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An ASHRAE Level 2 Model for Transparent Greenhouses

Michael R. Stiles, Ph.D. CEM

ABSTRACT

The transparent greenhouse, situated above either soil or a concrete floor, is gaining wintertime popularity in cold climates. These structures need to be energy efficient to be commercially competitive as growers diversify their wintertime crops. This article presents a quantitative hourly thermal model of transparent greenhouses suitable for an ASHRAE Level 2 analysis of transparent greenhouses. The basic model is for sensible heating and cooling loads. This article concludes with suggestions for broadening the basic model to cover thermal interactivity with electric lighting, humidity issues, vertical sub-grade perimeter insulation, and other greenhouse energy topics.

INTRODUCTION

The transparent greenhouse, situated above either soil or a concrete floor, is gaining wintertime popularity in cold climates like upstate New York [1, 2]. These structures need to be energy efficient to be commercially competitive as growers diversify their wintertime crops. To support these efforts, utility companies offer energy studies and equipment incentives for greenhouses, for example [3].

ASHRAE provides a systematic approach to thermal analysis of buildings by way of an energy audit. A Level 2 audit quantifies energy performance from site data and utility bills. It identifies opportunities for efficiency and operational improvements [4,5]. However, it has been the author's experience that Level 2 audits have not been systematically developed for transparent greenhouses.

Because of their relative simplicity, the thermal processes that impact greenhouse interior conditions are not difficult to enumerate [6, 7]. For passive liam W. Sheppard, Apopka, florida temperature response—that is, in the absence of active heating, cooling, and ventilation—the principal heat and moisture exchanges of a greenhouse occur with respect to:

- The exterior via conduction through the shell
- The exterior via infiltration/exfiltration
- The ground via conduction through the floor/soil
- Solar input.

Agricultural resources like those provided by NRAES [6, 7] provide a high-level description of these physical processes without offering a means to quantify their contributions to greenhouse interior temperature. This article presents a quantitative hourly model of these processes. This model is constrained by a heat balance analysis—all parameters contribute to greenhouse temperature interactively.

The development of this model was motivated by several developments. First, the appearance of publicly accessible weather data including hourly insolation measurements [8] has encouraged the relevance of hourly models. It is now possible to "tune" such a model to contemporary utility data instead of having to rely on long-term averages like TMY (typical meteorological year) data.

Second, as government legislation seeks ever greater regulation of energy usage, agricultural activities are expected to receive increasing scrutiny, as exemplified in Raynor [9]. Third, many states are legalizing recreational cannabis, which is a notoriously energy- and carbon-intensive cash crop. References [10, 11, 12] are representative of cannabis energy policy in the states of California, Vermont, and Massachusetts respectively.

This article is an extension of an earlier study that compared the thermal performance of an advanced super-efficient greenhouse with that of a simple hoop house [13]; the study was based on field measurements. This earlier work included consideration of thermal mass (time constants), which imposes a level of analytical complexity that is not typical of Level 2 audits [4, 5].

Subsequent analysis of the field data showed that for a simple structure like a hoop house, thermal mass effects can be neglected to a first approximation. This allows for considerable simplification of the equations needed for a heat balance analysis. The simplified equations became the basis of a Level 2 model deployed by the author for proprietary energy audits.

Because those audits are covered by non-disclosure agreements, there is no publicly available data at this time that can be published for the model. However, the model itself is not proprietary and is the subject of this article.

The next section develops the components of the model in terms of readily obtainable site data. A heat balance relationship is then applied to the model's interactive components for passive temperature response.

The heat balance emphasizes the greenhouse's sensible heat transfer relationships and is a defensible basis for a Level 2 model of heating season, when there is typically low absolute humidity at the cooler ambient temperatures. The available insolation has less opportunity to warm the soil mass because radiant losses are faster in low ambient temperatures.

A basic model is then offered for active heating and cooling calculations. The article concludes with high-level recommendations for modeling thermal interactivity with electric lighting, humidity issues, vertical sub-grade perimeter insulation, and other topics relevant to greenhouse energy performance.

OVERVIEW OF THE MODEL

The model lumps each major conductive pathway into a single (one-dimensional) equivalent thermal circuit. Infiltration is expressed as a constant seasonal average, and leakage area is assumed to be uniformly distributed across the shell. Because of the uniform transparency of the shell, insolation is quantified as global horizontal irradiance (GHI, Btu/h per square foot of footprint).

The model can be implemented in an Excel worksheet. In the absence of hourly heating, ventilation, and air conditioning (HVAC) energy data, a typical Level 2 interpretation would be an 8760 model that uses TMY3 data for a weather station in the vicinity of the greenhouse.

The heat balance equations given below are for the passive temperature response of the greenhouse and for active heating. Active heating can be modeled as an increment of power that raises the passive interior temperature to a given setpoint temperature and is addressed below.

TERMINOLOGY AND CONVENTIONS FOR STRUCTURAL THERMAL ANALYSIS

The basic equation for thermal conduction is shown in Equation 1.

$$Q = U\ A\ \Delta T\ \text{(Btu/h)} \qquad \text{Eq 1}$$

where

R is the thermal resistance (hr-ft^2 -°F/Btu)

U is the thermal conductance is the inverse of thermal resistance, $U = 1/R$ (Btu/hr-ft^2 -°F)

A is the area (ft^2)

T is the temperature (°F).

Subscript conventions for conduction are defined in Figure 1. Following these conventions, conduction across a thermal boundary between regions x and y is given in Equation 1b.

$$Q_{xy} = UA_{xy}\ (T_x - T_y) \qquad \text{Eq 1b}$$

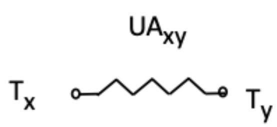

Figure 1. Thermal resistance at a boundary between locations x and y

Thermal convection (infiltration/exfiltration)

The basic shortcut formula for thermal convection by infiltration or exfiltration is shown in Equation 2.

$$Q_{inf} = 1.08 * CFM * \Delta T \qquad \text{Eq 2}$$

where

CFM (cubic feet per minute air flow rate, or ft^3/min)

ΔT (°F, temperature difference of air flow, condition 1 to condition 2)

Ventilation (infiltration or exfiltration) may be expressed in terms of CFM (cubic feet per minute) or air changes per hour (ACH). For a given room volume, you may convert from one form to the other.

Volume = Air Change

$$ACH = CFM\ (60\ min/h)/\ Volume\ (ft^3)$$

or

$$CFM = ACH/\ (60\ min/h)$$

Therefore, thermal convection may also be determined using Equation 2b.

$$Q_{inf} = 1.08 * (ACH/\ 60\ minutes/h) * \Delta T = 0.018 * CFhr * \Delta T \qquad \text{Eq 2b}$$

where

CFh = cubic feet/h = ft^3/h is used for the hourly time bins of an 8760 model.

Unprimed quantities indicate passive conditions, that is, interior temperature is solely a function of exterior temperature, ground temperature, insolation, and infiltration. Primed quantities (like Q' and T') denote a given variable during active heating.

Passive Temperature Response to Ambient Conditions

The simplified graphic in Figure 2 shows a domed roof, but the conventions also apply to other configurations (like gabled and gothic arch greenhouses). All that is required is a calculation of the UA value of the shell and of the interface to the ground.

The variable Qs in Figure 2 is for the net insolation admitted into the greenhouse. The factor α is solar input gain, $0 \le \alpha \le 1$. It lumps all physical properties that impact the accumulation of solar power into a greenhouse, including optical transmission and reflectance, radiant losses, and all other miscellaneous processes.

The factor α is adjusted to constrain interior temperature in response to insolation. This is done in practice by setting it to give a maximum calculated temperature during the shoulder seasons in the range of 100°F to 110°F. A typical range for α is between 0.2 and 0.8, depending on the

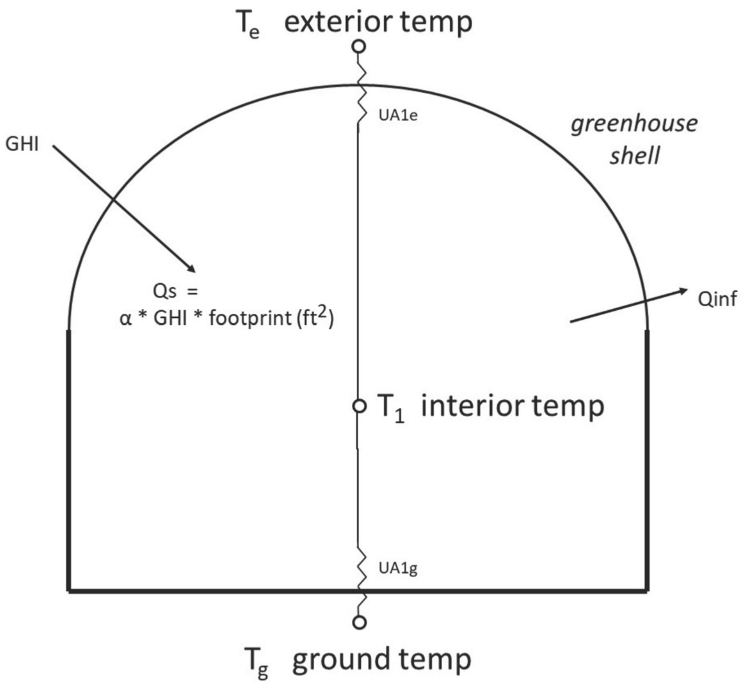

Figure 2. Variables for heat transfer analysis (Source: NRAES Cooperative Extension)

characteristics of the shell [13].

Ground temperature can be calculated using the Equation 3 [14].

$$T_{g_{out}}(y,p) \;=\; \bar{T} + A\,exp\left(-y\sqrt{\frac{\pi}{\alpha\, p_o}}\right)\cos\left(\frac{2\pi p}{t_o} - y\sqrt{\frac{\pi}{\delta\, p_o}}\right) \qquad \text{Eq 3}$$

where

$T_{g\,out}$ (y,p) = ground temperature outside the soil bed enclosed by the foundation, as a function of depth below surface (y) and period (p)

$\bar{T}$ = average annual outdoor air temperature

A = peak temperature minus $\bar{T}$ (= $\bar{T}$ minus minimum temperature); the annual "half temperature" excursion

δ = soil thermal diffusivity term (K/Cv) where

K is the soil conductivity (Btu/h-ft-°F),

Cv is the volumetric heat capacity (Btu/ft^3 -°F)

p_o = term of period over the year (365 days)

p = period (day) of the year (value ranges from 1 to 365)

Average temperature of $T_{g\ out}$(y,p) from grade to 2-ft below grade is taken as the ground temperature, T_g, of Figure 2 to adequately model ground conditions [13].

For greenhouses with dirt floors in regions with a mix of sand and clay with good drainage, a reasonable U value is about 0.25 Btu/h-ft^2 -°F. A typical U value for the same type of soil conditions with a 4-inch concrete floor is about 0.4 Btu/h-ft^2 -°F [13].

The heat balance for the passive temperature response of the greenhouse is shown in Equation 4.

$$Q_{1e} + Q_{1g} + Q_{inf} - Q_s = 0 \qquad \text{Eq 4}$$

from which the passive temperature T1 is found to be

$$T1 = [Q_s—Q_{inf} + UA_e T_e + UA_g T_g]/ [UA_e + UA_g] \qquad \text{Eq 5}$$

Active Sensible Heating and Cooling

The active heating requirement is found by adapting the conventions stated above in the following way. Let Tx' be the setpoint for active heating and Tx be the passive temperature response. The result is Equation 6.

$$Qxy' = (Tx' – Ty)\ UAxy = (Tx + (Tx'–Tx) - Ty)\ UAxy \qquad \text{Eq 6}$$

Let the setpoint temperature for the greenhouse be T1' = Tset. For the conductive pathway shown in Figure 2 from the interior to the exterior, for example, the equation during active heating becomes Equation 7.

$$Q1e' = (Tset - Te)\ UA1e \qquad \text{Eq 7}$$

The "trick" via Equation 6 for setting up the solution to the heat balance substitutes (T1 + (Tset—T1)) for Tset, where T1 is the passive temperature response.

The heat balance for active heating then requires the elements of Equation 8 and 9.

$$Q1e' + Q1g' + Qinf' - Qs \neq 0 \qquad \text{Eq 8}$$

and

$$Q1e' + Q1g' + Qinf' - Qs$$
$$= (Q1e + Q1g + Qinf—Qs) + \Delta Q1e + \Delta Q1g + \Delta Qinf \qquad \text{Eq 9}$$

The terms in parentheses on the right side of the above equation are for the passive temperature response and sum to zero by Equation 4. The remaining terms on the right side are the increments of heat supplied by mechanical equipment and are given by the 3 equations listed in Equation 10 (10a, 10b, 10c).

$$\Delta Q1e = (Tset - T1)\ UA1e \qquad \text{Eq 10a}$$
$$\Delta Q1g = (Tset - T1)\ UA1g \qquad \text{Eq 10b}$$
$$\Delta Qinf = 0.018\ CFhr\ (Tset - T1) \qquad \text{Eq 10c}$$

Equations 10 (a, b, and c) apply when Tset > T1 for heating, and when T1 > Tset for cooling. Note that the ΔQ terms in Equation 10 are for the greenhouse's heating or cooling load. Fuel consumption is determined by dividing the ΔQ terms by HVAC efficiency.

CONCLUSION AND DISCUSSION

This article presented a quantitative model of the basic thermal processes found in simple greenhouses [6, 7] that has been reconciled with field data [13]. It is offered as a set of calculations that are consistent with the standards for an ASHRAE Level 2 audit [4, 5].

The basic version of the model is best suited for heating season analysis for the reasons outlined in the Introduction. The basic version may be applied to cooling season analysis if soil thermal mass effects can be neglected [13]—which would be the case if a TMY bin model [4, 5] were used instead for a Level 2 audit.

The following suggestions and references may be helpful for broadening the applicability of the basic model, depending on the goals and scope of a given audit:

- Interactivity with electric lighting: Re-work Equation 5 after introducing a term "QL" into Equation 4. Let QL be the Btu/hour output of lighting fixtures and lamps to the interior of the greenhouse such that Q1e + Q1g + Qinf - Qs - QL = 0.
- Transparent greenhouses with opaque end walls: The ends of the greenhouse along the longitudinal axis are often light-colored corrugated metal. These "walls" thus have high thermal conductivity and low solar absorptance. For a Level 2 analysis for this type of structure, assume that whatever insolation falls upon the end walls is instantly conducted and radiated to the interior. Most of the insolation falls upon the transparent side walls. This allows the analysis to rely solely on Qs of Figure 2 as the predominant insolation variable.
- This Level 2 model can be upgraded to a Level 3 analysis if local weather data includes insolation as well as ambient temperature, and if heating fuel/cooling energy usage can be metered at hourly intervals.
- Greenhouse foundations: The model in this article assumes that the greenhouse has no foundation. Some greenhouses include perimeter skirting that extends from grade to 4-feet below grade. The skirting can range from styro board to sections of concrete or a combination of both. Modeling this requires an equivalent thermal circuit for the skirting and the volume of soil it encloses. Stiles [13] provides a thermal mass circuit model for the foundation that can be simplified for a Level 2 analysis.
- Modeling energy consumption for latent loads depends on the selection of HVAC equipment and details of the crop's watering regime. HVAC systems for mitigating humidity range from portable humidifiers (rated for input power/weight of water removed), to direct expansion units (rated for energy with respect to enthalpy of moist air flowing across cooling coils), to elaborate industrial systems. Attempt to model dehumidification separately from sensible cooling (Equation 10). This issue has drawn considerable attention for cannabis cultivation [15].

The following caveats should be considered when modeling cooling loads in transparent greenhouses:

- Commercial HVAC is based on Air-Conditioning, Heating, and Refrigeration Institute (AHRI) standards, which emphasize test conditions at 80°F dry-bulb/67°F wet-bulb [16]. Agricultural dehumidification equipment tends to align with Association of Home Appliance Manufacturers (AHAM) standards, which emphasizes test conditions at 80°F/60% relative humidity [17].
- Greenhouses operate at higher relative humidity levels than spaces conditioned for human comfort. As a result, the sensible heat ratio (SHR, ratio of sensible heat load to total heat load, [18]) of a greenhouse tends to be substantially less. Industry standard modeling tools for commercial HVAC equipment likely assume values of SHR that may not be applicable for modeling greenhouses—thereby requiring parametric workarounds for greenhouse analysis.

Finally, there are situations where the contributions of soil thermal mass to greenhouse temperature response are of interest. Analysis of field data [13] has shown that soil mass effects conspicuously delay peak greenhouse interior temperature with respect to peak solar availability by several hours in the summer. This would be of interest for calculating air conditioning costs if a utility company had a time-of-use schedule for electric rates. Adapting the model presented in this article to account for thermal mass effects will be the subject of a future publication.

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AUTHOR biography

Michael R. Stiles is a senior energy engineer at L&S Energy Services where he develops energy audits, feasibility studies for combined heat and power (CHP) and electrification projects, building energy models, and other activities in the commercial, industrial, and agricultural sectors. Dr. Stiles has 30 years' experience in energy analysis and technology and holds three US patents. This article results from his ongoing interest in the potential of greenhouses for growing winter crops locally with a minimal energy footprint. Dr. Stiles can be reached at mstiles@LS-energy.com.