Dynamic thermal modeling of a commercial greenhouse in Quebec with a new TRNSYS type to estimate evapotranspiration

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Abstract
This paper proposes a dynamic thermal model for a commercial greenhouse in Quebec, Canada, used for tomato cultivation. The study aims to improve the accuracy and efficiency of greenhouse simulations by considering the impact of plants' complex internal gains on the sensible and latent loads of the greenhouse. A new TRNSYS type is developed to account for latent and sensible gains/losses from evapotranspiration and evapotranspiration rates. A co-simulation approach is employed between TRNSYS for transient energy simulations and CONTAM for airflow rate calculations. One span out of eight is modeled. The span is 121.9 × 7.6 m² and 6.7 meters high. The model is able to estimate indoor temperature and relative humidity and the evapotranspiration rate. The evapotranspiration rates obtained in this study are consistent with those reported in the literature.

Keywords: Greenhouse, Evapotranspiration; Natural ventilation, TRNSYS; Numerical modelling.

I. INTRODUCTION

Greenhouses have become increasingly popular in recent years due to the increasing demand for food production and the need for sustainable and efficient methods of cultivation. The use of greenhouses allows for year-round cultivation of crops and better control of environmental factors such as temperature, humidity, and CO₂ concentration. Tomatoes are one of the most widely cultivated crops in greenhouses, and their growth and yield are greatly affected by the internal microclimate.

Several studies have been conducted to investigate the thermal behavior and energy performance of greenhouses. In particular, the use of computer models has become a popular tool for simulating and optimizing the performance of greenhouses. TRNSYS is one such tool that has been widely used for simulating the thermal behavior of greenhouses. Ahamed et al. [1] modelled the transient heating requirement of a Chinese solar greenhouse using TRNSYS and compared it to a validated model, named CSGHEAT. Adesanya et al. [2] conducted a validation work of internal temperature and heating demand using TRNSYS and experimental data. The model predicted accurately the temperature, but a significant deviation by up to 27% was reported for the heating demand. Recently, Labihi et al. [3] modelled the indoor climate of a greenhouse in France and results were satisfactory with experiments. However, these works did not account for heat rates from/to plants which might affect the indoor climate and energy demand prediction.

In recent years, researchers have focused on developing new models and methods to improve the accuracy and efficiency of greenhouse simulations. Evapotranspiration, which is the process of water vaporization from plants and soil, is a crucial factor in these models. Several evapotranspiration models are used depending on the availability of the input data and the ease of implementations in simulation tools. For field applications, the model of Allen et al. [4] is widely used for estimating reference evapotranspiration over a large surface area of grass crop, characterized by a height of 0.12 m, a crop resistance value of 70 s/m, and an albedo coefficient of 0.23, under conditions of non-limiting soil moisture. The model has been used in controlled environment agriculture (CEA) with some satisfactory results [5]. Stanghellini model [6] was formulated with the primary objective of estimating evapotranspiration (ET) in the context of CEA or indoor settings. The model employs a multi-layer canopy simulation approach, utilizing tomato crop as the representative crop, grown within a single glass Venlo-type CEA facility, equipped with hot-water pipe heating. This model has found widespread adoption among researchers for estimating ET in the context of CEA. The Fynn model [7] is derived from the Stanghellini model, using the crop canopy energy balance.

Ventilation is a critical aspect of greenhouse design and control, as it affects the microclimate and energy performance of the greenhouse. Several studies have investigated greenhouse ventilation control strategies specifically for sensible cooling and dehumidification, including natural [8], [9] and mechanical ventilation [10], [11].
When modeling a CEA space, the impact of the crop is often neglected. However, these complex internal gains can have a significant impact on the sensible and latent loads of the greenhouse. In this context, we propose to model and analyze the dynamic thermal behavior of a commercial greenhouse located in Quebec used for tomato production. The model considers latent and sensible energy fluxes from evapotranspiration, a new TRNSYS type to estimate evapotranspiration and the above-mentioned heat rates, and natural ventilation using a co-simulation between TRNSYS for transient energy simulations and CONTAM for airflow rate calculations.

II. MATERIALS AND METHODS

A. Greenhouse description

The Serres Royales is a commercial multi-span greenhouse for tomatoes cultivation located in Saint-Jérôme, Quebec, Canada (45.77° N, 73.96° W) and oriented in a NE direction. The greenhouse considered in this paper is a multi-span greenhouse (8 spans). Each span is equipped with roof vent openings, opened automatically when air temperature or relative humidity exceeds setpoints. Radiant heating pipes between each row of vegetation heat the greenhouse. Each span has the following dimensions: 121.9 x 7.6 x 6.7 m³ (Fig. 1).

![Figure 1: The span dimensions of the greenhouse in feet.](image)

Serres Royales use natural ventilation for the dehumidification and the fresh air intake. The natural ventilation is done through operable vent in the roof of each span. The CONTAM software was used in conjunction with the TRNSYS software to model natural ventilation and airflow inside the greenhouse.

![Figure 2: Thermal zones subdivision of the modelled greenhouse.](image)

Fig. 3 summarizes the steps to create the TRNSYS-CONTAM model. Prior to defining the 3D geometry in SketchUP, the model was created in 2D with the CONTAM Software dedicated to the calculation of building airflow rates and relative pressures between zones. Therefore, the airflow paths between the zones as well as the openings were defined in CONTAM. Control points for the openings were created as outputs from TRNSYS to CONTAM. These control points can be handled from TRNSYS by any desired conditions. The geometry is exported using CONTAM3DExport to apply modifications and finally imported by TRNSYS to add all required components.

B. TRNSYS model description

For the modelling purposes, only one span is selected to simplify the model and to reduce computing time. Therefore, the side walls were set to adiabatic. The envelope of the span consists of a base construction made with a layer of sprayed urethane foam insulation, two inches thick, covered by galvanized sheet. The upper part is made of polycarbonate. Since the greenhouse’s span is relatively large, it was subdivided into multiple zones: 4 by 3 by 6 with respect to the length, width and height, as shown in Fig. 2. The choice of the size relative to the height was made to consider the heating system represented by radiant pipes at the bottom level of the greenhouse, the smallest zone. The remaining zones were divided almost equally.
The TRNSYS model consists of components called types. Each type represents a given system and interacts with the other types in the model under a solver using successive substitutions. The types used in the model are described in Table I.

**Table I: TRNSYS main model types.**

<table>
<thead>
<tr>
<th>TRNSYS Types</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 56</td>
<td>Models the thermal behavior and contains the construction characteristics of the greenhouse.</td>
</tr>
<tr>
<td>Type 98</td>
<td>CONTAM-TRNSYS communication for co-simulation</td>
</tr>
<tr>
<td>Type 166</td>
<td>Control of openings with a temperature setpoint.</td>
</tr>
<tr>
<td>Type 604</td>
<td>Models the piping used for greenhouse heating</td>
</tr>
<tr>
<td>Type 15</td>
<td>Reads meteorological data</td>
</tr>
<tr>
<td>Type 77</td>
<td>Estimates the soil temperature.</td>
</tr>
<tr>
<td>Type 211 (user defined)</td>
<td>Estimates the evapotranspiration rate of tomatoes and the associated heat rates.</td>
</tr>
</tbody>
</table>

C. Evapotranspiration model

Evapotranspiration (ET) models are widely used to estimate water losses from land surfaces due to the combined processes of evaporation and plant transpiration. One possible model is the Stanghellini model [6], based on the Penman-Monteith equation. It uses the concept of reference crop evapotranspiration. The Stanghellini model is adopted here for its simple use and its ability to account for the effects of environmental factors such as temperature, humidity, wind speed, and solar radiation, as well as the characteristics of the vegetation being studied. The model equation is given by:

\[
ET_c = \frac{\Delta (I_n - G) + 2 \text{LAI} \rho_a C_p (VPD) \gamma r_a}{\lambda} + \frac{\Delta \gamma}{1 + \frac{\Delta r_a}{\gamma r_a}} \tag{1}
\]

where:

- \( ET_c \) - Daily Crop Evapotranspiration [mm/h]
- \( \lambda \) - Latent Heat of Vaporization [kJ/kg]
- \( \Delta \) - Slope of the Saturation Vapor Pressure-Temperature Curve [kPa/ °C]
- \( \gamma \) - Psychrometric Constant [kPa/°C]
- \( I_n \) - Daily Net Radiation [kJ/(h.m²) ]
- \( G \) - Soil Heat Flux [kJ/(h.m²)]
- \( \rho_a \) - Mean Air Density [kg/m³]
- \( C_p \) - Specific Heat of Air [MJ/kg °C]
- \( VPD \) - Vapor Pressure Deficit [kPa]
- \( \text{LAI} \) - Leaf Area Index [-]
- \( r_a \) - Aerodynamic Resistance [s/m]
- \( r_s \) - (Bulk) Surface or Canopy Resistance [s/m]

A new TRNSYS type (Type 211), inspired by Talbot et al. [12], was created to estimate both sensible and latent heat rates based on the energy balance of the crops and to estimate the evapotranspiration rate. The subroutine takes the solar radiation, air temperature, relative humidity, and leaf area index (LAI) as inputs. An average value of the aerodynamic resistance \( r_a \) is fixed to 185 s/m [13] whilst the surface resistance \( r_s \) is calculated [14] as:

\[
r_s = 200 \left[1 + \frac{1}{\exp \left(0.05(\mathcal{T} - 50)\right)}\right] \tag{2}
\]

Once the subroutine converges, the sensible and latent heat rates, which are outputs of the Type 211, are removed/added from the greenhouse and the evapotranspiration is added as absolute humidity. Fig. 5 represents the basic flowchart of the subroutine.
The control of the openings is managed in TRNSYS by both temperature and humidity setpoints. These are 19°C and 75% respectively. Setpoints are defined in the thermal zone in the middle of the greenhouse. Fig. 7 shows that the indoor temperature is maintained at the setpoint. The temperature exceeds the setpoint during some periods, which correspond to high insolation. This high temperature is caused by the lower ventilation rate originated mainly from the control strategy, since the humidity does not reach its setpoint during these peaks and thus the openings remain closed.

Fig. 8 presents the relative humidity inside the greenhouse. It is lower than that of outdoors relative humidity for several reasons: (i) heating which may dry the indoor air, (ii) less ventilation as mentioned earlier and (iii) low transpiration levels at early stages of crop development. As expected, relative humidity is lower during winter and higher during summer due to strong evaporation and the high relative humidity outside.

Fig. 9 shows the plant's evapotranspiration rate, which ranges from 0 to 0.025 kg.hr⁻¹.m⁻² in winter with a LAI of 0.1, up to 0.22 kg.hr⁻¹.m⁻² at full maturity with a LAI of 5.3. It is noticed that the evapotranspiration rate is highly impacted by solar radiation, as it follows the patterns of the latter. The findings are consistent with those reported by Rahman et al. [14], where the predicted evapotranspiration rate during full growth of the tomato plants was 0.283 kg.hr⁻¹.m⁻² against 0.22 kg.hr⁻¹.m⁻² for the present study.

IV. CONCLUSION

In conclusion, this study provides a preliminary analysis of the thermal behavior and energy performance of a greenhouse used for tomato production in a northern climate. Using TRNSYS in conjunction with CONTAM, a numerical model was developed to take into consideration the effects of natural ventilation on the greenhouse environment. A subroutine was created in TRNSYS to estimate evapotranspiration and heat rates from/to the plants, which allowed for the predictions of the greenhouse's thermal behavior.

The main findings of this study show that the developed model yields evapotranspiration rates on the same order of magnitude with those reported in other studies. However, further improvements in the ventilation control strategy were identified and will be studied in future works.

The results of subsequent research based on this could have important implications for the design and operation of greenhouses in cold regions, as they indicate that considering natural ventilation and evapotranspiration could play an important part in predicting the thermal behavior and energy performance of such structures. Further research is needed to optimize the control strategy of ventilation and to validate the model's predictions with experimental data. Overall, this study provides valuable insights into the thermal behavior and energy performance of greenhouses in cold regions, which could help improving the sustainability and efficiency of tomato cultivation in these regions.
Figure 7: Average indoor temperature of the greenhouse. (a) January, (b) June.

Figure 8: Average relative humidity of the greenhouse. (a) January, (b) June

Figure 9: Average evapotranspiration of the plants. (a) January, (b) June.
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