Chapter 6

Air Movement

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Contents

Introduction

Ecologists have long recognized the importance of wind, or air movement, in controlling plant growth under field conditions. Wind in the outside environment is an environmental factor of considerable importance and is likely to receive additional attention with projected changes in global climate. The biological effects of wind have been studied by a number of ecologists and crop scientists (Bernbeck, 1924; Businger, 1975; Campbell, 1977; Finnell, 1928; Grace, 1977, 1985; Hill, 1921; Humphries and Roberts, 1965; Monteith, 1973; Nobel, 1981, 1983; Whitehead, 1962). Only under rather extreme conditions, however, are the effects of wind readily noticed. Violent winds of short duration blow down trees and cause lodging and breakage of crops (Armbrust et al., 1974; Grace, 1977; Jacobs, 1954; Lawton, 1982; Nobel, 1981; Pinthus, 1973; Waister, 1972). Moderate wind velocities concentrated from a single direction can cause dwarfing and plant deformation if the wind is cold, or if it carries salt spray (Boyce, 1954; Holroyd, 1970; Noguchi, 1979).

Only during the past 10 to 20 years have investigators begun to appreciate the importance of measuring and controlling air movement in plant growth chambers. Because of its pervasive effect on leaf temperature, gas exchange, and boundary layer resistance, and hence photosynthesis and water loss, air movement exerts a profound impact on the morphology, physiology, and reproduction of the plant.

Recent findings on hormonally induced changes in cell structure and overall morphology after mechanical manipulation of a plant suggest that greater attention should be paid to the effects of air movement in producing mechanical perturbations on plants. Inadvertent manipulation may occur through handling of plants (e.g., spraying them with water or nutrients, moving them about on carts, or subjecting them to excessive vibration) as well as during data collection (e.g., obtaining measurements of growth and stomatal behavior). It should be recognized that wind-induced mechanical movements also are normal ecological factors in the field.

Definitions

Because terminology used to describe air movement or wind varies somewhat depending on the scientific discipline of the investigator, it is necessary to define some of the terms commonly used. Two handbooks used by meteorologists as standard references that may be helpful are the American Meteorological Society Glossary edited by R. E. Huschke (1970) and the Great Britain Meteorological Society Glossary compiled by D.H. McIntosh (1972). Many of the terms in these references, however, are not applicable to growth chamber conditions and are not listed below.

Air Velocity: The movement of air signifying rate of change of position with time in a specified direction. This term can be used to describe air movement in a growth chamber if measurements are made in a specified direction. Units are expressed in m s^{-1} (or ft min^{-1}) in a specified direction. Conversion factors: 1 m s^{-1} = 196.85 ft min^{-1} = ca. 200 ft min^{-1}; 1 ft min^{-1} = 0.005 m s^{-1}.

Air Movement: The flow of air signifying the rate of change of position with time, expressed in m s^{-1} or ft min^{-1} without specifying direction. This term is most commonly used to describe air flow in a plant growth chamber. Measurements can be made by using unidirectional or omnidirectional sensors.

Air Flow: The movement of air signifying rate of change of position with time, expressed as linear flow (m s^{-1} or ft min^{-1}) or as volume flow (m^3 s^{-1} or ft^3 min^{-1}) without specifying direction; this term is synonymous with air movement. This definition is commonly used by engineers to describe movement of a large volume of air.

Wind: The movement of air caused by a pressure gradient. This term is applied to air movement in an open environment but not for describing air movement in controlled-environment rooms and chambers (except in wind tunnel rooms).

Air Speed: The flow of air signifying rate of change of position with time without specified direction. It is synonymous with air movement and air flow but not used to describe air flow in growth chambers.

Turbulence: Random oscillations of finite size leading to irregularities in the path of air particles.

Turbulence Intensity: The standard deviation of air movement divided by the mean air movement is called turbulence intensity. Near vegetation outside, the turbulence intensity is about 0.4 (Nobel, 1983). The highest turbulence intensity measured in six types of downward-flow plant growth chambers was 0.25.

Plant Responses

Under growth chamber conditions, the biological effects of air movement are much less drastic than under field conditions, but they still exist. Air movement influences plant growth by determining the extent of: (1) sensible or conductive heat transfer from plant surfaces, substrate, and plant containers (Cook et al., 1964; Drake et al., 1970; Humphries and Roberts, 1965; Idso and Baker, 1967; Linacre, 1967; Matsui and Eguchi, 1972; Mellor et al., 1964; Nobel, 1981; Raschke, 1960; Vogel, 1968, 1970); (2) transpiration, evaporation, and latent heat transfer from plant surfaces and substrate (Briggs and Shantz,

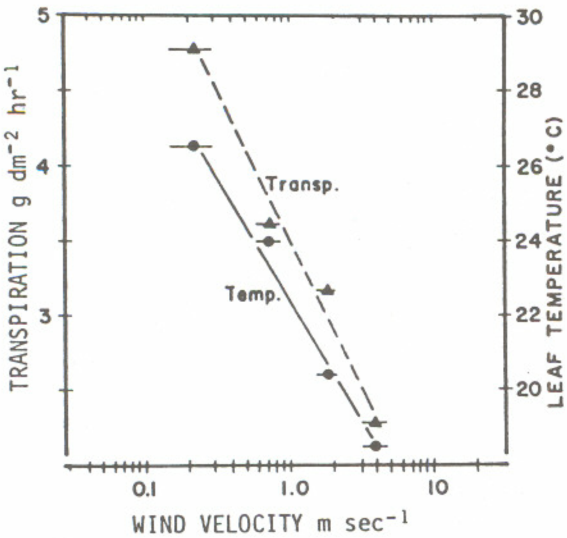

Figure 1. A striking example of decreasing transpiration with increasing wind speeds at high relative humidity. The apparent cause is the equally sharp drop in leaf temperatures and hence the greatly lowered vapor pressure difference between the leaf's internal spaces and the atmosphere. Radiant energy = 10,000 cal m^{-2} min^{-1}; air temperature =15 ± 0.5°C; relative humidity = 94 to 96%. (Mellor, Salisbury, and Raschke, 1964; Salisbury, 1979).

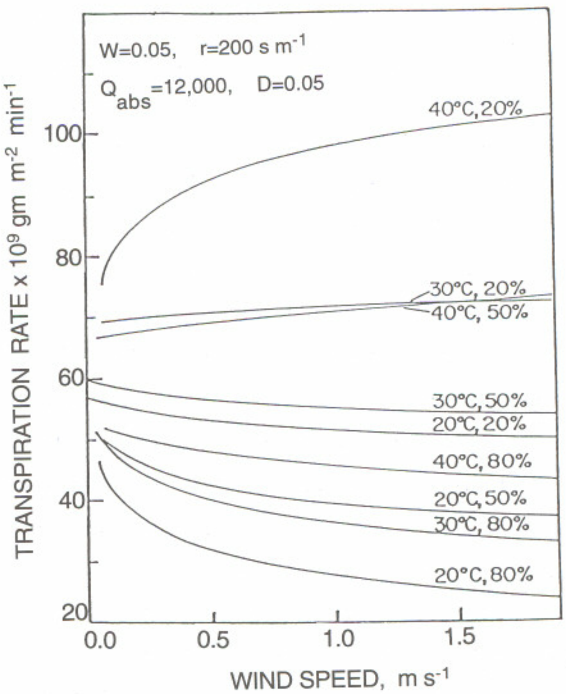

Figure 2. Computed transpiration rate as a function of wind speed for various air temperatures and high and low relative humidities for the fixed conditions given. Q_{abs} = radiation = 12,000 cal m^{-2} min^{-1}; D = leaf dimension in m in the direction of the wind; W = leaf dimension in m transverse to the wind; and r = internal diffusion resistance of the leaf in s m^{-1}. Illustrates that transpiration will increase in dry air and decrease in humid air with an increase of wind speed if the amount of radiation absorbed by the leaf is large. (Gates, 1968).

1916; Brown, 1910; Davies et al., 1974; Firbas, 1931; Gates, 1968; Gates and Papian, 1971; Gäumann and Jaag, 1939; Grace and Russell, 1977; Kucera, 1954; Martin and Clements, 1935; Monteith, 1965; Nakayama and Kodota, 1949; Pitcairn and Grace, 1982; Satoo, 1962; Stålfelt, 1932; Wooley, 1961) (Figs. 1 and 2); and (3) uptake of carbon dioxide by leaves and stems (Caldwell, 1970; Gäumann and Jaag, 1939; Morris et al., 1954; Nakayama and Kadota, 1949; Rao, 1938; Seybold, 1929; Stålfelt, 1932; Uchijima and Wright, 1964; Waggoner et al., 1963; Warren Wilson and Wadsworth, 1958; Wright and Lemon, 1970). As a result, leaf size, stem growth, and crop yield can be greatly affected by variations in air movement (Deneke, 1931; Wright and Lemon, 1970; Yabuki et al., 1972; Yabuki and Miyagawa, 1970). The primary drivers of plant responses to air movement, however, are vapor pressure deficit of the air and soil-plant-water transport capacity. Air movement serves as a removal agent to minimize boundary layer resistances.

Mechanical Stress

Numerous studies have been conducted on the effects of mechanical stress induced by shaking or rubbing the plant, or by subjecting plants to wind gusts, water sprays, or sand blasts (Beyl and Mitchell, 1977; Biddington, 1986; Biddington and Dearman, 1985, 1987; Grace and Russell, 1982; Grace et al., 1982; Hunt and Jaffe, 1980; Jaffe, 1973, 1976, 1980, 1985; Jaffe et al., 1984; Jaffe and Biro, 1979; Larson, 1965; Lattimer, 1991; Liptay, 1985; Mitchell et al., 1975; Neel and Harris, 1971, 1972; Nobel, 1981; Sinnott, 1952; Telewski and Jaffe, 1986; Todd et al., 1972; Turgeon and Webb, 1971; Wheeler and Salisbury, 1979; Whitehead and Luti, 1962; Wilson and Archer, 1977). These studies have shown that wind-gust- induced shaking of plants may have important effects on plant morphology.

Kidney bean plants showed a linear decrease in internode elongation and a corresponding increase in radial stem enlargement with air movements up to 4.5 m s^{-1} (Hunt and Jaffe, 1980). Ten daily gusts of air at 4.7 m s^{-1}, given for 10 s each, reduced stem growth of *Phaseolus vulgaris* plants by 40% (Jaffe, 1976). In sunflower, a threefold reduction in internode elongation was observed as the air movement was increased from 0.4 to 15 m s^{-1} for a 30-day period (Whitehead, 1962). Air movement of 6 to 10 m s^{-1} reduced the leaf area of aspen by 50 to 70% (Flückiger et al., 1978). Shaking *Liquidambar styraciflua* stems for 30 s per day for 27 days during greenhouse growth shortened stem length by 70-80%. Similar reductions in growth were observed in wind-blown trees outdoors (Neel and Harris, 1971).

In a number of woody and herbaceous species, mechanical rubbing of the internodes caused cessation of stem growth within minutes of treatment; several days passed before normal growth resumed (Takaki et al., 1977). It has also been found that gentle bending or rubbing of leaves can double the respiration rate (Audus, 1935; Godwin, 1935) and that shaken leaves have a reduced rate of photosynthesis (Kahl, 1951; Pappas and Mitchell, 1985). Indeed, any mechanical stimulation seems to have a negative effect on some phase of growth (Jaffe, 1976).

The conclusion that low air movement in plant growth chambers is the cause of spindly plants that fail to resemble their field-grown counterparts primarily has been drawn from experiments conducted under limiting radiation levels. When photosynthetic photon flux (PPF) levels in the growth chamber are similar to those found in open-field environments, the effects of mechanical stress have been minimal (Jones et al., 1990). Moreover, the field phenotype of tobacco plants has been duplicated in plant growth chambers where the mean air flow was 0.33 m s^{-1} (Raper and Downs, 1976).

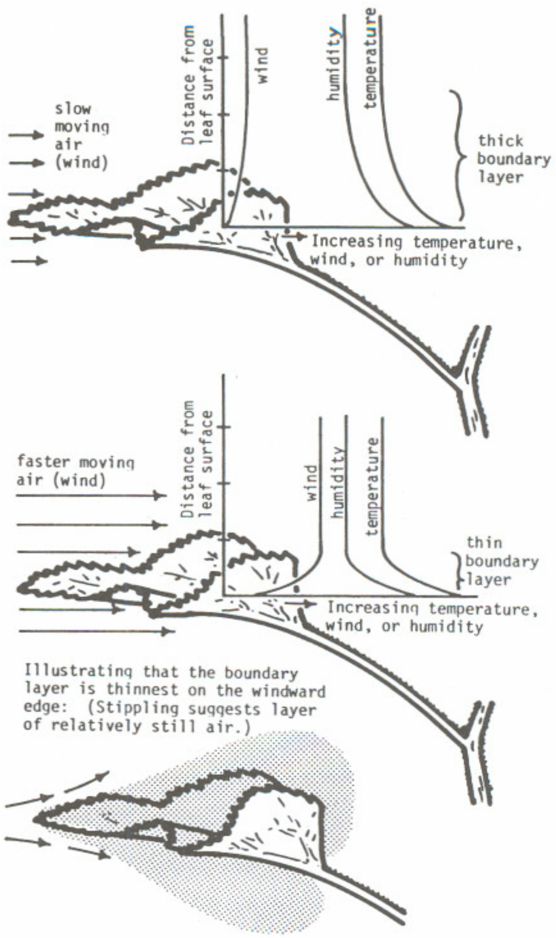

Figure 3. Some principles of the boundary layer and heat transfer by convection. The two upper leaves are assumed to be at the same temperature and in air at the same temperature; only wind speed is different. The thickness of the boundary layer decreases with increasing wind speed. (Salisbury, 1979.)

Temperature and Gas Exchange

The primary effect of air movement on heat exchange, CO_2 uptake, transpiration, and evaporation results from its influence on the boundary layer at the leaf surface (Fleagle and Businger, 1963; Gates and Papian, 1987; Nobel, 1974, 1983; Parlange et al., 1971; Perrier et al., 1973). The friction between the leaf and the air moving across it causes a layer of air to adhere to the leaf surface (Fig. 3). Heat is conducted across this layer relatively slowly, and water vapor and CO_2 must be exchanged by diffusion through this boundary layer. Because air velocity affects the thickness of the boundary layer, all temperature-dependent processes and gas-

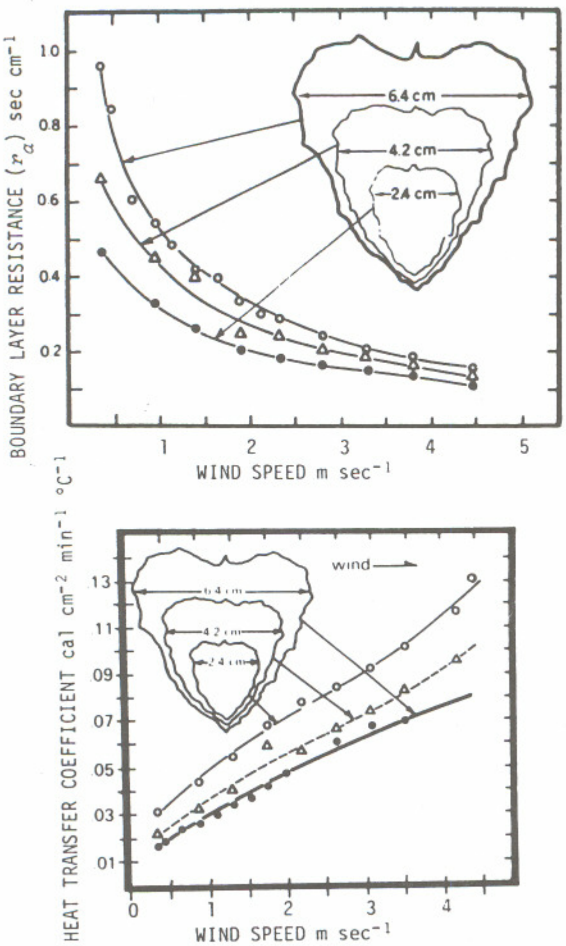

Figure 4. Boundary layer resistance and heat transfer coefficient, both shown as a function of wind speed over copper-plated leaves of cocklebur (*Xanthium strumarium*). Boundary layer resistance decreases with increasing wind and with decreasing leaf size, whereas the heat transfer coefficient, its reciprocal, increases with increasing wind and smaller leaf size. The heat transfer coefficient more closely approaches a linear function of wind speed. (Drake, Raschke, and Salisbury, 1970; Salisbury, 1979.)

exchange processes of the leaf are affected by air movement.

Air movement alters the mean thickness of the boundary layer (Fig. 4). For a laminar flow across a perfectly smooth surface:

boundary layer = $4\sqrt{d/v}$

where d is the distance in meters that the air flows across the surface and v is the air velocity ($m\ s^{-1}$) (Gates, 1980; Gates and Papian, 1971). For example, the boundary layer would be 1.33 mm if air flows at the rate of 0.45 $m\ s^{-1}$ across a surface 5 cm wide, but if air movement is increased to 1.0 $m\ s^{-1}$, the boundary layer would be reduced to 0.89 mm (Nobel, 1983).

However, calculations of boundary layer effects over leaf and plant surfaces are much more complex because of the pubescence, irregular nature of surfaces, and leaf movement. Consequently, values obtained from calculations using smooth surfaces are generally only approximations of the actual boundary layer effects in operation. Theoretical formulas and discussion of factors controlling boundary layer resistances are provided by Kramer (1969), Nobel (1981, 1983), and Slatyer (1967).

Regulation

Air Movement

When designing growth chambers and controlled-environment rooms for plants, we must decide on the air flow to be used. Should we try to use the average outdoor wind speed or an air movement that maintains optimum growth of the plants? Average wind conditions to which plants are exposed in nature are difficult to define. Meteorological wind speed measurements usually are made 10 m above the ground and show the average wind speed in the United States to be between 2.2 and 4.5 $m\ s^{-1}$ (Hellickson et al., 1983). Wind velocities at 10 m, however, rarely if ever represent the air movement at plant level and certainly not the air flow within the plant canopy.

Air flow at the top of the crop canopy is reduced because of the frictional drag from the plants. Drag resistance is greater within the canopy, and air movement is slower the deeper into the canopy; at or near ground level, air flow is often near zero. For example, data show that when the air flow is 2.5 $m\ s^{-1}$ two meters above a bean crop (about 3 m above the ground), it is reduced to 0.9 $m\ s^{-1}$ at the top of the canopy and to less than 0.25 $m\ s^{-1}$ near the middle of the canopy (Thom, 1971). Within-the-canopy profiles have been measured by a number of others with the same general result, a rapid decrease in air movement within the canopy (Cionco, 1965; Landsberg and James, 1971).

In simulating "natural" air velocities, one also must include the diurnal changes in air flow (Geiger, 1965), which begins to increase at about 0600 hours, reaches a maximum at 1200-1300 hours, then decreases to a minimum again by approximately 2000 hours.

Because a definitive number representing average natural air velocities is difficult to obtain, the air flow in most controlled-environment rooms is designed to provide optimum growth of the plant and at the same time minimize temperature gradients throughout the chamber.

The determination of desirable air movement rates for optimum growth has been studied, but no definitive conclusions have been reached. For general use, a growth chamber should have an air flow between 0.3 and 0.7 m s^{-1} (Morse and Evans, 1962; Wadsworth, 1959; Yabuki and Miyagawa, 1970). The phytotron at Gif-sur-Yvette, France, used 0.3 m s^{-1}, and the facility in Canberra, Australia, uses 0.55 m s^{-1}. The design requirement of the SEPEL phytotrons in North Carolina was 0.5 m s^{-1}, although the actual average air flow obtained is 0.33 m s^{-1}. This air movement rate causes a slight flutter of leaves on the plants.

Some investigators (e.g., Joffe, 1962; van Bavel, 1973) have recommended using air velocities of 1.5 m s^{-1} or higher to facilitate temperature control. Van Bavel (1973) even suggested that if high rates of transpiration and associated depression of leaf water potential and leaf water content are desired, an air speed up to 5 m s^{-1} should be used. The air flow required to maintain a small temperature gradient, however, is closely related to the thermal load from the lighting system. The greater the lamp wattage, the greater must be the air flow to maintain small temperature gradients in the growing area. In an installation at Kennedy Space Center that provides a photosynthetic photon flux of 700 µmol m^{-2} s^{-1} from high pressure sodium lamps, air flows up to 1.2 m^{-2} s^{-1} are being used (Wheeler et al., 1990). The lamp heating effect is much smaller so the requirement for air movement is reduced as long as the lamps are separated from the growing area by a barrier. Much of the conducted-convected heat is removed by the ventilation air or the cooling system of the lamp loft.

Air movement in a controlled-environment room varies according to the size and geometry of the room and the locations of the air inlet and air outlet (Chikushi et al., 1989). In most chambers, reducing the air flow is likely to compromise the control of temperature and relative humidity, and air movement usually can be increased only by installing larger fans or blowers. When designing a controlled-environment facility, it may be desirable to provide a means of adjusting air velocity. This may be done by using large fans or blowers equipped with motor speed controls, by using volume control dampers in the air stream, or both.

Air flow in controlled-environment rooms is usually established when the chamber is empty. Significant changes in air movement values may be expected when plants are placed in the chamber because their containers create a resistance to flow. When the plant area exceeds the container area, the resistance to flow is likely to increase further, and either the air velocity will be altered or the fan speed (rpm) must be changed to obtain the same velocity as when the containers were the chief form of resistance.

To obtain a theoretical natural air flow, diurnal changes in air velocity could easily be preprogrammed using electronic timers. However, if the objective of variable air speeds in the controlled-environment room is to study the biological effects of air velocity, then a wind tunnel would be more suitable (Grace, 1977).

Direction

Air in controlled-environment rooms can flow from bottom to top, top to bottom (often called downward or reverse air flow), or horizontal. The chief argument for moving the air from bottom to top is that this method provides a laminar flow of air through the plant growing area. Unfortunately, the laminar flow is quickly disrupted once plants are placed in the chamber, and uniform air flow cannot be maintained unless the plant containers are spaced evenly over the growing area. Moreover, the air movement across the leaf will change considerably depending upon the number and size of the plant containers per unit area of the growing space. For example, a plant growth chamber with an area of 2.97 m^2 might have an air flow of 0.5 m s^{-1} when empty. If the space were filled with 15-cm pots and about 112 could be used, the reduction in free area conceivably could result in a threefold increase in air velocity as the air passed between the containers.

From the point of view of both engineering and plant scientists, downward air flow is preferable to upward air flow because temperature gradients are smaller (Morse, 1963). Dimock (1963) noted that the results of intensive study at Cornell University showed that the vertical temperature gradient with downward air flow was only half as great as with upward flow. Matsui et al. (1980) also concluded from their studies on humidity distribution that downward air flow gave the most consistent pattern of air movement. In general, downward movement of air will more closely mimic humidity and temperature profiles found under field conditions. Humidity levels should always increase with depth in the canopy (Allen, 1975). Morse and Evans (1962) reported that plant growth of tomato, lucerne, and subterranean clover was slightly greater when the air flow was downward (Fig. 5).

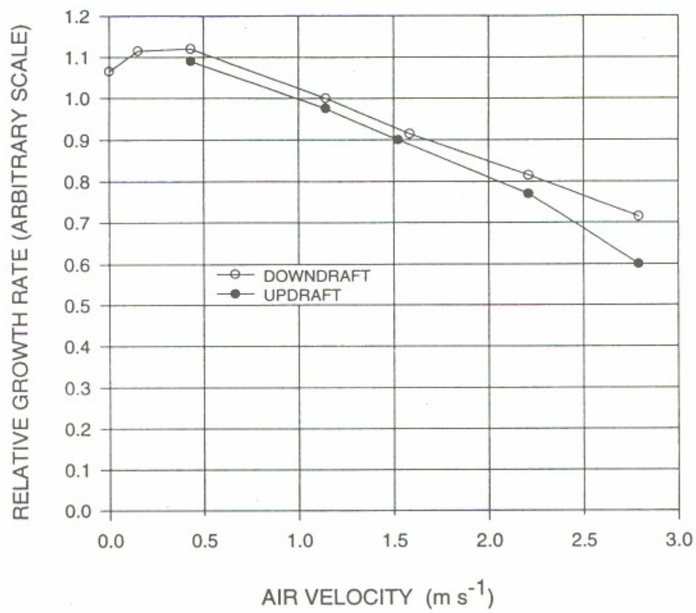

Figure 5. Effect of air velocity and direction of air flow on the relative growth rate of leaves. Data based on leaf areas taken in a series of experiments with tomato, lucerne, and subterranean clover in CERES, an Australian phytotron. Plants exposed to air velocities up to 3 m s^{-1}. (Morse and Evans, 1962.)

The argument for using horizontal air flow in a growth chamber is that canopy turbulence more closely resembles natural conditions than with an upward or downward air flow (Monteith, 1964; Doorenbos, 1972), although no data have been presented to verify this assumption. The obvious disadvantage of a horizontal air flow is that in the presence of the radiant lamp load, air temperature and humidity will rise as the air crosses the chamber. The greater the lamp load, the greater the horizontal gradient. Forrester (1979) claims that the plants create turbulence that reduces the gradient to a negligible level. Smeets (1978) claims that the temperature rise is not significant when the radiant heat is reduced by cold water running over the glass barrier that separates the lamps from the growing area. If the distance across a growth chamber is very great, however, this gradient in temperature and humidity may be quite large (Allen, L. H. Jr., Gainsville, Florida, Personal communication, 1989). On the other hand, even though a horizontal gradient is present, rooms can be used effectively for research studies by assigning blocks (replicates) along the horizontal gradient. Allen indicates that if humidity is kept low and air temperatures are high enough, the temperature will drop because of evaporative cooling by the plants. However, a horizontal humidity gradient is still produced.

Fresh Air Supply

Any discussion of air movement must also consider the need for a fresh air supply, commonly called makeup air. If no provision is made to inject CO_2 into the chamber atmosphere to compensate for the CO_2 taken up during photosynthesis, then makeup air is helpful, especially in tightly enclosed growth rooms or specially constructed closed chambers where CO_2 deficits can easily occur once the canopy becomes dense (Bailey et al., 1970; Downs and Hellmers, 1975; Krizek, 1986; Krizek et al., 1970). This is discussed in Chapter 4 on carbon dioxide.

Morse (1963) calculated that fresh air must be supplied at a rate of 0.017 to 0.025 $m^3 s^{-1}$ for each square meter of plant growing area to avoid a significant drop in CO_2 level. Thus the average 1.22 x 2.44 m plant growth chamber would need 50 to 67% of its air exchanged with outside air each minute. Morse's (1963) calculations demonstrate that most makeup air systems cannot meet this need for CO_2 exchange. It would be difficult to retrofit an existing chamber to exchange a sufficiently large volume of fresh makeup air from outside during extremes in outdoor temperature without overloading the heating and cooling system, unless the air was preconditioned before it was introduced. Preferably, the outside air should be introduced at the inlet side of the coil to preserve uniformity, but this is rarely done. If more than one cooling coil is used, the outside air must be equally distributed among the various coils.

Although air leakage of most commercially constructed plant growth chambers is quite low, some chambers may leak enough to exchange a significant amount of air with the outside. Thus, part of the need for additional CO_2 is satisfied through leakage. A large amount of leakage, however, can cause variation in CO_2 levels because CO_2 concentrations in the plant growth room could vary with the amount of human activity in the surrounding area.

Some researchers consider that even with CO_2 injection, some outside air should be introduced into the chamber to prevent buildup of ethylene and other volatile substances produced by the plant and various components in the chamber or buildup of ozone released by the fan motors. Air contaminant problems are discussed in more detail in Chapter 5 of this handbook.

Measurement

Instruments

Many instruments are available for measuring air velocity under field conditions (Fritschen and Gay, 1979; Grace, 1977; Hanan, 1984; Kilifarska and Kondacov, 1975; Mazzarella, 1972; Middleton and Spillhaus, 1953; Monteith, 1972, 1973; Ower and Pankhurst, 1977; Primault, 1979; Slatyer and McIlroy, 1961; Tanner, 1963; Wadsworth, 1968), but many of these devices are unsuitable for measuring the relatively low air velocities of plant growth chambers (Downs, 1975; Hanan, 1984).

Several criteria need to be considered in selecting an anemometer for growth chamber use (Grace, 1985): (1) the range of air velocities over which the sensor operates; (2) high sensitivity at low air velocity; (3) the linearity of output of the instrument; (4) the time constant or distance constant; (5) size of the instrument; (6) cosine response; and (7) temperature compensation. For those using meter readouts or output to a data logger, linearity of response of the instrument is of little consequence. Linearity of voltage/air velocity output, however, is of considerable value when strip chart recorders are used.

Many anemometers, such as hot-wire ones, are directional; that is, they do not measure air velocity equally from all directions. Indeed, the measured value can vary as much as 50% depending on orientation of the hot wire. Moreover, the presence of the person doing the measuring also can cause appreciable error. Therefore, the anemometer should be attached to a support such as a ring stand, oriented for maximum output, unless an omnidirectional transducer is used, and the output entered into a recording device so that the measurements can be taken while the observer is outside the chamber.

Hot-Wire Anemometers: In hot-wire anemometry, a fine metal wire with a large coefficient of resistivity, such as platinum, tungsten, nickel, or 80:20 platinum-iridium, is heated by an electrical current (Lomas, 1986; Perry 1982; Tanner, 1963). All hot-wire anemometers contain the same basic parts: a probe with its cable and an electronics package (Lomas, 1986). A typical hot-wire probe is shown in Fig. 6. Air flowing over the wire causes a decrease in temperature and an increase in electrical resistance. In some instruments, the change in resistance of the wire is used as a measure of the air velocity (Caborn, 1968). Resistance increases as the air velocity increases. In other instruments, the resistance is kept constant by altering the heater current or voltage to maintain a constant temperature (Fig. 7). In these instruments, the change in current or voltage is used as the indicator of the air velocity. In this case, the square of the current is proportional to the square root of the velocity. Generally, the constant temperature method has greater sensitivity than the resistance change method. Air temperature changes obviously will cause alterations in output that are not related to velocity. These variations, however, are minimized by keeping the wire temperature high relative to the air temperature. Air temperature

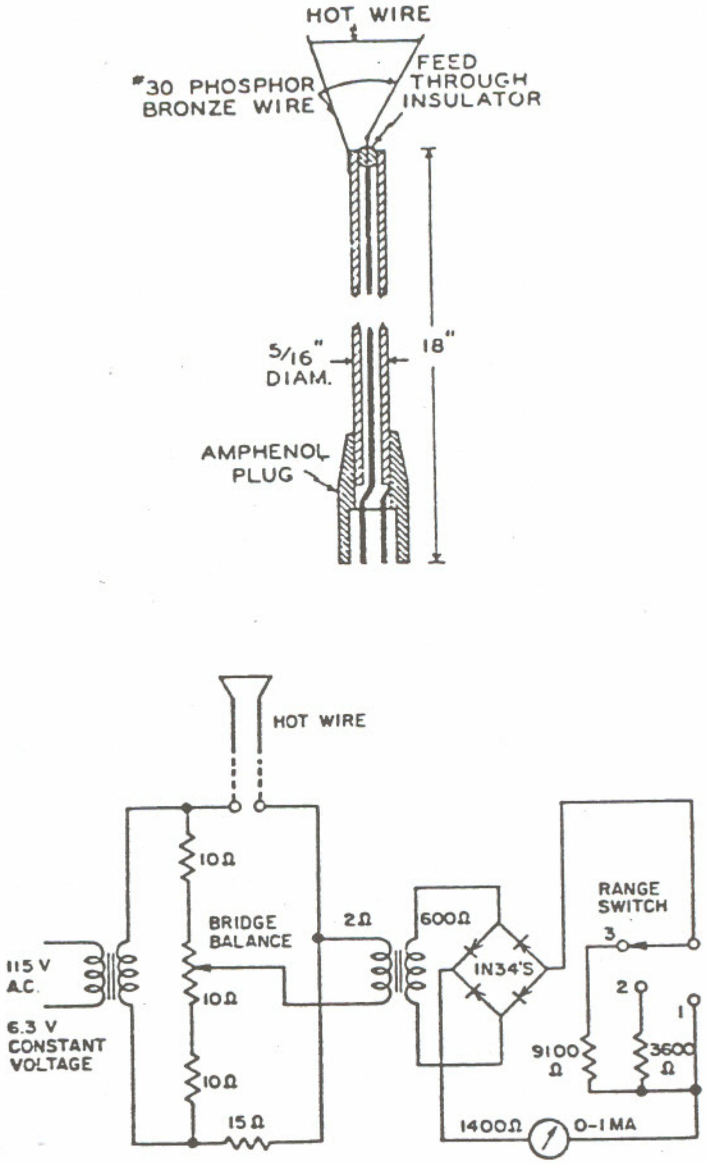

Figure 6. Sketch of a typical hot-wire anemometer probe (top) and its accompanying wiring schematic (bottom). This system is not linearized or temperature-compensated. (Anderson, 1959; Hanan, 1984.)

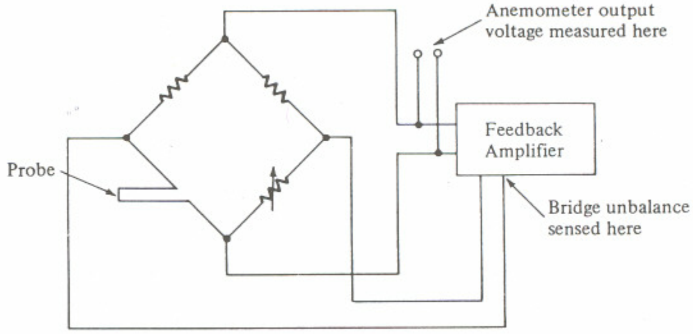

Figure 7. The block diagram of a constant temperature anemometer. A hot-wire probe acts as one resistor in the Wheatstone bridge, and the feedback amplifier automatically adjusts the current to maintain bridge balance. (Lomas, 1986.)

problems are also reduced by using two wires, one exposed to the air flow and the other maintained in still air, acting as an adjacent leg of the measuring bridge.

The hot-wire anemometer is one of the most commonly used instruments for monitoring air flow in plant growth chambers and controlled-environment rooms, especially at air flows between a few cm s^{-1} and 2 m s^{-1} (Anderson, 1959; Cowdrey, 1950; Deacon and Samuel, 1957; Hastings, 1948). It is an excellent instrument for characterizing air flow around leaves and throughout the plant canopy because it can be made quite small, fits in confined spaces, and has a rapid response time (Grace, 1977; Lomas, 1986; Perry, 1982). Commercially available instruments generally respond to less than 0.001 m s^{-1} air velocity. Hot-wire anemometers are also used extensively in wind tunnels and in air-conditioning applications to balance air flow in the ducts and adjust the discharge volume of diffusers.

The main disadvantages of most hot-wire anemometers for growth chamber applications are their directional response and the fact that most of them are hand-held, portable units without an analog output. However, omnidirectional and multidirectional hot-wire anemometers have been used in the past (Allen, 1968), and several manufacturers are currently producing omnidirectional transducers with signal processors that provide an analog output. Other disadvantages of the instrument are that the wire is easily broken and that the natural convection currents generated by their own heat may become large at extremely low wind speeds.

Obtaining a representative reading of air movement in plant growth chambers can be a problem because turbulence causes rapid fluctuations (1 s or less) in the reading. It is necessary to take at least 10 readings and average these to get a representative reading. The availability of computerized measuring instruments that integrate a series of readings is a significant advantage and is strongly encouraged for air movement readings. Recently, computerized methods of data collection have been developed to permit calculations of mean and turbulence intensity with these instruments (Grace, 1977). Because many strip chart recorders do not respond fast enough to keep pace with the rapidly fluctuating signal, an oscilloscope or oscillograph occasionally is used to display the results.

Heated thermistors (Bergen, 1971) and heated thermocouples (Kanemasu and Tanner, 1968; Simmons, 1949) are sometimes used instead of heated resistance wires. In these cases, the output depends on the heating current, and fluctuations in that current can cause large errors. A change in current of 1.5% can cause a 10% reading error.

Laser-Doppler Anemometer: This type of anemometer uses the Doppler shift of laser light scattered from air particles to measure the velocity of the particles. Because the size, concentration, and refractive index of the particles can alter the quality of the measurement, this type of instrument is rarely used in plant growth chambers, except for specialized studies on heat and mass transfer from plant leaves (Durst et al., 1975). The advantage of the laser-Doppler method over hot-wire anemometry is that measurements of air flow can be made near the heated surface (e.g., at distances closer than 1.0 to 1.5 mm, that is, inside the boundary layer). When comparable measurements were made with a hot-wire anemometer, faulty values were obtained because of contact with the leaf hairs, which caused greater heat transfer from the wire and hence higher velocity readings (Durst et al., 1975). The disadvantage of this technique is that sophisticated and expensive instrumentation is required to detect and analyze the signal (Grace, 1977). Laser-Doppler anemometers typically consist of a 5-mW He-Ne laser, an integrated optical unit, a light-collecting and imaging lens, and a photomultiplier to convert optical signals into electrical ones.

Other Procedures. Several semiquantitative methods exist for determining uniformity of air flow. These include the use of lightweight pieces of cloth or paper placed throughout the area, bubbles of soap or smoke released into the air stream, or Schlieren photography (Barnes and Bellinger, 1945; Bergen, 1975; Grace, 1985; Lines and Howell, 1963; Moen, 1974; Rutter, 1965). Unfortunately, none of these methods is very useful for determining rates of air flow in plant growth chambers.

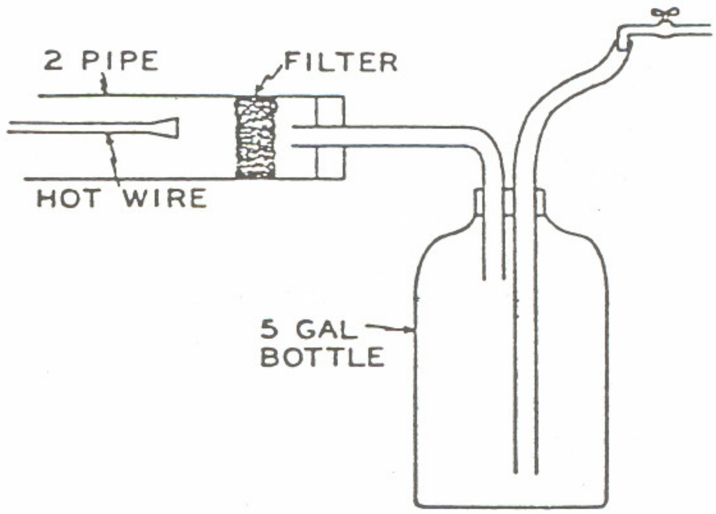

Figure 8. Anderson's (1959) system for calibrating hot-wire probes resulting in steady winds below 0.5 m s^{-1}. The 20 L container is connected to a water tap, and the displaced air is fed into a 5 cm diameter tube. The filter is steel wool. (Anderson, 1959; Hanan, 1984.)

Within Chambers

The average flow rate in the plant growth chamber should be determined by measuring the air flow at a minimum of five positions uniformly spaced throughout the plant growing surface. The measuring instrument should be located so that a maximum flow rate is monitored at each measured location. When using an instantaneous measuring instrument, such as a hot-wire anemometer without analog output, a series of at least 10 measurements should be taken at each location in succession and averaged.

Calibration of Sensors

Procedures for calibrating anemometers have been described (Hanan, 1984; Lomas, 1986). Sensors are generally calibrated directly in moving air past the sensor in a wind tunnel (Hanan, 1984). The wind tunnel is in turn calibrated by means of a pitot-static tube connected to a sensitive manometer. Because of the linear relationship between air velocity and fan speed in most wind tunnels over a certain range of fan speeds, once an initial calibration is made, the anemometer may be calibrated by simply selecting a given fan speed. However, most wind tunnels operate poorly below 1 m s$^{-1,}$ and the fan motor may stall at low speed. Also, pitot-tube calibration is inaccurate in this range. Because the wind tunnel procedure generally is unsatisfactory for calibrating anemometers at low air velocities, other methods have been described. Manca et al. (1988) described a calibration method that used volumetric flow from a glass tube with the air temperature controlled by a heat exchanger. Seifert and Graichen (1982) used free jet nozzles designed to overcome the boundary layer effect within the nozzle. Anderson (1959) described a method for calibrating wire probes below 0.5 m s^{-1} (Fig. 8). This involved use of a container connected to a water tap so that as the container was filled with water, the displaced air fed into a 5 cm diameter tube in which the hot wire probe was inserted. For higher wind speeds, larger containers may be used with smaller tubes (4 cm diameter) packed with 8-cm long soda straws.

Almquist and Legath (1965) descibe a method in which a bottle is filled with a constant flow of water to produce a low-velocity air flow for hot-wire calibration (Fig. 9). The water flow rate is

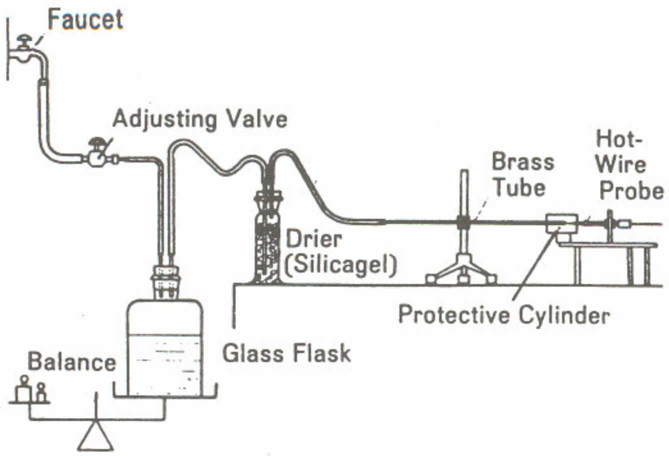

Figure 9. System for calibrating hot-wire anemometer probes described by Almquist and Legath (1965). A bottle is filled with a constant flow of water to produce a low-velocity air flow. This method is good from 0.15 to about 2 m s^{-1}. (Lomas, 1986.)

measured periodically by taking the weight of the bottle. This method is suitable over a range of 0.15 to 2.0 m s^{-1}. Lomas (1986) describes a similar technique in which water is allowed to drain from the bottom of a large tank with a probe inserted in an opening at the tip through which air enters (Fig. 10). The advantage of this system is that dry air passes over the probe.

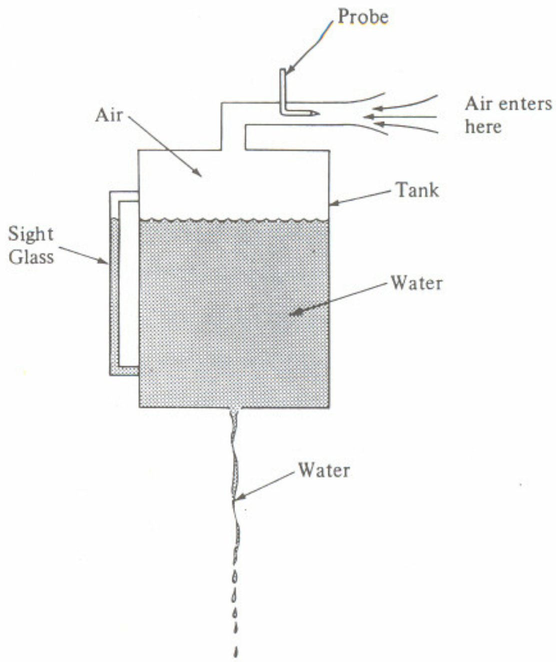

Figure 10. System for calibrating hot-wire anemometer probes described by Lomas (1986). The draining of a container is used to produce a low-velocity flow of air suitable for calibration of a hot-wire probe. (Lomas, 1986.)

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Appendix

Selected List of Manufacturers of Anemometers Suitable for Use in Plant Growth Chambers

1. **AirFlow Technical Products, Inc., 23 Railroad Ave., Netcong, NJ 07857, USA. (Mailing Address: P.O. Box M552, Landing, NJ 07850.) Tel. 800-247-8887, 201-691-4825; FAX 201-691-4703.** A subsidiary of AirFlow Development, UK. Manufactures and sells a number of hot-wire anemometers with and without temperature sensors. The Model TA-5 hot-wire anemometer has a range of 0-6000 fpm with 3 subranges, 0-400, 400-3000, and 3000-6000 fpm.

2. **Alnor Instrument Co., 7555 N. Linder Ave., Skokie, IL 60077, USA. Tel. 708-677-3500; FAX 708-677-3539.** Manufactures several mechanical and electronic anemometers. Analog units (e.g., Models 8500 and 9850) have a range of 10-2000 fpm (accuracy ± 2 fpm or 3% of indicated velocity whichever is greater). Digital units (e.g., Model 8575) have a range of 20-6000 fpm. Each thermal anemometer provides readings in English or metric units.

3. **Cole-Parmer Instrument Co., 7425 N. Oak Park Ave., Niles, IL 60714, USA. Tel. 708-647-7600; FAX 708-647-9660.** Sells a range of electronic, mechanical, and thermal anemometers manufactured by other firms.

4. **Dantec Measurement Technology, Inc., 777 Corporate Drive, Mahwah, NJ 07430-2008, USA. Tel. 201-512-0037; FAX 201-512-0120.** Manufactures a low-velocity anemometer (Model 54N50) with an omnidirectional spherical sensor with a 0.1 s time constant. Measuring range is 5-100 cm s^{-1} and 0.25-5 m s^{-1}. Has a linearized analog output. Also makes a multi-channel analyzer (Model 54N10) that can use up to 24 channels and has a RS 232C output.

5. **Davis Instruments Mfg. Co. Inc., Seton Business Ctr., 4701 Mt. Hope Drive, Suite J, Baltimore, MD 21215, USA. Tel. 800-368-2516, 410-358-3900; FAX 410-358-0252.** Sells a large number of hot-wire anemometers made by other firms as well as their own brand. These have a range up to 0-12,000 fpm; many are available in English or metric units.

6. **Dwyer Instruments, Inc., P.O. Box 373, Michigan City, IN 46361, USA. Tel. 219-879-8000; FAX 219-872-9057.** Manufacturers a Model 470-1 thermal hot-wire anemometer in the range of 0-600 and 500-6000 fpm and a Model 640 Air Velocity Transmitter with four ranges of 0-200, 0-1000, 0-3000, and 0-12,000 fpm.

7. **Epic, Inc., 150 Nassau St., New York, NY 10038, USA. Tel. 212-349-2470; FAX 212-406-2508.** Distributes a Model 642 microprocessor controlled thermal anemometer manufactured in Germany by Wilh. Lambrecht GmbHm (3400 Gottingen). The instrument utilizes a constant temperature method and measures air flow over the range of 0-2 m s^{-1} or 1-10 fps (± 5% accuracy) and 2-20 m s^{-1} or 10-100 fps (± 3% accuracy).

8. **Kane-May Measuring Instruments, c/o Universal Enterprises, Inc., 5500 SW Arctic Dr., Beaverton, OR 97005, USA. Tel. 800-547-5740, 503-644-8723; FAX 503-643-6322**. Sells two hot-wire microprocessor controlled digital thermal anemometers made in the U.K. by Komark, Model KM 4107 (10-6000 fpm, °F) and Model 4007 (0-30 m s^{-1}, °C) and Model DAFM-1 digital vane anemometer.

9. **Kernco Instruments Co., Inc., 420 Kenazo Ave., El Paso, TX 79927, USA. Tel. 800-325-3875, 915-852-3375; FAX 915-852-4084.** Distributes hot-wire thermal anemometers in the range of 0-300, 0-2000, 20-3000, 50-6000, 60-6800, and 40-7800 fpm manufactured by Alnor and AirFlow Technical Products, Inc.

10. **Kurz Instruments Inc., 2411 Garden Rd., Monterey, CA 93940, USA. Tel. 800-424-7356,**

408-646-5911; FAX 408-646-8901.** Manufactures two series of hot-wire anemometers, the 490 series in the range of 0-200 to 0-10,000 fpm and the 440 series in the range of 0-100 to 0-12,000 fpm. Metric versions are also available. The 490 series are pocket-size instruments; the 440 series are larger, microprocessor controlled instruments. Kurz sensors are based on a "constant temperature" thermal flow technology principle.

11. **Mitsubishi (Shibaura) International Corp., Non-Ferrous Metals (NFM) Div., 520 Madison Ave., New York City, NY 10022, USA. Tel. 212-605-2144; FAX 212-605-1745**. Manufactures several air flow sensors including units with a bar graph display. The F6000 Series flow sensors employ a highly stable, self-heated thermistor as a sensing element for air speed measurement and a second thermistor as a temperature compensator; they cover a range of 0 to 20 m s^{-1} air speed and 0 to 50°C temperature.

12. **Omega Engineering, Inc., 1 Omega Drive, P.O. Box 4047, Stamford, CT 06907, USA. Tel. 203-359-1660; FAX 203-359-7990**. Sells a thermal anemometer, 0-400 and 0-4000 fpm. Also distributes a microprocessor based portable anemometer with 0.5% accuracy over a wide range of 35 to 73000 fpm (0.2 to 40.0 m s^{-1}).

13. **Pacer Industries, Inc., 1450 1st Ave., Chippewa Falls, WI, 54729-1492, USA. Tel. 800-283-1141, 715-723-1141; FAX 715-723-7890.** Manufactures vane anemometers for indoor applications, with a range of 40-7800 fpm.

14. **Sierra Instruments Inc., 5 Harris Ct., Bldg. L, Monterey, CA 93940, USA. Tel. 800-866-0200, 408-373-0200; FAX 408-373-4402.** Makes a wide range of Thermal Mass flowmeters. The 600 model is a laboratory instrument with analog output in the ranges of 0-1.5, 0-3, and 0-6 m s^{-1}. Makes a portable, digital air velocity meter (Model 630) in the range of 0-6 m s^{-1}, that can average 1000 points and provide hard copy using a small tape printer.

15. **Solomat Neotronics Co., 26 Pearl Street, The Waterside Bldg., Norwalk, CT 06850, USA. Tel. 800-932-4500, Ext 3011, 203-849-3111; FAX 203-847-9320.** Manufactures three hot-wire anemometers and two vane anemometers. The hot-wire anemometers measure in the range of 10 to 2,400 fpm (0.05 to 12 m s^{-1}), from 32 to 100°F and come in three configurations - standard shaft (127 MSX), telescope (129 MSX) and gooseneck (129 GNX). The vane anemometers measure in the range of 200 to 8,000 fpm (1 to 40 m s^{-1}), from 15 to 160°F ± 2% accuracy and are available in telescope (228 MSX) and gooseneck (228 GNX) configuration.

16. **Sunshine Instruments, 1810 Grant Ave., Philadelphia, PA 19115, USA. Tel. 800-343-1199, 215-673-5600; FAX 215-673-5609.** Distributes thermal anemometers manufactured by Alnor and Pacer.

17. **TSI Inc., P.O. 64394, 500 Cardigan Rd., St. Paul, MN 55164, USA. Tel. 800-876-9874, 612-483-0900; FAX 612-490-3824.** Manufactures an omnidirectional flow transducer, with a range of 0-5 m s^{-1}. The transducer needs a power supply. TSI also manufactures several models of electronic, digital, autoranging thermal anemometers (VelociCalc) capable of measuring air flow in the range of 30-10,000 fpm (0.15 to 50 m s^{-1}) and other parameters including pressure, temperature, and relative humidity.

18. **Testo, Inc., 230 Rt. 6, Flanders, NJ 07836, USA. Tel. 800-227-0729, 201-252-1720; FAX 201-252-1729.** Manufactures hot-wire and vane anemometers and hot-ball velocity probes. The Testo 452 model instrument is a portable, hand-held, data acquisition system designed for accurate measurements of air velocity, temperature, relative humidity, differential pressure or any combination of the above. Manufactures a variety of hot-wire, hot-ball velocity, temperature, and pressure probes; the range of the thermal anemometer probe is from 0 to 2000 fpm, and the vane probe is from 40 to 9999 fpm. The three-function probe monitors temperature, relative humidity, and air velocity simultaneously. The Testo 491 model monitors temperature and air velocity.

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