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Bulletin

Evaluating Greenhouse Mechanical Ventilation System Performance - Part 3 of 3

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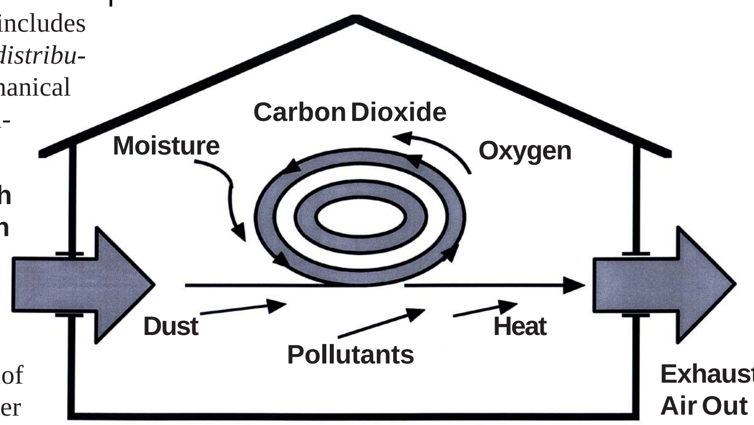
Introduction

Evaluation of a mechanical ventilation system includes measurements of *air exchange capacity* and *air distribution*, as well as the driving force behind mechanical ventilation, the *static pressure difference*. Evaluation techniques for determining the static pressure difference, fan capacity, and inlet airspeed are covered in this bulletin. In addition to the importance of exhaust fans in a mechanical ventilation system, the inlet and the controls are equally important. Greenhouse ventilation should be viewed as a system and changes to any of its components will have an effect on the other components.



Ventilation systems can have an adequate air exchange capacity as measured at the fans, but can be inadequate in terms of the uniform distribution of air throughout the entire greenhouse. Proper design and operation of the inlets ensures adequate fresh air distribution and helps to create desirable airflow patterns throughout the plant production area. Exhaust fans provide the motive force to keep the volume of air moving through the greenhouse, but it is the inlet that allows for proper distribution of the fresh air. Sufficiently fast inlet air speed will ensure a good mix of fresh air with greenhouse air as well as provide direction to the incoming air. Airflow visualization can provide information about whether fresh air is being distributed to all desired greenhouse areas. This bulletin discussed the various components needed for an evaluation of a greenhouse mechanical ventilation system.

Ventilation System Performance

Efficiency and performance are key to successfully ventilating greenhouses. A mechanical ventilation system that is not properly maintained performs poorly and costs more to operate as it consumes power inefficiently. Even though fans appear to be running correctly, the greenhouse may be subject to common environmental complaints such as cold drafts and stale air zones. Fortunately, troubleshooting tools are available to help diagnose greenhouse ventilation system performance. This bulletin features system performance and emphasizes an understanding of the static pressure difference, which drives ventilation air flow. The information is equally valid in other plant environments such as growth chambers, propagation areas, and germination rooms.

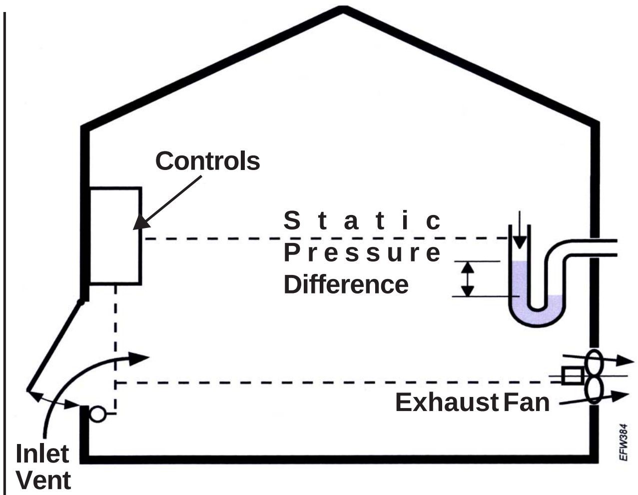
The two main functions of a ventilation system are to provide **air exchange**, which is simply fresh air in and stale air out, and **air distribution**, which is providing air movement throughout the entire structure. Sidewall fans provide air exchange; while air distribution is most influenced by the ventilation inlets. Static pressure difference links the fan and inlet performance. In some greenhouses, circulation fans, such as horizontal airflow fans (HAF) or fan-jet tubes, provide air distribution as they move air within the greenhouse without providing any fresh air exchange. A control system, e.g., thermostats or computer controller, integrates the ventilation equipment into a smoothly functioning system.

Most mechanically ventilated greenhouses use an exhaust, or **negative pressure system**. Fans mounted on an exterior wall exhaust air from the greenhouse. Tight construction creates a slight vacuum (negative pressure) that causes air to enter the greenhouse through the ventilation inlets. This vacuum is measured as the **static pressure difference**.

There are three primary features to check when evaluating a mechanical ventilation system: 1) static pressure difference, 2) fan capacity, and 3) inlet function. Evaluation techniques for these features are covered in this bulletin. Ventilation is a system; changes to any one of these features will affect the other two.

Static Pressure Difference

Static pressure difference is the driving force for air movement in a ventilation system. Air moves from regions of higher to lower static pressure so air enters or leaves the building because the interior static pressure is different from the outside static pressure. Likewise, air moves from room to room within a structure because of static pressure differences between the rooms. Static pressure is measured with a **manometer** and is indicated by changes in fluid level. In greenhouses, the static pressure difference between the ventilated space and the outside conditions is measured in inches of water. By maintaining a relatively constant static pressure difference between the inside and outside conditions, the speed of the air entering through the ventilation inlet will also be relatively constant. In mechanically ventilated systems, a proper static pressure difference is maintained by controlling the amount of opening of the ventilation inlets. A proper greenhouse static pressure difference is approximately 0.05-inches of water with an acceptable



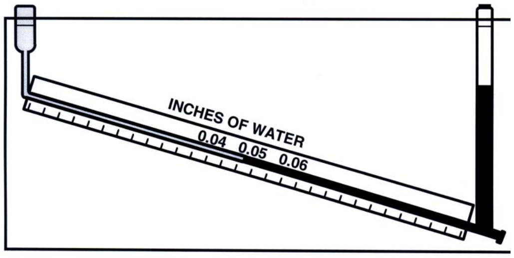
Negative pressure ventilation system components include exhaust fan, inlet vent, controls, and manometer for measuring static pressure difference.

operating range of 0.03 to 0.13-inches. Curiously, few greenhouses monitor static pressure difference.

The manometer is a very simple instrument that has two pressure-sensing openings, or measuring ports. Typically the manometer is located within the ventilated space with one measuring port open to the building interior. The second measuring port is connected to a long flexible tube, which has its open end positioned outside the ventilated space in conditions that represent air entering the inlets. Anywhere outside the mechanically ventilated space may be considered "outside" conditions. The manometer detects the pressure at the two locations and displays the static pressure difference, which influences air moving through the ventilation inlet(s).

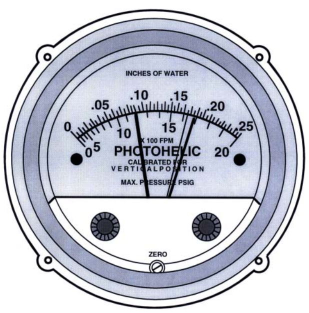
Care must be taken in positioning the tubes connected to the manometer measuring ports. Be sure they are not exposed to moving air. The objective is to measure a "static" pressure of still air and not the "velocity" pressure of moving air. Keep the interior port away from high air velocity areas in the greenhouse such as near the fans, heaters, ventilation inlets, or doors. The outside measuring port is positioned away from wind influences. Locations that represent an outside condition without wind effects include an outside hallway or an adjacent building's naturally-ventilated attic.

Inclined manometers are the most economical manometers (about $25) for use in troubleshooting greenhouse ventilation systems. A colored fluid (e.g., water with a food coloring) in a thin tube equilibrates to a position representing the pressure difference between the two measuring



Inclined Manometer

ports. Measuring units are in fractions of an inch of water. Usually, static pressure differences are so small, on the order of 0.02-inches to 0.15-inches of water, that an inclined rather than an upright manometer is needed to accurately determine a scale reading. This portable manometer can be used to determine that proper static pressure difference is being maintained and to verify the readings of a permanently installed **differential pressure sensor**, which is used to control inlet opening and closing.



Differential Pressure Sensor with inlet control capabilities.

Greenhouses should have a manometer permanently installed to provide an indication of the pressure difference the fans are operating against. This may be an inexpensive inclined manometer that simply displays the static pressure difference or a manometer with electronic control capacity for inlet positioning. Mechanical ventilation system computer controls often measure the static pressure difference to determine inlet opening size in relation to the fan capacity.

Greenhouse ventilation fans are designed to work at around 0.05-inches static pressure difference. Higher static pressure decreases the fan's capacity to exhaust air. Fans actually operate against more pressure difference than the 0.05-inches as measured by the manometer, which is associated with just the inlets. There is also a pressure drop associated with exhausting air through the fan enclosure, including the fan housing and accessories such as the safety guard and shutters. Many agricultural fans are now tested with shutters and a guard in place so the reported airflow accounts for these accessories. Dirty fan blades and shutters increase resistance to airflow. Fans are chosen for operating performance at 0.10-inch to 0.125-inch (1/10 inch to 1/8 inch) water pressure to account for fan accessories and inlet restrictions. Penn State University Factsheet; *Selecting Rated Ventilation Fans*, G-85, discusses fan performance in relation to static pressure and the accessories on a fan (see Additional Resources).

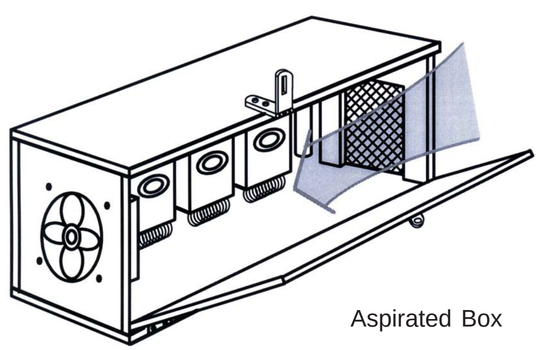
Evaporative cooling pads or other inlet airflow restricting devices (insect screens, heat exchangers and ducts) will offer additional resistance to airflow. Manometer readings should be taken when these devices are being used. The resulting static pressure is used for comparing actual versus expected fan performance. The inlet static pressure difference with an evaporative cooling pad in place is often 0.10-inch water—twice the original design pressure of 0.05-inches static pressure difference.

Plant Environment

In addition to the ventilation system performance, the environment directly surrounding the plants is crucial. The ventilation system will influence conditions within this plant zone, so environment measurements should be made near the plants along with observations of plant status. For example, the ventilation system may appear to be working correctly, yet air characteristics near the plants are unacceptable. The ventilation system air distribution and air exchange should be evaluated under typical plant densities and weather conditions.

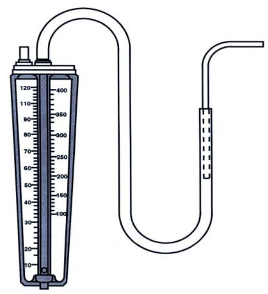
Control Sensors

A hand-held instrument check is useful for thermostats and computer control temperature sensor calibrations. House permanently installed greenhouse temperature sensors in an **aspirated box** so that solar radiation is not influencing the reading. Inexpensive humidity sensors do not perform well in the relatively humid greenhouse environment. Any control sensor should be



Aspirated Box

positioned to detect conditions near plant level. Many greenhouse sensors are positioned for convenience in walkways at human head height. Conditions at this location are usually not representative of conditions within the plant canopy. Units with remote sensor displays allow monitoring at plant level, but readings and adjustments can be made from a convenient location.



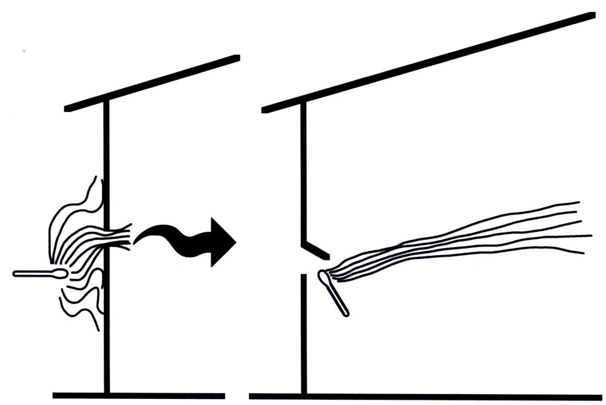
Air Velocity Manometer

Air Flow Visualization

Sometimes it is helpful to see where air mixing or unusual leaks are occurring in a ventilation system. Smoke may be added to the air stream to see where air is entering the greenhouse and how it moves around the interior. It may be surprising, but not uncommon, to learn that a good portion of airflow in the enclosure is coming through unplanned inlets. These may include leaks around the fan installation, doors, and window frames, cracks in walls, glazing junctions, and any other location of loose construction detail. These, sometimes significant, leaks are detrimental to the performance of a ventilation system. These "unplanned" inlets are not controllable and usually provide uneven airflow patterns, in turn creating uncontrolled and uneven air quality conditions inside the greenhouse. These leaks should be sealed as much as possible. Other disruptors of good airflow patterns in mechanically ventilated greenhouses are open doors and material handling passageways (conveyors, etc).

Visualizing airflow patterns in plant production facilities has a few limitations, but several methods have been used successfully. Thermal or chemical smoke can be used, but anything producing abundant smoke can quickly obscure airflow patterns. Thermal smoke will tend to rise, as it is warmer than surrounding air. Threads of material (streamers) can be calibrated to blow horizontally at a particular air speed and positioned in many locations as inexpensive indicators of minimum desired airflow (more information in *Instruments for Monitoring the Greenhouse Aerial Environment*, E 276).

A certain amount of creative license is allowed in using airflow visualization. A visualization tool such as a smoke candle can be placed just outside (or just inside) an inlet to see how far the fresh air jet is penetrating into the production facility. Similarly, a smoker can be positioned around and close to the exterior of a building to see where smoke is drawn in through building leaks. Smoke sticks can be held down into the plant canopy to look for drafts or dead air zones. Using common sense to identify where leaks and trouble spots may be occurring will lead to appropriate positioning of the air visualization equipment. Pure curiosity is allowed! Move around with the instruments and look for unusual airflow patterns. Temperature and/or velocity changes may cause sudden drafts of air. Try to explain your observations and think of remedies that can be implemented to correct undesirable airflow patterns.



Airflow visualization by positioning smoke devices

It is important that ventilation systems provide desired and stable airflow patterns inside greenhouses to ensure sufficient and continuous mixing of fresh air with inside air. In other words, internal and external conditions (e.g., fluctuating wind speeds, temperature changes, and ventilation rate changes) should have little or no effect on the greenhouse airflow pattern. Delivering desired airflow patterns is usually accomplished by maintaining sufficiently high air speeds (700 to 1000 fpm) through the ventilation inlet, while eliminating other air leaks.

Air Exchange Capacity of a Ventilation System

One way to calculate the air volume being moved by a ventilation system is to measure air speed and cross-sectional area through which air is moving.

Air speed (feet per minute, fpm) x Area (sq. ft.)

= ventilation rate (cubic feet per minute, cfm)

Measure the air speed moving through the fan and/or inlets. To determine cross-sectional area, measure the fan airflow opening, which is usually the fan diameter, or sum the total inlet areas.

Where to take measurements

It is easier to determine ventilation capacity by taking measurements at the fan. Inlet air speeds may seem easy to measure, but the effective inlet area and maximum air speed are not easy to determine. Particularly with small inlet slots and louvered openings, the real opening size is often irregular. The effective area of a louvered inlet is less than the rough wall opening due to air flow restriction caused by the louver blades. The amount of restriction is hard to estimate accurately, but approximately a 20% reduction in effective airflow area is common. Inlets screened with residential insect screens have about 66% open area but are even more restrictive to airflow due to the small opening size.

Air leakage through various cracks and holes in the structure can provide a significant amount of the ventilation air but is neglected when only the inlet area at vent windows or louvers is measured. Even tightly constructed buildings have some "unplanned" inlets (e.g., cracks in walls, at glazing junctions, and around doors, etc.) and these are very hard to account for. For fan jet tubes or other ducts used as fresh air inlets, the variation in duct air velocity and at the exit holes means that many measurements will be needed.

Greenhouse ventilation system capacity

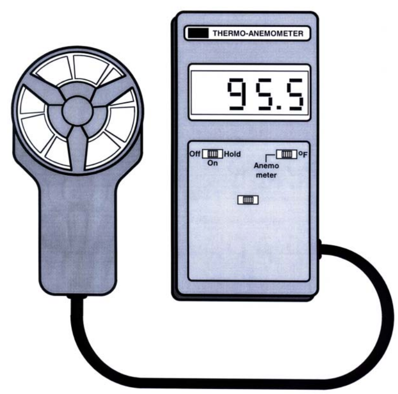
The ventilation system capacity equals the sum of all individual fan capacities. For each type of fan in a ventilation system, one set of representative data may be used if the fans are all the same model. When there are differences in fan types due to manufacturer, motor, blades, maintenance, or suspected reliability, air speed measurements will need to be taken for each. Fans in locations where obstructions or wind effects are dominant features also will need to be evaluated separately. There is no need to measure airflow at each and every fan unless an unusual airflow imbalance is suspected. For example, in a facility with 24-inch and 36-inch fans, determine an average airflow capacity from one (or two or three) of the 24-inch fans and one (or two or three) of the 36-inch fans. Total capacity at any ventilation stage would be estimated as the airflow capacity of a 24-inch fan times the number of 24-inch fans operating, plus the average airflow capacity of a 36-inch fan times the number of 36-inch fans operating. This technique, when performed carefully, may be within 10% of real fan capacity.

Maximum air exchange capacity target level

A guideline for maximum air exchange capacity in a greenhouse is to provide 8 to 10 cfm/ft^2 of floor area for greehouses with and without a shade curtain. For example, a 96-foot by 30-foot greenhouse has 2880 ft^2 of floor area. Multiply this by 8 cfm/ft^2 for an estimated 23,040 cfm of total fan capacity. Compare this recommended fan capacity to what is provided by the fans installed in the greenhouse.

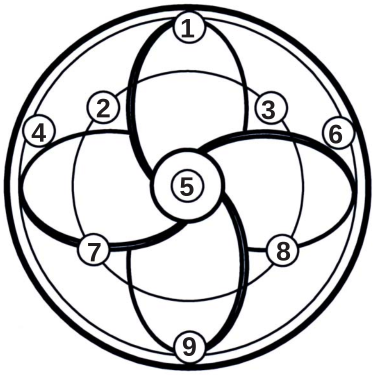
Fan Air Speed

Air speed can be measured with a **vane anemometer** at the discharge side or intake into a fan. Air speeds are more accurately determined on the discharge side of the greenhouse fan than on the inlet side. Many readings should be taken across the face of the fan to get an average air speed. Because this is a rather crude field measurement, include as many readings as possible. Use the nine readings shown in the fan figure as a minimum. Each measurement represents only a very small area of airflow over the fan face. Air speed varies greatly across the face of a fan, with highest velocities coming off the blade tips and minimal velocity near the drive shaft. Determine velocities near the blade tip, at the blade midpoint, and at the center of the fan. Some fans will have negative airflow at the center, indicating a draft of air short-circuiting backwards through the fan. Obstructions and wind gusts cause uneven air speed distribution over the fan face. A hooded fan will exhibit lower airflow at the top quadrant of the fan due to the resistance of the external hood. One-piece shutters hinged at the top and open at the bottom exhibit similarly restricted airflow.



Vane Anemometer

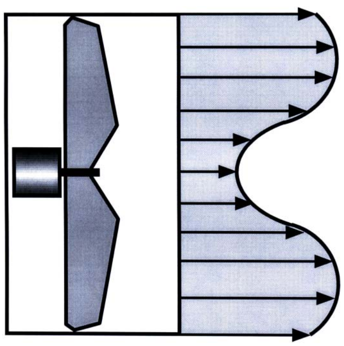
Minimize the amount of airflow that your body blocks as you position the anemometer. Step back out of the



Take air speed measurements at several locations across the fan face.

airflow, to the side of the fan when possible. Anemometers with a remote sensor vane that attach by cable to the air speed display unit offer an advantage here. Several instruments are appropriate for measuring the fast air speeds exiting a fan, listed in preferential order: vane anemometer, hot-wire anemometer, velocity manometer, or air speed streamer.

Cross-section of fan showing large variation in air speed coming off fan tips versus near fan hub.



Fan Capacity

Use the following simplified method to calculate airflow capacity of a fan in cubic feet per minute (cfm): multiply the average fan air speed [feet/minute (fpm)] by the area of the fan face [square feet (ft^2)]. The area of a circle = $\pi d^2/4$; where d = diameter in feet and π=pi = 3.14. For example, an 800 fpm average air speed through the face of a 24-inch (2-foot) diameter fan:

Air flow (cfm) = air speed (fpm) * area (ft^2)

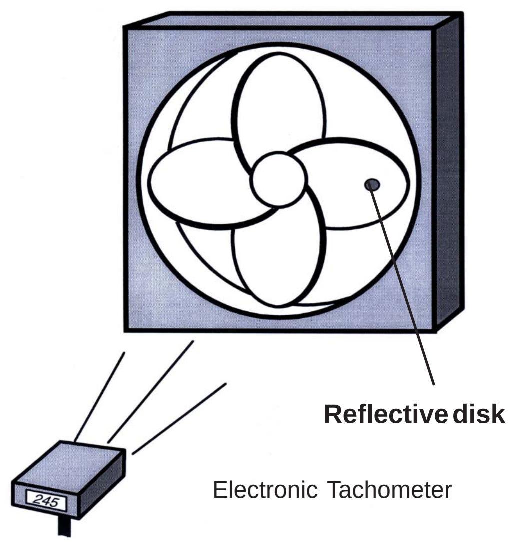
Air flow (cfm) = 800 fpm * π $(2)^2/4$ ft^2 = 2,513 cfm

This is the estimated capacity of that single 24-inch diameter fan.

Fan Speed (rpm)

A second way to determine fan capacity is by measuring the fan blade rotational speed, in revolutions per minute, or rpm. Because the amount of air a fan moves is directly proportional to its rotational speed, a fan running at 75-percent of its rated speed will move only 75-percent of its rated or intended airflow. Fan blade rpm is listed on the housing nameplate or may be obtained from the manufacturer rated data (see Penn State University Fact Sheet; *Selecting Rated Ventilation Fans*, G-85). For belt-drive fans, motor rotational speed will not equal blade rpm.

Fan rpm can quickly indicate if belts are loose or worn, or if the supply voltage level is too low. Inadequate wiring can lead to substantial voltage drops along the building length, causing fans to run at a lower rpm. Measuring fan speed is as important as other performance indicators, particularly for belt-driven fans, where slip of worn or poorly adjusted belts decrease fan performance.



Fan rotational speed can be measured using a **tachometer** or **stroboscope** (strobe light and tachometer). Tachometers can be either mechanical or electronic. With mechanical tachometers, the tachometer shaft is pressed against the center of the fan shaft so that both the tachometer shaft and fan shaft rotate at the same speed. Mechanical tachometers should be used carefully so that no personnel or equipment damage occurs if the tachometer shaft slips off the fan shaft. Electronic tachometers send light to a shiny, rotating object, such as a silver sticker attached to a fan blade or pulley, and the reflected light is measured by the tachometer and converted to an rpm measurement.

A **strobe light** produces flashes of bright light at an adjustable frequency (flashes per minute). As the frequency approaches the fan rpm, the blades appear to slow down, stop, and may even appear to reverse direction. The fan rpm is determined by adjusting the flash rate until a rotating part appears to be stopped. It is important to note that simply adjusting the flash rate until the fan blades appear to be stopped does not ensure an accurate reading because a blade may not be in the same position at each flash. For example, with a four-blade fan, running the strobe at 3/4 or 1 1/4 times the correct flash rate will appear to stop the blades as well, but the same blade will not be in the same position with each flash. The correct strobe flash rate and rpm can be obtained by tracking a unique rotating part, such as an oil fitting, bolt, or a shiny sticker that is half black and half shiny placed on a fan shaft or blade.

Additional Fan Performance Evaluations

Dust buildup and improper operation of the fan louvers can significantly affect fan performance. Fan louvers should open completely to a nearly horizontal position to minimize airflow restriction as the air passes through the fan. The more restriction, the less efficiently a fan converts electric energy into air movement. The weight of even a seemingly small amount of dirt buildup on louvers prevents them from opening fully. Dirt also prevents tight closure of louvers when the fan is off allowing leakage of air into the greenhouse.

Fan *noise* (and vibration) can be very intrusive to greenhouse workers; higher speed fans produce more noise. Similarly sized fans from different manufacturers sometimes produce significantly different noise levels. Keep this in mind when selecting new fans.

Inlet Air Speed

Air speed through inlets should be quite fast, at 700 to 1000 feet per minute (fpm), in a properly operated greenhouse mechanical ventilation system. Slower airspeeds allow drafts that are particularly detrimental during cold weather. Air speed above this recommended range is an indication of a static pressure difference that is higher than necessary for proper greenhouse ventilation system function.

Air speeds across inlet openings are not uniform. The air speed will be zero at the edges of the inlet and will typically increase to its maximum near the middle of the inlet opening. Take air speed measurements across the opening of the inlet to get a maximum air speed reading.

Hot Wire Anemometer

Unfortunately, the inlet gap of a ventilation window is sometimes so small, less than an inch wide, that the 3-inch diameter head of a typical **vane anemometer** cannot meaningfully determine air speed. The small probe head of a **hot wire anemometer** is most appropriate for measuring air speed at narrow inlet openings. A vane anemometer can be used to measure air speed out of some duct holes (rigid or polytube ducts) or other inlets with large openings, such as window vents during warm weather or louvered inlets. The key is to make sure the anemometer head is smaller than the air stream being measured. **Small-headed vane anemometers** can measure smaller width airstreams. Some relatively inexpensive models now come equipped with temperature and relative humidity sensors in addition to the air speed measurement. A low-cost **air velocity manometer** can be used with fast inlet air speeds.

Small Headed Vane Anemometer with Temperature and Relative Humidity

Summary

Evaluation of a mechanical ventilation system emphasizes measurements of *air exchange* capacity (fan cfm), *air distribution* (inlet air speed and air flow visualization), and the driving force behind mechanical ventilation, the *static pressure difference*. Ventilation is a system where these three features work together for proper performance. Sufficiently fast inlet air speeds of 700 to 1000 fpm encourage good air mixing and distribution within the greenhouse without contributing to cold air drafts. An anemometer is used to measure air speed, with various types (hot wire, vane, and velocity pressure) available for specific applications. Techniques such as airflow visualization can help identify trouble spots where non-uniform temperatures contribute to variable *conditions at plant level*. Ventilation problems are much easier to solve once good background information is obtained about location of the major malfunction. Changes in management, ventilation system operation, or equipment can then be made. With additional measurements, environment improvements can be evaluated and compared to previous conditions.

Additional Resources

Rutgers Bulletins

Environmental Control of Greenhouses, E213
Principles of Evaluating Greenhouse Aerial Environments; Part 1 of 3, E275
Instruments for Monitoring the Greenhouse Aerial Environment; Part 2 of 3, E276

Penn State fact sheets

Selecting Rated Ventilation Fans, G-85
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NRAES Publication

Greenhouse Engineering, NRAES-33. 1994. Aldrich, R.A. and J.W. Bartok. Natural Resource, Agriculture, and Engineering Service (NRAES), 152 Riley-Robb Hall, Ithaca, NY 14853-5701. Ph: (607) 255-7654.
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