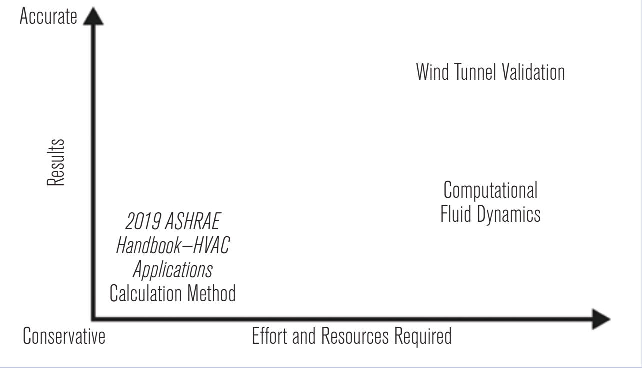
ANSI/AIHA Z9.5-2012 Appendix 3, Selecting Laboratory Stack Designs[3]

"The 10 ft (3.05 m) minimum stack height called for in the body of this standard is primarily intended to protect maintenance workers from direct contamination from the top of the stack. However, the minimum height of ***10 ft (3.05 m) is not enough by itself to guarantee that harmful contaminants would not be re-ingested***. (Emphasis is the author's.)

Similarly, a minimum 3,000 fpm (15.3 m/s) exit velocity is specified in the body of this standard, but ***this exit velocity does not guarantee that re-ingestion will not occur.***" (Emphasis is the author's.)

It has been the author's experience that stack height, exhaust plume exit momentum and physical location with respect to building massing, site topography and areas sensitive to air quality, such as outdoor air intakes, operable windows and populated areas, are critical variables that must be evaluated holistically to achieve optimum design outcomes.

FIGURE 1 Results vs. effort qualitative comparison of analysis methods.

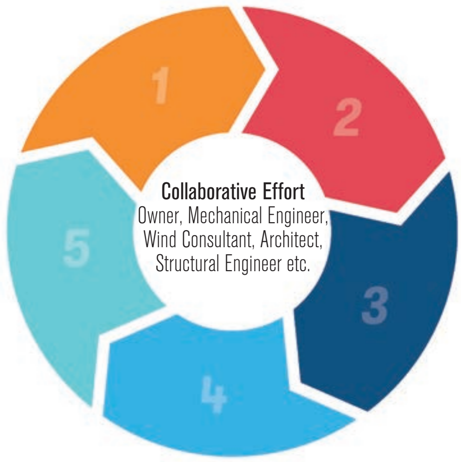


Many laboratory projects are developed as renovations; as such, the site topography and areas sensitive to air quality are typically fixed variables, and the options of locations to install the laboratory exhaust systems are often limited. Therefore, stack height and exit momentum are usually the remaining variables a design team can explore and evaluate. This column presents a basic framework for a design process and a case study highlighting the results of this process when applied to a laboratory renovation project.

Figure 1 presents three conventional methods to evaluate laboratory exhaust plume dispersion performance and qualitatively ranks what a designer can anticipate concerning the accuracy vs. effort trade-off between each method. The designer should exercise extreme caution when using computational fluid dynamics (CFD) to model exhaust plumes for laboratory pollutant sources, as CFD models can both over- and underpredict concentration levels by orders of magnitude, leading to potentially unsafe designs.[4] The author agrees with the *2019 ASHRAE Handbook—HVAC Applications*, Chapter 46 recommendation to use a wind-tunnel analysis to validate the results from a CFD analysis.

Figure 2 describes a process this author has used to collaborate with design team stakeholders to achieve optimum laboratory exhaust system design based on the project priorities and values. Step 5 is optional, but recommended by the author to achieve optimum design results; wind tunnel validation can yield substantially more accurate performance results with higher confidence than computational modeling or manual calculation results. The following case study is an example of how all five steps of the collaborative design process were used on a project.

FIGURE 2 Collaborative design input cycle to optimize design of lab exhaust system.



① Identify primary design variables and objectives.

② Collaborate with owner and design team to determine project priorities to optimize balance between variables. Develop early design concept based on this input.

③ Perform preliminary analysis of design concept performance based on the *2019 ASHRAE Handbook—HVAC Applications*, Chapter 46 Calculation Method or Computational Analysis. If preliminary results are not compatible with project requirements, return to Step 2 and iterate as necessary.

④ Produce detailed design layout and evaluate constructibility.

⑤ Confirm feasibility of design concept and execute wind tunnel validation of performance. Use results to finalize hardware and controls design. Iterate process as necessary to achieve optimum project solution.

Case Study—Institutional Research Laboratory in Southern California: Prescriptive vs. Performance Design

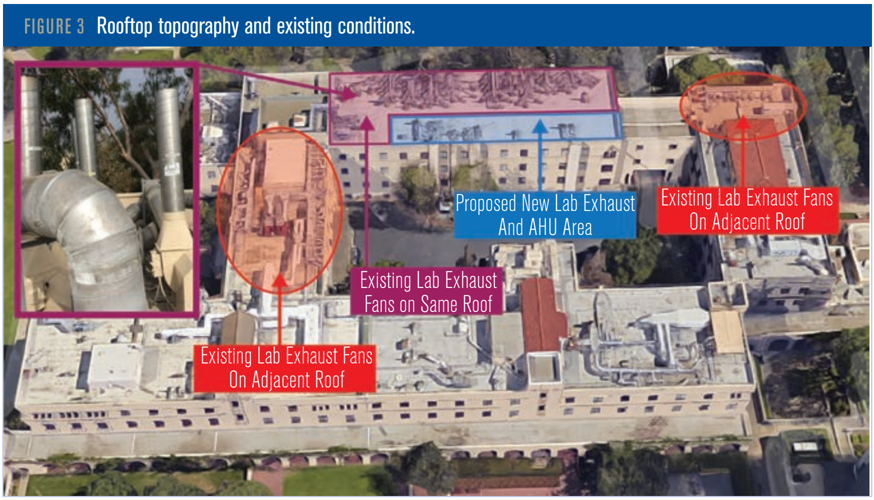
A research-focused higher education institution set out to renovate a historic building to provide a modern laboratory facility for a newly recruited principal investigator and her team. Given the potential for growth of the research, the laboratory program required a highly flexible HVAC system that could provide stable, responsive and reliable operation on day one, while also being capable of supporting rapid growth. This institution decided to use a design-build delivery to mitigate potential construction budget and schedule risks and provided the criteria as part of the bridging documents (*Table 1*).

The university requested a wind study to inform the design of the HVAC system and provide the university with metrics on air quality to mitigate the risk of odor or air quality concerns. The wisdom of this decision became immediately apparent upon inspection of the project site shown in *Figure 3*.

TABLE 1 Project background information and owner design criteria.

PROJECT BACKGROUND INFORMATION	UNIVERSITY DESIGN CRITERIA
1954 five-story building with three stories above grade.	Centralized laboratory exhaust system.
Continuously renovated to suit changing research needs.	*N* + 1 fan redundancy, minimum three fans total.
Organic addition of fume hoods over time.	Motorized isolation dampers and backdraft dampers.
New lab renovation requires additional lab exhaust infrastructure and new rooftop air-handling unit.	Perform study of wind and air quality conditions to inform design of laboratory exhaust stacks and rooftop air-handling unit outdoor air intake.

FIGURE 3 Rooftop topography and existing conditions.



A typical first cost vs. energy efficiency discussion took place within the design-build team. Our team agreed to compare a code-driven prescriptive lab exhaust design to a performance laboratory exhaust design (*Table 2*). The code-driven prescriptive lab exhaust design uses bypass air to enable variable air volume (VAV) laboratory ventilation controls within the building while maintaining a constant volume discharge.

The performance laboratory exhaust design is capable of eliminating bypass air and achieving VAV discharge to minimize exhaust fan energy consumption along with reduced sound power, operational complexity and wear on fan bearings. See *Figures 4* and *5* for screen shots of our model for the prescriptive exhaust system design option

TABLE 2 Exhaust system design features: prescriptive vs. performance.

PRESCRIPTIVE EXHAUST SYSTEM FEATURES	PERFORMANCE EXHAUST SYSTEM FEATURES
Separate exhaust stacks terminating at 10 ft above the finished roof.	Clustered exhaust stacks terminating at 24 ft above the finished roof.
Discharge nozzles to achieve target exit velocity of 3,000 fpm.	No discharge nozzles on stacks to promote fully developed turbulent airflow profile at exit of stack.[a]
Bypass air to maintain constant discharge air volume at the exit of each stack.	No bypass air.
"Hidden" outdoor air intake.	"Hidden" outdoor air intake.

[a] Many numerical distribution models use the Briggs plume rise formulas that were based on fully developed turbulent flow profiles at the stack exit.[5] It has been speculated that using a nozzle on the discharge of the stack could compromise the stack's ability to achieve fully developed turbulent flow profiles at their point of discharge.

FIGURE 4 Prescriptive exhaust system design concept, viewed from the south.

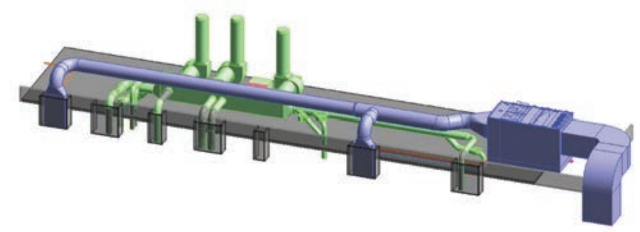


FIGURE 5 Prescriptive exhaust system design concept, viewed from the north.

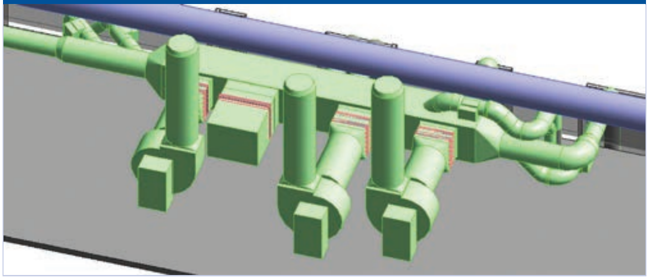


FIGURE 6 Performance exhaust system design concept, viewed from the south.

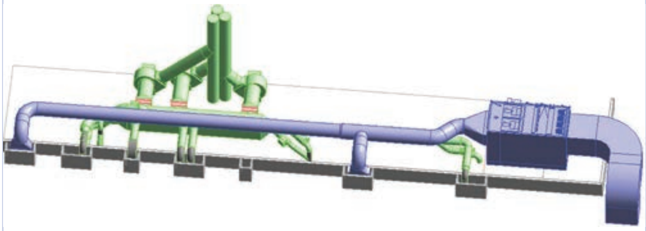
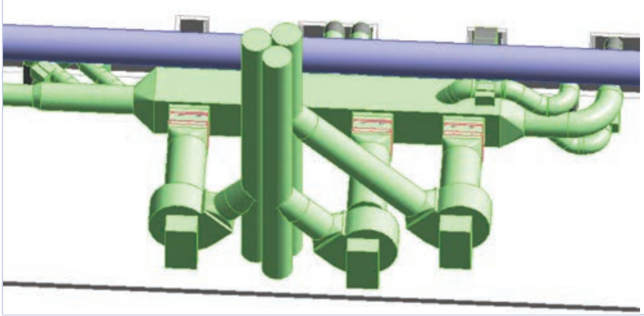


FIGURE 7 Performance exhaust system design concept, viewed from the north.



and *Figures 6* and *7* for the performance exhaust system design option.

Visual inspection of the existing rooftop conditions suggested that existing-to-remain nearby laboratory exhaust fans may render the rooftop air unsuitable as a source of outdoor air for the new air-handling unit. Therefore, our team decided to "hide" the outdoor air intake from the existing rooftop exhaust fans to passively enhance the air quality of the outdoor air brought in through the air-handling unit. Per the *2019 ASHRAE Handbook—HVAC Applications*,[4] a conservative dilution factor of 2.0 may be anticipated when the air intake is "hidden" from the line of sight of an emissions source. To provide an objective analysis of exhaust stack design, the air-handling unit outdoor air intake was kept identical in both design options evaluated.

The prescriptive-based and performance-based exhaust stack design options were both located as far from the roof edge as practical to minimize the effects of the wake zone formed by wind passing over the edge of the roof. Exhaust stacks that terminate within the "recirculation region" of a wake zone will tend to require substantially more power for their exhaust plume to escape the roof (*Figure 8*).

Laboratory exhaust plume dispersion performance tends to be strongly influenced by stack height and the momentum of the exhaust stream exiting the stack. Discussions with the facility owner confirmed that a maximum stack height of 24 ft (7 m) above the roof was aesthetically acceptable. So our team used this height to minimize the exhaust stream momentum required to achieve adequate exhaust contaminant dilution. Our team then applied the knowledge gained from ASHRAE research project RP-1167, "The Effect of Ganging on Pollutant Dispersion from Building Exhaust Stacks," to passively enhance the exhaust plume momentum by clustering the exhaust stacks. Per ASHRAE RP-1167, terminating stacks within a range of ~1.3 diameters of the stack centerline with similar discharge velocities from multiple active stacks will yield conditions where the plume from each active stack will tend to merge, combining momentum.[6]

The laboratory exhaust airflow demand profile in *Table 3* was determined for this project and used as the basis for the project's wind study. These parameters are essential because they establish upper and lower boundaries on the laboratory exhaust system operation for analysis. Designers can eliminate bypass air if the volumetric airflow rate for acceptable plume dilution is less than the absolute minimum volumetric airflow rate required by the laboratory exhaust system as determined by the wind-tunnel analysis (*Table 3*).

FIGURE 8 Figure 6, "Design Procedure for Required Stack Height to Avoid Contamination," from Chapter 46 of the *2019 ASHRAE Handbook—HVAC Applications*.[4]

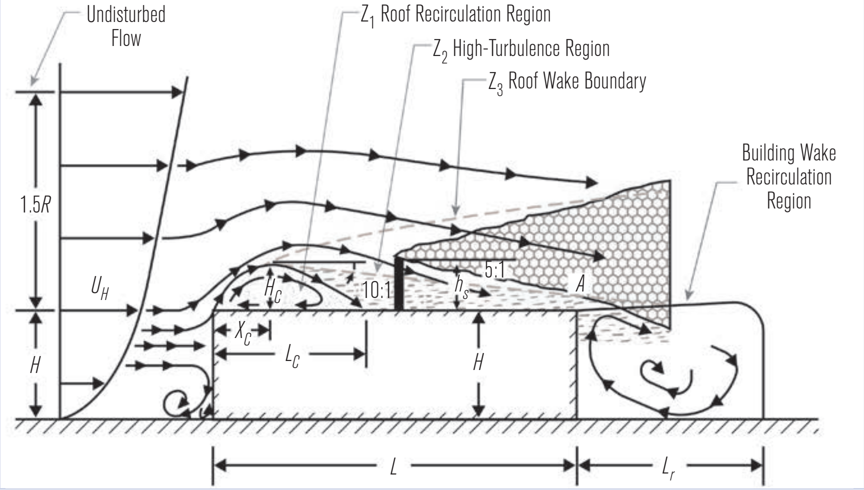


TABLE 3 Facility exhaust airflow demands for various operational scenarios.

OPERATIONAL SCENARIO	MIN. EA FLOW	MAX. EA FLOW
Day 1	10,060 cfm	13,125 cfm
Day 1 + Shell Spaces	11,455 cfm	17,300 cfm
Day 1 + Shell Spaces + Spare Capacity[a]	11,455 cfm	26,000 cfm

[a] Total overall system capacity provided is 39,000 cfm including redundant fan.

Wind Tunnel Analysis Results

The owner's design requirement stipulated that the laboratory exhaust system shall use a minimum of three fans with an operational redundancy of $N + 1$; N is the number of fans required to meet the design load. Our design team determined that a capacity of 26,000 cfm (12 271 L/s) was needed to meet the demand of the project. Therefore, a laboratory exhaust system composed of three 13,000 cfm (6136 L/s) capacity fans with individual exhaust stacks terminating at 10 ft (3 m) above the finished roof were studied under this option to represent an exhaust stack design that prescriptively complied with local code requirements.

Prescriptive Design Performance Observations

The *2019 ASHRAE Handbook—HVAC Applications*[4] publishes a general use laboratory exhaust dilution value of 400 µg/m^3 per g/s as an evaluation benchmark for locations sensitive to air quality. Our wind tunnel validation testing determined that a minimum exhaust stack exit velocity of 16,552 fpm (84.1 m/s) would be required to achieve this criterion at the outdoor air intake of the new air-handling unit. When compared to the commonly referenced prescriptive approach of 3,000 fpm (15.2 m/s) for exhaust stack exit velocity, these results highlight ANSI/AIHA Z9.5's disclaimer that the use of their prescriptive criteria does not guarantee that reingestion will not occur. Designers should carefully consider these disclaimers when applying broad, generalized rules for their applications.

For this project, a prescriptively designed exhaust stack would have operated with an exit velocity that is essentially an order of magnitude slower than the project conditions require to achieve acceptable dilution performance. The resultant air quality would have been significantly compromised using a prescriptive approach.

Our team then sought to determine at what height would an exit velocity of 3,000 fpm (15.2 m/s) yield our target dilution criteria. We discovered through additional wind tunnel testing that a 20 ft (6 m) stack would be needed, which is twice as tall as the minimum prescriptive criteria required by local code (*Figures 9* and *10*).

Evaluating the Impact of Stack Height and Volumetric Flow on Performance

The results from the single stack, single fan scenario show there is a strong correlation between stack height and associated minimum exit velocity to achieve acceptable exhaust plume dispersion performance (*Table 4*). This relationship has diminishing returns with the most significant potential reduction in minimum exit velocity achieved up to a height of 22 ft (6.7 m) and rapidly diminishing reductions beyond ~22 ft (6.7 m) for this specific project. While it has been the author's experience that this trend of diminishing returns is generally applicable, the height and rate of performance gains are particular to each project and should be evaluated for each project.

FIGURE 9 Single Fan Operation: Stack height vs. exit velocity required to achieve target dilution criteria.

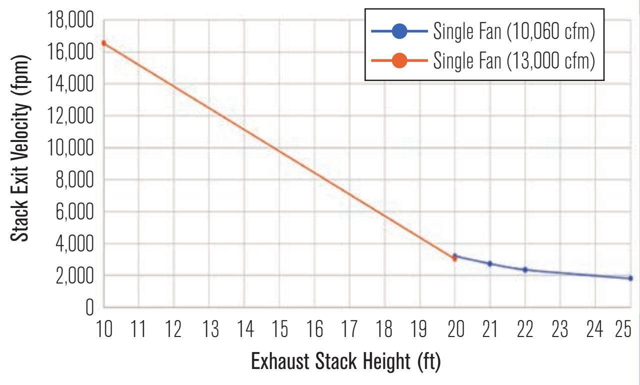
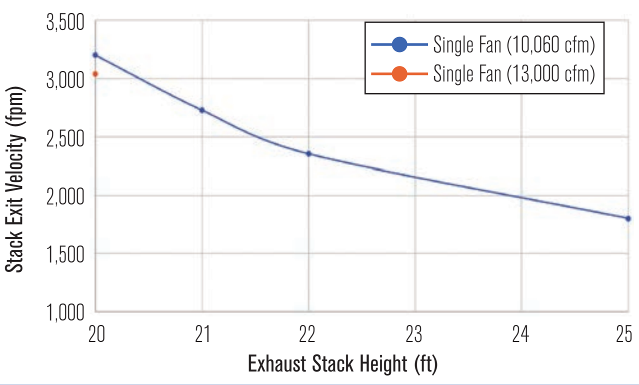


FIGURE 10 Single Fan Operation: Stack height vs. exit velocity required to achieve target dilution criteria (20+ ft height with higher *y-axis* resolution).



Airflow moving over the edge of a building tends to create a "wake zone" of turbulent airflow downstream of the building edge. Exhaust stacks that terminate within a wake zone experience a substantial exhaust plume dispersion performance penalty as the turbulent air will locally recirculate the exhaust plume back toward the surface of the roof. Significant exhaust plume momentum is required to overcome the forces exerted by the turbulent air within the wake zone. The single stack, single fan scenario results demonstrate the influence of the building wake zone. Lower stack heights within the wake zone recirculation region require significantly higher exit velocities than taller stack heights that terminate above the wake zone recirculation region.

While it may be possible to compensate for lower stack heights by increasing exhaust plume momentum through increased exit velocity, the designer will eventually need to consider increasing mass flow rate at the stack discharge. The stack discharge exit velocity tends to be practically limited to "near" 3,000 fpm (15.2 m/s) due to sound power emitted from the stack and fan power considerations. Both sound power and fan power tend to escalate quickly, as exhaust stack pressure drop is primarily a function of velocity squared. Our team tested adding 1,000 cfm (472 L/s) to the discharge flow rate to the 20 ft (6 m) stack scenario and found that increasing the flow rate from 13,000 cfm (6136 L/s) to 14,000 cfm (6607 L/s) decreased the minimum required exit velocity by a very modest 55 fpm (0.3 m/s) (*Table 5*).

TABLE 4 Stack height vs. reduction in exit velocity required to achieve target dilution criteria for a single stack in operation.

STACK HEIGHT	AVERAGE VELOCITY REDUCTION PER FOOT INCREASE	STACK EXIT AIRFLOW RATE
10 ft to 20 ft	1,351 fpm per ft	13,000 cfm
20 ft to 21 ft	474 fpm per ft	10,060 cfm
21 ft to 22 ft	375 fpm per ft	10,060 cfm
22 ft to 25 ft	184 fpm per ft	10,060 cfm

TABLE 5 Airflow rate increase vs. exit velocity reduction to achieve target dilution criteria for a single stack in operation.

STACK HEIGHT	AVERAGE VELOCITY REDUCTION PER 1,000 CFM INCREASE	STACK EXIT AIRFLOW RATE RANGE TESTED
20 ft	55 fpm per 1,000 cfm	13,000 to 14,000 cfm

Performance Design: Multiple Stack Operation

Our team's wind tunnel validation testing was able to quantify the benefit to plume dispersion performance that was achieved by clustering the exhaust stacks together (*Figure 11*). The data show that it is possible to achieve a reduction in volumetric airflow required at the exit of each stack when clustering stacks as a design strategy. In this case, two clustered stacks running at 6,250 cfm (2950 L/s) each with a stack height of 20 ft (6 m) require an exit velocity of 2,865 fpm (14.6 m/s) compared to the 3,040 fpm (15.4 m/s) needed for a single stack running at 13,000 cfm (6136 L/s) at the same stack height of 20 ft (6 m).

Our analysis of the two fans in operation scenario evaluated stack exit airflow rates of less than the Day 1 minimum airflow load to determine how low each stack could operate. This was used to inform the fan staging strategy to optimize fan power performance (*Figure 12*).

FIGURE 11 Clustered Stack Design: Stack height vs. discharge velocity with two fans running.

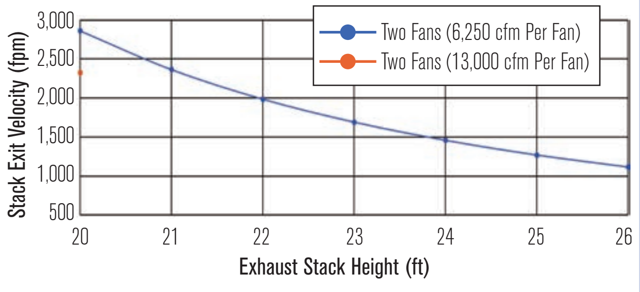
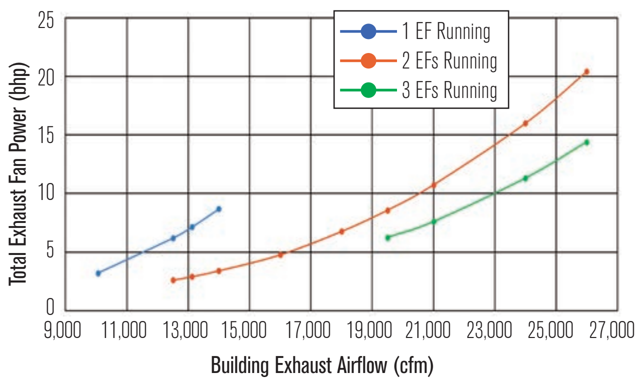


FIGURE 12 Exhaust system fan power.



We ran similar tests to evaluate the impact of increasing height and volumetric airflow rate on stack performance for the clustered stack design (*Tables 6* and *7*). Similar to the single stack scenario, raising the stack height yields a more significant impact on plume dispersion performance compared to increasing volumetric airflow rate.

Performance Design: Optimizing VAV Fan Power

With exhaust stack minimum airflow requirements established based on our wind tunnel validation testing, we were able to model the range of different exhaust fan operational scenarios to determine the aggregate system fan power required (*Figure 12*). Using these exhaust system power curves, we can decide on ideal staging points to stage up or down between the three fans provided in this system for energy efficiency and develop appropriate hysteresis to help promote stable system operation.

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TABLE 6 Stack height vs. reduction in exit velocity required for two clustered stacks in operation.

STACK HEIGHT	AVERAGE VELOCITY REDUCTION PER FOOT INCREASE	EXIT AIRFLOW RATE PER STACK
20 ft to 21 ft	497 fpm/ft	6,250 cfm
21 ft to 22 ft	379 fpm/ft	6,250 cfm
22 ft to 23 ft	294 fpm/ft	6,250 cfm
23 ft to 24 ft	233 fpm/ft	6,250 cfm
24 ft to 25 ft	189 fpm/ft	6,250 cfm
25 ft to 26 ft	154 fpm/ft	6,250 cfm

TABLE 7 Airflow rate increase vs. exit velocity reduction for two clustered stacks in operation.

STACK HEIGHT	AVERAGE VELOCITY REDUCTION PER 1,000 CFM INCREASE	STACK EXIT AIRFLOW RATE RANGE TESTED
20 ft	80 fpm per 1,000 cfm	6,250 to 13,000 cfm

TABLE 8 Prescriptive vs. performance design results summary.

PRESCRIPTIVE EXHAUST SYSTEM RESULTS	PERFORMANCE EXHAUST SYSTEM RESULTS
10 ft stack height.	24 ft stack height.
16,552 fpm minimum exit velocity required per stack when in use.	2,049 fpm minimum exit velocity required for single-stack operation.
13,000 cfm minimum volumetric airflow rate required per fan when in use.	1,462 fpm minimum exit velocity required per stack for two-stack operation; less if all three stacks are running in parallel.
	10,060 cfm minimum volumetric airflow rate required for single stack operation.
	6,250 cfm minimum volumetric airflow rate required for two-stack operation; less if all three stacks are running in parallel.

Prescriptive vs. Performance Design Results Summary

Table 8 summarizes the final results between the prescriptive vs. performance-based approach design options for the project evaluated within this case study. *Figures 13* and *14* show images from the performance-based approach design option installed.

Conclusions

A laboratory exhaust system prescriptive-based design approach does not yield consistent results across different applications and could result in higher contaminant concentrations than are acceptable. Using a performance-based design approach will give greater confidence in achieving higher performance and acceptable air quality. Laboratory exhaust system performance targets can be quantified and achieved through design team collaboration and modeling of stack dispersion performance with the performance-based approach. Design strategies using taller stack heights and clustering exhaust stacks can result in substantial improvement of laboratory exhaust dilution performance.

FIGURE 13 Performance exhaust stack design installed.

FIGURE 14 Close-up of cluster stack from performance design option installed

References

1. IAPMO. 2019. "2019 California Mechanical Code."
2. ICC. 2019. "2019 California Energy Code."
3. ANSI/AIHA/ASSP Z9.5-2012, *Laboratory Ventilation*.
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