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Design Guidelines for Laboratory Exhaust Fans and Stacks

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ABSTRACT

In this paper, design guidelines are presented for laboratory exhaust fans and stacks based on the contractor's installed experience in the field.

INTRODUCTION

The lifeline of every laboratory ventilation system is the exhaust fan. With a working laboratory exhaust fan, removal of hazardous chemicals and biohazards in the building can be accomplished even after failure of the supply fan with sufficient infiltration. This paper presents tried and true design guidelines based on decades of maintenance and operating experience with hundreds of laboratory buildings.

REDUNDANCY AND RELIABILITY

Although not usually required by local codes, the greatest degree of reliability would be to place the laboratory exhaust fans on emergency power. If the exhaust fans are placed on emergency power, splitting the exhaust capacity into more fans with lower horsepower would mean a lower in-rush current as each fan is started.

Greater reliability is achieved by having each exhaust fan system consist of a minimum of two or more exhaust fans. This ensures that at least some exhaust capacity will be available if one fan fails. Maximum safety is achieved with 100% redundancy but at a large cost penalty. This redundancy would mean having the same number and size of backup fans as there were active fans. Sufficient reliability is often achieved by having N+1 redundancy, but also at a first cost penalty. For example, two fans operating and one standby would be N+1 redundancy. Four fans operating and one fan standby would also be N +1 redundancy. N + 1 redundancy allows one of the active fans to fail and still be completely backed up. However, two fans failing simultaneously would lead to reduced exhaust fan system capacity.

If 100% redundancy or N+1 redundancy imposes too large a first cost penalty, the recommended multiple fans on each system should be slightly oversized so that as much capacity is retained in the system as possible when one of the fans fails. This oversizing will also give some allowance for future expansion, which is quite common over time in laboratory exhaust systems. Having all fans in continuous operation avoids keeping bearings lubricated when on backup and on rotating fans.

If the exhaust fans are equipped with variable-frequency drives, the service factor of the fan motor can be used to overspeed the remaining fans after one of the fans has failed. However, care should be taken not to over-amp beyond the service factor of the drive, which is usually less than the service factor of the motor. (Rotation of lead and backup fans on a weekly basis helps keep fans in working order if the system is staged for 100% redundancy.)

INDIVIDUAL FAN PER LABORATORY HOOD VS. MANIFOLDING

The ANSI/AIHA Z9.5 committee (AIHA 1992) reached a consensus that manifolding fume hood exhausts was safer in almost every case when compared with one individual fan per laboratory hood because the manifolded system achieves greater dilution. An individual fan per fume hood is acceptable. However, with one fan per fume hood there is no exhaust if a fan fails and it is more costly to apply heat recovery or vari-

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able-air-volume (VAV) controls. An individual fan per hood is also generally used for hazards requiring special filtration or decontamination procedures such as perchloric acid and radioisotopes. Perchloric acid and radioisotope hoods are generally not candidates for heat recovery or variable-volume controls.

SELECTING LABORATORY EXHAUST FAN VOLUMES AND STACK HEIGHT

Necessary measures must be taken to protect the laboratory building and adjacent buildings from toxic fume blowback. Some state laws mandate a minimum 7 ft (2.13 m) laboratory exhaust stack above the roof. This is primarily intended to protect maintenance workers from direct contamination from the top of the stack. ANSI/AIHA Standard Z9.5 (AIHA 1992) calls for a 10 ft (3.05 m) laboratory exhaust stack for the same reason. However, these minimum heights are not enough by themselves to guarantee that harmful contaminants will not be blown back into the building's outside air intakes.

In addition, Standard Z9.5 recommends that exit velocities should not drop below 3,000 ft/min (15.24 m/s) or the minimum exit velocity necessary to throw contaminants away from the laboratory and surrounding buildings.

Chapter 15 of the *1997 ASHRAE Handbook—Fundamentals* (ASHRAE 1997) describes the geometric method. This method is most appropriate for use by laboratory building ventilation designers. When the laboratory building does not pass the geometric method of analysis, specialist consultants in airflow around buildings should be called in. These specialty consultants can use wind tunnel modeling or other computer or calculation methods to ensure that safe dilution levels have been achieved in the laboratory exhaust before it impacts any building outside air intakes or anyone's breathing zone.

The geometric method applies to rectangular buildings that do not have taller buildings, taller trees, or taller hills in the area adjacent to the laboratory building. Provided these conditions are met, the geometric method can be applied as follows:

- Calculate the length of the recirculation zone downwind of the building.
- Calculate the effective stack height due to throw and add it to the fan and stack height.
- Use a five-to-one downward slope for the stack plume from the height of the throw and make sure it does not impact any part of the downwind recirculation zone.

Geometric Stack Selection Example

A laboratory building is 100 ft wide, 200 ft long, and 60 ft high. The laboratory exhaust is manifolded into a two-fan system. Each fan is 10,000 cfm (283 m³/m). The two-fan system is located in the center of the roof. Calculate the combination of stack height, volume, and velocity that will satisfy the geometric method.

The length of the recirculation zone is as follows:

$$R = B_{small}^{0.67} \cdot B_{large}^{0.33} = 60\text{ ft }(18.3\text{ m})^{.67} \cdot 100\text{ ft }(30.5\text{ m})^{.33} = 71\text{ ft }(21.6\text{ m})$$

The exhaust fans must throw 100 ft (30.5 m) to the edge of the roof from the center of the roof plus an additional 71 ft (21.6 m) to clear the recirculation zone.

The plume is pushed downward at a five-to-one slope from the top part of its throw. The throw length of 171 ft (52 m) when divided by 5 gives 34.2 ft (10.4 m). This is the height of the fan and stack and the effective stack height or throw above the fan. If the fan and stack are 10 ft (3.05 m) high, meeting the minimum requirements of Standard Z9.5 (AIHA 1992), the effective stack height or throw must be 24.2 ft (7.38 m).

The equation for effective stack height from the ASHRAE Handbook (ASHRAE 1997) is

$$\text{Effective stack height, } h = 3 \times \text{stack diameter} \times \text{stack exit velocity}/1\%\text{ wind velocity}$$

Assuming a 15 mph (6.7 m/s) wind velocity and a minimum exit velocity of 3,000 ft/min (15.2 m/s), the existing fan gives only a 14 ft (4.27 m) effective stack height. Solving for the minimum volume with a 15 mph (6.7 m/s) wind velocity and a minimum exit velocity of 3,000 ft/min (15.2 m/s) gives a minimum volume of approximately 30,000 cfm (849 m^3/m). The 10,000 cfm (283 m^3/m) fan will need to be increased by an additional 20,000 cfm (566 m^3/m) to a total of 30,000 cfm (849 m^3/m) in order to satisfy the geometric method. This additional fan volume can be added to the fan at roof level with unconditioned outside air without upsetting the building pressurization and air balance.

Tables 1a through 2b provide additional information that can be used to calculate geometric examples for buildings of other size.

CAUTION IN USING EXHAUST FAN PENTHOUSES

Hitchings (1997) and Knutson (1997) have recently provided field data on the levels of chemical contaminants that can result from enclosing laboratory exhaust fans in penthouses. Hitchings (1997) recommends that laboratory exhaust fans be placed on the roof outside the buildings so that leakage does not pose a health risk to maintenance workers. Leakage was measured using tracer gas methods similar to *ANSI/ASHRAE 110-1995, Method of Testing Performance of Laboratory Fume Hoods*. Hitchings identified and measured the leakage sources to be the discharge flex connector, duct, fittings, fan housing, and fan shaft seal. The largest single contribution to the hazard was the flex connectors that leaked almost twice as much as the next biggest contaminant source. For an existing installation where moving the exhaust fans outside the penthouse might be costly, Hitchings recommends decreasing the leakage sources and increasing the penthouse ventilation.

Knutson (1997) measured leakage in a university chemistry building with 100 laboratory hoods. Individual exhaust fan stack heights had been increased along with stack exit

TABLE 1a

Length of Downstream Recirculation Zone (ft)*

Building Width or Length (ft)	Number of Stories (Building Height)						
	1 Story† (15)	2 Stories (30)	3 Stories (45)	4 Stories (60)	5 Stories (75)	6 Stories (90)	7 Stories (105)
50	22.3	35.5	46.6	53.1	57.2	60.7	63.9
75	25.5	40.6	53.3	64.6	75	79.7	83.8
100	28.1	44.6	58.6	71	82.5	93.2	101.6
150	29.8	51	67	81.2	94.3	106.5	118.1
200	29.8	56.10	73.6	89.3	103.7	117.1	129.9
250	29.8	59.60	79.2	96.1	111.6	126.1	139.8
300	29.8	59.6	84.2	102	118.5	133.9	148.5
500	29.8	59.6	89.4	119.2	140.3	158.5	175.7
1000	29.8	59.6	89.4	119.2	149	178.8	208.5

* Formula for table is: length of downstream recirculation zone is Bs^0.67 *BL^0.33 where Bs is smaller of height and width or length and BL is the larger of the two (ASHRAE 1997). Where BL is > 8 Bs, use BL = 8Bs.

† Each story is 15 ft high.

TABLE 1b

Length of Downstream Recirculation Zone (m)*

Building Width or Length (m)	Number of Stories (Building Height)						
	1 Story† (4.57)	2 Stories (9.14)	3 Stories (13.7)	4 Stories (18.3)	5 Stories (23)	6 Stories (27.4)	7 Stories (32)
15.2	6.8	10.8	14.2	16.2	17.4	18.5	19.5
22.9	7.8	12.4	16.2	19.7	22.9	24.3	25.5
30.5	8.6	13.6	17.9	21.6	25.1	28.4	31
45.7	9.1	15.6	20.4	24.7	28.7	32.5	36
61	9.1	17.1	22.4	27.2	31.6	35.7	39.6
76.2	9.1	18.2	24.2	29.3	34	38.4	42.6
91.4	9.1	18.2	25.7	31.1	36.1	40.8	45.3
152.4	9.1	18.2	27.2	36.3	42.8	48.3	53.6
304.8	9.1	18.2	27.2	36.3	45.4	54.5	63.6

* Formula for table is: length of downstream recirculation zone is Bs^0.67 *BL^0.33 where Bs is smaller of height and width or length and BL is the larger of the two (ASHRAE 1997). Where BL is > 8 Bs, use BL = 8Bs.

† Each story is 4.57 m high.

velocities in a remodeling project. Mitigation recommendations included increasing penthouse general ventilation to 8 air changes per hour, replacing duct with welded airtight duct, and replacing flex connectors. The cloth flex connector was replaced with a flexible molded rubber boot.

CAUTIONS WITH WEATHER CAPS, GOOSENECKS, AND FLAPPER DAMPERS

The *1995 ASHRAE Handbook—HVAC Applications* strongly recommends against the use of weather caps, goosenecks, or flapper dampers. These devices provide rain protection but are hazardous because they direct the contaminated flow down at the roof where it is a danger to maintenance workers.

PLENUM INLET FOR MULTIPLE FANS

For reliability purposes, laboratory exhaust fans should have two or more multiple fans on each fume hood manifold. These multiple fans should have a plenum inlet rather than a ducted inlet. This plenum inlet will help ensure that the fans will have the same inlet conditions so that they can be balanced properly.

TABLE 2a
Volume Necessary to Achieve Throw off Edge of Building and Recirculation Zone*

Distance from Fan to Edge of Recirculation Zone (ft)	Volume (cfm)
75	1267
100	5068
150	20272
200	45612
250	81088
300	126700

* Assume stack is 10 ft high and fan exit velocity is 3000 fpm with 15 mph wind speed.

TABLE 2b
Volume Necessary to Achieve Throw off Edge of Building and Recirculation Zone*

Distance from Fan to Edge of Recirculation Zone (m)	Volume m^3/s
22.9	0.6
30.5	2.39
45.7	9.56
61	21.5
76.2	38.2
91.4	59.8

* Assume stack is 3.05 m high and fan exit velocity is 15.2 m/s with 6.7 m/s wind speed.

PUSH-PULL FAN ARRANGEMENTS

Push-pull fan arrangements use a single fan for each fume hood duct, which exhausts into a common plenum served by several "pull" fans. This system has worked successfully in some cases, but it is difficult to apply. In the push-pull design, the push fans serve as a booster to reduce the pressure requirements of the pull fans. The push fans should be kept at or near the entrance to the pull fan plenum. Care must be exercised not to create too much turbulence into the plenum. The static pressure at the outlet from the push fan must be zero or slightly negative to ensure that barometric dampers are not blown in the reverse direction and that the pull fans are not overpowered. Such a condition could destroy the exhaust fan and/or burn out the fan motor due to overload.

Also, the designer must be careful that there are no lengths of positively pressurized duct in either the building, fan rooms, or penthouses. This positively pressurized duct after the push fan but before the pull fan can leak contaminants back into the building.

FANS USING A COMMON STACK

Multiple laboratory exhaust fans that use the same common stack have been used. They have the advantage of increasing the throw and effective stack height compared to each individual fan. However, it is difficult to design the piece that joins the fans into a common stack so all the fans can run in parallel.

SELF-SUPPORTED FAN STACKS WITH NO GUY WIRES

Lab exhaust fan stacks should be self-supported without guy wires and rated for 100 miles per hour or greater winds. Guy wires usually will rip the roof membrane if they are pulled out, which can allow water leaks into the building.

LEVEL INSTALLATION

Exhaust fan and motor mount must be level to prevent uneven belt wear.

DIRECT DRIVE INCREASES RELIABILITY WITH NO FAN BELTS

Since the laboratory exhaust fan's primary job is safety, increased reliability is desired. If a major component of the exhaust fan breaks or slips, building occupants may be endangered.

One major component liable to cause total failure of the fan is the fan belt. Standard Z9.5 calls for belt-operated laboratory exhaust fans to be stopped monthly, the belt guard removed, and the belt's tension checked. This frequent maintenance inspection is necessary because of the real danger of a fan belt breaking or stretching and causing fumes to back up into the laboratory. The total lack of flow after fan failure also causes the laboratory to become positively pressurized at the exact same time that the laboratory hood loses its ability to contain. The positive pressurization occurs in the laboratory if the supply air continues after exhaust fan failure. Fumes can then migrate readily from laboratory to nonlaboratory spaces such as offices, lobbies, and cafeterias.

FAILURE MODES

Common causes of belt-drive failures according to AMCA (1988a) Publication 202-88 include:

- Belt too loose. Adjust for belt stretching after 48 hours of operating.
- Belt too tight.
- Belt worn.
- Wrong belt length or cross section.
- Misaligned sheave.
- Belt oily or dirty.
- Belt cracks due to non-use (on backup fan) or from caustic or high-temperature atmosphere.

Some direct-drive laboratory exhaust fans have been operating more than 40 years without stopping. Continuous operation for multiple decades is not possible with belt-driven fans. Belt-driven fans also have an average energy penalty of 5% to 15% due to belt friction.

Similarly, reliability is increased when the fan motor is not in the contaminated airstream.

After belt failure, the next most common failure mode is bearing failure. Because laboratory exhausts usually operate continually for multiple year periods, bearing reliability needs to be increased. Fans with 40,000 hour rated bearings at L-50 need to be upgraded to 100,000 or 200,000 hour at L-50 bearing lives.

The use of direct drive eliminates two out of four bearings required by belt-drive fans and increases the life of the motor bearings by as much as five times by reducing radial loads. This significantly reduces the chance of failure.

An isolation/backdraft damper is a helpful option. In case of exhaust fan failure, this damper prevents reverse flow due to wind effects back down into the laboratory. For multiple-fan systems, this isolation damper may be a necessary ingredient so that fans can be shut down when not needed or to be maintained. On multiple-fan installation, if there is no isolation damper, the air can be short-circuited through the idle fan with roof air, preventing the fan system from reaching the desired level of exhaust volume from the building. This isolation damper should not be a gravity damper due to ineffective operation if the bearings corrode and become stuck in the corrosive exhaust airstream.

ELIMINATION OF SPRING ISOLATION AND FLEX CONNECTORS

Spring isolators can be eliminated with proper fan selection. A rule of thumb might be 0.5 mil (0.0127 mm) radial vibration at the blade pass. Axial vibration should be less than 50% of the radial vibration. Belt-driven fans require spring isolation to compensate for belt stretching and its associated rocking motion. The fan should be designed by the manufacturer for low vibration levels so as to make spring vibration isolation unnecessary. Similarly, flex connectors are not needed when the vibration level of the fan is minimized by the fan manufacturer. As previously discussed, flex connectors are a prime source of contaminant leakage. The average flex connector may fail within its first year of operation, causing frequent maintenance downtime and risk of exposure to maintenance personnel.

REDUCTION OF SYSTEM EFFECT AND EXCESS PRESSURE LOSS

AMCA Publication 200 (AMCA 1988b) on "Air Systems" cautions the users of centrifugal and axial fans to prevent system effects.

> Experience indicates that the range of tolerance that can be expected between calculated and actual system resistance can be ±30% under good conditions and may exceed 100% in some cases. The tendency is for the system resistance to be higher than anticipated because of the system effects that are not accounted for in the design.

In addition, the flex connectors used on centrifugal fans can have large unanticipated system effects if the material of the flex connector is twisted or indented.

Fan accessories need to be carefully designed so as to minimize excess pressure loss. It may be advisable to have the fan manufacturer be charged with the single source responsibility to design, test, and provide to the installing contractor both the fan inlet piece and the fan stack so as to make sure that these pieces do not cause excessive system effect when combined with the laboratory exhaust fan. This responsibility of designing and testing fan accessories would serve to level the playing field between fan manufacturers. Fans insensitive to inlet and outlet conditions could more cost-effectively be provided with inlet and outlet accessories. Sensitive fans would be penalized, and their true overall costs noted, by being forced to provide more expensive flow straighteners and other devices to decrease the total losses due to system effects.

VARIABLE-AIR-VOLUME CONSIDERATIONS

For utility cost savings, variable-air-volume systems are increasingly becoming the norm in laboratories. Substantial savings in conditioned air in the laboratory are possible, provided that the accuracy, reliability, and maintainability of the VAV controls is sufficient.

The important consideration for variable-air-volume laboratory exhausts is that exit velocities should not drop below 3,000 ft/min (15.24 m/s) or the minimum exit velocity necessary to throw contaminants away from the laboratory and surrounding buildings. With a single fan, the most common method is to employ a roof bypass damper. Raw roof air is admitted to the inlet of the fan in an inverse relationship to the building exhaust. As the building exhaust drops, the bypass air rises. This bypass damper is usually controlled by a static pressure sensor 66% of the hydraulic distance down the exhaust ductwork. Variable-frequency drives may also be used as long as the minimum speed does not allow the laboratory exhaust fan to drop below 3,000 ft/min (15.24 m/s) or the minimum exit velocity necessary to throw contaminants away from the laboratory. Another choice on larger manifolded systems is to have three or more fans and stage them on and off to provide the appropriate exhaust volumes. The bypass damper can be used with multiple-fan systems to vary the flow smoothly between staged units.

EXHAUST HEAT RECOVERY

Exhaust heat recovery for contaminated exhausts tends to be a long payback item because of unanticipated maintenance costs and fouling of the heat exchanger surfaces. Despite these maintenance costs, exhaust heat recovery is gaining in popularity. Crossover of chemical or biological contaminants between exhaust and supply must be prevented. The design engineer should conduct a maintenance study with impacts on first cost, energy cost, and operating cost to confirm the feasibility of using a recovery system.

SOUND CONSIDERATIONS

The high outlet velocities recommended by Standard Z9.5 (AIHA 1992) to blast toxic fumes away from the roof can cause high noise levels. However, unitized inlet and outlet silencers can be used on laboratory exhaust fans with little impact on the total system cost. While some engineers have specified packless silencers due to possible erosion of fiberglass, the units have a tendency to be costly and large in size. Therefore, they should be considered for use only where the installation location would be difficult to access for eventual replacement. Where silencers can be placed before and after the fan on the roof, the less costly packed silencers with caustic and weather resistant liners are recommended. Acoustical louvers on the bypass dampers may also be required. As a rule of thumb, the silencer should approximate the motor cost on a replacement basis and should be readily accessible for changeout.

DUCTWORK MATERIALS AND CONSTRUCTION

The scope of this paper does not allow space to discuss all the material and construction choices suitable for laboratory exhaust ductwork. Careful evaluation of the corrosive materials to be transported, their concentration, and temperature must be made by the owner and design engineer. The most commonly found duct material is type-316L stainless steel with all welded construction. For some chemicals, stainless steel does not have good resistance. Many designers have used a galvanized duct coated inside and out with 4 mil (0.102 mm) of PVC. Ductwork that is concealed in risers or otherwise inaccessible should have more corrosion resistance because of the difficulty of replacing it. Where first cost budgets are tight, ductwork exposed on the roof or easily accessible may be made of less costly materials because of the ease of replacement. In manifolded systems, because of the large amount of dilution, some designers have even used galvanized duct with well-mated flanges for the exposed roof ducts.

CONCLUSIONS

The design guidelines formed from practical experience for laboratory exhaust fans are as follows:

- Make sure that stack height and effective stack height combined are sufficient to carry hazardous fumes away from the building.
- Place laboratory exhaust fans on the roof outside of any penthouses.
- If exhaust fans cannot be placed outside penthouses, increase ventilation. Also, reduce leakage by improving flex connectors and minimizing leakage from ducts, fittings, and shaft seals.
- Use direct-drive fans, longer-life fan and motor bearings, and low vibration fans.

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