Design of A System for Measuring Canopy Gas Exchange

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Abstract. To improve upon crop modeling work being conducted for advanced life
support system studies at the NJ-NSCORT, four environmentally controlled open top
plant growth chambers have been designed and constructed to monitor canopy net
photosynthesis and dark cycle respiration of various advanced life support (ALS) food
crops (soybean, potato and tomato). The plant chambers (0.55 m²; 0.43 m³) were
housed within a walk-in environmental control chamber (9.3 m²; 28 m³), which provided
the source of radiation for plant growth, and temperature and CO₂ controlled air for
cooling/enriching the environment of chambers. Air entered the plant chamber from
bottom, and was exhausted through the top to provide a highly uniform spatial
environment of air temperature and velocity. The controllable environment of the walk-in
growth chamber induced the plant responses to air temperature, CO₂ concentration and irradiance during the complete plant life cycle. Plants were grown with an ebb and flood hydroponic system. Continuous, real-time gas exchange measurements were completed with a high precision infra-red gas analyzer and an integral multiplexer throughout the 90-day lifecycle of soybean to document the plant response to the environmental control capabilities of the four growth chambers. Specific emphasis was on the spatial uniformity of irradiation, air flow and air temperature.

**Keywords.** Canopy gas exchange, Plant growth chamber, Environmental control, CO₂, Air temperature, Irradiance, Soybean
**Introduction**

Canopy photosynthesis and transpiration measurement has been conducted by using various types of plant growth chambers in both field studies and controlled environment to study the response of the plants to environmental conditions. Precise measurement provides consistent, nondestructive, and consecutive growth data to the investigator, and the information is a useful data source for modelers to develop refined crop models (Wheeler, et al, 1993; Cavazzoni, 1997; Grant, 1992). Determination of precise crop life cycle gas-exchange data in artificial environments are necessary for the NASA's Advanced Life Support System program to develop a regenerating plant production system for long-term manned space missions (Wheeler, et al, 1993; Wheeler, 1992). One of the objectives of the NJ-NSCORT (New Jersey - NASA Specialized Center of Research and Training) System Studies and Modeling team was to demonstrate explanatory models for ALS candidate crops. In order to provide nondestructive crop growth data for this effort, four environmentally controlled plant growth chambers were designed and constructed to measure canopy gas-exchange rates for the entire crop life cycle. This project was initiated by collaboration between NJ-NSCORT and Jet Propulsion Laboratory (JPL, Pasadena, CA), with the goal of meeting the modeling objectives of both the NJ-NSCORT’s energy cascade model and JPL’s development of crop models using artificial neural networks. The data will also be used for multivariable polynomial regression techniques as part of the NJ-NSCORT Systems Study and Modeling Team objectives.

In this paper, we describe the design of the gas-exchange monitoring system and the operation of the plant growth chamber, which were developed to achieve the above modeling objectives. A unique design improvement included a vertical cooling airflow pattern (fresh air introduced at the bottom, exhausted at the top of the chamber), as an alternative to the traditional horizontal airflow cooling procedures.

**General design considerations**

The plant growth test chambers were to be utilized within the controllable environment of a walk-in environmental growth chamber. The walk-in chamber would provide automated control of air temperature, moisture, and CO₂ concentration, as well as, irradiance throughout the plant life cycle.

Plant response of carbon (net photosynthesis) and water (transpiration) exchange were to be continually monitored 24 hours per day for as much as 90 days.

The environment of the plant growth test chambers would be heated by the radiant load from the artificial lamps of the environmental growth chamber, and would require precise air temperature control by air exchange with the surrounding environmental growth chamber.

Adequate water and nutrient supply, and uniform irradiance were required by the plants and/or the experiment design.

All materials for construction of the chambers, as well as, for all supporting systems, were selected to minimize the introduction of contaminates that might affect the growth of the plants.

In addition, the design would strive to achieve:

- uniform environmental conditions among all plants within each chamber
• uniform airflow through the chambers to cool the plant environment while preventing any condensation of water vapor
• adjustable airflow for each chamber to allow for different air temperatures in each of the four chambers
• sealed chambers, except for the inlet and outlet of airflow to insure that the change in gas concentrations in the air is a result of only the plant’s effect on these gases, and not of infiltration from outside air
• a separated plant root zone from the plant aerial zone, but allow gas exchange between both
• easy access to the inside of each chamber to monitor plant growth.

The following parameters were required to be accurately and continually measured:
• Inlet and outlet CO$_2$ and water vapor concentration of each chamber.
• Mass flow of moist air through each chamber.
• Irradiation at the plant canopy.
• Irradiation within the environmental growth chamber.
• Plant canopy air temperature and leaf tissue temperature.

Each chamber consisted of the following inter-related subsystems, which will be listed below and then discussed.

**Irrigation Control** -- electronic controller, pump, relay, manual over-ride

**CO$_2$ Control** -- electronic controller, solenoid valve, CO$_2$ gas cylinder, pressure regulator, distribution tubing

**Chamber Structure** -- Clear acrylic rigid plastic cover, opaque, rigid PVC plastic base.

**Air Exchange/Cooling** -- Fans, filter, fan/filter housing, air distribution pipes, flow control valve, screening, mass flow monitor.

**Plant Culture**
- *nutrient delivery* -- pump, flow control valve, by-pass valve, discharge wye, flexible tubing; automatic emergency fresh water source
- *plant support* -- framework with open mesh netting
- *Perlite root zone* -- particulate size distribution

**Shading** -- attachment of shade material to top and side of chamber

**ADC 2250 Gas Analyzer** -- sampling tubing, dry-rite canister, particulate filter

**Data acquisition and sensors** -- thermocouples, quantum sensors

**Support Framework** -- Metal frame to support chambers above floor
Chamber System Components

Each chamber consisted of a removable, four-sided cover, with lid, and open bottom, constructed of 0.63 mm transparent acrylic, with dimensions of 91 x 64 x 76 cm (L x W x H, respectively, Figure 3). The lid of the cover was a detachable acrylic sheet, positioned on pins, to provide an adjustable area, exhaust perimeter slot. The cover was placed on a rectangular interface tray of dimensions which match the cover (91 x 64 cm), and together complete the chamber borders. All materials were carefully selected to avoid CO₂ and water absorption.

The interface tray is the intersection for several systems (Figure 2). It provided the support for the plant root zone, and seating for the removable transparent cover. The water-tight tray was filled with nutrient solution by flooding and draining. Ventilation air exchange occurred through 43 inlet nozzles from a plenum chamber located below the tray, and the exhaust slot located at the lid. The inlet nozzles were constructed of white PVC tubing (4.2 cm diameter x 15 cm) that extended from the air plenum chamber located below the tray up to a point above the maximum nutrient solution water line. The pressurized air flowed upward though the crop and exited from the 7 mm wide perimeter slot created by where the lid meets the vertical sides of the plant growth chamber. A 10.2 cm diameter PVC duct provided air from the center of the walk-in chamber to the plenum chamber (Figure 1). The plenum chamber contained a diffuser constructed of 2 layers of window screening to improve the uniformity of air distribution to each of the inlet nozzles. This design allowed the cooling air system and the irrigation system to operate independently and simultaneously.

The air exchange/cooling system provided a means for measuring the change in concentrations of atmospheric CO₂ and water vapor due to plant respiration, photosynthesis, and transpiration, and it removed the heat generated from the 100 -160 watts per square meter of irradiation supplied to the plants by the fluorescent and incandescent lamps of the environmental growth chamber. The cooling air was filtered, and the flow rate was adjustable, and was continually measured within a straight section of pipe with a mass flow meter. Each chamber was independently monitored and controlled, and thus could have its own unique air exchange rate and air temperature. The walk-in chamber provided similar inlet air properties (temperature, gaseous components) to each of the four chambers.

The nutrient solution was pumped into the interface trays at regular intervals to a depth of 2 cm, through flexible tubing, and then returned to the 114 L storage tank by gravity through separate hoses. The floor of the interface tray was slightly convex, and the placement of the fill/drain hole was located near the outside edge, to insure that most of the unused nutrient solution drained from the interface tray. The plants were seeded and grown within 7.6 cm rock wool cubes and transplanted directly onto the interface tray at a density of 31 plants m⁻². The area between the rockwool cubes was filled white Perlite aggregate [~ 7.6 cm deep] to cover the roots that emerged along the bottom of the tray. The white aggregate further prevented the growth of algae within the tray, and provided consistent reflective properties at the base of the plants. The nutrient solution was monitored daily and adjusted to proper EC and pH as required.

Light was provided to the plants from combined fluorescent and incandescent artificial light sources mounted in the ceiling of the walk-in growth chamber. The lights were adjustable in
elevation, relative to the plants, so light intensity could be changed. In order that the perimeter plants receive the same amount of light as the interior plants, the outer walls of the plant growth chamber were wrapped with a flexible shading material. The material could be extended up the sides of the chamber as the plants grew in height.

An electronic irrigation controller regulated the frequency, duration and depth of nutrient solution delivered to the root zone of the plant growing area.

Carbon dioxide (99%) was metered into the walk-in growth chamber from pressurized cylinders. It was monitored by the ADC2250 high resolution IRGA and automatically regulated by a solenoid controller system.

A diagram of the system for sampling the inlet and outlet airflow of the plant chambers is shown in Figure 4. Sample gas from the inlet air is taken from the center of the walk-in chamber as a representative inlet air value for all four plant growth chambers and delivered to the CO₂ and H₂O infrared gas analyzer (ADC model 2250; ADC, England). The outlet air is taken from the opening slot at the top of the plant growth chamber at the side closest to the center of the walk-in chamber and delivered to the analyzer via the gas handling unit (ADC model GHU; ADC, England). GHU continually cycled sampling from each chamber, every five minutes; therefore, gas samples from each individual chamber were measured every 20 minutes and 5 minute averages were recorded throughout their life cycle.

The atmospheric CO₂ concentration of the plant growth chambers were controlled with a 21X Micrologger (Campbell Scientific Inc.) by monitoring the CO₂ concentration of the walk-in environmental chamber at the inlet air source of the plant growth chambers ventilation system. A solenoid valve and needle valve modulated the flow of pure CO₂ gas into the air distribution systems of the walk-in environmental growth chamber. The significant leakage of the walk-in chamber (1.1 air exchange per hour), required continuous monitoring to maintain 1000 ± 10 ppm within the walk-in chamber.

Air temperature, relative humidity and light intensity were controlled by programming the control unit of the walk-in environmental growth chamber. Six thermocouples within each plant growth chamber measured the air temperature (at canopy height, 5 cm below and above the canopy, at the root zone, and inside of the plenum chamber), and the temperature in moist rockwool cubes. The infrared sensors located in the plant growth chamber measured the leaf temperature. The line quantum sensors, which monitored the light absorption by comparing the light intensity at the bottom and top of the plant canopy.

**Operations and Procedures**

Soybean (cv. Hoyt) seedlings were transplanted into the plant growth chambers at 14 days after seeding (DAS) at a density of 31 plants m⁻² (20 plants per chamber), where they were grown until maturity. The plants were seeded and grown in 7.6 cm rockwool cubes, placed on the interface tray, and irrigated with half-strength Hoagland nutrient solution by the flood and drain technique. The lighting source was cool white fluorescent lamps. The incandescent lamps were not used. Light-cycle/dark-cycle air temperature (26/22 °C), aerial CO₂ concentration (1000 µmol mol⁻¹ for the first crop life-cycle experiment, 400 µmol mol⁻¹ for the second), and light intensity (400 and 650 µmol m⁻² s⁻¹, two replicated treatments for each CO₂ treatment) were controlled for a 12 hour photoperiod for 90-day crop life-cycles.
Short-term experiments were superimposed on the crop life-cycle experiment during the vegetative (~ 25 DAS), early reproductive (~ 45 DAS), and late reproductive (~ 65 DAS) stages of plant development. For these short-term tests, the environmental set-points were adjusted to produce step changes in air temperature, irradiance and CO₂ concentration. The infrared gas analyzer (ADC 2250, ADC BioScientific Ltd., UK) continuously monitored canopy gas-exchange for CO₂ and water vapor for the duration of the long-and short-term experiments.

Results

System Response --- Environmental conditions in the plant chamber

Light Distribution

The spatial distribution of photosynthetic photon flux within the plant growth chambers was measured with a line quantum sensor. Figure 6 shows the distribution of the light intensity at three heights (12, 38 and 64 cm from the bottom of the chamber), averaged within 4 regions, each, 24 x 67 cm in area (centered 12, 36, 60 and 84 cm from the end of the chamber, see figure 7). The line quantum sensor consisted of a 60 cm long stick with 5 quantum sensors equally spaced along its length to provide an average representative PPF value within the each location. There was no shade screening material on the top of the box. However, there was a single layer of gray-colored fiber-glass window screening attached to the vertical sides of the box and spanning the entire perimeter. This screen was fixed at 12, 38 or 64 cm from the bottom of the box to match the location of the sensor at each measurement height. This perimeter screen reduced the amount of side lighting that could enter the box, thereby imitating the situation of a semi-infinite crop canopy, and eliminating growth responses caused by edge effects of lighting on the outer rows of plants. Therefore light uniformity was improved for all locations (x-y plane), at a given height throughout the box.

Light uniformity was also important in the vertical direction, since the plants increased in height as they matured. Figure 8 contains PPF measurements obtained similar to Figure 6, except that a single layer of gray-colored fiber-glass window screening was attached to the top surface of the acrylic cover of the box. The average vertical difference in PPF for all horizontal positions in the box was reduced from 109 to 74 μmol·m⁻²·s⁻¹. Furthermore, this difference was reduced from 62 to 20 μmol·m⁻²·s⁻¹ when the 12 cm is compared to the 38 cm position. These positions represent the plant height for the significant portion of its growth period.

Airflow rate

Maintaining a uniform environment, including air temperature and humidity, and irradiance, within the plant microclimate is the most crucial factor in establishing an accurate gas-exchange measurement, particularly in a dense plant canopy. In addition, stagnant air pockets can readily form between border plants and the walls of the plant growth chamber. (Garcia et al, 1990) To minimize this problem, the plant chamber was designed to have fresh air flow through the plant canopy from the bottom to the top of the growing area. Air was uniformly introduced from 43 inlets located adjacent to the base of the plants at the interface tray. The exit air velocity of each inlet pipe was measured with a thermo-anemometer (Model-175 and
Multi-Purpose Meter ALNOR APM360, ATSI company). Table 1 contains the average air velocity measurement in m s$^{-1}$ of all inlets for each of the four plant growth chambers, including the mean and standard deviation at an air volumetric flow rate of 2 volume air exchanges per minute (A.C. min$^{-1}$), which is equivalent to 0.86 m$^3$ min$^{-1}$. A Student's t-test (P < 0.01) indicated no significant difference in air velocity.

Table 1. Discharge air velocity (m s$^{-1}$) from inlet pipes for each of the plant growth chambers. Volumetric air flow was 2 volume air exchanges per minute (A.C. min$^{-1}$), (0.86 m$^3$ min$^{-1}$).

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Mean</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber 1</td>
<td>0.51</td>
<td>+- 0.05</td>
</tr>
<tr>
<td>Chamber 2</td>
<td>0.52</td>
<td>+- 0.05</td>
</tr>
<tr>
<td>Chamber 3</td>
<td>0.51</td>
<td>+- 0.03</td>
</tr>
<tr>
<td>Chamber 4</td>
<td>0.52</td>
<td>+- 0.05</td>
</tr>
</tbody>
</table>

Thermal Profile

To further verify that uniform vertical air flow at all points along the base of the plant growth chamber was attained, a steady-state thermal profile was established and measured. After 30 days of growth, the plant height was 51 cm, and 15 thermocouples were placed, 5 each, within the horizontal planes located at 15, 30, and 50 cm above the base of the plant. Air temperature was recorded for an additional 90 minutes after the inside air temperature of the plant growth chamber had reached steady-state (Table 2). This test was repeated for the volumetric airflow rates: 0.43 m$^3$ min$^{-1}$ (1.0 air exchange per minute), 0.86 m$^3$ min$^{-1}$ (2.0 air exchange per minute), 1.29 m$^3$ min$^{-1}$ (3.0 air exchange per minute), 1.72 m$^3$ min$^{-1}$ (4.0 air exchange per minute), and 2.15 m$^3$ min$^{-1}$ (5.0 air exchange per minute).

For all of the airflow rates, the air temperature difference among the five locations remained within ± 0.4°C, when measured within the same horizontal plane. Therefore the plant growth chambers established a uniform thermal distribution for the plants at each height. The vertical temperature gradient in the canopy growing area (from the bottom of the canopy to the maximum plant height at 51 cm) shows less than one degree of difference for all of the airflow rates except for 1.0 A.C. min$^{-1}$, which was approximately 1.4 °C due to the reduced air movement. Thus a volumetric airflow rate greater than 1.0 is desired for uniform temperatures. However, a lower operational volumetric airflow is desired for accurate measurement of CO$_2$ changes within the system, since a lower rate increases the effective resolution of the infra-red gas analyzer. An airflow rate at 2.0 A.C. min$^{-1}$ was chosen as a compromise for all future tests.
Table 2. The Mean (°C) and standard deviation of plant growth chamber air temperature for volumetric airflow rates of 1 to 5 air exchanges per minute (A.C. min\(^{-1}\)). Average of five locations within the horizontal plane at each elevation and airflow rate. (A.C. min\(^{-1}\) = 0.43 m\(^3\) min\(^{-1}\))

<table>
<thead>
<tr>
<th>Elevation from the bottom of the growing area</th>
<th>A.C. min(^{-1})</th>
<th>15.2 cm</th>
<th>30.5 cm</th>
<th>50.8 cm</th>
<th>63.5 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(°C)</td>
<td>(°C)</td>
<td>(°C)</td>
<td>(°C)</td>
<td>(°C)</td>
</tr>
<tr>
<td>1.0</td>
<td>21.9 ± 0.29</td>
<td>22.1 ± 0.34</td>
<td>23.3 ± 0.31</td>
<td>24.2 ± 0.35</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>21.7 ± 0.23</td>
<td>21.6 ± 0.33</td>
<td>22.6 ± 0.36</td>
<td>23.5 ± 0.37</td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>21.5 ± 0.20</td>
<td>21.3 ± 0.25</td>
<td>22.2 ± 0.23</td>
<td>23.0 ± 0.34</td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td>21.3 ± 0.20</td>
<td>21.2 ± 0.22</td>
<td>22.0 ± 0.19</td>
<td>22.7 ± 0.36</td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>21.5 ± 0.19</td>
<td>21.5 ± 0.23</td>
<td>22.3 ± 0.21</td>
<td>23.0 ± 0.32</td>
<td></td>
</tr>
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</table>

**Plant Response --- Environmental conditions in the plant chamber**

The system was capable of producing a crop at desired environmental conditions, with sufficient consistency and reliability to measure significant differences in plant responses such as biomass production. Table 3 includes the harvest data (seed dry weight and total plant biomass) for soybean (cv. Hoyt) grown at each combination of 400 and 1000 µMol Mol\(^{-1}\) atmospheric carbon dioxide, and 400 and 650 µMol m\(^{-2}\) s\(^{-1}\) photosynthetic photon flux (PPF) within the plant growth chambers.

Table 3. Harvest data, seed dry weight and total plant biomass (g) for soybean (cv. Hoyt) grown at each combination of 400 and 1000 µMol/Mol atmospheric carbon dioxide, and 400 and 650 µMol m\(^{-2}\) s\(^{-1}\) photosynthetic photon flux (PPF) within the plant growth chambers. (NJ-NSCORT Monthly Report Biomass Team, June)

<table>
<thead>
<tr>
<th>PPF</th>
<th>Seed Dry wt</th>
<th>Total Plant Biomass</th>
<th>Seed Dry wt</th>
<th>Total Plant Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO(_2) µMol Mol(^{-1})</td>
<td>400</td>
<td>1000</td>
<td>400</td>
<td>1000</td>
</tr>
<tr>
<td>400 µMol m(^{-2}) s(^{-1})</td>
<td>373</td>
<td>731</td>
<td>428</td>
<td>1071</td>
</tr>
<tr>
<td>650</td>
<td>448</td>
<td>905</td>
<td>555</td>
<td>1404</td>
</tr>
</tbody>
</table>
Conclusion

A plant growth chamber which utilized vertical airflow direction for cooling and air exchange was designed and tested. Results from measurements of air velocity, air temperature gradients and irradiance gradients, as well as, plant response data, indicated that this design could reduce plant microclimate variability in the horizontal and vertical planes.

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