Development and Evaluation of an Advanced Water-Jacketed High Intensity Discharge Lamp

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ABSTRACT

During the period July 2001 to March 2002, the performance of a water-jacketed high intensity discharge lamp of advanced design was evaluated within a lamp test stand at The University of Arizona (UA), Controlled Environment Agriculture Center (CEAC) in Tucson, Arizona. The lamps and test stand system were developed and constructed by Mr. Phil Sadler of Sadler Machine Company, Tempe, Arizona, and supported by a Space Act Agreement between NASA-Johnson Space Center (JSC) and UA. The purpose was for long term testing of the prototype lamp and demonstration of an improved procedure for use of water-jacketed lamps for plant production within the close confines of controlled environment facilities envisioned by NASA within Bioregenerative Life Support Systems. The lamp test stand consisted of six, 400 watt water-cooled, high pressure sodium HID lamps, mounted within a framework. A nutrient delivery system consisting of nutrient film technique re-circulation troughs and a storage tank was also included, but plants grown in the system were not evaluated in this time period. The unique physical and operational characteristics of the Sadler Water-Jacketed Lamp provided distinct advantages over other existing water-jacketed lamps. The quartz annulus has no seals that could degrade and potentially leak. The glass water jacket is not fused to the bulb, and it is not discarded when the commercially available HID bulb fails. In addition, the lamp is compact and has a horizontal orientation, allowing for a reduced vertical profile. Previous studies have illustrated alternative designs to remove heat with water jackets (Davis, 1994).

The following report describes a series of tests performed with the water-cooled high pressure sodium (HPS) lamp system. The primary purpose of these tests was to quantify and document the performance of the water-cooled lamps during long term operation.

INTRODUCTION

During the period July 2001 to March 2002, the performance of the Sadler water-jacketed high intensity discharge lamp was evaluated within a lamp test stand at The University of Arizona (UA), Controlled Environment Agriculture Center (CEAC) in Tucson, Arizona. The lamps and test stand system were developed and constructed by Mr. Phil Sadler of Sadler Machine Company, Tempe, Arizona, and supported by a Space Act Agreement between NASA-Johnson Space Center (JSC) and UA. The lamp test stand and nutrient delivery system were utilized for demonstrating an improved procedure for use of water-jacketed lamps for plant production within the close confines of controlled environment facilities envisioned by NASA within Bioregenerative Life Support Systems. The lamp test stand consisted of six, 400 watt water-cooled, high pressure sodium HID lamps, mounted within a framework (Figure 1). A nutrient delivery system consisting of nutrient film technique re-circulation troughs and a storage tank was also included, but plants grown in the system were not evaluated in this time period.

The unique physical and operational characteristics of the Sadler Water-Jacketed Lamp provided distinct advantages over other existing water-jacketed lamps. The quartz annulus has no seals that could degrade and potentially leak. The glass water jacket is not fused to the bulb, and it is not discarded when the commercially available HID bulb fails. In addition, the lamp is compact and has a horizontal orientation, allowing for a reduced vertical profile. Previous studies have illustrated alternative designs to remove heat with water jackets (Davis, 1994).

The following report describes a series of tests performed with the water-cooled high pressure sodium (HPS) lamp system. The primary purpose of these tests was to quantify and document the performance of the water-cooled lamps during long term operation.

OBJECTIVES

The primary objectives were to:
Determine the photosynthetic photon flux (PPF) measured as μmol m\(^{-2}\) s\(^{-1}\) and spectral irradiance measured as μmol m\(^{-2}\) s\(^{-1}\) nm\(^{-1}\) of the lamps for both the instantaneous and long duration time periods. Determine the reduction of PPF and the change of spectral irradiance caused by the water jacket and compare to the non-water-jacketed lamp. Monitor the energy flows of the lamp cooling system, and determine the proportion of input power (W), the radiant energy output, the recovered heat in the cooling water, and the losses to the chamber environment.

**MATERIALS AND METHODS**

The lamp test stand (Figure 1) consisted of a free-standing metal framework, with upper and a lower levels, each containing three, 400 W high pressure sodium water-cooled lamps. The stand had a length of 1.8 m (6 ft), a width of 0.9 m (3 ft) and a height of 2.1 m (7 ft). Six plant troughs for hydroponic crop production of compact crops, such as lettuce, were located within each level. No evaluation of crop growth was completed during this reporting period, although plants were successfully grown.

Each HPS lamp (GE LU400/TD, 2 cm diameter, 25.5 cm long) was centered within the air space of a double-walled glass annulus (Figure 2). The annulus formed a jacket around the lamp, and water was pumped through the double-walled glass. The lamp was surrounded by air within the center of the annulus, and the air was opened to the atmosphere at both ends. Light from the lamp had to pass through the interior wall of the annulus, the water contained within the double-walled annulus, the outer wall of the annulus, and then to the target area. Water was never in contact with the lamp. The glass annulus jacket was designed of two concentric glass cylinders of slightly different diameters. The cylinders were mounted inside each other to create a water channel surrounded by interior and exterior walls created by the concentric cylinders. These cylinders were fused to allow water to flow between them while creating a hollow interior air space. A lamp was fit into the interior air space. Inflow and outflow connections were fused into the glass for the flow of cooling water. There was no reflector attached to the water-jacket lamp.

The 245 mm long jacket was made of Quartz glass with an inside wall thickness of 1.8 mm, a 4.5 mm deep water channel and an outside wall thickness of 2 mm. The heat from the lamp imparted to the water through the interior wall of the glass annulus was cooled by a heat exchanger. The heat exchanger consisted of coiled plastic tubing submerged in a 200 L (55 gallon) container of water that was used as the heat sink. The heated water from the lamps was circulated at 5.9 L min\(^{-1}\) (1.6 gal min\(^{-1}\)) through the heat exchanger for cooling. The cooling water system was plumbed in parallel to each lamp, providing an assumed (but not measured) equal flow rate for each lamp of approximately 1 L min\(^{-1}\).

A Campbell Scientific Datalogger was utilized to monitor and record data values for thermocouples (copper/constantan Omega Engineering) which measured the inlet and outlet water temperatures (°C) of each of the 6 glass water jackets; heat sink water temperature (°C); and room air temperature (°C), as well as, a quantum sensor (Q8651 Li-Cor Inc.) to record the PPF (μmol m\(^{-2}\) s\(^{-1}\)). Each sensor was monitored every 60 s, and 15 minute averages were recorded.

The spectroradiometer (S1000 Ocean Optics, Inc.) measured and recorded data on monthly intervals, independent of the Campbell recorder, and provided the spectral irradiance curve between 300 – 900 nm. The quantum and pyranometer sensors had been calibrated prior to the tests, whereas the spectroradiometer had not been calibrated and thus provided only relative data during the monthly samples.

This work was performed over the 9-month time period from July 2001 through March 2002. The lamps were operated with a duty cycle of 16/8 on/off each day (excluding 576 hours of down time due to the related experiments that required one of the lamps to be taken from the system). The total operation time for the lamps during these tests was 4208 h. The lamps had been operated for 1500 hours prior to beginning these experiments. Therefore, the cumulative operation time for the lamps was 5708 hours, or approximately 28% of the manufacturers estimated life for the lamps which was 20,000 hours.

Additional tests were completed with one single, water-cooled lamp that was installed within the test apparatus described by Shimomachi, 2001. The water-cooled lamp without a reflector was placed within a structure that could estimate its total energy flows including 3-dimensional irradiance output, electrical energy input, heat extracted by the water-cooling system, and the energy conversion losses of the lamp-ballast-water-jacket system.

**LONG TERM TESTS**

Weekly measurements of each of the six individual lamps within the lamp test stand were completed to quantify the PPF (μmol m\(^{-2}\) s\(^{-1}\)) of the lamps over time. Monthly measurements were completed of the spectral irradiance (μmol m\(^{-2}\) s\(^{-1}\) nm\(^{-1}\)). A PVC plastic box with dimensions 38.0 cm by 68.6 cm by 46.0 cm was designed for attachment to the lamp test stand framework beneath each individual lamp (Figure 3). The box completely surrounded a single lamp, and it could easily and repeatedly be moved into the same relative position beneath each individual lamp for each sample date. The box housed the sensors that recorded PPF and spectral irradiance of the lamps. The box isolated the radiant output for each individual lamp, and oriented the instruments into the same relative position for each lamp during measurements. The two sensors (PAR, 400 – 700 nm; and spectroradiometer, 300 – 900 nm) were mounted on the base of the box, and were
centered 32 cm directly under the centroid of the lamp in the direction perpendicular (x axis) to the longitudinal dimension of the lamp (y axis) (Figure 4.) The lamp had no reflector.

The interior of the box had a diffusive white color surface finish. The data collected with the box was relative among the 6 lamps, since the geometric positions and reflecting surfaces of the box were consistent for all lamps. Therefore only the changes in PPF, and spectral irradiance values are meaningful. The absolute values of the measurements were over-estimates of the actual radiant values because of the reflectivity of the instrument box.

Power consumption of the lamps was determined by simultaneously measuring the voltage and the amperage directly at the lamp. This was completed weekly during the long term testing (between 1600 to 3250 cumulative hours of hours of operation), and then monthly from 3250 to 5700 hours of operation for each of 6 lamps (September 2001 through February 2002). The voltage and amperage were measured with a digital multimeter (Fluke Model T5 – 1000) at the input of each individual lamp during the same time in which PPF, and spectral irradiance data were recorded. This measurement included the lamp ballasts. The volt-amps do not directly equate to the power in watts, since the power factor was unknown. However, assuming a constant power factor, the differences in volt-amps would equate to differences in watts.

**SHORT TERM TESTS**

Tests were completed to determine the cold start-up performance characteristics of the lamps. During the initial start of operation of the lamps there was a delay to reach steady-state output. A cold start test was performed on Lamp # 3 to determine the response from a cold start-up to normal operation in terms of the photosynthetic photon flux (PPF) under two scenarios, including: 1) water-jacket in place and the cooling system operating normally, and 2) water-jacket removed. At the time of this test, Lamp #3 had 5708 hours of operation.

Three replicates of each test treatment were performed. Each replication began from a cold start (room temperature, 20°C) to reproduce the initial conditions of the duty cycle of the lamp. To isolate Lamp # 3, the instrument box previously described, containing a quantum sensor was placed 32 cm under the centroid of the lamp. Each test continued approximately 15 minutes until the PPF reached a steady-state condition. The data logger recorded the measurements as a 60 second average of samples monitored every 2 seconds.

Tests were conducted to compare the performance of one of the lamps, in terms of PPF, and spectral irradiance, for each of the following conditions: 1) normal operation (water jacket in place with coolant water flowing), 2) water jacket in place without coolant water flowing, and 3) without the glass jacket in place. Lamp #6 within the lamp test stand was used for this experiment.

Tests were conducted utilizing the instrumentation and hardware described by Shimomachi, 2001, to determine the water-cooled lamp energy balance, and the effect of coolant water temperature and water flow rate on the energy balance. One water-cooled lamp (lamp #6 without reflector) was placed within the Shimomachi structure to estimate energy flow including: electrical energy input, heat extracted by the water-cooling system, 3-dimensional irradiance output and the energy conversion losses of the lamp system (Figure 5).

The purpose of this series of tests was to determine power distribution within the water-cooled lamp system by simultaneously monitoring the irradiance output, electrical energy input, change in thermal energy of the water as it passed through the lamp jacket, and then calculating the energy conversion losses of each component of the lamp system. The lamp was cooled by the water-filled glass jacket at a flow rate of approximately 1 L min⁻¹. Coolant water from the temperature-controlled water tank (47.5 °C) was pumped to the inlet of the glass jacket and returned to the water tank. Water temperature thermocouples were placed on the input and output ports of the water-jacket. The room air temperature and heat exchanger heat sink water temperature were also recorded. These temperatures were continuously monitored with a frequency of one minute and then recorded as 2-minute averages. Input power was measured both before and after the lamp ballast by wattmeters (Model 380660 Extec Instruments). The power was delivered by a 120 volt source. Figure 5 is a schematic diagram of the test system. The irradiance of the lamp was measured by an Eppley radiometer that was sequentially re-positioned to 12 locations uniformly located in 3-D space, equidistant about the lamp to measure the 3-dimensional output of the lamp as described by Shimomachi, 2001. The total equivalent power from the lamp irradiance was calculated by summing the measurements for all of the locations and multiplying by the area inscribed by the sensor lamp relative positions. The entire area was enclosed by a black felt curtain in order to minimize reflections and to eliminate any outside light sources from the room.

The lamp was maintained at operating conditions identical to that used during the long term testing. The inlet water temperature was maintained at 47.5 °C, and the flow rate was maintained at approximately 1 L min⁻¹. The energy (joules) extracted by the water was calculated from the enthalpy equation as the multiplicand of the specific heat of water (4.81 J g⁻¹ K⁻¹), the mass flow rate of the water (g min⁻¹), and the change in water temperature between inlet and outlet of the lamp (°K).

The distribution of the PPF from the lamp without the reflector was evaluated. Using a quantum sensor placed on a horizontal grid beneath the lamp, a light map
was developed. The irradiance was measured 32 cm beneath the lamp within the x-axis (see Figure 4) ranging from 15 cm to the left of the horizontal line parallel to the centerline of the lamp to 15 cm to the right of the centerline of the lamp. It was repeated for each 5 cm along the centerline (y-axis) of the lamp.

A series of tests were performed at NASA Johnson Space Center which investigated the tolerance of the water-jacketed lamp to off nominal conditions including working pressure and temperature. The tests were conducted using a hydrostatic pressurization system located within NASA Johnson Space Center’s Energy Systems Test Area. The water-jacketed lamp assemblies were connected to the hydrostatic pressurization system using reinforced silicon tubing (Tygon 3370) held by either nylon or stainless steel hose clamps. The cooling water, which was not recirculated, was heated in place to a desired working temperature by manually turning the lamp on and off. Deionized water was used.

The first test, performed on two replicated water-jacketed lamp assemblies, was conducted to determine burst pressure. Nominal operating cooling water temperature was maintained at 50 °C, and the system cooling water pressure was raised in 69 kPa (10 psig) increments until failure occurred.

The second group of tests, performed on a single water-jacketed lamp assembly, subjected the sample lamp to three types of off nominal operating conditions, including:

- **Combined high temperature and pressure**: The pressure of the lamp cooling water was raised to 690 kPa (100 psig) while simultaneously increasing the lamp water cooling temperature to 100 °C by energizing the lamp;
- **Loss of coolant water temperature control**: The cooling water supply to the inlet of the water jacket was closed off and the cooling water return at the outlet of the water jacket was opened to equalize to atmospheric pressure. The lamp was energized and the coolant temperature was allowed to increase in an uncontrolled fashion;
- **Introduction of cooling water into a dry water jacket during lamp operation**: A water-jacketed lamp without cooling water was energized for 5 minutes to become hot, after which ambient temperature cooling water was rapidly introduced into the jacket.

**RESULTS AND DISCUSSION**

The average photosynthetic photon flux (PPF) of the 6 lamps decreased steadily from 1350 to 1100 μmol m⁻² s⁻¹ during the first 1520 hours (approximately 3020 h of cumulative operation time), and then remained between 1200 to 1300 μmol m⁻² s⁻¹ (Figure 6). The average PPF during the initial 1520 hours was 1258 with a standard deviation of 35 μmol m⁻² s⁻¹. The PPF averaged 1241 with a standard deviation of 39 μmol m⁻² s⁻¹ over the next 2496 hours (cumulative operation time of 5516 hours).

The spectral irradiance was measured for each of the 6 lamps and averaged for each monthly period to provide an average spectral irradiance curve for each of the 8 months of the test period. Figure 7 is a graph of the relative spectral intensity between 300 and 900 nm and was the first in the series of monthly spectral irradiance measurements between July 2001 and February 2002. Figure 8 is a graph of the average of the 6 lamps spectral irradiance measured for the following cumulative hours of operation: 368, 944, 1408, 2448, and 3040. Figure 9 is the area under the spectral irradiance curve versus hours of operation, as determined from Figure 8. The trend is for a reduction in the area, which represents a decreased irradiance from the lamps. The trend indicated a 16.4% reduction of area under the spectral irradiance curve during the 8-month test period.

To better characterize this trend, the area under the spectral irradiance curve was evaluated by separating it into 3 wavebands: 333 to 530 nm, 530 to 700 nm, and 700 to 903 nm. The wavebands were selected because of the spectral activity that occurred within their respective ranges (Figure 8). Figure 10 is a graph of the change of area under each of the three wavebands relative to their initial area value as measured on July 24, 2001 (560 h into the experiment, 2060 h cumulative on each lamp). Most of the change of area occurred in the range from 530 to 700nm, while the spectral area changes in the other two wavebands were small and nearly identical. After 5500 hours of operation, the 530 to 700 nm waveband had the greatest percent change which was a reduction of 18.8%. The 333 to 530 nm and 700 to 903 nm ranges had a smaller maximum percent change, 4.2% and 2.1 %, respectively. In Figure 10 it is clear that the spectral area in the 530 and 700 nm waveband decreased significantly, while the spectral area changed much less in the other wavebands (333 - 530 nm and 700 - 903 nm).

Figures 11a & b include the average trend of 3 replicates of lamp # 3 for both treatments of the cold start test, (a) lamp without the water-jacket attached, and (b) the lamp with water-jacket cooling system attached and operational. Approximately 10 minutes was required to reach normal-operating conditions for each of the treatments. With the cooling system in place and operational, the average measured values for PPF was 1201 μmol m⁻² s⁻¹. With the cooling system removed, the average measured value was 1386 μmol m⁻² s⁻¹.

Therefore there was a 13.3% reduction in PPF, as a direct result of the water-jacket. This is nearly twice the reduction compared with the results from the subsequent experiment (see Figure 13), however, this was a cold start test, not a lamp at steady-steady for an extended period.

The highest PPF was exhibited by the treatment in which the glass jacket was removed from the lamp (Figures 12 & 13). The treatment in which the glass jacket was in place, but without water produced a spectral irradiance curve smaller than that of the bulb in normal operation (glass jacket plus flowing water) (Figure 12). Potentially the reduction of PPF for the bulb plus glass jacket without water treatment resulted from the thermal insulation and the subsequent increase lamp temperature caused by the glass jacket without water. Although the actual lamp temperature was not measured, without the
heat transfer of the cooling water, it would be expected to experience an increase lamp temperature.

The most dramatic changes in spectral irradiance for each of the treatments occurred within the 565 and 619 nm waveband. The effect of water-cooling significantly reduced the intensity between 575 and 600 nm (Figure 12). Furthermore without water in the jacket, the intensity at 600 nm was again reduced an equivalent amount.

There was no indication of premature failure of the lamps that were enclosed by the double-walled, water-jacket during this 9-month testing period from July 2001 through March 2002. The total operation time for the lamps was 5,708 hours or about 28% of the 20,000 hours of manufacturers estimated life for the lamps. The averaged inlet and outlet temperature difference (during lamp operation) for the entire experiment was 4.3 °C with a standard deviation of 0.6 °C during the 8 months of lamp operation.

The power distribution of the water-cooled lamps is listed in Table 1. Of the 438 W provided to the lamp during the power distribution/energy balance test, 77 W (18%) was lost to the ballast giving a ballast efficiency of 82%; 162 W was measured as light radiation, giving a lamp (with ballast) conversion efficiency for light of 37%; 183 W was removed by the cooling water, giving a heat exchange efficiency of the cooling system of 42%; and 16 W (<1%) was unclassified losses. Note that the sum of these wattages is 438 W. Each was compared to the input wattage of 438 to determine the efficiencies listed above. The efficiency of heat extraction from the lamp by the water-cooling system was estimated as the ratio of 183 W to 361 W, or approximately 50%.

Table 1. Power Distribution of water-cooled lamps.

<table>
<thead>
<tr>
<th>Average Power at Source (W)</th>
<th>Average Power after Ballast (W)</th>
<th>Average Irradiance (W)</th>
<th>Average Power removed by water (W)</th>
<th>Average Power loss (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>438</td>
<td>361</td>
<td>162</td>
<td>183</td>
<td>16</td>
</tr>
<tr>
<td>100%</td>
<td>82%</td>
<td>37%</td>
<td>42%</td>
<td>0.03%</td>
</tr>
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</table>

Testing the effect of coolant water temperature and flow rate on power distribution for inlet water temperatures of 47.5 °C (normal operation), 52.5 °C (+ 5 degrees), and 42.5 °C (- 5 degrees), determined that the irradiance was not significantly affected when the water coolant flow rate was doubled, or when the water coolant temperature was increased or decreased by 5 °C (no data provided). The spectral irradiance was also unchanged during these tests.

Subsequent testing of a 1000 W HPS water-jacketed lamp with 19 °C cooling water demonstrated that the average power removed by the water increased to as much as 75%.

Tests at NASA-JSC to determine water jacket response to off-nominal coolant water temperature and pressure conditions demonstrated that the water-jacket withstanded temperatures of 100 °C or pressures approaching 1500 kPa (218 psig) without failure. However, the tube connecting the water jacket to the test structure providing the coolant water system became the limiting factor, which failed in each test. On three separate tests to determine burst pressure of the water jackets, the connection assemblies failed at 1225 kPa (178 psig), 1345 kPa (195 psig), and 1455 kPa (211 psig), respectively. Failures resulted from the water hoses slipping off at the hose barbs, either at the facility water source (first run) or at the water jacket (later two runs).

The three additional off nominal tests that were completed on a single sample lamp demonstrated that the glass water jackets could withstand a wide range of off-nominal conditions without failure. The water jacket and hose assembly maintained integrity when lamp cooling was water was pressured to 690 kPa (100 psig) and maintained at a temperature of 100 °C. Simulating the loss of control of water temperature by stopping the flow of the lamp coolant water or simulating the restoration of coolant water flow by introducing a sudden flow of coolant water into a hot empty jacket resulted in the coolant water boiling vigorously within the jacket, but both the connecting tubing and the glass water jacket did not fail under either situation. Under all tests performed the quartz jackets maintained integrity, without failure.

CONCLUSION

The operational performance of the Sadler water-jacketed lamp was determined in terms of its electrical consumption, radiant output, water-cooling capability, and its longevity. Safe operational conditions were demonstrated. Its unique physical characteristics, such as the quartz annulus that is independent of the bulb, eliminates the need for water-tight seals in contact with the bulb. In addition, the lamp is compact and has a horizontal orientation, allowing for a reduced vertical profile.

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Figure 1. Double-level Lamp Test Stand with six lamps.

Figure 2. Double-walled glass water jacket (above), and HPS lamp (below).
Figure 3. Instrument box attached to the lamp test stand framework beneath individual lamps to measure radiant energy. Instrument box located on upper level, center lamp (as shown).

Figure 4. Plan view of relative location of the two sensors placed underneath one lamp within the instrument box. Lamp centered along y-axis. Sensors aligned on x-axis.
Figure 5. Schematic diagram of the experimental hardware to determine the power distribution of the water-cooled lamp system during short term tests.

Figure 6. Average PPF ($\mu$mol m$^{-2}$ s$^{-1}$) of 6 lamps versus hours of operation.
Figure 7. Spectral irradiance curve after 1886 hours of operation. Average of 6 lamps.

Figure 8. Spectral irradiance from 24 Jul 01 to 26 Feb 02 (1948 to 5708 hours of operation, respectively). Average of 6 lamps.
Figure 9. Area under the spectral irradiance curve versus hours of operation. Average of 6 lamps.

Figure 10. Percent changes in area under spectral irradiance curve over time relative to the initial area under the spectral irradiance curve.
Figure 11. Trend in PPF and power consumption of Lamp # 3 with and without a water jacket during warm-up from a cold start, average of 3 replicates.

(a) lamp without the water-jacket attached

(b) with water-jacket cooling system attached and operational.
Figure 12. Spectral irradiance for a lamp under: 1) without the glass jacket in place (bulb only), 2) no coolant water flowing, with the glass jacket in place (jacket + bulb), and 3) normal operation (coolant water flowing).

Figure 13. PPF and Irradiance measurements for 1) without the glass jacket in place (bulb only), 2) no coolant water flowing, with the glass jacket in place (jacket + bulb), and 3) normal (coolant water flowing).