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Improved Instrumentation and Controls for Biomass Heating and Impact on Greenhouse Profitability

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Abstract. An adaptive real time crop and greenhouse model was implemented in a Nebraska commercial double-poly greenhouse during 2008 and 2009. Biomass heating using a pellet-burning furnace was alternated with a traditional propane heating system. Data collected included three spatial measurement zones within the greenhouse, including air and furnace temperatures, plant temperature, floor temperature, potting soil temperature, and inside roof glazing temperature using low-cost IRT/c sensors. Humidity, total and photosynthetically Humidity, total short wave radiation and photosynthetically active radiation (PAR) and the outside conditions were also measured. Ventilation fan, unit heater, and biomass burner operations were monitored with split core current sensors attached to the electric supply and control wires. National Instruments LabVIEW® software was developed to collect data and to report energy usage, moisture condensation potential, and production performance of the greenhouse. The zone loggers communicated using wireless technology with a master computer located at one end of the house. Moisture condensation potential on the leaves, floor, and inside glazing was continuously monitored throughout each day. Night time heat loss over the growing periods ranged from 25,000 to 160,000 BTU per hour. Greenhouse moisture condensation was found generally less for biomass than with the propane heating operation. Furnace performance was reported and a fuzzy logic control system is still being tested. Biofuel energy content was measured using an adiabatic bomb calorimeter. Considerable fuel savings were found possible with the system providing feedback to the grower.

Keywords. Biomass heating, greenhouses, biomass energy content, instrumentation, controls.

Introduction

Nebraska has great resources of solar radiation and water for greenhouse production especially during colder months of the year. Solar radiation usually meets the needs of daytime heating in greenhouses during these cold periods. However, night time heating is always required. Local weather conditions such as night time temperatures and humidity may be quite variable for managing the greenhouse environment efficiently. High early morning humidity can produce considerable moisture condensation under the glazing and on leaves, a good condition for fostering disease and pests. Some growers will increase heating temporarily to evaporate the moisture from these surfaces, increasing their fuel bill. The greenhouse and crop energy balance may be simulated using mathematical models which follow the principles of thermodynamics and heat transfer (Akhter, et al,1987; He, et al, 1991; Lee, et al, 2000; Al-Faraj et al. 2000; and Takakura, et al, 2007).

Most Nebraska greenhouse growers produce annual bedding plants, perennials, vegetable transplants and herbs in small single span greenhouses. Crops are grown for direct sell from a greenhouse or at a regional farmers market. Their goal is to grow unique, high quality, and useful plant material utilizing environmentally sensitive production methods. Most growers easily identify primary production expenses such as: energy, growing supplies, plant liners, and labor. Currently, many country-side growers heat with propane fuel, where the cost per gallon has increased 34% in 2004, 7% in 2005,and 16% in 2006, but has dropped in Spring 2009. Expected return of high fuel prices increase product cost and may reduce profitability, according to the marketability of the products. The availability and use of biomass fuels such as shelled corn or distillers' grains may help to control energy costs. However, biomass fuels have variable combustion properties according to their carbon and moisture content. A typical biomass burner usually has a mechanical auger system to feed granular biomass to a burn-pot ignition fire box. Heating may be potentially uneven with slower response times than gas-fired furnaces. Such systems were controlled manually in older times. But now, some type of automatic control is desirable.

A sensor–based greenhouse adaptive model is essentially a mathematical simulation model which utilizes real time sensor data directly and immediately predicts consequences (conservation measures), information for management, and/or quantitative output for automatic final control of heating, cooling, irrigation, and CO_2 fertilization (e.g. solenoids, valves, dampers, etc.). A primary application of sensor-based models in greenhouse production is the control of the environment, at both operational and tactical levels (Baker et al.1995). Greenhouses are semi-closed systems, thus crop and climate interact continuously. A goal for control is to insure good crop water/fertilizer use, which in turn means good CO_2 uptake. The optimization of CO_2 concentration, canopy temperature, and aerial humidity is based on factors affecting the mass and energy balance of the crop, which in turn, affects transpiration and net photosynthesis rates. Timing of crop development is also under grower control. Stem elongation, leaf unfolding rate branching, number of flowers and time to flower are examples of the many growth characteristics that may be fine tuned through selection of crop genotype and control of the environment to achieve optimal productivity and meet expected market dates. A sensor-based greenhouse model is therefore both a desirable and essential tool, especially when it can transform data into meaningful information for the grower.

Researchers have used energy balance methodology in greenhouses. Van Meurs, et al (1992) studied the transpiration rate of rose crop grown in a soilless mix and its interaction with the greenhouse microclimate and energy balance during summer conditions in Greece. Measurements of transpiration (λE_c), canopy net radiation (R_n), inside air and canopy temperature (T_i and T_c, respectively), and air vapor pressure deficit (VPD_i) were carried out during June and July 1998 in a white-washed glasshouse equipped with only fan-assisted ventilation. The sensible heat flux of the canopy (H_c) was calculated from data using λE_c and R_n. The results indicated that, although high air VPD occurred in the greenhouse (up to 5 kPa), the transpiration rate remained high throughout the day at a level equivalent to double the net radiation. Canopy temperature was found to be significantly lower than air temperature during most of the day. The canopy conductance to water vapor transfer (g_c) was estimated from a relationship linking transpiration to canopy-to-air VPD. The ability of the crop to respond to the high evaporative demand created by environmental conditions was also ascribed to the high crop LAI (about 4), roof whitening, and an adequate water supply, associated to a well-developed root system.

Elings et al (2005) developed comprehensive energy balances for tomato in the Netherlands. Solar radiation, primary and secondary heating circuits and CO_2 from the flue gasses of a heating system were quantified as energy sources. As energy use for air and leaf temperature increased, crop photosynthesis, crop transpiration, as well as energy losses through the roof, walls and ground surface were quantified. Subsequently, they reported the effects of eleven energy conservation measures. Consequences for gas consumption and production were also simulated. Consequences for fruit quality were assessed on the basis of expert knowledge, and economic consequences were simulated with a cost-benefit model. For tomato, most energy was saved by increased insulation of the greenhouse cover (23% saving) and a lower temperature set point (16%), followed by an increased set point for air relative humidity, screen gap control in steps, and temperature integration (all about 5%). Other modeling and CO_2 enrichment work for tomatoes was reported by Nederhoff et al. (1992), Papadakis et al. (1994), and Fierro et al. (1994).

Takakura, et al (2007) reported an energy balance model used to estimate evapotranspiration in a greenhouse, and instrumentation for this purpose was developed. It was found that a sensor-based modeling method was simpler than that using the traditional Penman-Monteith equation and the estimated values by this method were in good agreement with measured data. Other greenhouse energy saving methods have been reported by Both, et al (2005, 2007).

Reliable and quick assessment of energy conservation measures in greenhouse cultivation supports growers in their operations Elings, et al (2005). A sensor-based model could quantify the consequences of changes in energy flows for total energy consumption, amount and quality of production, and profitability. Fresh tomato production fell in most cases, except when there was increased light transmission by the greenhouse cover. Sensor-based models can also be used for the education of students and workers. Greenhouse production systems have become very complex, and many decisions have to be made daily. Training can be faster by using simulators that enable the users to compare an unlimited number of policies of climate or plant control. The success of the first examples of such simulators proves that education is a promising application of crop models (Power et al 1994, Bakker, el al 1995, and Challa and Bakker 1998).

Plants may be considered as a complex control system (i.e. stomata), Al-Faraj et al. (2000, 2001a). Al-Faraj discovered that plant temperature response follows transient behavior with different time constants that occur according to the abiotic stress imposed. Thus, leaf temperatures in greenhouses are always readjusting (Bahri et al., 1994). However, plant canopy temperature measurements depend on the effective use and understanding of infrared thermometry (Woebbecke et al., 1994). If a step or impulse of a short wave (e.g. clouds, shadows) is induced to a plant, the canopy temperature will change over a short time period with various response patterns (Al-Faraj et al. 2000). Moderately stressed plants approach critical and under-damped response conditions. Severely stressed plants respond closely to a first-order dynamic model. One practical application is to focus greenhouse instrumentation and control more toward plant response, in particular plant temperature and water use imply water vapor and CO_2 pass through the same stomata, so there should be a correlation.

The overall project goal was to obtain better control of greenhouse heating expense and to also move into a more complete environmental sensitive *production circle*. Growers want to utilize renewable energy sources available in the community (i.e. corn, wheat, beans, woody biomass) that would also support area agricultural producers. In this project, we began investigating the operation and how to utilize and control a typical biomass pellet furnace to meet the heat demand of a greenhouse. Specific objectives were to:

1. Develop a data base of combustion properties and moisture relationships for local alternative biomass fuels (biofuel) and determine response times and efficiencies of the heating system.

2. Simulate, test, and validate the controller with greenhouse crop temperature response for biomass heating using a mathematical energy balance model.

3. Develop and test an improved control system to provide uniform and dependable temperatures and humidity.

4. The final project objective not reported here is to evaluate economics, sustainability, and environmental impact on increased use of biomass as an alternative fuel.

Materials and Methods

Greenhouse studies are divided into three categories: (a) efficiency of low heat output biomass pellet furnaces, (b) adaptive modeling of the greenhouse environment based thermodynamics and heat and mass transfer principles and (c) instrumentation and control of the biomass heater and the greenhouse environments. Two single span, double polyethylene curved roof greenhouses are used, including a commercial cooperator unit and an on-campus house of similar size. Working in cooperator houses is sometime tentative, because the grower's primary goal is market a high quality crop, with little interference of the research. On-campus houses allow more precise research and replication. The cooperator greenhouse was instrumented for two annual growing seasons. The on-campus house has just come on-line through multistate project NE1035, and is not yet equipped with a pellet burner.

A commercial greenhouse in Firth, NE was used. It would be classified as a small family operated Nebraska greenhouse and is shown in Figure 1. This house produces ornamentals, bedding plants, hanging baskets, and annuals for in-house and farmers market sales during each spring for the last five years. The greenhouse is a 23,000 ft^3 volume house with a floor area of 2000 ft^2. The house is covered with 6-mil, double polyethylene plastic, where the layers are inflated by a small fan for wind resistance. The house has a 162,000 BTU per hour, propane single-stage heater with an advertised 81% furnace efficiency and two 20-inch ventilation fans. Control of each unit is ON/OFF by thermostat located in the middle of the 92-foot long house. A biomass pellet furnace was originally installed through an NCR SARE project. This burner was tested for efficiency and used during the growing seasons of 2008 and 2009. Figure 2 shows the inside of early plantings in February 2008. Figure 3 shows a full house ready for market in late April 2008.

Shelled corn was purchased at $3.05 per bushel during Fall 2007 and at $3.21 during Fall 2008. Propane during Fall 2007 was also purchased at $1.89 per gallon and at $1.78 during Fall 2008. Shelled corn was mostly burned during a three week period during February 2008 and met most of the night time heat loss needs, except for a couple of nights where the propane unit heater came on automatically to make up the difference.

Figure 1. (Left) Commercial Greenhouse used in this study (Right) Corn storage bin and biofurnace flue pipes (Note the outdoor pyranometer and wind speed sensor at top of the bin).

Figure 2. Greenhouse in early February 2008.

Figure 3. Greenhouse in late April, 2008.

Figure 4. Biomass pellet burner (left) and combustion fans on right.

This probably meant that the pellet burner was slightly undersized and could not meet all of the night time heat loss for this cold period. One would need a larger furnace.

A laboratory study was undertaken to obtain standard gross caloric values for various locally-obtained biomass fuels. Fuels included shelled corn, hazelnut shells, pecan shells, walnut shells, distiller grain pellets, and wood pellets. Data was acquired with a Parr® adiabatic oxygen bomb calorimeter (Parr Instrument Company, Moline, IL) using the American Society Testing and Materials (ASTM) procedure designation D2015. The bomb calorimeter shown in Figure 5 is located in the Industrial Agricultural Products Center (IAPC lab), Chase Hall on East Campus. An isothermal jacket for calorimeter water was used. Small samples of biofuel were burned under high pressure pure oxygen.

A typical bomb calorimetric test with a single biomass sample (approximately one gram) requires 30-40 minutes. A detailed example analysis sheet for this procedure is shown in Appendix A. Most biomass contains small amounts of nitrogen and sulfur. The ASTM D2015 procedure accounts for energy tied up in nitrogen oxides and sulfur dioxides. These energy amounts are adjusted by pH titration. A small amount of energy is also lost with the fuse wire during the test. Additional samples and the effect of moisture content are to be completed the summer. Samples also included the ash from pellet burner efficiency tests.

Both the campus and commercial greenhouses have a fully operational real time, adaptive model which collects the appropriate measurements and calculates crop energy components and production performance of a greenhouse. The model is essentially a thermodynamic model, based on the First and Second Laws. The model accounts for heating and ventilation by calculating sensible and latent heat exchanges for the greenhouse and its surroundings. The First Law energy balance includes both short wave and long wave radiation exchanges with the crop. Entropy production or eternal heat loss verifies the integrity of the calculations. The net energy rate of heat storage $\dot{Q}$ by the canopy is given as:

$$\Delta\dot{E}_{canopy} = \dot{Q}_{SW\,rad} + \dot{Q}_{LW\,rad} + \dot{Q}_{sensible} + \dot{Q}_{latent} + \dot{Q}_{metabolic}, \qquad (1)$$

where:

- $\dot{Q}_{SW\,rad}$ = Short wave radiation exchange ($W \cdot m^{-2}$),
- $\dot{Q}_{LW\,rad}$ = Long wave radiation exchange ($W \cdot m^{-2}$),
- $\dot{Q}_{sensible}$ = Sensible heat exchange of the canopy with the surrounding air ($W \cdot m^{-2}$),
- $\dot{Q}_{latent}$ = Latent heat heat exchange of the canopy with the surrounding air ($W \cdot m^{-2}$),
- $\dot{Q}_{metabolic}$ = Metabolic heat exchange (assumed negligible) ($W \cdot m^{-2}$).

Equation 1 represents the First Law of Thermodynamics of a plant canopy surface. $\Delta\dot{E}_{Leaf} = 0$ would represent a near-steady condition with little on change in leaf temperature for a short time interval. Sensible and latent heat fluxes (watts/m^2) have been defined in various ways. However, Monteith and Unsworth (1990), Campbell (1977), and Al-Faraj, et al (1994) have defined them as:

$$\dot{Q}_{sensible} = \frac{\rho \cdot c_p \cdot (T_c - T_a)}{r_H}, \qquad (2)$$

and:

$$\dot{Q}_{latent} = \frac{\rho \cdot c_p \cdot (P_{sat,\,Tc} - P_{v,\,Ta})}{\gamma \cdot (r_c + r_H)}, \qquad (3)$$

where:

- ρ = air density (1.1 kg· m^{-3}),
- c_p = heat capacity of the air (1.006 kJ·kg^{-1} $^oC^{-1}$),
- T_c = canopy temperature (^oC),
- T_a = air Temperature (^oC),
- $P_{sat,Tc}$ = saturated vapor pressure at canopy temperature (kPa),
- $P_{v,\,Ta}$ = vapor pressure of the air or $\phi \cdot P_{sat,Ta}$ (kPa),
- ϕ = relative humidity, decimal.
- r_H = leaf surface aerodynamic resistance ($s \cdot m^{-1}$),
- r_c = canopy or stomatal resistance ($s \cdot m^{-1}$), and
- γ = psychrometer coefficient (kPa·$^oC^{-1}$).

Substituting equations 2 and 3 into equation 1 yields net energy as:

$$\Delta \dot{E}_{canopy} = Q'_{SW\,rad} + Q'_{LW\,rad} + \frac{\rho \cdot C_p \cdot (T_c - T_a)}{r_H} + \frac{\rho \cdot C_p \cdot (P_{sat} - P_v)}{\gamma \cdot (r_c + r_H)}, \qquad (4)$$

The canopy energy balance has been extensively tested in a CONVIRON E-15 growth chamber used as a calorimeter for several years using the same sensors shown in Appendix B. A sample energy balance is shown in Figure 5. The model is written in LabVIEW® and Mathscript® (National Instruments, Austin,TX). Figure 6 shows the LabVIEW Front Panel for the greenhouse version. The model relies on psychrometric properties and quantitative relationships that are outlined in Cengel and Boles (2002). The model produces estimates of plant water use which is essential in evaluating plant growth and development. The key unknown parameter is the canopy resistance which can change according various abiotic stresses and age of the plant. It is extremely difficult to measure this resistance directly and has been shown to have its own dynamic response time (Al-Faraj, et al, 200). Various solvers using canopy resistance as the control parameter are currently being tested. One of the best approaches to date uses the LabVIEW proportional-integral-derivative (PID) controls add-on to balance the energy system with a variable adaptive canopy resistance.

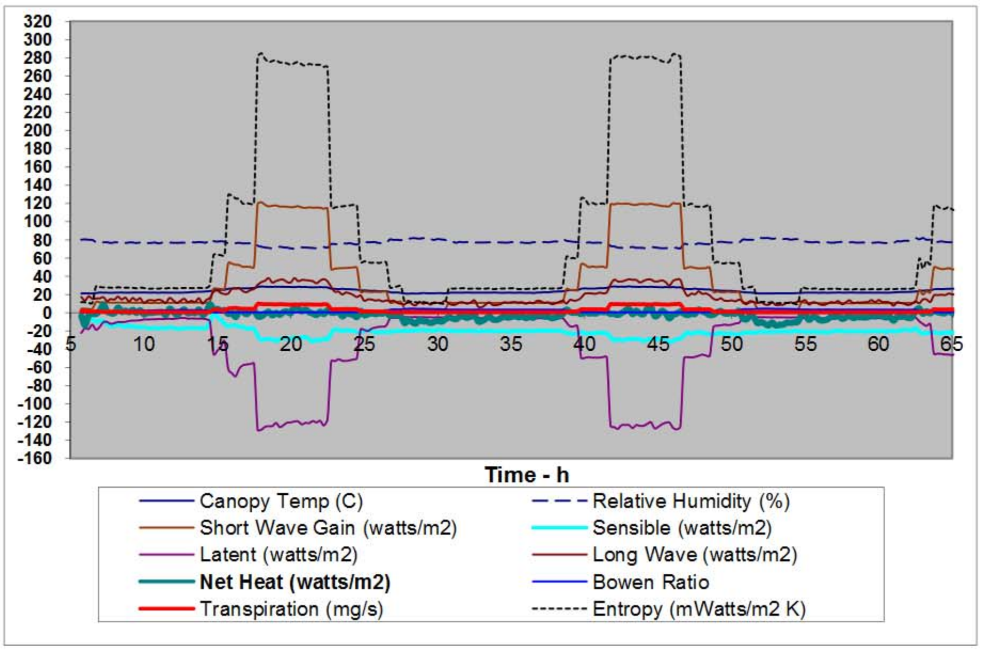

Figure 5. Adaptive energy balance for fescue *(Festuca Arundina)* under controlled conditions.

The process control drives net energy to close to zero. Transpiration values from 0 to 10 mg/s of water use were obtained (canopy resistance 525 sec/m for 8.7 mg/s). Appendix B lists the loggers and sensors used. Radiation impulse canopy temperature response times can also be used to observe canopy resistance behavior.

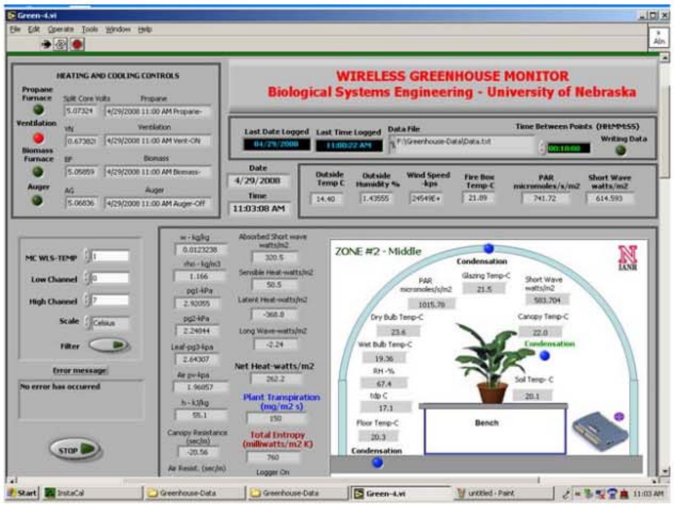

Figure 6. LabVIEW Front Panel of the Greenhouse Real-time Adaptive Energy Model and Monitor in Operation –April 29, 2008 11:03 AM, Firth, NE. (Ventilation fans are ON. Heaters are OFF. Condensation only noted on the floor at this time at the north or cold end of the greenhouse.)

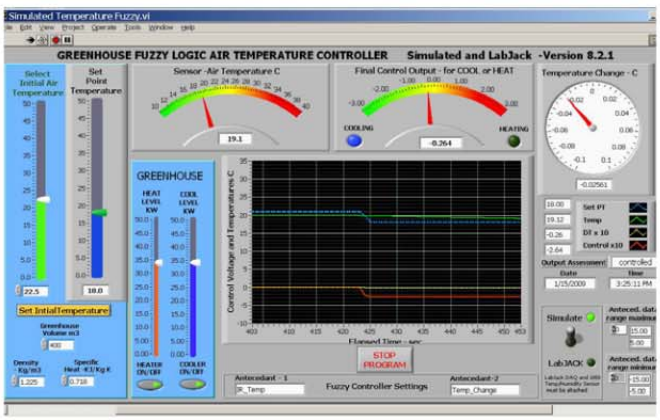

Figure 7. Front Panel for a Fuzzy Logic proportional greenhouse temperature controller. The virtual instrument uses the NI Controls Add-on.

A possible approach to a biomass heating control system is a rule-based, Fuzzy-Logic (FL) inference system (Zadeh, 1965; Li, et al 1995; Babuska, 1998; Chao, et al. 1998a; Chao, et al. 1998b; and Chao, et al. 2000). The basic rule-based, FL controller is used world-wide in many applications, Ross (2004). Greenhouse environmental control is more complex than standard room temperature control, because of moisture from plants and variable outside conditions. Fuzzy logic controllers have been used to integrate vague human decision making with precise sensor measurements. FL controllers can be developed with neural network methods (Sugeno), and/or possibly simpler Mandami linguistic methods (Babuska, 1998). The control logic can be easily developed with MATLAB®, LabVIEW® as shown in Figure 7, or other suitable software development packages. FL is easy to implement on personal computers or even very low cost, embedded controllers. Low cost, 16-bit and 32-bit embedded micro-controllers with instrumentation capabilities are commercially available.

A detailed literature review involving greenhouse heating and biomass furnace technology is being undertaken. We have not found any detailed applications of fuzzy or proportional controls for biomass furnace operations itself other than the review by Kalogirou (2003). Such software will be tested this Spring. The objectives for such a controller would be: to maximize biomass burn efficiency, to increase heat output by variable adjustment of auger speeds, and to adjust hot side heat exchanger air flow rates to control gases and oxygen. The biofuel pellet feed rate can not exceed what can be burned in the fire box and delivered efficiently through the heat exchanger. Trier, et al (2006) presented data that ignition temperature for corn is considerably higher than for wood. A counter flow heat exchanger with sufficient contact area between the hot and cold sides should also increase efficiency, along with a stack recovery heat exchanger (Treier, et.al. 2006). Incidentally, Trier, at al (2007) have developed and patented fluidized bed, biomass burning technology in Ohio. Fluidized bed systems can burn wet corn, but are probably best for larger greenhouse operations. Standard pellet furnaces need shelled corn 14 percent moisture content or less.

The adaptive LabVIEW energy balance model also monitors moisture condensation at three key locations within the greenhouse: the leaf surface, interior glazing, and the floor. Moisture condensation and water drip on plant leaves is a primary factor in disease and insect infestation. Greenhouse thermal models are driven by weather data collected at the site and supplemented as needed by the High Plains Automated Weather Station Network (http://www.hprcc.unl.edu/awdn/) for Lincoln, NE.

Results and Discussion

The biomass furnace had a lower combustion efficiency than the propane furnace. The unit has a fixed sprocket feed twin auger system. Much higher efficiencies would seem possible with some auger speed adjustments. Since the hot side fans run at a fixed air velocity, auger speed needs to be adjusted to prevent choking of the fire. Additional heat recovery at the flue stack might be a possibility. Additionally, there is good potential for proportional control to meet night time heat loss rates.

Gross heats of combustion values from the bomb calorimetry studies are shown in Table 1 and Figure 8. Biomaterials with additional oil content showed higher gross heat contents. Samples of the ash from 2008 and 2009 greenhouse studies indicated significant levels of unburned fuel. The unburned fuel had high heat contents determined by bomb calorimetry.

Table 1. Summary of Bomb Calorimetric Tests

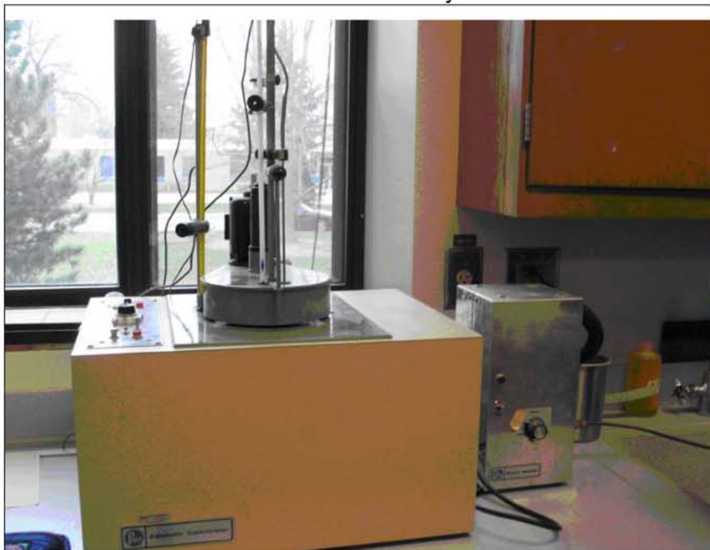

Figure 8. Adiabatic Bomb Calorimeter – Industrial Agricultural Products Center, University of Nebraska.

Fuel Type	**Average Gross Heat of Combustion (BTU per lbm)**
Hazelnut Shells	8,159±624
Pecan Shells	8,983±527
Shelled Corn	7,857±349
Walnut Shells	8,951±680
DDG Pellets	8,364±257
Wood Pellets	8,217±27
Ash from Greenhouse Furnace	7,044±1204
Sorghum	6,890±3

Furnace efficiency calculations are outlined in Cengel and Boles (2002) and Albright (1990). During the efficiency tests, temperature and humidity of the inlet and exit heat output air (cold side of the heat exchanger were continuously measured for an hour after a predetermined warm up time. Mass air flow rate was computed from air density and volumetric airflow rates. Volumetric air flow rates are computed from the inlet opening and a set of air velocity profiles with a Kurtz™ hotwire anemometer probe (Kurtz Instruments, Monterey, CA). Infrared sensors were also used to monitor heat exchanger and fire box temperatures. Fuel consumption was determined volumetrically by measuring a leveled depth after fuel usage. This also required a bulk density measurement. Fuel usage during propane tests was obtained by a pressure gage at the tank.

The test is automatically controlled with a virtual timer for one hour (3600 s) after a predetermined warm up time. The furnace heat output rate was computed after one hour using a LabVIEW® program. The Front Panel is shown in Figure 9. During the efficiency tests shown in Figure 10, temperature and humidity of the inlet and exit heat output air (cold side of the heat exchanger) were also continuously measured with LabJack™ 1050 temperature and humidity probes. Mass air flow rate is computed from air density (psychrometric equations – Cengel and Boles (2006)) and volumetric airflow rates. Volumetric air flow rates are computed from the inlet opening with a set of air velocity profiles using the hotwire anemometer probe. Air velocities were loaded manually into the front panel. Infrared temperature sensors are also used to monitor the heat exchanger and the fire box temperatures. Test results indicated efficiencies for this biomass furnace from 45 to 58 per cent.

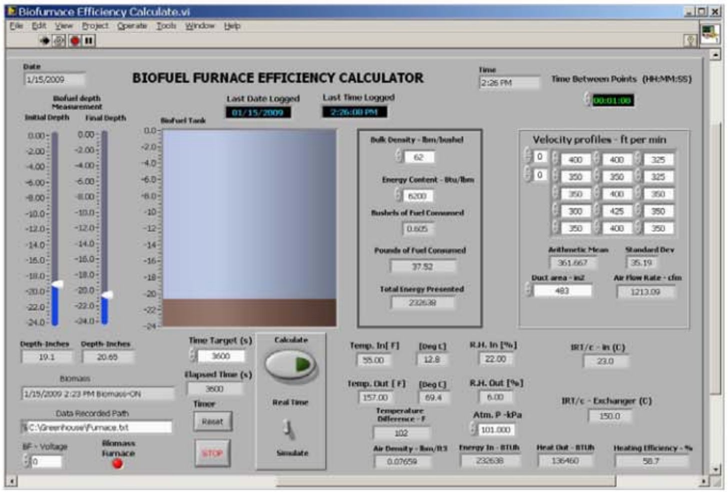

Figure 9. LabVIEW Front Panel for Furnace Efficiency Measurements.

Figure 10. (left) Biomass furnace efficiency test in-progress (inlet air side). (Right) Uneven draw down of shelled corn makes continuous volumetric fuel usage measurement difficult.

A digital FLIR® thermal imaging camera (FLIR Systems, Boston, MA) was used to determine furnace temperatures and other heat losses from the greenhouse, furnace, and flue. Figure 11 shows a series of infrared images used to determine the temperatures. These images not only capture visual information as a series of false colors, but also include temperature data. These images were analyzed later in the office using the FLIR Thermacam Researcher Pro 2.9®. This system allows individuals to take temperature measurements spatially and dynamically from remote and safe distances.

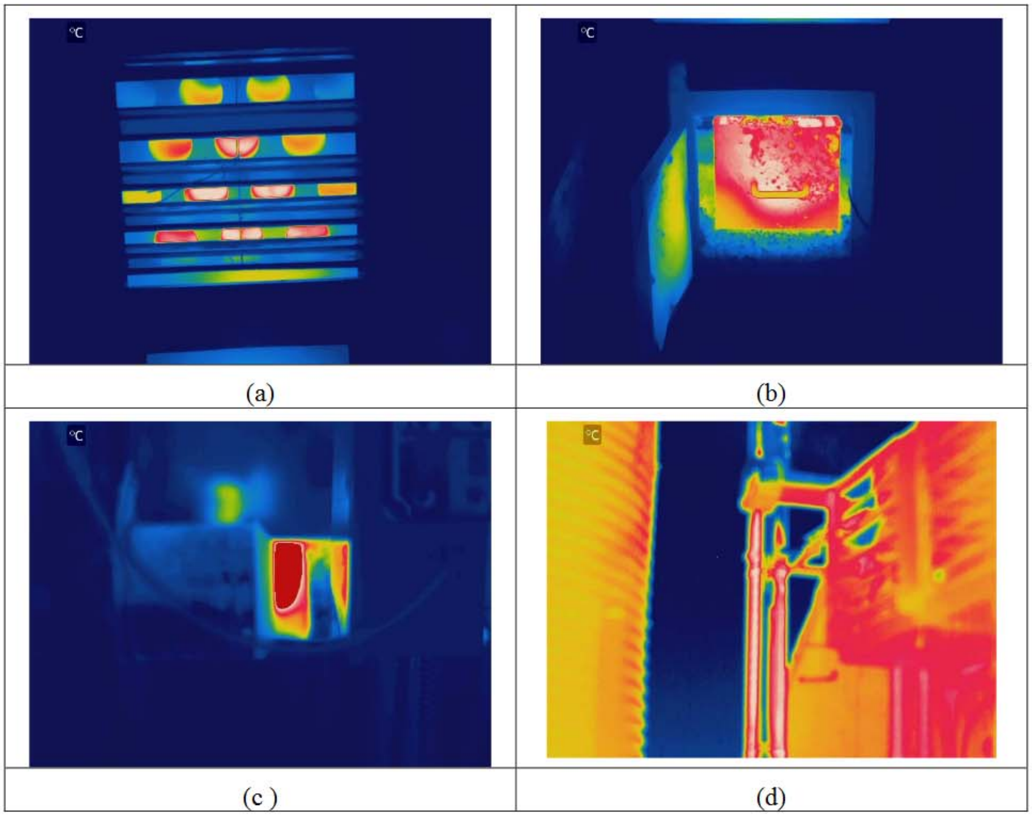

Figure 11. Thermal infrared images of the biomass pellet furnace. (a) hot air outlet port with louvers open and heat exchanger tubes exposed (407-470 ^{o}C, measured). (b) Fire box open with red hot, shelled corn (407 - 573^{o}C measured). (c) Exhaust pipe at rear of furnace (some heat loss here). Exhaust pipe is a triple wall pipe installed by the cooperator. (d) Outside triple wall pipe temperature is misleading due to incorrect emissivity (However, exhaust gas temperatures were measured with a Raytek™ hand held infrared thermometer to be around 150 ^{o}C).

This furnace can generate a 60^{o}C air temperature rise (inlet to outlet) on the cold side of the heat exchanger. Installation of a secondary heat exchanger system to recover stack heat losses would improve output and efficiency. The pellet auger runs continuously for calls of full heat output. We believe adjustments of a variable auger speed and combustion fan air velocities relative to fire box temperature control and an improved burn bucket design could also help to improve the burn rate and efficiency.

The cooperator greenhouse environment and surroundings was monitored on 10-minute interval, 24-hours per day by a set of data loggers. The house was monitored internally in three measurement zones for air temperature and humidity, total and photosynthetically active radiation (PAR), plant temperature, floor temperature, potting soil temperature, and inside roof glazing temperature. The latter were used to calculate sensible and latent heat exchange rates of the crop with their surroundings and moisture condensation potential on the leaves, floor, and inside glazing throughout each day from early February to late April. Outside air temperature, total solar radiation, and wind speed were also measured, but backed up with hourly data from the Lincoln station supplied by the High Plains Automated Weather Data Network.

The loggers communicated with a central computer located in the North end of the house using wireless technology. An additional set of Campbell CR10X battery operated loggers were used for backup and data collected once a week. Figure 12 shows sample greenhouse environment data recorded for 2008. Figure 13 also shows a comparison of biomass corn with propane nighttime heating. Note the smooth biomass heating temperature maintenance and apparent 10% reduction in night time relative humidity. The propane burner is probably oversized for this house as it requires numerous on/off cycles to find the temperature set point. Dry bulb air temperature rise increases the potential saturation vapor pressure and thus more evaporation from wet surfaces may occur during the night. We can see from Figure12 that the night time relative humidity was less for the pellet burner than for the propane burner. As the glazing gets colder toward the early morning, condensation occurs and sometimes results in an early morning rain.

Ventilation fan, unit heater, and biomass burner operations were monitored with non-intrusive, split core current sensors, placed on the appropriate electric supply and control wires. The north end of the house seemed to be most susceptible to condensation. Continuous records and calculation of greenhouse nighttime heat losses and daytime heat gains were acquired using these data and the formulae of the ANSI/American Society of Agricultural and Biological Engineering Standard EP404.3 “Heating, Ventilating and Cooling Greenhouses”. Results are shown in Figure 14. Night time heat loss over the growing period ranged from 25,000 to 160,000 BTU per hour. Note the smooth biomass heating temperature maintenance and apparent 10% reduction in night time relative humidity.

Table 2 summarizes the fuel economics of shelled corn versus propane and projected savings for 1000 bushels using Fall 2007 and Spring 2009 prices. Savings for corn purchased during the Spring 2008 were less because of increased corn and propane prices, except for Spring 2009 where there was a significant drop propane price. Other key information to note is the furnace efficiency, test weights, and the heats of combustion. Our burn tests currently indicated a low pellet furnace efficiency which contributes to reduced savings. Further modifications are necessary to improve efficiency. While pellet burning in small greenhouses seems attractive, the long term sustainability needs to be investigated.

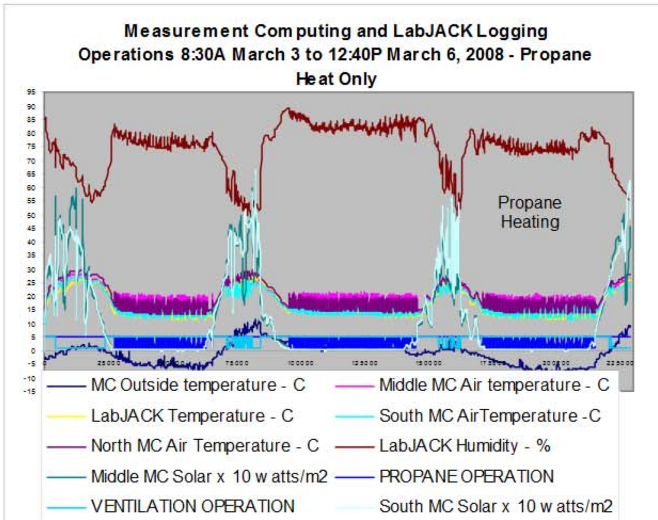

Figure 12. Heater and Ventilation Fan Operations. A single stage, oversized propane heater may go through as many as 50 ON/OFF cycles per night.

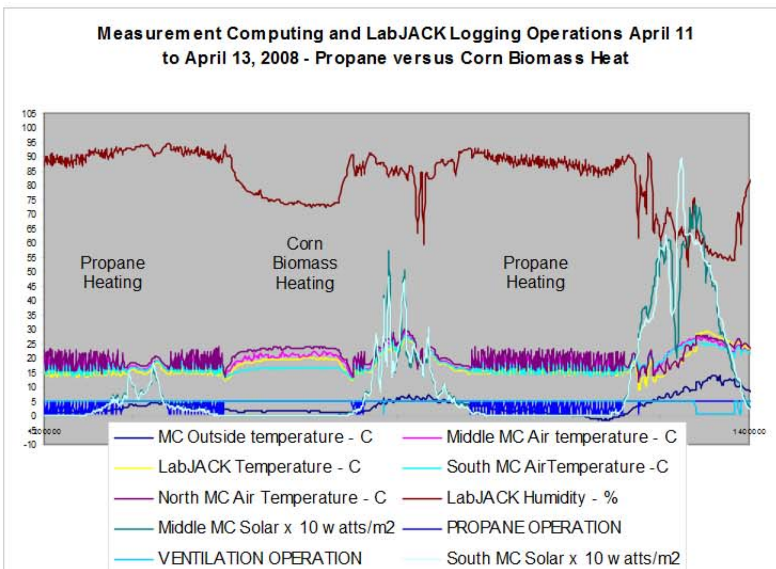

Figure 13. Comparison of biomass corn with propane nighttime heating.

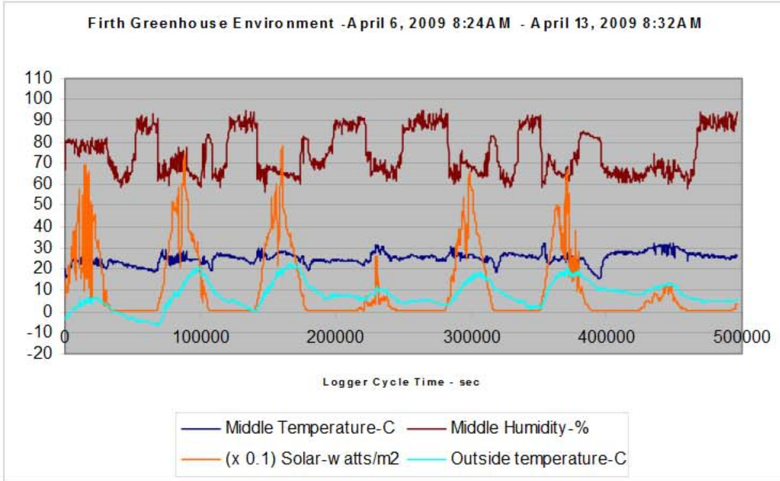

Figure 14. Greenhouse temperatures and relative humidity's during 2009 growing season.

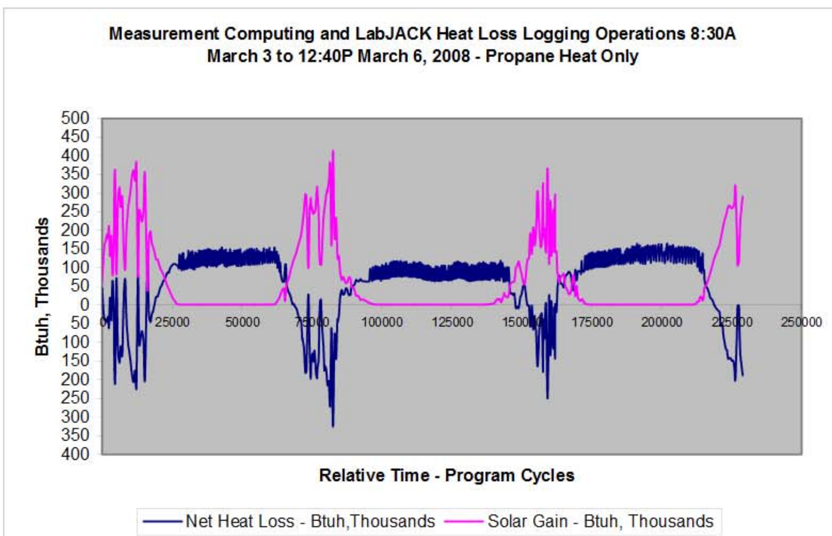

Figure 15. Sample night time heat loss and day time solar gain with the house for three days during March 2008.

Table 2. Fuel cost analysis and comparison for shelled corn versus propane.

Fuel Purchase Period	Fall 2007	Spring 2008	Fall 2009	Spring 2009	Units (English)
Fuel Type	**Shelled Corn**	**Shelled Corn**	**Shelled Corn**	**Shelled Corn**	
Bulk Density	62	62	62	62	lbm per bushel
Amount Fuel Used	**1000**	**1000**	**1000**	**1000**	bushels
	62,000	62,000	62,000	62,000	lbm
Energy Content	7,800	7,800	7,800	7,800	Btu per lbm
Total Energy	483,600,000	483,600,000	483,600,000	483,600,000	Btu
Pellet Furnace Efficiency	**0.50**	**0.50**	**0.50**	**0.50**	
Total Heat	**241,800,000**	**241,800,000**	**241,800,000**	**241,800,000**	Btu
Unit Fuel Price	**$3.05**	**$5.35**	**$3.21**	**$3.69**	per bushel
Total Fuel Cost	**$3,050**	**$5,350**	**$3,210**	**$3,690**	
Fuel Type	**Propane**	**Propane**	**Propane**	**Propane**	
Energy Content	91,600	91,600	91,600	91,600	Btu per gal
Gas Furnace Efficiency	**0.81**	**0.81**	**0.81**	**0.81**	
Equiv. Amount Used	3,259	3,259	3,259	3,259	gallons
Total Energy	298,518,519	298,518,519	298,518,519	298,518,519	Btu
Total Heat	**241,800,000**	**241,800,000**	**241,800,000**	**241,800,000**	Btu
Unit Fuel Price	**$1.89**	**$1.95**	**$1.78**	**$1.19**	per gallon
Total Fuel Cost	**$6,159**	**$6,355**	**$5,801**	**$3,878**	
Potential Savings	**$3,109**	**$1,005**	**$2,591**	**$188**	

Conclusions

Heat contents determined by adiabatic bomb calorimetry are similar to published averages found in the literature and on various internet web sites.. However, a measurement check of locally obtained biomass fuels is in order, because of possible variance. We do not know at this time if fuels other shelled corn could be accommodated or available in quantity for this application.

A National Instruments LabVIEW® greenhouse and crop model virtual instrument along with fuzzy logic control is being currently investigated with several objectives: to maximize biomass burn efficiency and to increase heat output by auger speed adjustment and/or hot side heat exchanger air flow and to meet greenhouse night time heat loss. The biofuel pellet feed rate needs to meet what can be burned in the fire box and delivered efficiently through the heat exchanger. Modeling the combustion process would be worthwhile. Ideally, a counter flow heat exchanger with sufficient contact area is used between the hot and cold sides for maximum efficiency and effectiveness. With these models, they can be used either in real-time or off-line to simulate other scenarios.

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The real-time adaptive energy model is working correctly. Low-cost electronic and instrumentation technology is available and feasible to monitor and control greenhouse environments and monitor crop production on the basis of water use.

Biomass heating did result in some savings over propane, but a full cost return analysis is not yet available in this report. The long term sustainability and profitability of these heating operations is not currently known and will be investigated.

Modern thermal imaging is an excellent tool for safely monitoring the levels and spatial distribution of high temperatures in pellet burners.

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Appendix A: Sample Calculation Sheet - Heats of Combustion (ASTM 2015) for Pecans and Hazelnut Shells.

Date:	1/4/2008	1/4/2008	1/4/2008	1/4/2008	1/4/2008	1/4/2008
Mass of Water in Bucket (g)	2000.00	2000.00	2000.02	2000.01	2000.00	2000.01
Fuel Sample (g)	0.919	0.982	0.993	0.988	0.961	0.975
Initial Length of fuse wire (cm)	10.1	10.0	10.0	10.1	10.0	10.0
Length of fuse remaining (cm)	4.75	4.80	4.65	1.80	2.35	4.45
Fuse consumed (cm) (c3)	5.35	5.15	5.35	8.25	7.60	5.55
Starting Temp (C)	24.850	24.860	25.240	24.510	24.970	25.205
Ending Temp (C)	26.687	27.020	27.210	26.650	26.840	27.080
Temp Difference (C) (t)	1.837	2.160	1.970	2.140	1.870	1.875
Initial titration reading (ml)	0.0	0.0	0.0	0.0	0.0	0.0
Ending titration reading (ml)	4.86	4.88	4.44	4.29	4.86	9.28
Amount of Titrate (ml) (c1)	4.86	4.88	4.44	4.29	4.86	9.28
Percent Sulfur (c2)	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Normality of Solution	0.145	0.145	0.145	0.145	0.145	0.145
Fuel Type	Pecan Shells			Walnut Shells		
e1	4.86	4.88	4.44	4.29	4.86	9.28
e2	0.019755	0.019755	0.019755	0.019755	0.019755	0.019755
e3	12.305	11.845	12.305	18.975	17.48	12.765
W (Calories per deg C)	2428.0	2428.0	2428.0	2428.0	2428.0	2428.0
Gross Heat of Combustion (calories)	4,443	5,228	4,766	5,173	4,518	4,530
Fuel Energy (cal)	4,443	5,228	4,766	5,173	4,518	4,530
Gross heat of combustion (calories per gram)	4,835	5,323	4,800	5,235	4,701	4,647
Gross heat of combustion (BTU per lb)	8,710	9,591	8,647	9,432	8,470	8,371
Average Gross Heat of Combustion (BTU per lb)	8,983			8,951		
STDEV Gross Heat of Combustion (BTU per lb)	527			680		

Appendix B. Summary of Sensors and Loggers used in the Nebraska Greenhouse Environmental and Energy Balance Studies[1].

Unit	Sensor	Purpose
Measurement Computing – WLS-TC Wireless with WLS-IFC USB Transmitter-Receiver Primary data Logger. 8 differential, 24-bit. 16 ksamples per sec. (Measurement Computing Corporation, Norton, MA). (Licor, Inc., Lincoln, NE)	Omega sub-miniature infrared thermocouples. (OMEGA Engineering, INC. Stamford, Connecticut)	Canopy temperature.
		Floor temperature.
		Inside glazing temperature.
	Type K thermocouple.	Psychrometer – inside wet and dry bulb temperatures.
		Potting soil temperature.
		Outside air temperature.
	Licor LI-200 pyranometer	Total radiation inside greenhouse.
	Licor LI-190 quantum sensor.	Photosynthetically-active-radiation inside greenhouse.
	Eppley black and white pyranometer.	Used in chamber plant calorimetry.
LabJack U12 USB Datalogger 8 Single-Ended, 4 Differential 12-Bit Analog Inputs ±10 Volt Analog Input Range. PGA with Gains of 1, 2, 4, 5, 8, 10, 16, or 20 V/V. Up to 8 kSamples/Sec (Burst) or 1.2 KiloSamples/Second (Stream). (LabJack Corporation, Lakewood, CO)	EI1050 Digital temperature/humidity probe. (LabJack Corporation, Lakewood, CO)	Inside air and relative humidity.
	Mikron MI-N3000 Infraducer system	Wall and background temperatures in Chamber calorimerty.
	CR Magnetics CR9380 NPN Current Switch.	Monitors on/off operation off all fans and motors in greenhouse.
Campbell CR10/10X Backup Data Logger (Campbell Scientific, Logan, UT)	Eppley PSP Pyranometer.	Outside solar radiation.
	HMP 35C Temperature and Humidity Probe. (Vaisala Inc. Woburn, MA)	Inside air temperature and relative humidity.
	Cup anemometer.	Outside wind speed.

[1]Additional hourly data provided by High Plains Automated Weather Station Data Network.