# An Introduction to Entrained Air Exhaust (High Plume Jet Fans) Systems

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## Learning Objectives

1. The Purpose of Exhaust Systems (Conventional & Entrained Air)
2. Design criteria for the Exhaust Systems (Conventional & Entrained Air)
3. What is an Entrained Air Exhaust (high plume jet fan system)
4. Test Standards for high plume jet fan system

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## Background

Many educational institutions/hospitals/research /chemical & electronic plant facilities use laboratories for teaching and research. Operating laboratory workstations present problems to owners and facilities managers that may include:

- issues of indoor air quality (IAQ)
- pollution abatement
- HVAC equipment/system acquisition and operating costs
- odor prevention
- roofline aesthetics

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## Background

There is a greater Public awareness of pollution

Increasing public concern over air pollution in general and because adverse exposure to air pollutants in the workplace can affect employee health and productivity.

In some cases, releases of toxic pollutants may lead to litigation.

**Design of exhaust stacks and air intakes requires careful consideration!**

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## Background

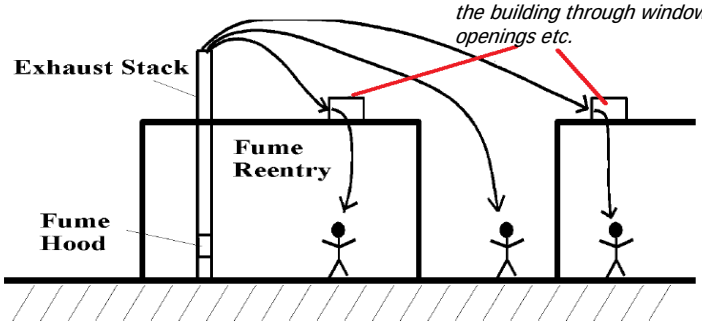



*Figure extracted from: Cochran, B., Petersen, R., & LeCompte, J. (2002). Specifying Exhaust Systems That Avoid Fume Reentry and Adverse Health Effects. ASHRAE Transactions, 108.*

If an exhaust stack is not properly designed, fumes from the exhaust may re-enter the building, or adjacent buildings, or impact pedestrians at unacceptable concentration levels.

To avoid re-entry, taller stacks, higher volume flows, and/or optimum locations on the roof may be necessary.

## Standards & Recommendations

Several organizations have published standards or recommendations regarding laboratory exhaust stack design.

These are summarized below.

1. Maintain a minimum stack height of 10 ft (3.0 m) to protect rooftop workers (NFPA 1996).

2. Locate intakes away from sources of outdoor contamination, such as mobile traffic, kitchen exhaust, streets, cooling towers, emergency generators, and plumbing vents (ASHRAE 1999).

3. Do not locate air intakes within the same architectural screen enclosure as contaminated exhaust outlets (ASHRAE 1999)

## - Continued

4. Locate the air intake at the base of a relatively tall stack or tight cluster of stacks, if this location is not adversely affected by exhaust from nearby buildings. Intakes should not be located near the base of highly toxic stacks due to potential fan leakage (ASHRAE 1999).

5. Avoid locating intakes near vehicle loading zones. Canopies over loading docks do not prevent hot vehicle exhaust from rising up to intakes above the canopy (ASHRAE 1999).

6. Use high-efficiency particulate air (HEPA) filters or ultraviolet germicidal irradiation (UVGI) systems of similar efficiency in isolation room exhaust streams (CDC 1994).

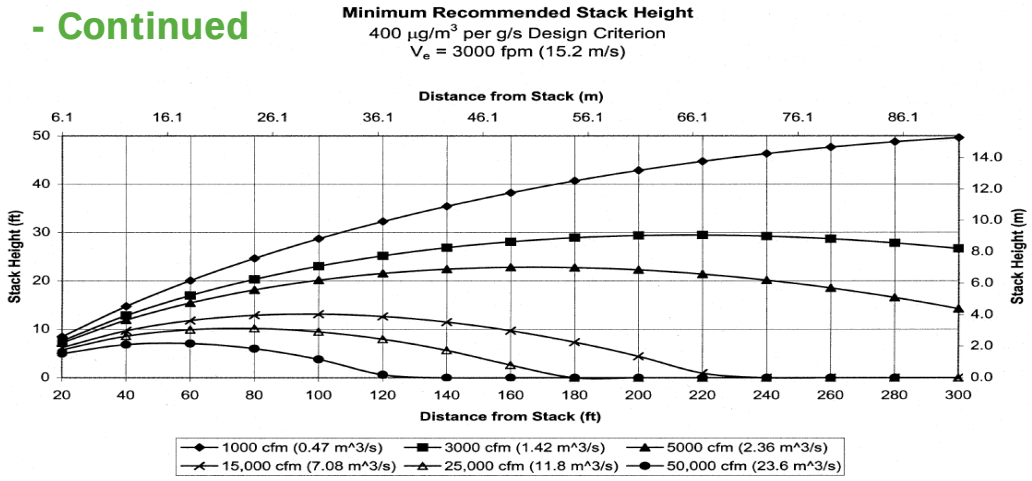
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7. Combine several exhaust streams internally to dilute intermittent bursts of contamination from a single source as well as producing an exhaust with greater plume rise. Additional air volume may also be added to the exhaust at the fan to achieve the same end (ASHRAE 1999).

8. Group separate stacks together (where separate exhaust systems are mandated) in a tight cluster to take advantage of the increased plume rise from the resulting combined jet (ASHRAE 1999). Note that all the exhausts must operate continuously to take full advantage of the combined jet.

9. Avoid rain caps or other devices that limit plume rise on exhaust stacks. Conical rain caps often do not exclude rain because rain does not fall straight down. Alternative design options are provided in chapter 43 of the ASHRAE Handbook— HVAC Applications (ASHRAE 1999).

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*Minimum stack heights for rooftop air intakes based on the ASHRAE criteria*

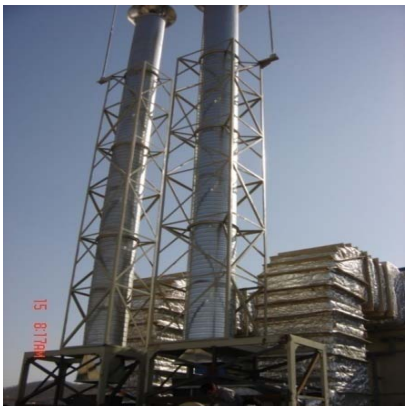
Lower stack heights can be realized through increasing the volume flow rate while keeping the exit velocity constant at 3000 fpm (15 m/s).

## Conventional vs Entrained Air Exhaust

### Entrained Air Exhaust Approach



### Conventional Air Exhaust Approach



## Plume rise

$h_e = hr + hs$

$h_e = [3.0 \times V \times d/U] + h_s$

*(From ASHRAE Laboratory Design Guide, Equation 9-2)*

$h_e$ = effective stack height [m]

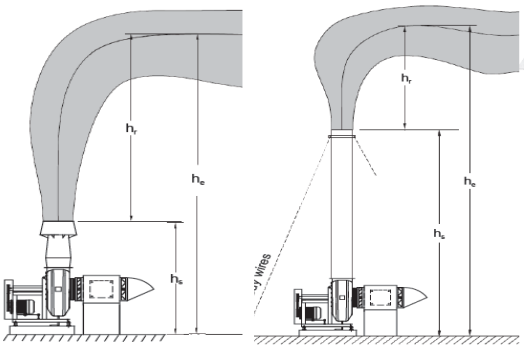
$h_s$ = equipment height

$h_r$ = plume rise [m]

V = stack discharge velocity [m/s]

d = effective stack diameter [m]

U = cross wind velocity [m/s]

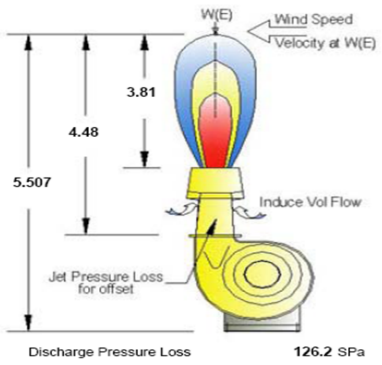



- important for escaping the high turbulence and recirculation zones on the building roof.
- increases with increased exit momentum and decreases with increased wind speed (Briggs 1969).
- ↓ diameter to ↑ exit velocity will ↑ plume rise.
- However, a high exit velocity in itself does not guarantee adequate plume rise since the volume flow rate, and thus momentum, are factors as well.
- Plume rise is also reduced by increased atmospheric turbulence since the vertical momentum of the exhaust jet is more quickly diluted.

## Sample Selection

**Fume Jet Fan Selection**

| | |
|---|---|
| **Input** | |
| Volume | 0.4 m3/s |
| Fan static | 500 Pa |
| Fan size | Chem 315 |
| Wind speed at W(E) | 10 Mile/hrs |
| **Jet Performance** | |
| Eff Dispersion at Jet Outlet(L(B)) | 3.81 m |
| Fume Jet Height | 0.664 m |
| Eff Dispersion Ht at Fan Outlet(PH) | 4.48 m |
| Eff Dispersion Ht at Fan Base(TH) | 5.507 m |
| Induce Draft Exhaust Flow Vol | 2880 m/hrs |
| Discharge Pressure Loss | 126.2 SPa |
| New Fan Actual Static Pa Required: | 626.2 SPa |



## Some challenges to good design for both conventional & entrained air exhaust systems

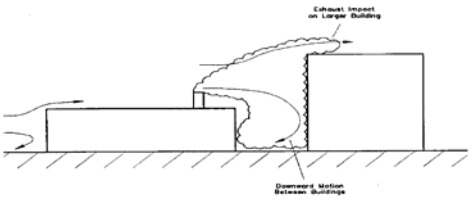
**Topography of surrounding terrain** – affects wind profile gradient (e.g. level rural areas typically experience higher winds at lower elevations than urban areas)

**Meteorology Conditions** – Wind influence direction & discharge of plume, create wake areas that greatly reduce plume height & in some cases trap the plume

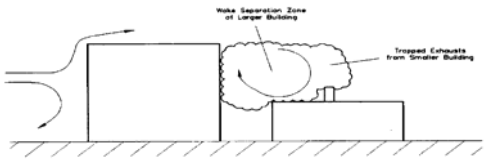
**Atmospheric stability**, **temperature gradients & local turbulence** – strong stable atmosphere creates a boundary layer, or inversion which keep exhaust plume from penetrating the atmosphere or instead direct it back towards the exhaust point.

## - Continued

**Existing Building Environment** – presents a challenge when building heights vary significantly. If a new laboratory building is being designed that is shorter than surrounding buildings, it will be difficult to design a stack such that the exhaust will not impact neighboring buildings.




*Plume impact on taller downwind building*




*Plume impact on taller upwind building*

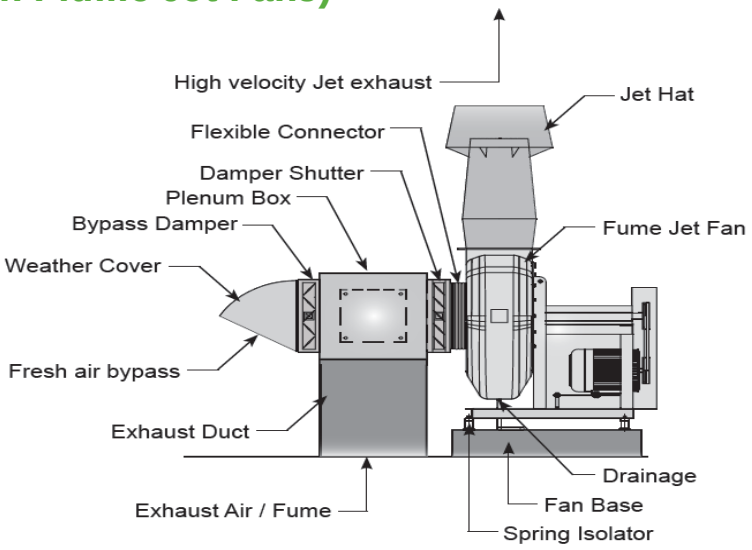
*Figures extracted from: Cochran, B., Petersen, R., & LeCompte, J. (2002). Specifying Exhaust Systems That Avoid Fume Reentry and Adverse Health Effects. ASHRAE Transactions, 108.*

## Contraints on Good design

- The minimum stack height is desired for aesthetics and cost effectiveness.
- The exit momentum (exit velocity and volume flow rate) is restricted by capital and energy costs, noise, & vibration.
- Design becomes a balance between these constraints and obtaining adequate air quality at surrounding receptors (air intakes, plazas, operable windows, etc.)

To determine the optimal exhaust design, predictions of the expected concentrations of pollutants in the exhaust stream at air intakes and other sensitive locations are needed to compare with local health limits and odor thresholds.

## Components of Entrained Air Exhaust System (High Plume Jet Fans)



## Key Terms

**Bypass Air ($Q_B$)**
Ambient air that is drawn through the bypass air plenum and mixed with the lab exhaust to increase dilution and plume rise. Bypass air is primarily used in variable volume applications to maintain a constant discharge volume but can also be used to increase overall exhaust volume and dilution.

**Dilution Ratio (D.R.)**
The ratio of the total fan outlet volume to the lab exhaust volume. (Total Volume/Lab Exhaust Air Volume). Value includes any additional bypass air in the calculation.

Dilution Ratio = D.R. = $Q_T$ / $Q_L$

Entrainment Ratio = E.R. = $Q_T$ / $Q_F$

$Q_B$ = Bypass Flow

$Q_E$ = Entrained Flow

$Q_F$ = Fan Flow

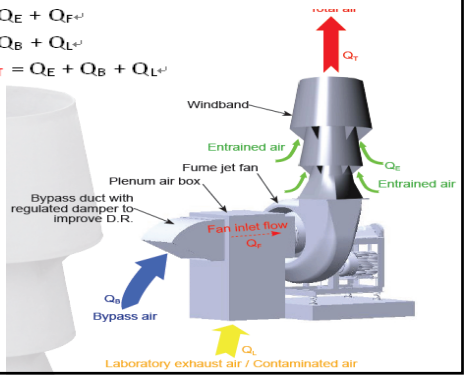
$Q_L$ = Laboratory Flow (Conta

$Q_T$ = Total Flow

$Q_T = Q_E + Q_F$

$Q_F = Q_B + Q_L$

$\therefore Q_T = Q_E + Q_B + Q_L$




## Key Terms

**Entrainment Air ($Q_E$)**
Air that is entrained (induced flow) through the windband and fan housing, mixed with the laboratory exhaust to increase the dilution ratio and plume rise.

**Entrainment Ratio (E.R.)**
The ratio of the total fan outlet volume to the fan inlet volume. (Total Volume/Fan Inlet Volume)

**Total Airflow ($Q_T$)**
The total airflow exiting the windband, including fume exhaust, bypass air, and entrainment air.

Dilution Ratio = D.R. = $Q_T$ / $Q_L$

Entrainment Ratio = E.R. = $Q_T$ / $Q_F$

$Q_B$ = Bypass Flow

$Q_E$ = Entrained Flow

$Q_F$ = Fan Flow

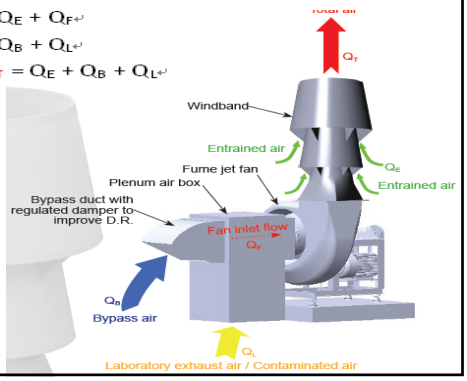
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$Q_T = Q_E + Q_F$

$Q_F = Q_B + Q_L$

$\therefore Q_T = Q_E + Q_B + Q_L$



## What is Dilution ?

**Indirect Dilution** – Occurs when plume of air leaving the exhaust fan is dispersed and diluted by the atmosphere before it reaches the property line, air intakes to ventilation systems, doors or windows, pedestrian walkways or other inhabited areas.

**Direct Dilution** – Achieved directly by diluting exhaust stream before it leaves the fan.

Most effective when diluted airstream is projected upward at velocities in excess of 3,000 ft/min (min. specified by ANSI Z9.5 standard for laboratory ventilation)

**Dilution eliminates the perception of odor!**

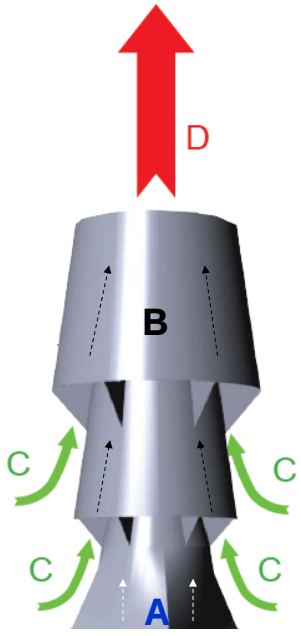
## Dilution Principle

**A)** Diluted process air is accelerated through a discharge nozzle/windband

**B)** Nearly twice as much additional fresh air is drawn into the exhaust plume before leaving the fan assembly

**C)** The Windband creates a protective envelope around the emerging discharge plume and keeps the surrounding air stationary to improve entrainment

**D)** Combination of added mass and high discharge velocity minimises the risk of contaminated exhaust being re-entrained into building's air intakes, doors or other openings



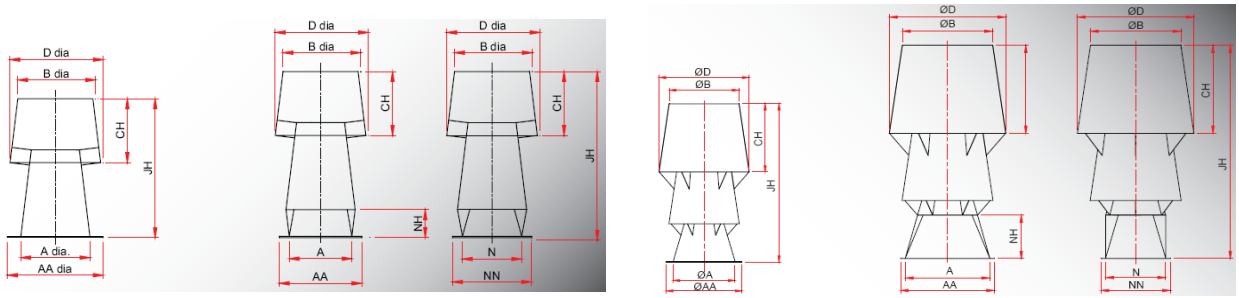
## Entrained Air Exhaust System – Additional Considerations

**Key design parameters that must be optimised to ensure effective operation:**

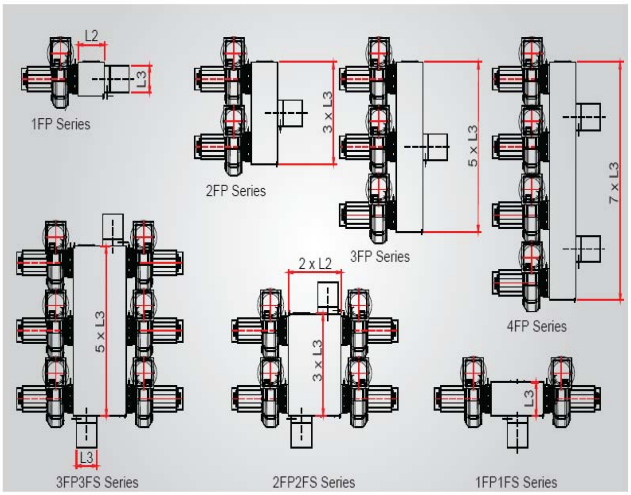
- **Mechanical efficiency & energy consumption** – evaluated by comparing different fan models available
- **Maintenance requirements & sustainability** – cost of maintaining the equipment vs other models, & whether models can be adapted or expanded to meet future requirements.
- **Sound generation** – noise levels must comply with local ordinances.

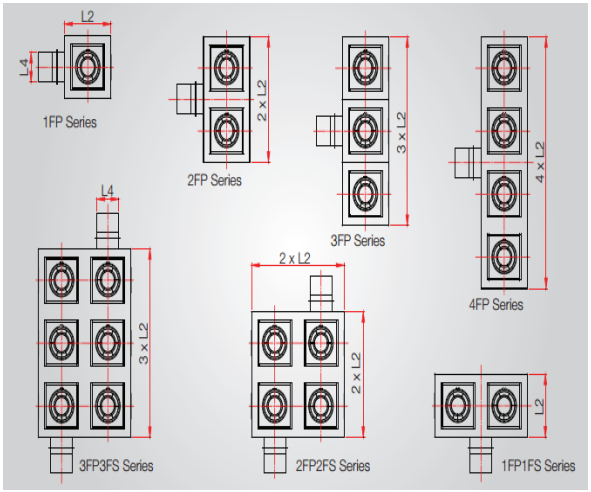
## Nozzle / Windband Designs

Various Designs available to cater for different entrainment and dilution ratios



## Fan / Plenum Configuration




## Advantages of High Plume Jet Fan System

**Prevent re-entrainment** – A Vertical "Jet Plume" can be discharged up to 100m high, providing atmospheric disbursement and preventing exhaust re-entrainment

**Eliminate odour** – Dilution capabilities of Jet Fans (up to 200% of free outside air is introduced into airstream above the roof) eliminate odors

**Reduce Noise at the property line** – Possibility of direct driven motors, high efficiency operation with more efficient blade design contributes to quieter operation.

## Advantages of High Plume Jet Fan System

**Comply with architectural aesthetic requirements** – Low profile & often not visible from the property line. Eliminate problems associated with tall, unsightly stacks including perception of exhausting polluted air in the neighborhood.

**Lower energy costs**– Possibility of Direct Drive Motors consume less energy per kilowatt compared to belt driven motors.

**Easy mounting** – Does not require expensive mounting hardware (bases, guy wires, roof curbs etc) usually associated with tall stacks.



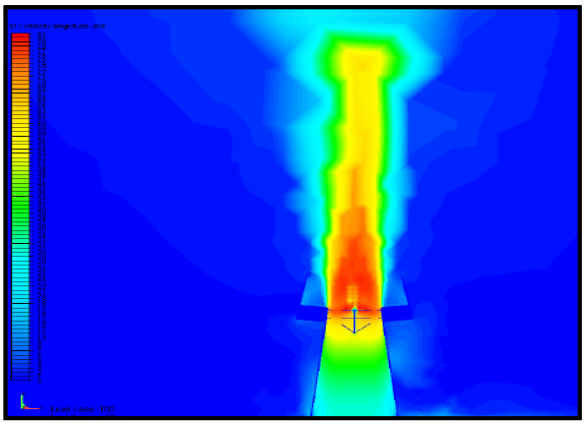
## Disadvantages of High Plume Jet Fan System

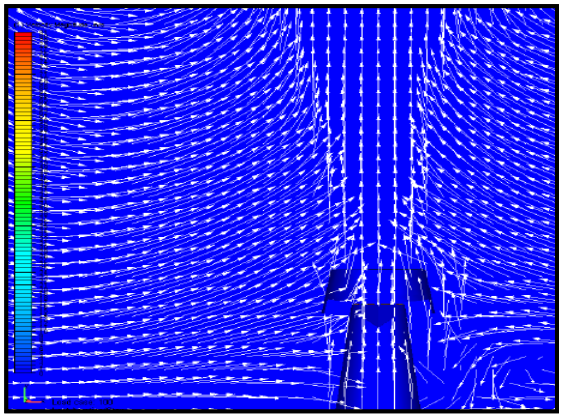
**Performance under high wind conditions** – Most fan manufacturers assumes that the stacks are able to entrain as much airflow under high wind conditions as they can under low wind speeds.

Since the entrained air exhaust stacks generally service high volume flow exhaust systems, high wind speeds are likely to be the most critical.

If these stacks do not entrain as much airflow at high wind speeds as they are able to entrain at lower wind speeds, the advantages of an entrained exhaust stack may be less than stated.

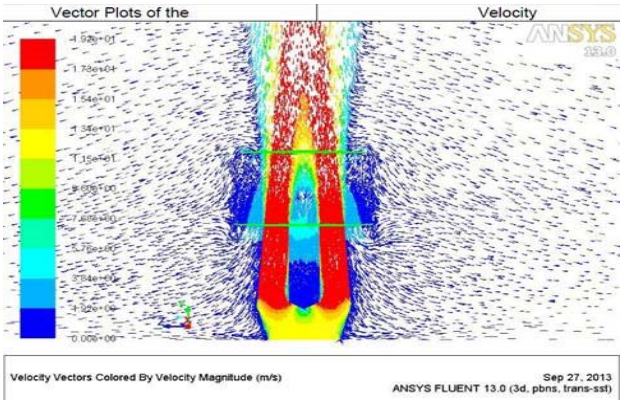
## CFD Simulation

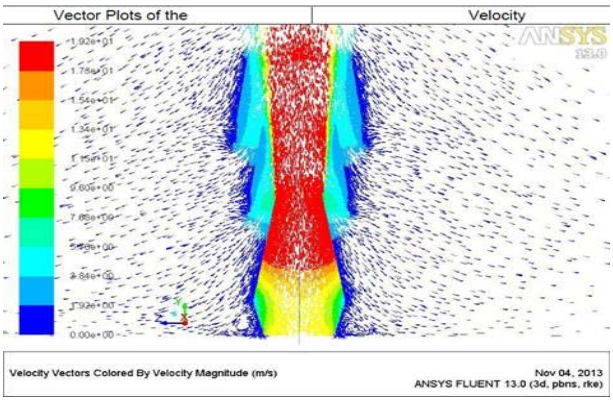




**Plume height and velocity vector plots**

## CFD Simulation




CFD simulation on Induction and Entrainment

## Why Do We Need Laboratory Testing Standards?

**Standards specify consistent & repeatable test conditions**

- Fan Manufacturers
  - To assist with product development
  - To compare the results of design changes
- Consulting Engineers
  - To compare products from different product lines
  - To compare products from different manufacturers
- Acoustical Engineers
  - For use in acoustical calculations for system designs

## Primary AMCA Standards

**AMCA 210-07**

- Defines uniform methods for conducting laboratory tests on housed fans to determine airflow rate, pressure, power and efficiency, at a given speed of rotation

**AMCA 300-08**

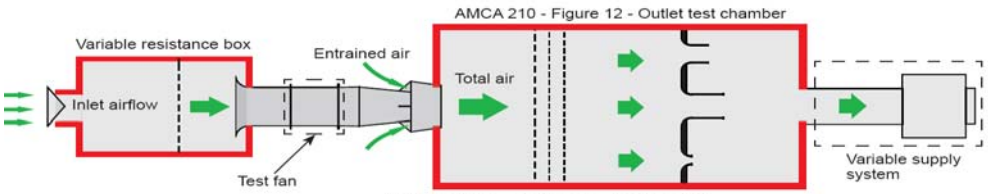
- This is the most commonly used AMCA acoustical test method
- Based on ISO 3741 & ANSI S12.51
- Used in conjunction ANSI/AMCA 210-07

## Primary AMCA Standards

**AMCA 260-07**

- Establishes a uniform method of laboratory testing of induced flow fans in order to determine their aerodynamic performance in terms of inlet and outlet airflow rate, pressure developed, power consumption, air density, speed of rotation, and efficiency.
- Used in conjunction ANSI/AMCA 210-07

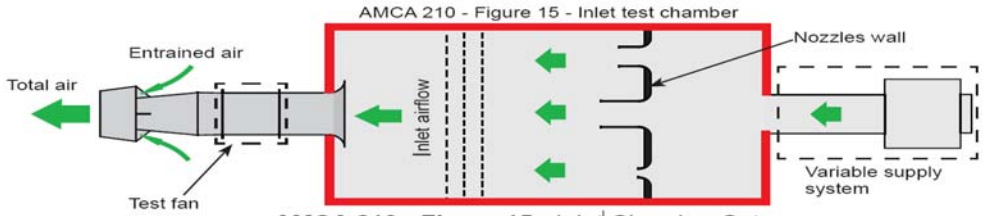
## AMCA 260 Testing




**AMCA 260 - Figure 1** - Test Setup
*(Determines induced flow outlet airflow)*

- Determines the total laboratory exhaust fan discharge flow.
- Total discharge flow is the sum of inlet airflow and entrained airflow.
- Key requirement to AMCA 260 is the variable resistance box.
- This box allows the measurement of total discharge flow (Ps = 0 S.Pa.) to simulate discharging the fan to atmosphere) at all points along its fan curve.

## AMCA 260 Testing



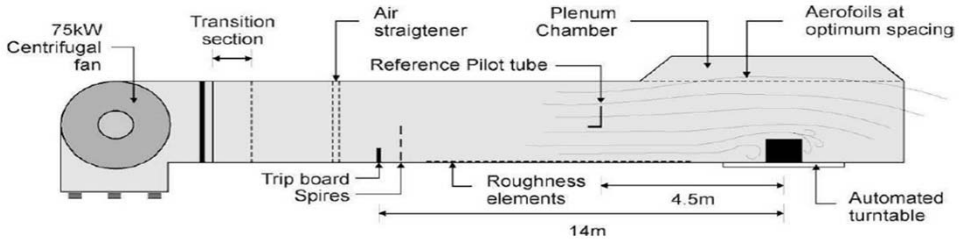

**AMCA 210 - Figure 15** - Inlet Chamber Setup
*(Determines the inlet airflow)*

- Without the variable resistance box, the entrained airflow can only be measured at the free air point of its fan curve.
- The entrained airflow obtained can be used to calculate an effective plume height.
- Therefore, AMCA 260 is necessary to ensure the laboratory exhaust fan specified is providing the plume rise and entrainment submitted.

## AMCA 260 Testing - Video



## Physical Wind Tunnel Testing




- To test for chemical downwash under different cross wind speed conditions.
- 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 a negative plume rise, a condition referred to as “stack-tip downwash.”
- This downwash defeats some of the effect of a taller stack and can lead to high concentrations at the building surface.
- To obtain reliable scientific proof of the induction and entrainment characteristics of the product.
- Important for Engineers specifying these types of systems especially when dealing with laboratory exhaust and public safety.

## Physical Wind Tunnel Testing - Video



**Instrumentation on Nozzle**



**Fume Jet Nozzle in Wind Tunnel**



**Fume Jet Nozzle in Wind Tunnel under 10MPH Cross Flow Wind Speed Conditions**

# Wolter Chemco Fume Jet Flow Visulation (Febuary 2014)

WINDTECH












## Summary

Regardless if conventional or entrained air exhaust systems are used:

- The important parameters are the physical stack height, exhaust volume flow rate, exhaust velocity, and expected pollutant concentration levels at air intakes and other sensitive locations.

- The overall performance should be evaluated using the appropriate criterion, i.e., ensuring acceptable concentrations at appropriate locations.

## References

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**Thank you for listening!**

**Questions?**