Comprehensive Mass and Energy Balance Model for a Forced Ventilated Polyhouse

Highly Experienced Researcher
(Agricultural Engineering, Environmental Physics, Control Systems)

March 31, 2025

1 Introduction and Objectives

Purpose

This document details a dynamic mass and energy balance model developed to predict the internal air temperature (T_{in}) and relative humidity (RH_{in}) within a typical single-span polyhouse equipped with a forced ventilation system (fan and evaporative cooling pad).

Intended Use

- To gain a fundamental understanding of the complex interactions governing the polyhouse microclimate dynamics.
- To simulate and evaluate the performance of the fan-and-pad cooling system under varying external weather conditions.
- To assess the impact of design parameters (materials, dimensions) and operational strategies on the internal environment.
- To provide a robust simulation tool for optimizing environmental conditions for specific crop requirements.
- To serve as a foundation for the future development and testing of advanced climate control algorithms.

Importance

Maintaining optimal temperature and humidity is critical for maximizing crop yield, quality, and resource-use efficiency while minimizing disease prevalence in protected cultivation. Polyhouses in many regions face significant challenges from high solar radiation and ambient temperatures, necessitating effective cooling strategies like fan-and-pad systems. Understanding the dynamics is key to effective management.

Scope

- **Included:** Dynamic balances of water vapor (humidity) and thermal energy (temperature) for the internal polyhouse air. Major heat and mass transfer processes: solar radiation transmission, longwave radiation exchange, convection, conduction (through cover), ventilation (forced), transpiration (crop), evaporation (soil/pad), condensation (cover).
- **Excluded:** Carbon dioxide (CO_2) balance, detailed multi-layer soil heat/water transport, complex airflow patterns (Computational Fluid Dynamics - CFD), structural analysis, nutrient dynamics, detailed physiological crop growth modeling (uses simplified representation), air infiltration/leakage (assumed negligible compared to forced ventilation when active).

Simplifying Assumptions

- The internal polyhouse air is considered well-mixed (uniform temperature and humidity).
- One-dimensional heat transfer through the polyhouse cover.
- Uniform surface temperatures for the cover, crop canopy, and soil (within each element).
- Thermal properties of materials are constant.
- The thermal mass of the polyhouse frame (GI structure) is negligible compared to air, soil, and crop.
- Evaporative cooling pad efficiency is constant or a simple function of airflow/water flow.
- Soil surface evaporation is simplified based on potential evaporation and surface wetness.
- Transpiration is modeled using a simplified approach suitable for greenhouse conditions.
- Condensation forms as a film; droplet effects are neglected.

2 Polyhouse System Description

Geometry

- Type: Single-span, gable roof.
- Dimensions: Length (L) = 8 m, Width (W) = 5 m, Side Wall Height (H_{side}) = 3 m.
- Roof Angle (β): Assumed 26.5°. Ridge height $H_{\text{ridge}} \approx 4.25\,\text{m}$.
- Ground Area (A_g): $L \times W = 40\,\text{m}^2$.
- Cover Surface Area (A_c): Approximately $129\,\text{m}^2$. (Exact value depends on detailed geometry).

- Volume (V): Approximately $145\,\text{m}^3 . Orientation : Assume Length (8\,\text{m}) runs East - West.$

Construction Materials

- Cover: 200 µm UV-stabilized Polyethylene (PE) film.
    - Solar Transmittance (τ_{sol}): ≈ 0.85.
    - Longwave Emissivity (ϵ_c): ≈ 0.88.
    - Solar Absorptance ($\alpha_{\text{sol},c}$): ≈ 0.10.
    - Solar Reflectance ($\rho_{\text{sol},c}$): ≈ 0.05.
    - Thermal Conductivity (k_c): $\approx 0.33\,\text{W}/(\text{m}\cdot\text{K})$ (convection/radiation dominate).
- Frame: Galvanized Iron (GI) pipes. Thermal mass assumed negligible.

Ventilation System

- Type: Forced ventilation with evaporative cooling pad.
- Fan: One exhaust fan (1 m x 1 m box, 36 inch / 0.914 m blade) on 5 m end wall. Rated flow $\approx 15\,000\,\text{m}^3/\text{h}$ to $20\,000\,\text{m}^3/\text{h}$ (4.2-5.6 m^3/s). Actual flow Q_{vent} depends on pressure drop.
- Cooling Pad: Opposite 5 m wall. Assumed dimensions: $W = 5\,\text{m}$, $H = 1.5\,\text{m}$. Cellulose pad (15 cm thick). Efficiency $\eta_{\text{pad}} \approx 0.70 - 0.85$.

Internal Components

- Crop: Generic canopy, full ground cover ($f_{\text{crop\_cover}} = 1$). Leaf Area Index (LAI) = $3\,\text{m}^2/\text{m}^2$. Albedo $\alpha_{\text{crop}} \approx 0.25$. Emissivity $\epsilon_{\text{crop}} \approx 0.95$.
- Soil/Floor: Bare soil/ground cover. Albedo $\alpha_{\text{soil}} \approx 0.15$. Emissivity $\epsilon_{\text{soil}} \approx 0.94$.
- Irrigation System: Drip irrigation. Influences soil moisture and transpiration.

3 Model Development: Mass Balance (Humidity)

The rate of change of water vapor mass in the polyhouse air volume (V) is given by the balance of vapor fluxes (assuming constant air density ρ_a for the derivative):

$$\rho_a V \frac{dW_{\text{in}}}{dt} = \dot{m}_{\text{Tr}} + \dot{m}_{\text{Evap,soil}} - \dot{m}_{\text{Cond}} + Q_{\text{vent}}\rho_a(W_{\text{pad}} - W_{\text{in}}) \quad [\text{kg}_\text{w}/\text{s}] \tag{1}$$

Where:

- ρ_a: Density of moist air inside ($\approx 1.2\,\text{kg}_{\text{da}}/\text{m}^3$).
- V: Polyhouse air volume (m^3).
- W_{in}: Absolute humidity ratio of internal air ($\text{kg}_\text{w}/\text{kg}_{\text{da}}$).
- t: Time (s).

$\dot{m}_{\mathbf{Tr}}$ **(Crop Transpiration) [kg$_\mathrm{w}$/s]:** Using a simplified Penman-Monteith type model:

$$\dot{m}_{\mathrm{Tr}} = \frac{\Delta \cdot R_{n,\mathrm{crop}} \cdot LAI \cdot A_g + \rho_a c_{p,\mathrm{air}} \cdot \mathrm{VPD}_{\mathrm{in}}/r_{a,\mathrm{crop}}}{\lambda\,(\Delta + \gamma(1 + r_s/r_{a,\mathrm{crop}}))} \tag{2}$$

Where: Δ = slope of saturation vapor pressure curve (kPa/K), $R_{n,\mathrm{crop}}$ = net radiation on crop (W/m^2), LAI = leaf area index, A_g = ground area (m^2), $c_{p,\mathrm{air}}$ = specific heat of air ($\approx 1010\,\mathrm{J/(kg\cdot K)}$), $\mathrm{VPD}_{\mathrm{in}}$ = vapor pressure deficit inside (kPa), $r_{a,\mathrm{crop}}$ = aerodynamic resistance ($\approx 100 - 300\,\mathrm{s/m}$), λ = latent heat of vaporization ($\approx 2.45 \times 10^6\,\mathrm{J/kg}$), γ = psychrometric constant ($\approx 0.066\,\mathrm{kPa/K}$), r_s = canopy stomatal resistance ($\approx 50 - 500\,\mathrm{s/m}$).

$\dot{m}_{\mathbf{Evap,soil}}$ **(Soil Evaporation) [kg$_\mathrm{w}$/s]:**

$$\dot{m}_{\mathrm{Evap,soil}} = f_{\mathrm{wet}} \cdot \frac{\Delta \cdot R_{n,\mathrm{soil}} \cdot A_g + \rho_a c_{p,\mathrm{air}} \cdot \mathrm{VPD}_{\mathrm{in}}/r_{a,\mathrm{soil}}}{\lambda(\Delta + \gamma)} \tag{3}$$

Where: f_{wet} = fraction of wet soil surface (0 to 1), $R_{n,\mathrm{soil}}$ = net radiation on soil (W/m^2), $r_{a,\mathrm{soil}}$ = aerodynamic resistance near soil (s/m).

$\dot{m}_{\mathbf{Cond}}$ **(Condensation) [kg$_\mathrm{w}$/s]:** Occurs if the inside air is saturated relative to the cover temperature (T_{cover}):

$$\dot{m}_{\mathrm{Cond}} = h_m A_c (W_{\mathrm{in}} - W_{\mathrm{sat}}(T_{\mathrm{cover}})) \quad \text{if } W_{\mathrm{in}} > W_{\mathrm{sat}}(T_{\mathrm{cover}}),\ \text{else } 0 \tag{4}$$

Where: h_m = convective mass transfer coefficient ($\approx h_{c,\mathrm{in}}/c_{p,\mathrm{air}}$, kg/(m$^2\cdot$s)), A_c = cover surface area (m^2), $W_{\mathrm{sat}}(T_{\mathrm{cover}})$ = saturation humidity ratio at T_{cover} (kg$_\mathrm{w}$/kg$_\mathrm{da}$).

$Q_{\mathbf{vent}}\rho_a(W_{\mathbf{pad}} - W_{\mathbf{in}})$ **(Ventilation Mass Flux) [kg$_\mathrm{w}$/s]:** Net water vapor advected by ventilation. Q_{vent} = ventilation rate (m^3/s), W_{pad} = humidity ratio of air leaving the pad (kg$_\mathrm{w}$/kg$_\mathrm{da}$).

4 Model Development: Energy Balance (Temperature)

The energy balance for the internal air volume, tracking the rate of change of enthalpy:

$$\rho_a V c_{p,\mathrm{air}} \frac{dT_{\mathrm{in}}}{dt} = Q_{\mathrm{conv,surfaces}} + Q_{\mathrm{vent,sens}} + Q_{\mathrm{equip}} - Q_{\mathrm{latent,phasechange}} \quad [\mathrm{W}] \tag{5}$$

Where:

- $c_{p,\mathrm{air}}$: Specific heat capacity of moist air ($\approx 1010\,\mathrm{J/(kg\cdot K)}$).
- T_{in}: Internal air temperature (K or C). Use K for radiation terms.

$Q_{\mathbf{conv,surfaces}}$ **(Convective Heat Exchange with Surfaces) [W]:**

$$\begin{aligned}
Q_{\mathrm{conv,surfaces}} &= Q_{\mathrm{conv,cover}} + Q_{\mathrm{conv,crop}} + Q_{\mathrm{conv,floor}} \\
Q_{\mathrm{conv,cover}} &= h_{c,\mathrm{in}} A_c (T_{\mathrm{cover}} - T_{\mathrm{in}}) \\
Q_{\mathrm{conv,crop}} &= h_{c,\mathrm{crop}} LAI\, A_g (T_{\mathrm{crop}} - T_{\mathrm{in}}) \\
Q_{\mathrm{conv,floor}} &= h_{c,\mathrm{floor}} A_g (T_{\mathrm{floor}} - T_{\mathrm{in}})
\end{aligned}$$

Where: $h_{c,\ldots}$ = convective heat transfer coefficients ($\approx 2\,\mathrm{W/(m^2{\cdot}K)}$ to $10\,\mathrm{W/(m^2{\cdot}K)}$), $T_{\mathrm{cover}}, T_{\mathrm{crop}}, T_{\mathrm{floor}}$ = surface temperatures (K or C).

$Q_{\text{vent,sens}}$ (Sensible Heat Transfer by Ventilation) [W]: Includes cooling effect from the pad:

$$Q_{\text{vent,sens}} = Q_{\text{vent}}\rho_a c_{p,\text{air}}(T_{\text{pad}} - T_{\text{in}}) \tag{6}$$

Where: T_{pad} = temperature of air leaving the pad (K or C).

Q_{equip} (Sensible Heat from Equipment) [W]: Primarily from the fan motor.

$$Q_{\text{equip}} = \text{Fan Power} \cdot (1 - \text{Motor Efficiency}) \cdot \text{Duty Cycle}$$

$Q_{\text{latent,phasechange}}$ (Energy Consumption by Phase Change) [W]: Latent heat consumed by evaporation/transpiration within the main volume:

$$Q_{\text{latent,phasechange}} = \lambda(\dot{m}_{\text{Tr}} + \dot{m}_{\text{Evap,soil}}) \tag{7}$$

Note: Latent heat effect of the pad is included in T_{pad}.

Implicit Terms (Handled via Surface Temperatures):

- **Solar Radiation (I_{sol}):** Transmitted radiation ($\tau_{\text{sol}}I_{\text{sol}}$) absorbed by cover ($\alpha_{\text{sol},c}$), crop ($\alpha_{\text{crop}}$), and soil ($\alpha_{\text{soil}}$), heating these surfaces.
- **Longwave Radiation (LW):** Exchange between internal surfaces (cover, crop, soil) and between the cover and the external environment (sky, ground), influencing surface temperatures ($T_{\text{cover}}, T_{\text{crop}}, T_{\text{floor}}$).

5 Auxiliary Equations and Relationships

Psychrometric Relationships

- Saturation Vapor Pressure (e_{sat}, kPa): e.g., $e_{\text{sat}}(T) = 0.6108 \exp\left(\frac{17.27T}{T+237.3}\right)$ (T in C).
- Actual Vapor Pressure (e_a, kPa): $e_a = RH \cdot e_{\text{sat}}(T)/100$.
- Absolute Humidity (W, $\text{kg}_\text{w}/\text{kg}_\text{da}$): $W = 0.622 \cdot e_a/(P_{\text{atm}} - e_a)$. $P_{\text{atm}} \approx 101.3\,\text{kPa}$.
- Relative Humidity (RH, %): $RH = 100 \cdot e_a/e_{\text{sat}}(T)$.
- Wet-Bulb Temperature (T_{wb}): Requires iterative solution or psychrometric chart/calculator.
- Dew Point Temperature (T_{dp}): $T_{\text{dp}} = \frac{237.3 \cdot \ln(e_a/0.6108)}{17.27 - \ln(e_a/0.6108)}$.
- Psychrometric Constant (γ, kPa/K): $\gamma = c_{p,\text{air}}P_{\text{atm}}/(0.622\lambda)$.
- Slope of Sat. Vapor Pressure Curve (Δ, kPa/K): $\Delta = \frac{de_{\text{sat}}}{dT}$.

Ventilation and Pad Model

- Ventilation Rate (Q_{vent}, m^3/s): Assume constant when ON (e.g., $4.5\,\text{m}^3/\text{s}$) or use fan curve $f(P_{\text{static}})$.
- Pad Efficiency (η_{pad}): Constant (≈ 0.75) or $f(\text{Airflow}, ...)$.
- Pad Outlet Temperature (T_{pad}): $T_{\text{pad}} = T_{\text{out}} - \eta_{\text{pad}}(T_{\text{out}} - T_{\text{wb,out}})$. ($T_{\text{wb,out}}$ is outside air wet-bulb temp).
- Pad Outlet Humidity (W_{pad}): $W_{\text{pad}} \approx W_{\text{out}} + \eta_{\text{pad}}(W_{\text{sat}}(T_{\text{wb,out}}) - W_{\text{out}})$.

Radiation Calculations

- Net Radiation (R_n): Sum of absorbed shortwave (solar) and net longwave for each surface. $R_n = (1-\alpha)I_{\text{sol,inc}} + \epsilon(L_{\text{inc}} - L_{\text{emitted}})$.
- Solar Radiation on Surfaces: Partition transmitted solar radiation ($\tau_{\text{sol}} I_{\text{sol}}$) between crop and soil (e.g., Beer's Law based on LAI). Account for angles.
- Longwave Radiation ($L = \epsilon\sigma T^4$): Calculate exchange between internal surfaces (using view factors F_{ij}) and between cover and external (sky L_{sky}, ground L_{ground}). Sky radiation depends on T_{sky}, ϵ_{sky}. $\sigma = 5.67 \times 10^{-8}\,\text{W}/(\text{m}^2 \cdot \text{K}^4)$.

Heat Transfer Coefficients

- External Convection ($h_{c,\text{out}}$, $\text{W}/(\text{m}^2 \cdot \text{K})$): Function of wind speed v_{wind} (m/s). E.g., $h_{c,\text{out}} \approx 2.8 + 3.0 v_{\text{wind}}$.
- Internal Convection ($h_{c,\text{in}}, h_{c,\text{crop}}, h_{c,\text{floor}}$): Assumed constant ($\approx 5\,\text{W}/(\text{m}^2 \cdot \text{K})$) or linked to internal air speed (influenced by Q_{vent}).
- Overall Heat Transfer Coefficient (U_{cover}): Often $\approx 5 - 8\,\text{W}/(\text{m}^2 \cdot \text{K})$ for single film, considering convection and radiation.

Surface Temperature Approximations (if not solving full balance)

Surface temperatures ($T_{\text{cover}}, T_{\text{crop}}, T_{\text{floor}}$) ideally come from their own dynamic energy balances. Simpler models might relate them algebraically to T_{in}, T_{out}, and radiation. E.g., $T_{\text{crop}} \approx T_{\text{in}}$.

6 Model Parameters and Input Data

Parameters

- **Geometric:** $L, W, H_{\text{side}}, \beta, A_g, A_c, V$. (Values Section 2).
- **Material (Cover):** $\tau_{\text{sol}}(\approx 0.85)$, $\alpha_{\text{sol},c}(\approx 0.10)$, $\rho_{\text{sol},c}(\approx 0.05)$, $\epsilon_c(\approx 0.88)$.
- **Material (Crop):** LAI (≈ 3), $\alpha_{\text{crop}}(\approx 0.25)$, $\epsilon_{\text{crop}}(\approx 0.95)$, r_s parameters, $r_{a,\text{crop}}(\approx 200\,\text{s/m})$.
- **Material (Soil):** $\alpha_{\text{soil}}(\approx 0.15)$, $\epsilon_{\text{soil}}(\approx 0.94)$, $f_{\text{wet}}(\approx 0.1)$, $r_{a,\text{soil}}(\approx 250\,\text{s/m})$.
- **Ventilation:** $Q_{\text{vent,rated}}(\approx 4.5\,\text{m}^3/\text{s})$, $\eta_{\text{pad}}(\approx 0.75)$.
- **Thermal/Physical:** $\rho_a(\approx 1.2\,\text{kg}_{\text{da}}/\text{m}^3)$, $c_{p,\text{air}}(\approx 1010\,\text{J}/(\text{kg} \cdot \text{K}))$, $\lambda(\approx 2.45 \times 10^6\,\text{J/kg})$, $\sigma(5.67 \times 10^{-8}\,\text{W}/(\text{m}^2 \cdot \text{K}^4))$, $P_{\text{atm}}(\approx 101.3\,\text{kPa})$.
- **Heat Transfer:** $h_{c,\text{in}}, h_{c,\text{crop}}, h_{c,\text{floor}}(\approx 5\,\text{W}/(\text{m}^2 \cdot \text{K}))$, $h_{c,\text{out}}$ parameters (e.g., 2.8, 3.0).

Input Data (Time Series)

- Outside Air Temperature (T_{out}, C).
- Outside Relative Humidity (RH_{out}, %) or Dew Point ($T_{\text{dp,out}}$, C).
- Global Solar Radiation ($I_{\text{sol,global}}$, W/m^2).
- Diffuse Solar Radiation ($I_{\text{sol,diffuse}}$, W/m^2) (Optional).
- Wind Speed (v_{wind}, m/s).
- Wind Direction (Optional).
- Cloud Cover (Optional).
- Control System State (Fan ON/OFF, Pad Pump ON/OFF).

7 Model Output and Analysis

Primary Outputs

- Time series of Internal Air Temperature (T_{in}, C).
- Time series of Internal Relative Humidity (RH_{in}, %) or Absolute Humidity (W_{in}, kg$_{\text{w}}$/kg$_{\text{da}}$).

Secondary Outputs

- Time series of $T_{\text{cover}}, T_{\text{crop}}, T_{\text{floor}}$ (C).
- Time series of energy balance terms (Q_{conv}, $Q_{\text{vent,sens}}$, etc., W).
- Time series of mass balance terms ($\dot{m}_{\text{Tr}}$, $\dot{m}_{\text{Evap}}$, etc., kg$_{\text{w}}$/s).
- Ventilation rate (Q_{vent}, m^3/s).
- Pad outlet conditions (T_{pad}, W_{pad}).
- Vapor Pressure Deficit (VPD$_{\text{in}}$, kPa).

Analysis Applications

- Evaluate $T_{\text{in}}/RH_{\text{in}}$ profiles against crop optima.
- Perform sensitivity analysis on design and operational parameters.
- Assess effectiveness of control strategies (setpoints, schedules).
- Compare different polyhouse designs or materials hypothetically.
- Identify periods of potential crop stress (temperature, humidity extremes).

8 Model Limitations and Future Work

Limitations

- Assumes well-mixed internal air (no spatial gradients).
- Uses simplified or approximated surface temperature calculations.
- Simplified models for crop transpiration (r_s) and soil evaporation (f_{wet}).
- Neglects air infiltration/leakage (can be significant).
- Simplified condensation model (filmwise, no droplet effects).
- Assumes static parameters (properties, efficiencies).

Future Work

- Develop multi-node model (separate balances for cover, crop, soil layers).
- Integrate or couple with CFD for spatial climate details.
- Incorporate a dynamic physiological crop model.
- Add a CO_2 mass balance model.
- Explicitly model advanced control algorithms and actuators.
- Add an air infiltration module based on wind and temperature difference.
- Include a model for fogging systems if applicable.
- Calibrate and validate the model against experimental data.