RUTGERS COOPERATIVE EXTENSION

NEW JERSEY AGRICULTURAL EXPERIMENT STATION

Instruments for Monitoring the Greenhouse Aerial Environment

Part 2 of 3

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Introduction

Aerial environment characteristics are quantified with instruments that provide numbers. With these numbers we can compare the environment under investigation with a predetermined standard and then seek improvement in greenhouse conditions. We can also evaluate changes in the environment over time. For example, a simple thermometer tells us that the air temperature in a greenhouse is 85ºF, yet we determined the optimum plant temperature is around 75ºF or colder. Our goal would be to lower the temperature or compensate for the heat stress in other ways.

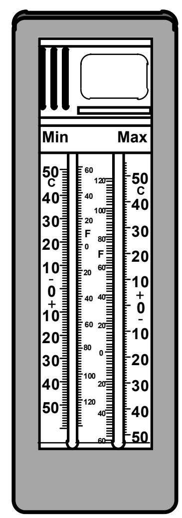
This publication examines portable, hand-held, field-quality instruments commonly used to diagnose greenhouses and other plant production environments (propagation rooms, growth chambers, etc.). Limited discussion is provided about some permanently installed greenhouse sensors and portable dataloggers. It does not discuss ventilation system controls or instruments used to obtain scientific data. A table of instrument costs and suppliers is provided. Hand-held instruments can offer sophisticated computer interface capabilities, datalogging, and simple data evaluations such as maximum, minimum, and average readings. Expect to pay more for these capabilities and instruments with high accuracy. One responsibility of instrument use is the proper maintenance of instrument calibration.

Aerial environmental features that can be reasonably measured:

Common	*Special Circumstances*
Air Temperature	Air Flow Visualization
Humidity	Surface Temperature
Air Speed	Gases
Light Level	

Temperature

Air temperature can be measured with a common **thermometer**. Not surprisingly, the thermometer indicates the temperature of the exposed sensor tip, or bulb, which has reached equilibrium with the surrounding environment. The sensor tip must not be exposed to radiant energy, such as from direct sunlight or a heating system radiator, as this will increase the sensor tip temperature. In that case, the measurement taken would not be representative of the surrounding air temperature. An aspirated box is recommended for shielding permanently installed greenhouse sensors from solar heat gain. Be sure that the temperature you measured is representative of the air in the area directly surrounding the plants. Air temperature in a work aisle, where air mixing is relatively unrestricted, is probably not indicative of the air temperature within the plant canopy.



Max-Min Thermometer

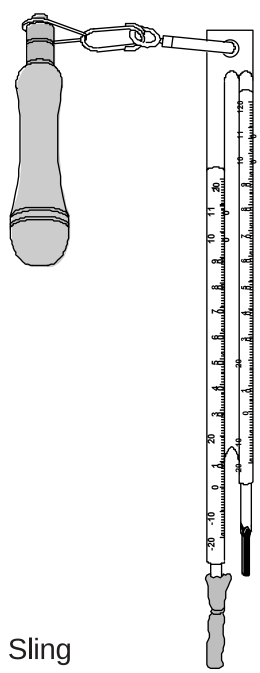
A simple **maximum-minimum thermometer** that can be left in the area of interest is an inexpensive tool that can help determine whether wide temperature swings occur over a period of time. Digital thermometers are becoming more common. They are easier to read, offer remote sensing capabilities in hard-to-reach areas, and sometimes have data logging capabilities. However, digital readouts may offer a false sense of accuracy. For example, some sensors have an accuracy of ±3 percent, yet the readout displays temperature to an astonishing resolution of one-tenth of a degree.

Humidity

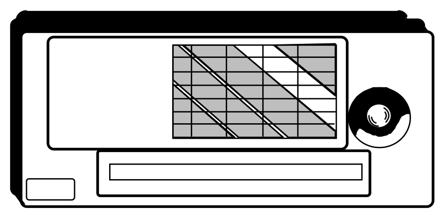
There are several terms that describe humidity and several ways to measure humidity. Relative Humidity indicates the "relative" fraction of water vapor in a volume of air to how much water vapor that air would contain at saturation at the same temperature and pressure. The traditional way to measure relative humidity is a two-step process: both **wet bulb** and **dry bulb** temperatures are obtained, and then converted to relative humidity using a psychrometric chart. Use of the psychrometric chart and description of other humidity terms is covered in fact sheet *Psychrometric Chart Use*, G-83 (see Additional Resources).

The dry bulb temperature is commonly measured with a standard thermometer. The wet bulb temperature is determined from a standard thermometer modified with a wetted fabric wick covering the sensor bulb. Sufficient airflow is provided over the wick material so that as water evaporates from the wet wick, the temperature falls and the thermometer reading reflects the wet bulb temperature. A clean bulb wick (e.g., a hollow, white shoelace from a sneaker) soaked with distilled water (to prevent salt buildup on the wick) provides the best accuracy. The wick will have to be wet continuously if continuous measurements are required. With a wet wick, measured temperatures must be above freezing. Air movement can be provided through an aspirated box (with a fan) or by whirling the dry bulb/wet bulb thermometer through the air.

The traditional relative humidity instrument, called a **sling psychrometer**, contains both dry bulb and wet bulb thermometers. The sling around swiftly (creating an airspeed of approximately 900 feet per minute [fpm] around the thermometer bulbs) on a jointed handle for about three minutes to obtain sufficient air movement needed to extract an accurate wet bulb temperature. A mechanically **aspirated psychrometer** operates on the same principles as the sling psychrometer, except that a battery powered fan moves air over the wet wick. Air speed over the wet wick is better controlled by an aspirated psychrometer than it is by whirling a sling psychrometer. In order to take a reading with a sling psychrometer, the chrometer must be stopped, which immediately begins to change the properties of the wet wick. Hence, the mechanically aspirated readings are usually more reliable. Accuracy of the thermometers, careful reading of temperatures, and psychrometric chart interpretation are important.

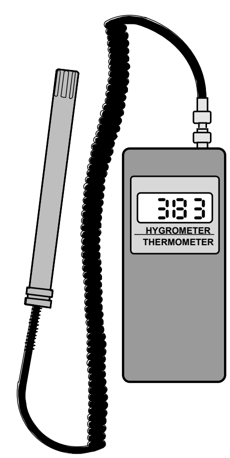


Sling Psychrometer



Aspirated Psychrometer

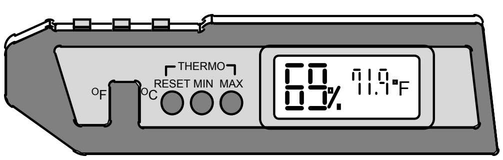
Relative humidity can be measured directly, rather than being determined from two temperatures and the psychrometric chart, by an instrument called a **hygrometer**. Newer hygrometers determine relative humidity with solid-state devices and electronics. The sensor is a matrix material in which electrical properties change as water molecules diffuse into or out of the matrix material in response to air moisture content. Other hygrometers use materials, which indicate electrical changes as water molecules adhere to their surface. Sensor material changes are interpreted and displayed by the hygrometer. Careful calibration is essential. The sensor materials may not tolerate conditions near saturation. So reliability of many relative humidity sensors is questionable when the relative humidity rises above 95%. Condensation on the hygrometer surface coats the matrix material so that water molecules no longer diffuse in or out. Until the condensation is evaporated, the hygrometer will often display inaccurate humidity



Hygrometer

readings or there may be a permanent change in electrical properties. For greenhouse use, look for sensors that can withstand condensing conditions. Most hygrometers also provide a measure of dry bulb temperature.

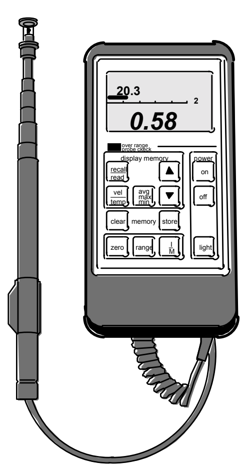
Hygrometers offer the advantage of direct relative humidity measurements and are available in several categories based on price and accuracy. For example, a relatively inexpensive, thick, pen-shaped instrument can provide digital dry bulb temperature and relative humidity readings. These pens can take several minutes to display a correct reading and provide relative humidity measurements with an unimpressive accuracy of ±5 percent. More accurate hygrometers (with an accuracy of ±1 percent) are preferred but are more expensive. Generally, hygrometer prices have gone down and reliability has improved over the past several years. On some models, maximum and minimum temperature and relative humidity can be captured over a pre-determined time period.



Pen-shaped Hygrometer

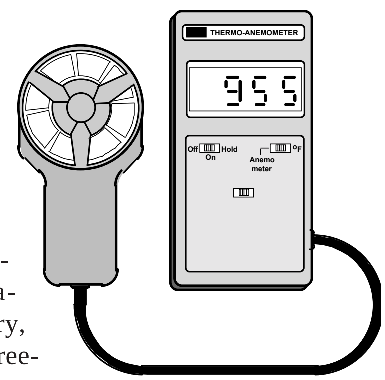
Air Speed

Air speed is measured with an **anemometer**. Two types of anemometers are common, depending on the type of airflow being measured: vane anemometers and hot-wire anemometers. Both instruments are composed of two connected parts: one is the sensing probe and the second displays air speed. One key concern in using an anemometer is to take measurements while air speed and direction are minimally altered by the instrument's placement. In addition, the operator should stand away (as much as possible) from the airflow being measured. For reference, air moving less than 50 fpm is considered still air.



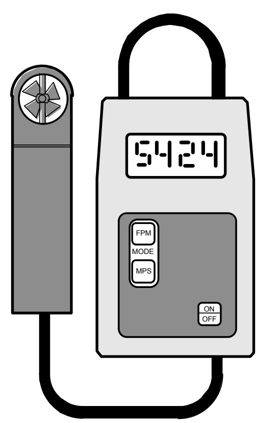
Hot-wire Anemometer

A **hot-wire anemometer** has a very fine, short wire, often the thickness of a human hair, positioned between two supports. A more rugged design uses a thicker wire, which incorporates a temperature-sensing thermistor. The wire is heated by electronic circuitry and air flowing over the wire causes its temperature to decrease. By detecting this temperature decrease, or by evaluating the amount of current supplied to keep the temperature of the wire from decreasing, the anemometer determines the speed of the passing air. Calibration is important for relating hot-wire temperature effects to air speed. The hot-wire portion of the instrument is fragile and care must be taken to protect it from physical damage, which can be caused, for example, by large airborne dirt particles. A hot-wire anemometer is the instrument of choice for low air speed measurements. Air that is virtually still (<50 fpm) exists in many greenhouses, especially away from ventilation inlets and outlets. Due to their small size, hot wire anemometers can be used in small places, such as the inlet opening of a ventilation system, or in hard to reach spaces, such as ducts.



Vane Anemometer

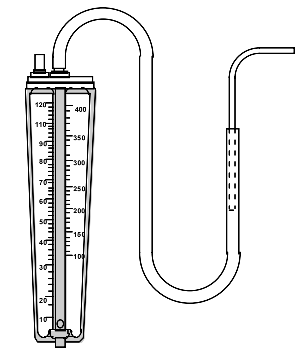
A **vane anemometer** is more rugged and usually less expensive than a hot-wire anemometer. It is well suited to evaluate several agricultural applications. Designs vary, but most have a three-inch-diameter vane propeller, which starts turning when the propeller is held in an air stream. Since it takes air speed measurements based on a larger area than the hot-wire anemometer, it is better for determining airflow over the face of a fan, in a large duct, or across a large ventilation inlet opening. Dust and other small airborne debris usually do not impact the readings. Vane anemometers do not measure low air speeds because the mass of the vane requires a fair amount of air movement to induce rotation. Vane anemometers are not considered accurate below 50 to 70 fpm, even though the meter displays a velocity at these low air speeds. Vane anemometers



Small-headed
Vane Anemometer

must be used in air streams that are at least as wide as the vane diameter. They will not accurately measure narrow inlet air jets that are smaller than the diameter of the vane anemometer propeller. Vane anemometers with small, one-inch diameter vane heads are available for small air stream measurements, yet they still cannot detect low air speeds. For low speed (< 50 fpm) air measurements, a hot-wire anemometer is required. One of the available options on a vane anemometer is an averaging mode where velocity is displayed as a running average value over time. This is a helpful feature when scanning a fluctuating air stream.

Finally, so-called **velocity manometers** may be used in well-defined air streams of relatively high velocity air (> 400 fpm). A Pitot tube is positioned so airflow directly affects the sensing tip, and therefore streamlined air is more desirable than turbulent flow. A velocity pressure is detected, from which air speed is determined. A floating ball in the instrument's air tube indicates the velocity reading. Although some models are relatively inexpensive, these flow meters provide accurate, if fluctuating, readings.

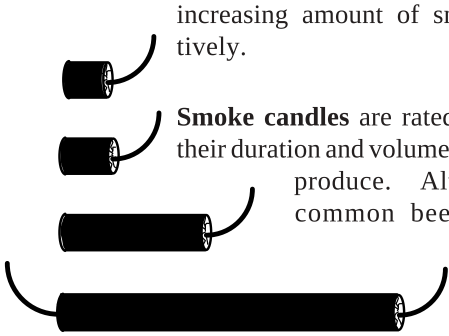


Velocity Manometer

Airflow Visualization

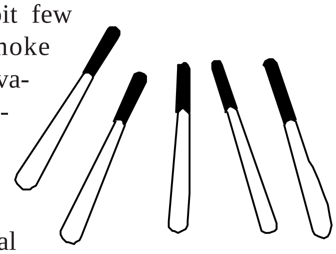
It is sometimes helpful to visualize airflow to determine how air is mixing or where it forms dead zones. Unusual air leaks (open doors and windows, or cracks in the structure) affect the operation of a ventilation system. Visualizing streamline patterns in greenhouses has some limitations, but nevertheless several methods can be used. Devices that generate **smoke** are the most common and come in gun, stick, candle, and bomb formats, with an increasing amount of smoke, respectively.

Smoke candles are rated according to their duration and volume of smoke they produce. Alternatively, a common beehive smoker provides an inexpensive and more controllable diagnostic tool to visualize airflow patterns. **Smoke bombs** have been used, but the abundant smoke quickly obscures visualization of the airflow patterns and is frequently an irritant to humans. Smoke bombs are sometimes used to release fumigants in plant production facilities to control various pests. Plants should not be present if harmful techniques are used, but since their presence usually affects how airflow patterns develop under normal conditions, their removal may provide unrealistic airflow patterns. It is best to keep the plants in place and use compatible airflow visualization methods. The above mentioned smoke devices use combustion to produce smoke, so they also generate heat. This thermal effect tends to produce rising smoke.

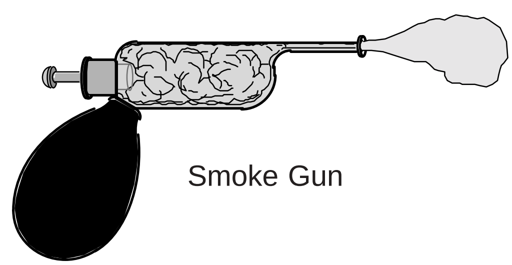


Smoke Candles

Smoke sticks and guns use chemical reactions to produce smoke, so they exhibit few thermal effects. Smoke sticks produce the equivalent of several cigarettes' smoke and look like glass tubes filled with cotton. They produce smoke for several minutes once the end is broken off with a cap on the tip) provides small smoke puffs. This allows smoke to be produced intermittently, rather than the unstoppable stream provided by the combustion devices. A rubber bulb on the handle of a smoke gun provides smoke in puffs or in a continuous stream. The disadvantage is that the small amount of smoke dissipates quickly and may not visualize well, especially in bright light. In addition, the smoke is irritating and the stored sticks can be corrosive once broken. Even rubber parts of the smoke gun may deteriorate from chemical corrosion.

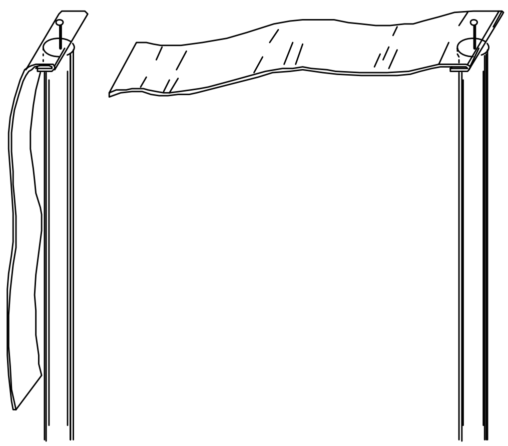


Smoke Sticks



Smoke Gun

Very small, **neutrally-buoyant soap bubbles**, filled with helium and released with compressed air, can last long enough to show airstreams within an enclosure. The soap bubbles are surprisingly durable in a free air stream but will not tolerate many impacts with obstructions. The apparatus used to generate bubbles is cumbersome and expensive compared to other airflow visualization devices. Children's **soap bubble toys** are the least expensive option and can be useful in faster-flowing airstreams but they are not neutrally buoyant. These bubbles exhibit downward gravitational effects (due to the weight of the soap film), which obscures accurate visualization of the true airflow. **Theatrical smoke** units produce large quantities of a non-irritating fog through the heating of glycol fluid. This is the atmosphere enhancing fog used for special effects in a theater (dry ice may also be used). Since the theatrical smoke is warmer than ambient air it will exhibit upward convection. The unit is rather large, being similar in size to a breadbox, relatively expensive, and heavy at about 30-pounds.



Air Speed Streamers

A set of **air speed streamers** may be used to detect air speed at various greenhouse locations. Threads of string or ribbons of plastic tape can be "calibrated" to a specific size so that they blow horizontally at a particular airflow of interest. Attached to small posts, these inexpensive free-to-spin streamers can be positioned in many locations as indicators of the local airflow and direction. As conditions are changed in the structure under investigation, a quick survey of the streamers will indicate which areas are receiving the desired airflow. For example, if a mechanical ventilation system inlet air speed of 700 fpm or faster is desirable, streamers which have been "calibrated" to blow horizontally at 700 fpm are positioned at various inlet locations to observe whether inlet air speeds are indeed at least 700 fpm. Fact sheet *Make Your Own Ceiling Inlet Air Speed Monitors* (G-94) provides guidance on constructing air speed streamers (see Additional Resources).

What to do when an anemometer is not available?

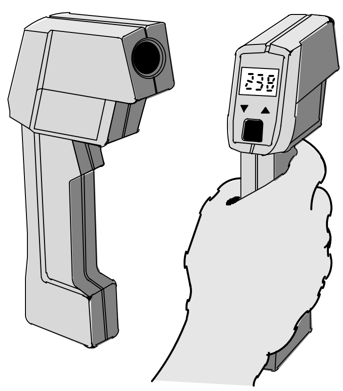
Since anemometers are specialized and relatively expensive (especially hot-wire anemometers), the use of less precise air velocity measurements may be necessary. These measurements, even when performed carefully, usually offer only an "adequate" or "inadequate" evaluation of the measured airflow. A **smoke stick**, **watch**, and a **measuring tape** will allow for an estimate of low air speeds. The time it takes smoke to travel a certain distance can be converted into air speed (e.g., in feet per second). For faster air speeds, such as inside ventilation ducts, near inlets or exhaust fans, a pre-calibrated **air speed streamer** can determine whether the air speed is a least minimally adequate. After the streamer is "calibrated" to blow horizontally at a desired air speed, it can be positioned in various air streams and its streamer orientation (angle) observed.

Surface Temperature

In cases where large differences in temperature exist between greenhouse plants and surrounding surfaces such as walls, glazing, and floor, the radiant temperature of those surfaces can influence the effective plant temperature. Surface temperatures are often ignored in environmental analyses but can have a significant impact on plants. For example, the hot air volume near the roof of the greenhouse can provide a large radiant load on the plants below. On the other hand, very cold surrounding surfaces can chill plants even though the surrounding air temperature seems adequate. Even a surface outside the structure can cause heat or cold stress if the plants can "see" it. For example, the black sky during a clear, cold winter night can cause the plants to radiate enough energy through the greenhouse structure to induce severe cold stress. These examples of radiant load would not be detected by an aspirated, dry-bulb thermometer.

Radiation is a very strong form of heat transfer, yet is purely a surface phenomena that can be characterized by the surface temperatures of the objects radiating to each other. An object must "see" another surface in order to feel its radiant heat transfer effect. "Line-of-sight" is a straight, unobstructed pathway where radiant energy wavelengths can travel. Temperatures of the surrounding walls, glazing, and floor influence the plants, even though they have limited or no contact with these surfaces. Plant leaf surface temperature is an important indicator of the amount of incoming and outgoing radiation. Leaf temperature has a significant impact on the rate of photosynthesis. Therefore, leaf temperature measurements reveal important information about plant status.

An **infrared thermometer** measures surface temperature. This is a line-of-sight instrument and detects the radiant temperature of object(s) it can "see". Infrared thermometers look like hand-held hair dryers with a small, circular sensing element that is aimed at a surface. It does not touch the surface, but it detects the wavelength of thermal energy emitted from that surface, which is displayed as a radiant temperature. The instrument's field of view widens with increasing distance between the object of interest and the instrument. Therefore, be sure that it is not also detecting adjacent surfaces. Measuring the surface temperature of small objects will require having the instrument close up. A large object, such as a ceiling, can be evaluated while standing several feet away. Be sure to evaluate all surfaces the plants can "see" from their vantage point.



Infrared Thermometer

Gases

Carbon Dioxide: Plants use carbon dioxide [CO_2] to grow and develop in a process called photosynthesis in which they convert carbon dioxide and water into necessary building blocks. They use (solar) radiation as their energy source and produce oxygen during the conversion process. Greenhouse growers frequently increase plant production through supplementation of carbon dioxide in the greenhouse environment. The carbon dioxide concentration is commonly expressed in units of parts per million (ppm), i.e., the number of molecules of carbon dioxide per one million molecules of air. The so-called ambient carbon dioxide concentration is around 350 to 400 ppm. Growers usually enrich the greenhouse environment to a level of around 1,000 ppm. This moderately elevated carbon dioxide concentration has no ill effects on animals or humans. During the night (without light for photosynthesis) or during periods when ventilation is required to maintain the target indoor temperature, carbon dioxide enrichment is discontinued.

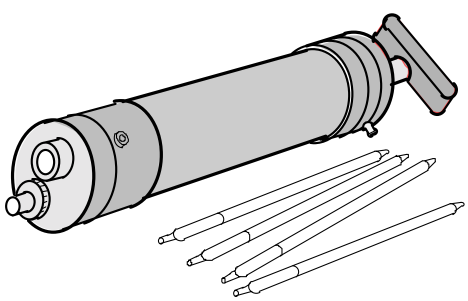
Continuous monitoring of CO_2 concentration is done as part of some greenhouse environmental control systems. Accurate carbon dioxide sensors are relatively expensive and in need of frequent and somewhat cumbersome calibrations. They can be temperature sensitive, meaning that their readings are influenced by the changes in air temperature surrounding the sensor. Most carbon dioxide sensors determine the carbon dioxide concentration by measuring the absorption of infrared light as an air sample passes through a small detection chamber. **Portable carbon dioxide monitors** can be even more expensive than permanently mounted units.

Portable Carbon
Dioxide Monitor

Contaminant Gases: Carbon monoxide [CO] and NO_x (nitric oxide NO, and nitrogen dioxide NO_2) gases are common by-products of the incomplete combustion of fossil fuel in heating systems. Proper maintenance and operation of heating systems should prevent the accumulation of these gases in greenhouses. Ethylene [C_2H_4] gas is a by-product of plant metabolism. It is considered a plant hormone because it can stimulate stem elongation and flowering, and promote ripening of fruits. In properly ventilated plant production facilities, ethylene concentrations rarely cause problems, but in closed germination rooms ethylene accumulation can cause undesirable plant responses (e.g., leaf epinasty and flower abortion).

Relatively inexpensive carbon monoxide sensors for use in homes are widely available. They are an excellent choice for monitoring carbon monoxide concentrations where combustion heating systems are used. They are powered by either batteries or by regular 110 VAC line voltage.

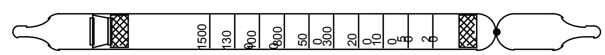
A portable and relatively inexpensive way to detect gas levels is with a hand-held **sampler pump**. This manually-operated, piston-type pump draws an accurate sample of ambient air through a **detector tube**. It is very important to hold the pump so the air pulled in through the detector tube comes from the location of interest; this means holding it near the plant during the sampling period for plant-level measurements. Remote sampling is possible for hard-to-reach areas. Dozens of gas- and vapor-specific detector tubes are available, including ones for carbon dioxide, carbon monoxide, NO_x, and ethylene. Several types of sampling pumps are available, such as a design with rubberized bulb that is squeezed for sampling. The pump and detector tubes must be compatible. As with other instruments, the sampling pump needs to be periodically checked for leakage and calibration.



Gas Sampler Pump and Detection Tubes

The thin glass detector tube is specific to the type of gas that is being measuring. For example, if the presence of carbon monoxide is a concern in the boiler room, a detector tube filled with a carbon monoxide-sensitive material would be attached to the pump. The contents of the tube react with the air contaminants and change color. The length or shade of the color change in the detector tube indicates the concentration of gas in the sample. Tubes come in a choice of measurable ranges so that accurate analysis is possible. Each tube is used once to obtain a reading and then discarded.

Diffusion tubes are an option for monitoring gas levels over a long period of time rather than the spot check provided by the sampler pump and tubes. Diffusion tubes are glass tubes filled with a reactive material specific to the gas of interest. Once both glass end tips are broken off, the tube is placed into the greenhouse environment for a number of hours (tube directions will help determined sampling time by type of tube and anticipated gas level in the environment). The average gas level over the measured time period is easy to calculate based on the distance of color change in the tube. This is a lower cost solution compared to the sampler pump and tube system, is equally reliable, and provides an indication of average gas level over a longer time interval.

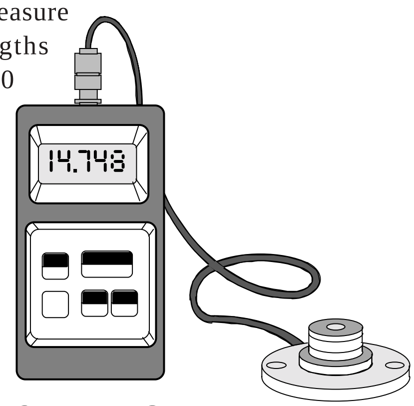


Gas Diffusion Tube

Light Level

Although not distinctly a part of the aerial environment, light level has such a major impact on greenhouse aerial environment that it is hard to ignore. Instruments for measuring light come in a variety of formats which emphasize the wavelengths of light being measured. Various wavelengths of radiation are designated into ranges of interest for specific applications such as visible light, ultraviolet light, photosynthetically active radiation, etc. The units of measurement may appear confusing as different light meters may measure in different units that are not easily convertible to wavelengths of interest for plant growth.

Of most interest for plant growth is a meter that measures photosynthetically active radiation (PAR). These **quantum sensors** measure light wavelengths from 400 to 700 nm, which approximate the photosynthetic response of plants. Units of measure are micromoles per square meter per second ($\mu mol\ m^{-2}s^{-1}$). Special-



Quantum Sensor

Photometric Sensor

ized manufacturers offer quantum sensors. More commonly found light meters measure visible light, or illuminance, and are known as **photometric sensors** (approximately 380 to 770 nm). These meters measure light radiation as perceived by the human eye. Units of measure include foot-candle (fc), which is the U.S. system unit of measure, or lux, which is the S.I. measure [1 fc = 10.76 lux]. Many visible light meters offer display of light readings in both fc and lux. Visible light is similar in range of wavelength to PAR with more visible light meters available at less cost than quantum meters. A **pyranometer** measures solar irradiance that includes ultraviolet, visible, and infrared wavelengths (approximately 280 to 2,800 nm). Units of measure are energy units (W m^{-2}).

Expose the sensor to the light level of interest. Avoid shading the sensor and keep it level. It is important to stand away from the sensor as a human body can not only cast shadow on the sensor but provides a dark surface from which little diffuse light reflects. Place the sensor near the top of the plant canopy to determine light level. Obviously, the light level will be brighter near the top of a plant canopy or near the greenhouse glazing. More sophisticated sensors provide a choice to display the light intensity based on the light source (e.g., sunlight, incandescent, fluorescent, or high intensity discharge (HID) such as high pressure sodium and metal halide)

Combination Instruments

Combination Instrument for
Air Speed, Temperature and Humidity

In the past few years, instruments with a modest price tag have been developed which incorporate sensors for several environmental features. Humidity combined with temperature has been common but more affordable and reliable instruments are now available which monitor relative humidity directly rather than from wet bulb and dry bulb calculations. A small-headed vane anemometer has been included in units that sense air speed, temperature, and relative humidity.

Dust

Dust is a difficult environmental parameter to measure and the appropriate equipment is expensive. Dust particles need to be separated by size to determine the respirable portion. This dust goes directly to the lungs and contributes to health problems. Dust, in general, is detrimental to animals, workers, equipment with moving parts, and, in extreme cases, to plants as well. Air samples may be taken and submitted to a lab where a cascade impactor, or similar device, is used to determine dust levels in a range of sizes.

Opportunities for automation

Chart recorders and **dataloggers** are available for the measurement and recording of many environmental parameters (commonly, temperature and relative humidity). Thus, data may be collected over time and analyzed later to study production system performance. Chart recorders are affordable, but require manual data analysis. Small, electronic, battery-powered dataloggers have become affordable for temperature and humidity sensing in agricultural environments. Some temperature-humidity combination electronic dataloggers are weatherproof; they cannot be submerged but will tolerate most precipitation or condensation events. Several electronic temperature dataloggers are submersible. If a computer is already available, the cost of electronic dataloggers is similar or less expensive compared to chart recorders. Chart recorders offer an immediately visible record of conditions where as electronic dataloggers must typically be downloaded to a computer for data observation. More sophisticated and convenient electronic datalogging is worthwhile for substantial data collection. In addition, several computerized environmental control systems are able to collect and store greenhouse data such as temperature, relative humidity, opening of the ventilation inlet, fan run time, etc.

Instrument Cost and Suppliers (Prices typical of year 2001)

Price ranges reflect hand-held, portable instruments suitable for agricultural applications. All display a reading. Higher priced instruments generally have more features, such as data logging, and improved accuracy compared to lower priced models. Permanently installed sensors are usually less expensive.Instrument Purchases

With the price of instrumentation, professional advisors to greenhouse growers may be the most likely purchasers. Professionals such as equipment suppliers and Extension agents may provide service in helping to diagnose greenhouse conditions or through the loan of instruments. Growers would benefit from some simple hand-held instruments which can double-check permanently installed environment control sensors and be used in unmonitored areas of the facility. One benefit of the hand-held instrument is that it can be stored for prolonged reliability in a less harsh environment than the greenhouse. Instrumentation prices have had a generally downward trend with increased reliability and accuracy. Each air quality characteristic, such as temperature, relative humidity, air speed, and flow pattern, can be measured in more than one way. The cost of instruments often is weighed against accuracy of the readings and simplicity in obtaining them. The *Instrument Cost and Suppliers* table offers detail for choosing instruments.

Contact information for companies listed in table of *Instrument Cost and Suppliers*.

Cole-Parmer
Cole-Parmer Instrument Company
625 East Bunker Court
Vernon Hills, IL 60061
800-323-4340
Web site: www.coleparmer.com

Davis
Davis Instruments Corporation
4701 Mount Hope Dr.
Baltimore MD 21215
800-368-2516
fax: 800-433-9971
email: sales @DavisOnTheWeb.com
Web site: www.DavisOnTheWeb.com

Double L
Double L Group, LTD
2020 Beltline Rd , P.O. Box 324
Dyersville, IA 52040-0324
800-553-4102
fax: 319-875-6258
email: doublel @double.com
Web site: www.doublel.com

Gemplers
Gempler's
100 Countryside Dr., P.O. Box 270
Belleville, WI 53508
800-382-8473
Web site: www.gemplers.com

Grainger
W.W. Grainger, Inc.
100 Grainger Parkway
Lake Forrest, IL 60045
Dozens of branch locations. Contact any to order. Philadephia area office: 610-534-5600
Web site: www.grainger.com

Omega
Omega Engineering, Inc.
One Omega Drive
Stamford, CT 06907
P.O. Box 4047
800-848-4286
Web site: www.omega.com

Tek Supply
Tek Supply (Farm Tek)
1440 Field of Dreams Way
Dyersville, IA 52040
800 835-7877
fax: 800-457-8887

Instrument Cost and Suppliers (Prices typical of year 2001)

Instrument	Measures	Cost	Cole-Parmer	Davis	Double L	Gemplers	Grainger	Omega	Tek Supply
Thermometer	Dry Bulb Temperature	\$10 – \$50	X	X		X	X	X	X
Min-Max Thermometer	Dry Bulb Temperature	\$30 – \$60	X	X	X	X	X	X	X
Infrared Thermometer	Surface Temperature	\$80 – \$600	X	X		X	X	X	X
Sling Psychrometer	Humidity via Dry & Wet Bulb Temperature	\$55 – \$75	X	X		X	X	X	
Aspirated Psychrometer	Humidity via Dry & Wet Bulb Temperature	\$140 – \$250	X	X					
Hygrometer	Humidity & Dry Bulb Temperature	\$40 – \$200	X	X	X	X	X	X	X
Hot-wire Anemometer	Air Speed	\$350 – \$1,700	X	X	X	X	X	X	
Vane Anemometer	Air Speed	\$90 – \$1,000	X	X	X	X	X	X	X
Velocity Manometer	Air Speed	\$20 – \$1,000		X			X	X	
Smoke Gun	Visualization of Air Speed	\$130 + refills	X	X					
Smoke Sticks & Candles	Visualization of Air Speed	\$3 – \$5 each	X	X					
Gas Monitoring	Carbon Dioxide	\$500 – \$3500	X	X			X		
Gas Monitoring	Trace Gases	\$430 – \$1,000	X	X			X		
Gas Sampler Pump	Gases CO_2, CO, NO_x	\$225 + \$4 – \$5 per tube		X					

Price ranges reflect hand-held, portable instruments suitable for agricultural applications. All display a reading. Higher priced instruments generally have more features, such as data logging, and improved accuracy compared to lower priced models. Permanently installed sensors are usually less expensive.

Summary

Determining aerial environmental characteristics in greenhouses allows us to evaluate problems and their potential causes. This is the first step in correcting any problems that are detrimental to plant production. Hand-held instruments are used to quantify aerial environmental characteristics such as temperature, relative humidity, air speed, carbon dioxide concentration, light level, and possible contaminant gas levels. Changes in environmental conditions and management practices are the next step. Then, the aerial environment can again be quantified for comparison. Progress in improving the environment can be determined and plant status changes documented.

Instruments are often appropriate only for specific applications. The best readings are obtained when the basic principles of how the instrument detects an environmental characteristic are understood. This fact sheet has outlined how various instruments work so that more effective measurement and diagnosis can follow. Following proper measurement techniques will provide reliable readings and minimize human impact on the aerial environment being investigated. This has been emphasized in this fact sheet and in *Principles of Evaluating Greenhouse Aerial Environments*, Bulletin E275. Troubleshooting ventilation systems is covered in *Evaluating Greenhouse Mechanical Ventilation Systems*, Bulletin E277. Periodic checks of environmental conditions, with instrument readings, are a supplement to the everyday observation of facility conditions, plant status, and production records.

Other Instrument Sources

Gas Diffusion Tubes [about $6 each]

Western Safety Products, Inc. Seattle WA 888-823-0808
Web site: http://www.westernsafety.com

Draeger Safety, Inc. Pittsburgh PA 412-787-8383
Web site: www.draeger.net

Visible Light Meters [$120 to $465]

Davis Instruments (contacts listed above)

PAR Light Meters

Apogee Instruments, Inc. Logan, UT 435-512-5025
Web site: www.apogee-inst.com

LI-Cor Products, Environmental Division Lincoln NE 800-447-3576
Web site: env.licor.com.prohome.htm

Spectrum Technologies, Inc. Plainfield, IL 800-248-8873
Web site: www.specmeters.com

Theatrical Fog Generator [starting at $300]

Abyss Special FX, Inc. 330-273-1221
Web site: www.abyssfx.com

LightWave Research/High End Systems Austin, TX 800-890-3063

This list and table are not intended as an exhaustive list of instrument suppliers. Companies represent a mix of catalogs typically found in grower offices and educational institutions. Mention of trademark, proprietary product, or vendor is for information purposes only. No endorsement implied.

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