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QUANTIFYING ENERGY AND MASS TRANSFER IN CROP CANOPIES: SENSORS FOR MEASUREMENT OF TEMPERATURE AND AIR VELOCITY

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ABSTRACT

Here we report on the *in situ* performance of inexpensive, miniature sensors that have increased our ability to measure mass and energy fluxes from plant canopies in controlled environments: **1. Surface temperature.** Canopy temperature measurements indicate changes in stomatal aperture and thus latent and sensible heat fluxes. Infrared transducers from two manufacturers (Exergen Corporation, Newton, MA; and Everest Interscience, Tucson, AZ, USA) have recently become available. Transducer accuracy matched that of a more expensive hand-held infrared thermometer. **2. Air velocity** varies above and within plant canopies and is an important component in mass and energy transfer models. We tested commercially-available needle, heat-transfer anemometers (1 x 50 mm cylinder) that consist of a fine-wire thermocouple and a heater inside a hypodermic needle. The needle is heated and wind speed determined from the temperature rise above ambient. These sensors are particularly useful in measuring the low wind speeds found within plant canopies. **3.** Accurate measurements of **air temperature** adjacent to plant leaves facilitates transport phenomena modeling. We quantified the effect of radiation and air velocity on temperature rise in thermocouples from 10 to 500 μm. At high radiation loads and low wind speeds, temperature errors were as large as 7° C above air temperature.

INTRODUCTION

Scientific advances are the result of improved measurements coupled with improved models. A surprising number of scientific advances have been the result of better measurement tools and more exact measurements, which showed that theories were incorrect. We sought to improve our understanding of energy and mass transfer in plant canopies. These parameters determine the partitioning of radiant energy into latent and sensible heat exchange, which in turn controls evaporation from vegetated surfaces. This goal requires accurate measurements of small temperature gradients (<0.5° C) between plant leaves and the air, coupled with accurate measurements of air velocity adjacent to plant leaves. These measurements are imperative in controlled environment studies because the spatial and temporal variability of air temperature and wind velocity is accentuated by forced convection. In addition, the measurement of canopy temperatures and the characterization of wind profiles within plant canopies is complicated by the effects of impinging radiation on the sensors themselves.

Research reported in this paper was supported by NASA Cooperative Agreement 2-139, administered through the Ames Research Center, Moffett Field, CA; and from the Utah Agricultural Experiment Station. Mention of brand names is for information only and does not constitute an endorsement to the exclusion of other products that might also be suitable.

This paper describes: 1. Calibration tests of a series of infrared transducers for the measurement of surface temperatures, and 2. Tests of a miniature heat-transfer anemometer for the measurement of air velocity, and 3. Tests of the effect of thermocouple wire diameter on temperature measurement accuracy in high radiation environments.

MEASUREMENT OF SURFACE TEMPERATURE: INFRARED TRANSDUCERS

Infrared thermometry has been widely used for determining canopy temperatures, which are a sensitive indicator of plant water stress in the field (Tanner, 1963; Jackson *et al.*, 1981). The low wind speeds in plant canopies mean that transpirational cooling has a relatively greater effect on canopy temperature than in isolated leaves, where energy transfer by convection and radiation are more important (Jackson *et al.*, 1981). Canopy temperature has been modeled from air temperature and wind speed profiles but canopies are not isothermal (Huband and Monteith, 1986). Wide angle infrared thermometers (transducers) integrate temperatures over the field of view of the sensor.

In field environments, errors are introduced when longwave radiation emitted by the surroundings (due to sky radiant emittance and solar zenith angle) is reflected from the canopy surface into the transducer (Fuchs and Tanner, 1966; Huband and Monteith, 1986). This introduces variability as a result of changing cloud cover, sensor viewing direction, and sensor field of view. These complications are minimized in controlled environments if a water filter is used below the lamps to maintain the ceiling and chamber surface temperatures close to the canopy temperature.

The following transducers were selected for testing because of their small size and low cost:

	Exergen IR t/c-37[1]	Exergen IR t/c-0.2[1]	Everest 3000AL[2]
Power supply	none	none	± 5V
Output	μV	μV	mV
Response time	1 s	1 s	~ 100 s
Cost	$ 199.	$ 299.	$ 795.
Size	13 x 44 mm cylinder	13 x 44 mm cylinder	16 x 32 mm cylinder

[1]Sensors from the Exergen Company (Newton, MA, 800-422-3006)
- model IRt/c -K-27°C (wide angle) One sensor calibrated at 37°C also tested.
- model IRt/c .2-K-27°C (narrow angle) Two replicate sensors were tested.

[2]Sensor from Everest Interscience, Inc. (Tucson, AZ, 800-422-4342)
- model 3000 AL (narrow angle)

Sensor accuracy and stability was determined in a water cooled, controlled environment chamber that provided stable air temperature. Sensors were calibrated against a black body reference that consisted of a stainless steel, water-filled, 15-cm cube. The sensors were pointed towards a 10-

cm deep, cone shaped insert on one face of the cube. The interior of this cone was painted with a special flat black paint to provide an emissivity (ϵ) near 1.0. The cone and sensor were wrapped in aluminum foil to minimize reflected radiation and radiant heating. Water in the cube was stirred and its temperature was varied to create different black body surface temperatures. In a separate series of tests, the air temperature of the chamber was varied and the black body temperature held constant, in order to characterize the effects of changing sensor body temperature. Sensor body temperature was measured by a thermocouple, which was covered by insulation and aluminum foil to minimize radiative heating. This measurement provided the response of the sensor body to fluctuating air temperatures.

The results are shown in the following series of graphs.

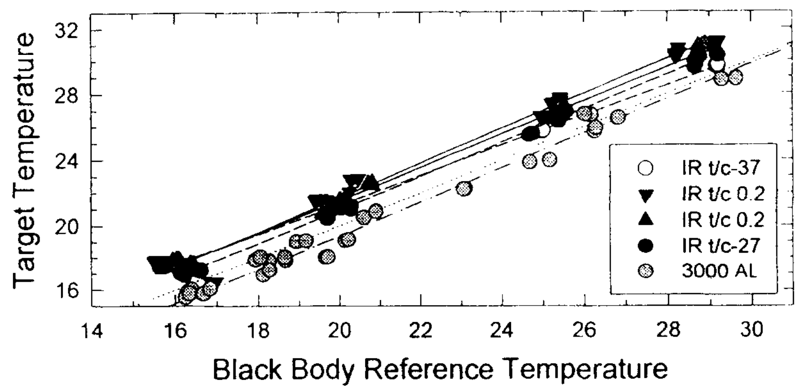

Fig. 1. The relationship between the black body reference temperature and the uncorrected output from the infrared transducers as provided by the manufacturers. Transducer output is shown on the Y axis as the target temperature. The mV output of the 3000 AL transducer was linearized with a fifth order polynomial that was supplied by the manufacturer. The Exergen IR t/c's have a thermocouple output that does not require linearization.

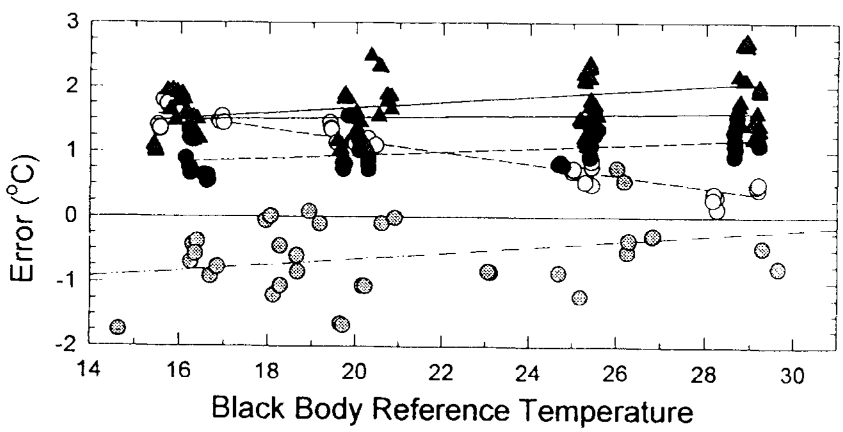

Fig. 2. Uncorrected error from the data in Fig. 1. Symbol legend same as Fig. 1. Dashed lines (with circles) are the Exergen wide angle sensors. Solid lines (with triangles) are two Exergen narrow angle sensors. The Exergen narrow angle sensors were calibrated by the manufacturer at 27°C. The Exergen transducer indicated by the open circles was originally calibrated at 37°C.

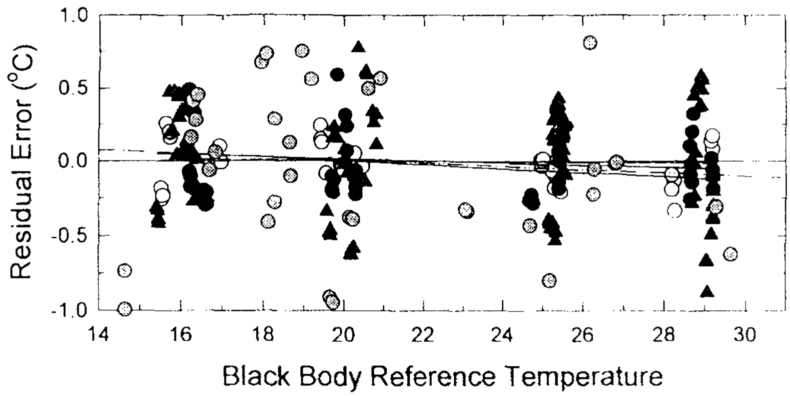

Fig. 3. Residual error of the transducers after correcting for offset and slope errors. With the exception of the IRt/c-37° C, the slope errors were insignificant.

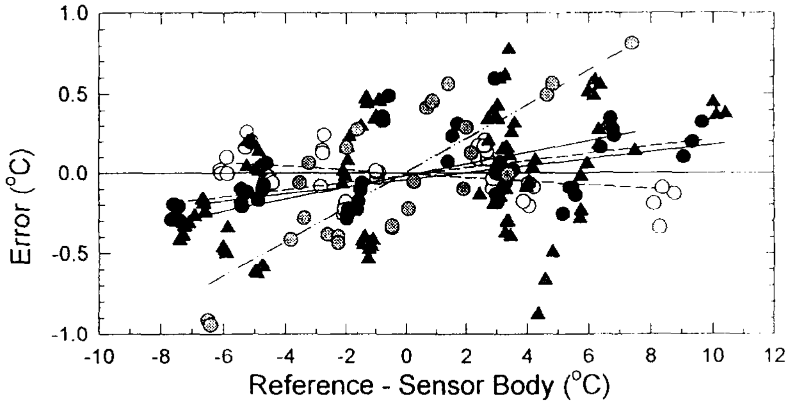

Fig. 4. The effect of differences between the black body target temperature and the sensor body temperature on measurement accuracy. All infrared devices must be referenced to the temperature of the internal detector. The sensor body temperature was measured with a thermocouple wrapped around the transducer.

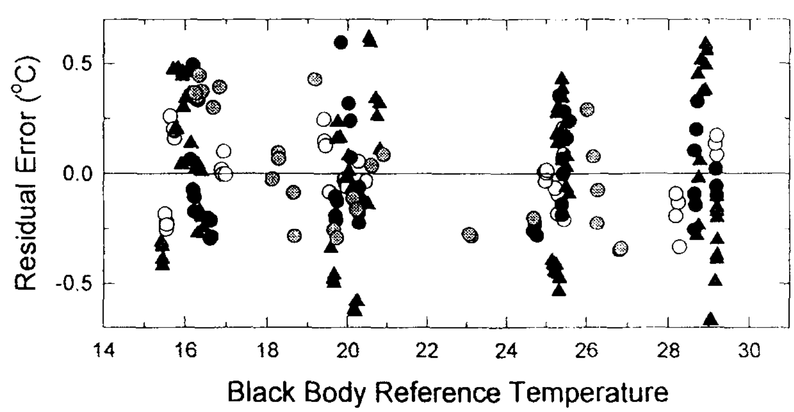

Fig. 5. The residual error after correction for offset, slope, and sensor body temperature. In these tests the final residual error was ±0.7° C between 14 and 30° C.

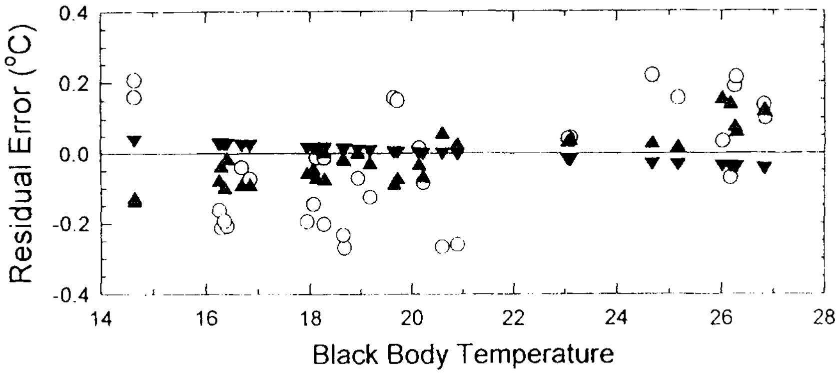

Fig. 6. The final residual error after correction for offset, slope, and sensor body temperature in a separate replicate test. Measurement accuracy was improved in this test (±0.3° C), but the conditions for the test were identical to those shown in the previous five figures. As in previous tests, the offset correction was the largest of the three corrections, but the offset correction was reproducible within 0.3° C among tests.

HEAT-TRANSFER NEEDLE ANEMOMETER

Air flow within canopies is characterized by high wind speeds in the upper canopy and low wind speeds at lower levels. This results in considerable spatial variability, which complicates models for evaluating water and heat transport processes. The aerodynamic surface roughness of a canopy and the penetration of wind into it are affected by foliage density and the magnitude of the air velocity flowing over it (Baldocchi et al., 1983). Wind profiles in controlled environments are even more variable than in the field because of turbulence due to forced convection.

The response of five needle anemometers (Soiltronics, 111 Myrtle Drive, Burlington, WA 98233; 206-757-2400; about $100. each) was determined in a miniature wind tunnel, which was designed to calibrate small, heat-transfer anemometers at very low air velocities. The air velocity in the wind tunnel was determined from measurements of air mass flow rate using a calibrated mass flow meter (Model 730, Sierra Instruments, CA).

The wind tunnel was designed by the late C.B. Tanner at the University of Wisconsin. Full construction details are available upon request. The tunnel consists of five sections of polycarbonate, 15 x 15 x 2.5 cm thick. Four of the sections were center bored to a 6.985 cm diameter. Stainless steel screens (100 mesh) were inserted between each polycarbonate section and the sections were bolted together. The screens flattened the velocity profile so that the velocity was uniform for up to 2 cm from the screen.

The heat transfer anemometers were calibrated up to wind speeds of 5 m s^{-1}. The anemometers consist of a resistive heater and a thermocouple, embedded in a hypodermic needle. Temperature measurements were made before and after heating of the needle. The temperature difference between the cold needle and the hot needle is proportional to the square root of wind speed [(wind speed)^0.5] (Campbell, 1977). The needle was kept hot throughout the measurements.

Anemometer response is shown in the following graphs.

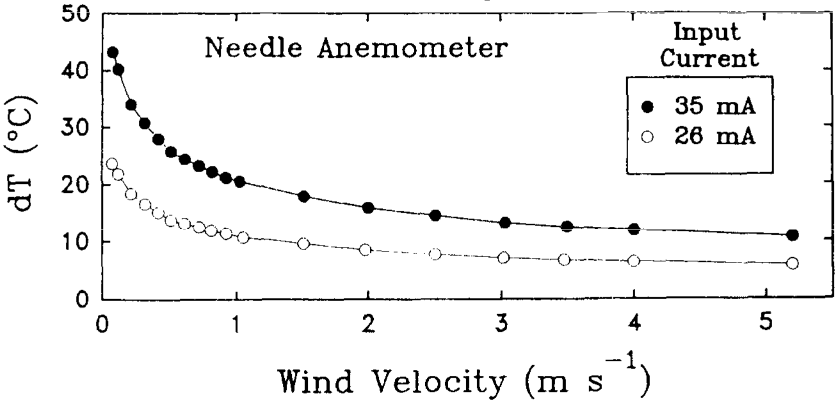

Fig. 7. The effect of air velocity on temperature rise of the needle anemometers. The Y axis (dT) indicates temperature rise above ambient for two input currents. A large input current and a correspondingly large temperature rise, minimizes radiation errors and reduces the dependance on precise measurement of air temperature.

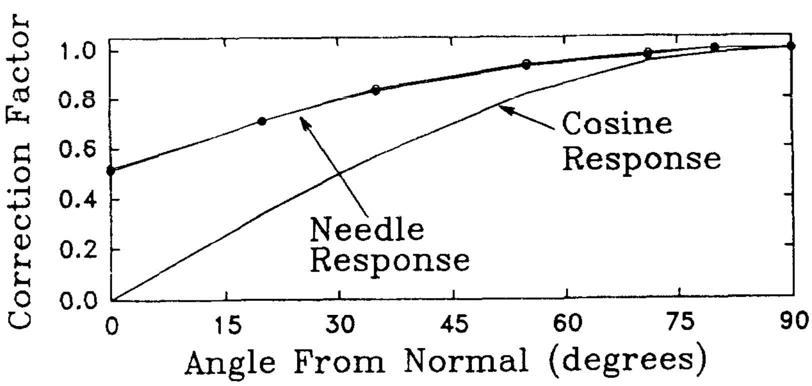

Fig. 8. Anemometer response in relation to the direction of wind flow. Zero degrees was measured with the tip of the needle pointing directly into the wind. The cosine response curve indicates a perfect cosine relationship. The anemometers are omnidirectional when placed perpendicular to the direction of wind flow, but have an angular dependence when the air flow is not perpendicular to the needle.

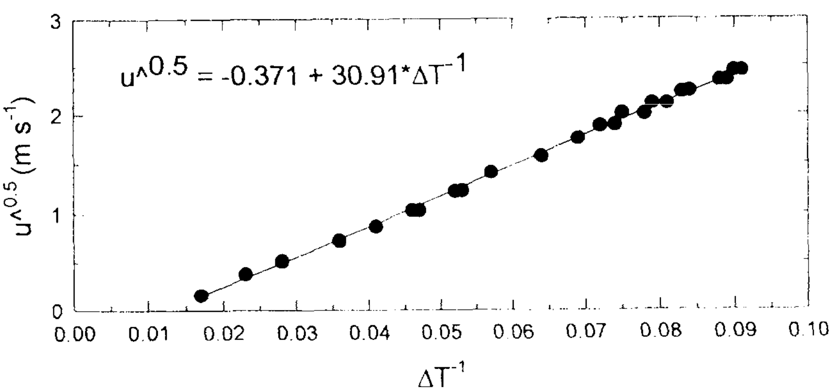

Fig. 9. A calibration curve the five needle anemometers. The X axis is the inverse of the temperature rise (1/ΔT); the Y axis is the square root of wind speed. The calibration curve was linear up to a wind speed of 5 m s^{-1}. The five anemometers had a nearly identical response.

RADIATION ERRORS IN THERMOCOUPLE MEASUREMENTS

Thermocouples are routinely used for measuring leaf and air temperatures in high radiation environments, but they must be shielded and aspirated to eliminate radiant heating. Although the temperature sensing occurs at the junction (tip) of the dissimilar metal wires, heat is conducted along the wires to the tip, causing overestimates of true air or surface temperatures. Heating of the tip can be greatly reduced by the use of very fine wires, which minimize the absorbing surface area exposed to radiation (Tanner, 1979). Radiant heating can be completely removed when the thermocouples are shielded (from incident radiation) and aspirated (causing air to flow over the wire) (Huband and Monteith, 1986), but this results in bulky apparatus (insulation, fans).

We examined the effect of wind speed and net radiation on the accuracy of thermocouples of varying diameters. Measurements were made inside a growth chamber in radiation environments ranging from darkness to full sunlight. Thermocouple output was measured with a datalogger (Campbell Scientific, model CR-7). The measurements were compared to an extremely fine wire thermocouple (10 μm diameter wire). The results are shown in the following figures.

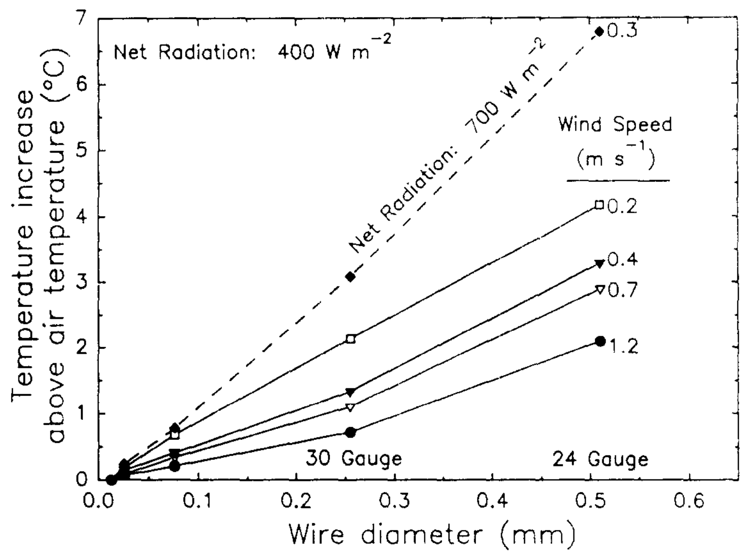

Fig. 10. The effect of wind speed and net radiation on thermocouple accuracy. All measurements were made with Type E thermocouples with soldered junctions of similar diameter to the wire diameter. Data represent averages of 3 thermocouples, the standard error of the mean for the three replications was smaller than the symbol size. All thermocouples read within 0.005 °C of each other in the dark. The three smallest thermocouples were American wire gauge 56, 50, and 40. Measurements indicated by the three solid lines were made in a growth chamber with chilled water flowing below the lamps. In this condition the net longwave radiation was zero so the incident shortwave radiation was 400 W m^{-2}. Measurements indicated by the dashed line (net radiation = 700 W m^{-2}) were made in the same growth chamber but without the chilled water below the lamps. The temperature rise of the thermocouple junction at all wind speeds was exactly proportional to the incident radiation (700/400 = 175% increase in temperature at the higher radiation level). The wind speeds represent the typical range that would occur at the top of a plant canopy in a growth chamber. Thermocouples were positioned vertically for these measurements.

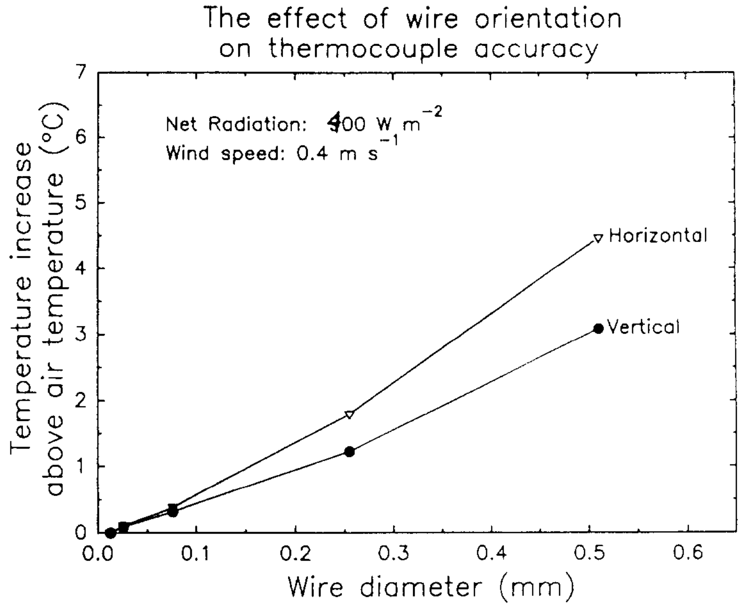

Fig. 11. The effect of wire orientation on thermocouple accuracy. The data for the vertical position is the same as the 0.4 m s^{-1} wind speed in Fig. 4. The temperature rise was typically about 50% greater for horizontally orientated wires at all radiation levels and wind speeds. This temperature increase was probably caused by the increased radiation absorbed in the horizontal orientation.

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