Controlled Environment Systems ABE 483/583

Dr. Gene A. Giacomelli
Professor & Director Controlled Environment Agriculture Center
Department of Agricultural and Biosystems Engineering
Shantz Building, Room 504, Ph: 520 621-1412
and
CEA Building, Room 101, 1971 E. Roger Road, Ph: 520 626-9566
giacomel@ag.arizona.edu

Lecture #7A Greenhouse Energy Balance

Hannan:	**Chapter 4, Temperature,**
	pps. 167 - 171 Energy Balance [focus of this first lecture!]
	pps. 171 - 186 Effects of Temperature on Plants [minor focus!]
	pps. 186 - 199 Temperature Measurement and Its Manipulation
	pps. 199 - 223 Heating Systems and Energy Sources
	pps. 223 - 236 Energy Conservation
	pps. 236 - 260 Ventilation and Cooling

'HeatVent' software by Wei Fang

Others:
ASHRAE 1985 Fundamentals Chapter 6, pps 6.1 – 6.20
The Greenhouse Climate Control Handbook, Engineering Principles and Design Procedures by ACME Engineering & Manufacturing Corp.

Strategy

We will begin the 'Temperature' discussions with a look at the greenhouse with its components and crops in terms of energy flow, energy storage, and the resulting air and leaf temperatures. Collectively this is known as developing an **Energy Balance** for the greenhouse system. This lecture is provided below, and presented first.

Subsequent lectures will follow the subtopics of Chapter 4 of the Hannan's book.

The '**Effects of Temperature on Plants**' is developed and summarized in the text. You should review this, but it will not be emphasized in this course, save to emphasize why greenhouse designers and operators need all the systems that we will study.

Temperature Measurement and Its Manipulation will be covered to outline the mechanisms for heat gain and loss, and to develop the simplified equations for calculating these gains and losses.

We will then look to **Heating Systems and Energy Sources** to understand techniques that have been developed to manipulate the air temperature, and promote plant growth.

Costs associated with heating a greenhouse have required the development of **Energy Conservation systems,** so these will be reviewed and compared.

Finally, we will evaluate the problems of too high greenhouse air temperature, and the procedures of **Ventilation and Cooling** systems.

Sensor and measurements

Hannan: pps. 186 - 199 Temperature Measurement and Its Manipulation

Show energy balance of Temperature sensor such as a thermistor, using radiation, cond/convection and infiltration heat loss components. Show how they affect the time constant and the $T_{sensor} = T_{\infty}$ reading.

Time constants
Accuracy

Aspiration
Location

Thermal mass

Heat Losses

Hannan: pp 191 – 199

Energy Conservation
[from original HortGlazing paper, never publish as this exactly]
The greenhouse must also provide protection from variable weather conditions, such as winds, hail, snow, and excessive heat or cold. The heat retaining properties of the covering system during the long nights and cloud-covered days of the cold season are particularly important. Comparisons of energy conserving capabilities of greenhouse covering systems in combination with movable nighttime insulation systems have been extensively documented. A summary can be found in NRAES-3 (Roberts, et al, 1989).

The thermal environment of the greenhouse is based on the relative input and outflow and 'storage' of energy.
The energy sources are primarily daily solar radiation and/or supplemental heating devices.
These sources must balance with the energy losses from the greenhouse to the outside environment to maintain the desired inside air conditions.
As energy is lost, the air temperature inside the greenhouse decreases; and,
As the energy is gained, the air temperature inside the greenhouse increases.

Greenhouse Heating Energy Balance

Solar Energy + Supplemental Heat + [Stored Energy] = Energy Losses
[at steady-state condition]

Energy is lost from the greenhouse by a combination of convection, radiation, and infiltration through, plus condensation on, the surface covering of the greenhouse.
Energy is also 'stored' temporarily in the greenhouse structure, components, etc for later release.

Energy Losses = Convection + Radiation + Infiltration + Condensation

Convective heat losses are generally similar for all single, thin-layer materials, while most double-layer coverings are nearly alike. Convective heat losses are dependent upon the insulating value of the cover material. The insulation value is significantly increased when a second layer is added. For example, when double layers of plastic film are separated by a small air space, the result is an approximate 30% reduction in energy transfer compared to a single glass layer (Roberts and Mears, 1969).

Radiation heat losses are directly related to the physical properties of the cover material. These include the emissivity and the transmissivity (in the infrared and thermal wavebands) of the covering material. The emissivity is a material property which defines its ability to emit radiation energy that it has absorbed. Energy absorbed by the cover from inside the greenhouse and emitted to the outdoor environment as long wave radiation provides a heat loss from the greenhouse environment. The larger the emissivity, then the greater the rate of radiation heat loss. The transmissivity is a material property which determines its ability to transmit radiation energy. In this case, it is not the visible radiation which is of concern, but infrared and thermal radiation. This energy is directly transmitted by the cover from inside the greenhouse and it creates a heat loss from the greenhouse environment. The larger the transmissivity for infrared or thermal radiation, the greater the rate of radiation heat loss.

The **net radiation** of the greenhouse is important for evaluation of the greenhouse energy situation. Net radiation is the difference between the energy received and energy lost by radiation. During the day, the sun which generally provides a large amount of radiation assures a net gain of energy, because the losses are much smaller. This net gain of energy causes a subsequent greenhouse air temperature rise. However, at night, the warm masses within the greenhouse (earthen floor, concrete paths, metal benches, plants, etc) produce significant radiation losses to the colder outdoor environment. The net energy loss is caused by transmission of infrared and thermal radiation through the cover, as well as emission of radiation from the cover to the cold sky. The amount of this radiation energy loss depends, not only on the properties of the cover, but also on the temperature of the cover, and the atmospheric conditions (water vapor, carbon dioxide, and ozone content).

Because of the potential radiation heat loss, it is important to consider the transmittance properties of the cover material in the infrared and thermal wavelengths, which includes those greater than 850 nanometers. Laboratory tests have documented these transmittance properties for most glazing materials (Ametek, 1984; Godbey, et al, 1979; Robins and Spillman, 1980). However, just as previously described for PAR transmission, these values should only be a relative indicator among the various materials, and not a true measure during greenhouse operation. Simpkins, et al, 1984, studied the net radiation and convective energy losses from single-bay, polyethylene-covered greenhouse structures. They confirmed that a combination of night sky conditions (cloud cover, atmospheric humidity) and the location of adjacent, heated structures (other greenhouses or buildings) directly affected the net radiation losses. The proximity of other structures also affected energy transfer by altering wind induced infiltration and convective heat losses.

Infiltration energy losses are related to the openings within the structure and covering material, as well as, on the outside wind speed and direction. The amount, size and location of the openings affect infiltration. These may include the required access doors, heater intake/exhaust openings, and fan/ventilator openings. They also include the undesirable cracks and joints within the structure and covering system. Infiltration attributed directly to the covering system is highly dependent on whether the covering material is a continuous film such as a sheet of polyethylene, or whether modular in design, such as glass or rigid structured panels. The latter case has many edges which provide access for gas and moisture exchange. Infiltration rates may vary from as little as 0.5 volumetric air changes per hour (VAC hr^{-1}) for continuous sheet film-covered structures, to 0.75 - 1.5 VAC hr^{-1} with newer glass panel glazings (Aldrich and Bartok, 1989).

Condensation of water vapor from the warm moist air onto the cool surface of the covering material represents an indirect method for heat loss from the greenhouse. The change of water vapor to liquid results in a release of energy called latent heat. As condensation occurs on the cover this latent heat energy can be lost from the greenhouse by convective heat transfer through the cover. This condensation, however, will help to reduce radiation heat losses, as water reduces the transmission of infrared radiation. However, as the surfaces become covered, droplets of water are formed and may fall to the crop below. This is an undesirable situation as excessive moisture can damage the crop by overwatering, and encourage the spread of disease. Efforts to incorporate inhibitors to droplet formation, particularly on plastic coverings, have somewhat reduced this problem.

Radiation

$Q_{rad\ LW} = \varepsilon\sigma (T_p{}^4 - T_s{}^4)$, W m^{-2}

Where:
ε = ~0.95 for most ‘dark’ surfaces, or for green leaf
σ = 5.67 x 10-6 W m^{-2} $^oK^{-4}$
T_p = instantaneous air temperature radiating surface, K
T_s = instantaneous air temperature of absorbing surface, K
Note that K = 273 + ^oC, or K = 454 + ^oF

Conduction/Convection

$Q_{cond/conv} = h A (T_i - T_o)$, W

Where:
h = heat transfer coefficient for cond/conv, W m^{-2} $^oK^{-1}$
A = (‘SA’ more appropriate) = surface area of heat loss, m^2
T_i = instantaneous air temperature inside the GH, K
T_o = instantaneous air temperature outside the GH, K

Infiltration

$Q_{infiltration} = 0.5 V N (T_i - T_o)$, W

Where: V = volume of GH, m^3
N = number of air exchanges per hour, hr^{-1}
T_i = instantaneous air temperature inside the GH, K
T_o = instantaneous air temperature outside the GH, K

Greenhouse Engineering, Aldrich & Bartok, pps 64 – 68

$Q_{infiltration} = 0.02\ M\ (T_i - T_o)$, BTU hr^{-1}

Where: M = air exchange of GH, $ft^3\ hr^{-1}$
T_i = instantaneous air temperature inside the GH, F
T_o = instantaneous air temperature outside the GH, F

Note: 0.02 is derived from $c_{p,\ air}$ = 0.24 B $lb^{-1}\ {}^oF^{-1}$ divided by specific volume, v = ~14 $ft^3\ lb^{-1}$ It is more specifically 0.0017 having units of B ${}^oF^{-1}\ ft^{-3}$

Air infiltration is expressed in volume air exchanges per hour. Air infiltration is a function of wind speed and duration. It can be determined more precisely by measuring the carbon dioxide decay rate of an empty greenhouse which was given an initial high concentration charge.

The CFM of air exchange multiplied by the temperature difference between inside and out, then multiply by 1.08 will equal B hr^{-1} of heat lost due to infiltration:

$$Q = m\ c_p\ \Delta T$$
$$= \text{CFM} \times 60 \text{ min hr} \times 0.075 \text{ lb } ft^{-3}{}_{air} \times 0.24 \text{ B } lb^{-1}\ {}^oF^{-1} \times \Delta T$$
$$= \text{CFM} \times 1.08 \times \Delta T,\ (\text{B } hr^{-1}) \quad \text{(infiltration heat loss)}$$

Using the psychrometric chart, find enthalpy value of the air at the current state point. Btu lb^{-1} then divide by specific volume, v = ~14 $ft^3\ lb^{-1}$, multiply by M = air exchange of GH, $ft^3\ hr^{-1}$ and then by temp difference.

Condensation

Latent heat of vaporization of water, h_{fg} ~ 1050 BTU lb^{-1} of condensate. This varies slightly with air temperature. For example, at sea level, for two common night air statepoint conditions in the greenhouse,

at 75 ${}^oF$ & 80% RH, h_{fg} = 1051 BTU lb^{-1}
while at 65 ${}^oF$ & 80% RH, h_{fg} = 1057 BTU lb^{-1}
there is only a 0.6% difference

Overall Heat Transfer Coefficient

Combining the conduction, convection and radiation into an overall heat transfer coefficient, U BTU $hr^{-1}\ ft^{-2}\ {}^oF^{-1}$, which can be generalized and approximated [with reasonable accuracy, especially for sizing the heating system] for various common types of greenhouse glazings, and used in the equation:

$Q_{overall} = U \; SA \, (T_i - T_o)$, BTU hr^{-1}

Where,
U = overall heat transfer coefficient, W m^{-2} $^oK^{-1}$ or BTU hr^{-1} ft^{-2} $^oF^{-1}$
SA = surface area of heat loss, m^2 or ft^2
T_i = instantaneous air temperature inside the GH, K or ^oF
T_o = instantaneous air temperature outside the GH, K or ^oF

Where U has been determined to be as shown in Table 4-4, Hannan.
To convert to W m^{-2} $^oK^{-1}$ to BTU hr^{-1} ft^{-2} $^oF^{-1}$ divide by 5.68

Warning on use of Table 4-4. First the U values were determined without including infiltration, therefore you must add $Q_{infiltration}$ as shown in equation 4.13. Second, Hannan use ‘h’ instead of ‘U’. Third, Table 4-5 contains ‘h’ values which are not overall heat transfer coefficients, but more correctly heat transfer values at specific conditions, i.e. Clear sky/overcast sky, windspeed of 4 m/s, temperature difference of 30 C.
The U value is generic [averaged over many types of weather conditions in the field], and it is used for estimating heating loads and sizing heaters. The h value is used for specific conditions and for rigorous heat transfer analyses.

Evaluate the use of ‘HeatVent’ for determining the greenhouse heat losses.