Simple Model of Temperature in the Pomona College Organic Farm Greenhouse

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Abstract

The Pomona College Organic Farm Greenhouse constantly overheats to temperatures well above the optimal level. Natural ventilation is currently being considered as a way to lower the internal temperature of the greenhouse. The purpose of this research is to develop a simple model of greenhouse temperature to describe the effects of natural ventilation. Using previously developed and validated greenhouse models as a basis, a model for the Pomona College campus greenhouse was constructed. The model was validated using experimental data, and has a prediction accuracy of 1.8°F mean absolute deviation from actual greenhouse temperature. It is concluded that this model could be applied to evaluate the performance of natural ventilation and serve as a tool for designing greenhouses.

Introduction

In 2013 the students of Pomona College built a greenhouse on the Pomona College Organic Farm, located in Claremont, CA. With limited space and budget, the construction of the greenhouse was kept compact and simple. As of now, the configuration of the ventilation system is less than ideal such that the internal temperature is far too high. Due to limited access to monetary resources it is imperative that each decision be optimized. At the request of Adam Long, the farm manager, we were tasked with developing a model that can accurately predict the temperature in the greenhouse and the effects of natural ventilation. Ultimately, these temperature predictions would be used to determine if such ventilation is a viable, money-saving solution to improving the climate of the greenhouse.

Background

Many models of Greenhouse temperature have been developed and validated over the years. Early models such as Froehlich et al. (1979) and Jolliet (1994) established the greenhouse model as steady state-time-dependent and incorporated transpiration of crops, respectively [3][4]. The elements of these early models made their way into subsequent models. We largely based our model off of C. Chen et al. (2011), which developed a simple greenhouse model studying the effects of shading nets on temperature [2]. This model was chosen as a basis for our model because of its incorporation of elements from the earlier models mentioned above, relevant parameters and variables, and simplicity.

The Chen et al. (2011) model made the following assumptions, amongst others, which we chose to incorporate into our model:

1. No temperature gradient existed in each layer.
2. Heat transfer coefficient of cover materials were constant.
3. The temperatures of the internal air, crops and cover materials were in a steady state.
4. Crops were planted in medium containers, the ground was covered with weeds-inhibiting nets and the soil thermal energy was not considered because crops covered most parts of the floor.

The 1st assumption was incorporated into our model because of the small size of the campus farm greenhouse, while the 2nd and 3rd assumptions were incorporated because we considered minor fluctuations in these parameters to be trivial. We used the 4th assumption because, like the greenhouse referenced in the C. Chen et al. (2011) model, the campus farm greenhouse contains small crops placed on top of the ground which was covered with weeds-inhibiting nets. As such, we do not consider soil thermal energy in this model.

In addition to those four, we added three additional assumptions to our model:

5. Previous temperature affects current temperature.
6. Solar radiation in Claremont was assumed to follow the Los Angeles average for a clear day, and that there was no radiation after sunset.
7. Ventilation opened after noon and remained open through midnight.

We felt that an omission in the C. Chen et al. (2011) model was that it did not consider that previous temperature affects current temperature in a greenhouse [1]. Thus we include the 5th assumption in our model. In gathering our data, we did not have access to a pyranometer, a device that measures solar radiation. So we instead used Los Angeles' average solar radiation data in our model due to Claremont's proximity to the city, forming our 6th assumption [5]. Finally, our 7th assumption was based on information the farm manager, Adam Long, provided on ventilation hours. Thus, in our model the campus greenhouse's ventilation system was assumed to have set hours from noon to midnight. With these assumptions serving as guidelines, we now proceed to the development of the greenhouse model.

Model Development

We incorporated three main components in our model: energy absorbed by the greenhouse from solar radiation Q_S, energy flow to ambient atmosphere by heat transfer Q_1, and energy exchange by natural ventilation Q_2. Q_S is dependent on the total radiation emitted by the sun and the surface area of the greenhouse which is exposed to sunlight. Q_1 is dependent on the temperature gradient between the greenhouse and the surroundings, the heat transfer coefficient of the greenhouse materials, and the total surface area of the greenhouse. Finally, Q_2 is dependent on the natural air exchange rate, the density and specific heat of the air, and the temperature gradient between the greenhouse and the surroundings. Figure 1 below shows a schematic diagram of the thermal transfer model for the farm greenhouse.

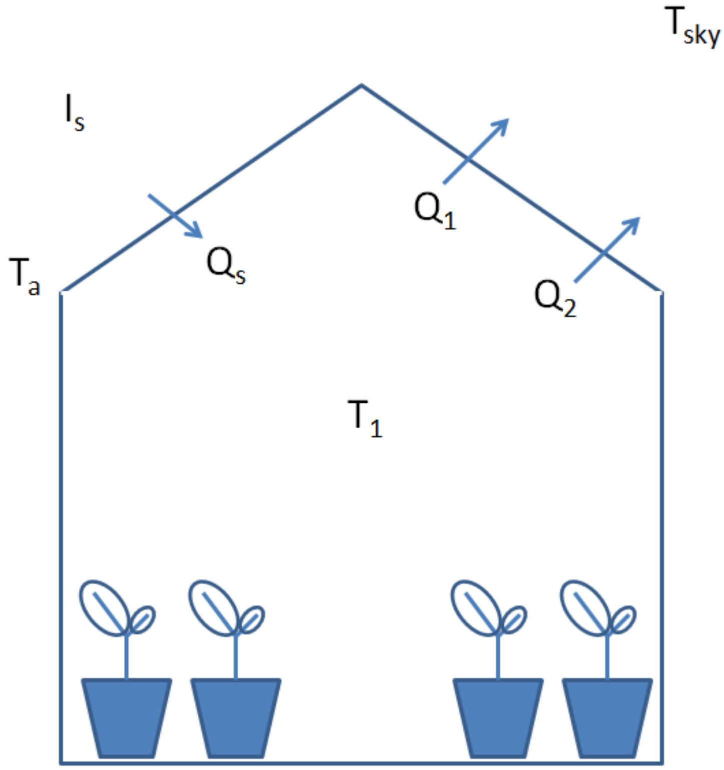

Figure 1: Schematic diagram of the thermal transfer model for the farm greenhouse; I_s, solar radiation; T_{sky}, sky temperature; T_1, internal temperature; T_a, ambient temperature; Q_s, solar energy; Q_1, energy flow to ambient atmosphere by heat transfer; Q_2, energy exchange by natural ventilation.

The farm greenhouse bottom part is 3m x 2m x 2m, and the top part is 3m x 2m with a height of 1m. It is made of twin wall polycarbonate panels. Using these dimensions and details, we construct the following model equations:

Q_1 : *energy flow in/out to ambient atmosphere by heat transfer*

$Q_1 : A_1(U_{W1})(T_1 - T_a)$

$A1$: *surface area of greenhouse* $\approx 3*6*2+3*3*2+2*\frac{1}{2}*3*1+6*\sqrt{1.5^2+1}*2$

$\approx 78.6333\ m^2$

UW_1 : *thermal heat transfer constant of greenhouse materials* $= 6.2\ Wm^{-2}F^{-1}$

T_1 : *temperature inside of greenhouse*

T_a : *ambient temperature*

Q_2 : *energy exchange due to natural ventilation*

$Q_2 = AR\rho C_\rho(T_1 - T_a)$

AR : *natural air exchange rate of greenhouse*

ρ : *air density* $= 1225\ gm^{-3}$

$C_\rho : air\ specific\ heat = 1.012 J g^{-1} F^{-1}$

$$AR = \frac{1}{2} * Area\ of\ Ventilation\ Openings * Discharge\ Coefficient * \sqrt{gravity * (T_1 - T_a) * (height\ of\ window)/2T_a}$$

$$AR = \frac{1}{2} * A_v m^2 * .35 * \sqrt{9.8 m s^{-2} * (T_1 - T_a) F * 1m/2T_a F}$$

$$AR = \frac{1}{2} * .35 * \sqrt{(9.8 * (T_1 - T_a)/2T_a)}\ m^3 s^{-1}$$

$Q_s : heat\ input\ from\ solar\ energy$

$Q_s = A_s * I_s$

$I_s : solar\ radiation\ in\ W m^{-2}$

$A_s : surface\ area\ with\ direct\ sunlight\ in\ m^2$

$$Q_1 = 78.6333 * 6.2 * (T_1 - T_a)\ W$$

$$Q_2 = \frac{1}{2} * A_v * .35 * \sqrt{(9.8 * (T_1 - T_a)/2T_a} * 1225 * 1.012 * (T_1 - T_a)\ W$$

$$Q_1 + Q_2 = 487.5265(T_1 - T_a) + A_v * 616.3162 * \sqrt{(T_1 - T_a)/2T_a} * (T_1 - T_a)\ W$$

$Balance\ equation : Q_s = Q_1 + Q_2$

This balance equation works for consistent temperatures. However, throughout the day, the present temperatures of the greenhouse are affected by temperatures in the recent past. Therefore, a moving average model using exponential smoothing was used where

$$T(ma)(t) = \alpha * T(t-1) + (1-\alpha) T(f)(t)$$

Where T(t-1) is the temperature of the greenhouse at t-1, T(f)(t) is the temperature forecasted for time t using the balance equation, and T(ma)(t) is the value for the moving average model. α was chosen to be .25 because that minimizes the mean absolute deviation of the model to 1.8 degrees Fahrenheit.

As per assumption 6, solar radiation was assumed to follow the Los Angeles average for a clear day (7600 W m^-2 per day), with peak solar radiation between 10 a.m. and 3 p.m, and no radiation after the sun set. Ventilation was opened after noon and remained open through midnight.

Methods/Experimental Details

We used sample farm greenhouse temperature data to verify our model. On Tuesday, April 15, 2014, we recorded temperature data using a dual sensor temperature probe. One probe was affixed to the outside doorknob to record ambient temperature while the other was hung in the middle of the greenhouse to record internal temperature. Temperature was recorded every two hours for sixteen hours.

We then compared the data collected with our forecasted temperatures, which we got by solving for the greenhouse temperature using the area of ventilation, the ambient temperature, the solar radiation and the area of the roof hit directly by solar radiation. We kept in mind that a moving average model could be useful to take into account previous temperatures. Next, we used a combination of the data and our forecasting model to determine the constant α in the moving average model by comparing the mean absolute deviations of different values of α. If $\alpha = 0$ was the value with the minimum mean absolute deviation, that would have implied that the model would not be more effective as a moving average model; however, as our intuition suggested, the value of α that minimized the mean absolute deviation was .25.

Results

The moving average model, shown below in Figure 2, has a mean absolute deviation from the actual greenhouse temperatures by 1.8°F. It was very accurate for the warmest parts of the day and accurate as the day cooled off.

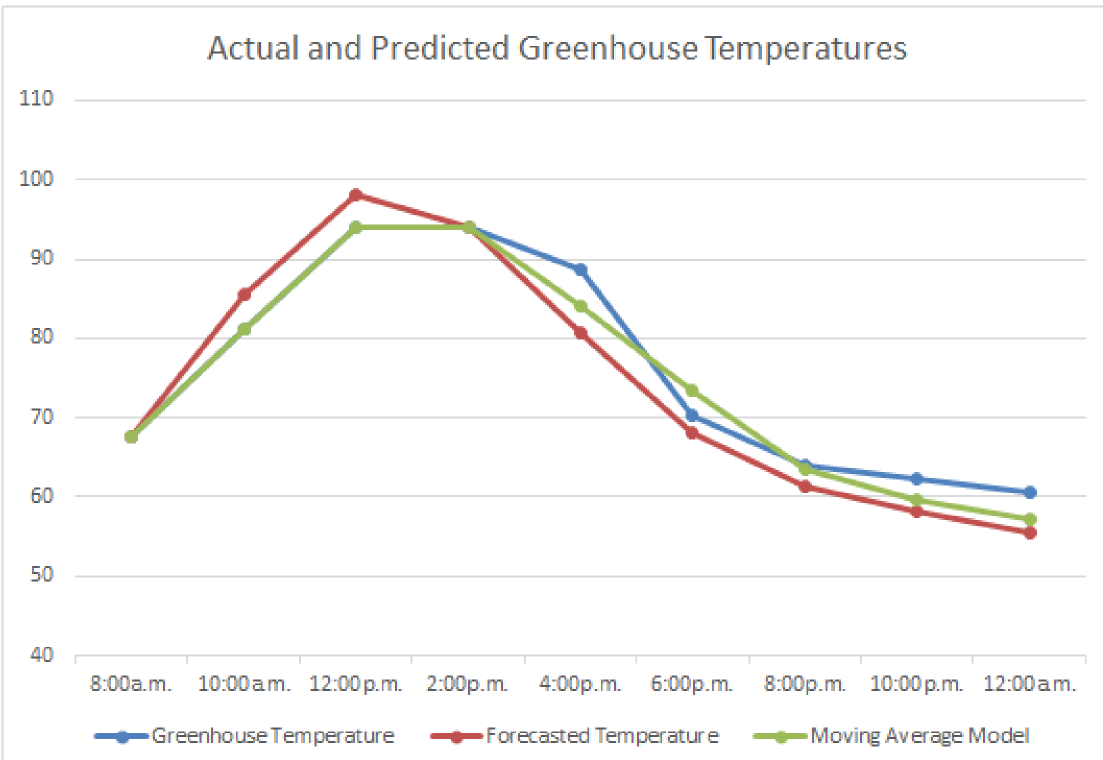

Figure 2: Actual vs. predicted greenhouse temperatures

One of the ultimate goals is to make sure the greenhouse does not get too hot for the plants to survive. Right now, the farm has two ventilation windows, but no rooftop or mechanical ventilation. Thus, we could suggest that when Adam opens the farm he opens the windows at 9:00a.m. and closes them when he leaves at 5:00p.m. With this suggestion, the forecasted greenhouse temperatures remain a few degrees under the actual greenhouse temperatures during the day, shown in Figure 3. Still, this model demonstrates that additional measures will have to be taken to cool the greenhouse further, as natural ventilation itself will not lower the temperature down to <83°F throughout the entire day.

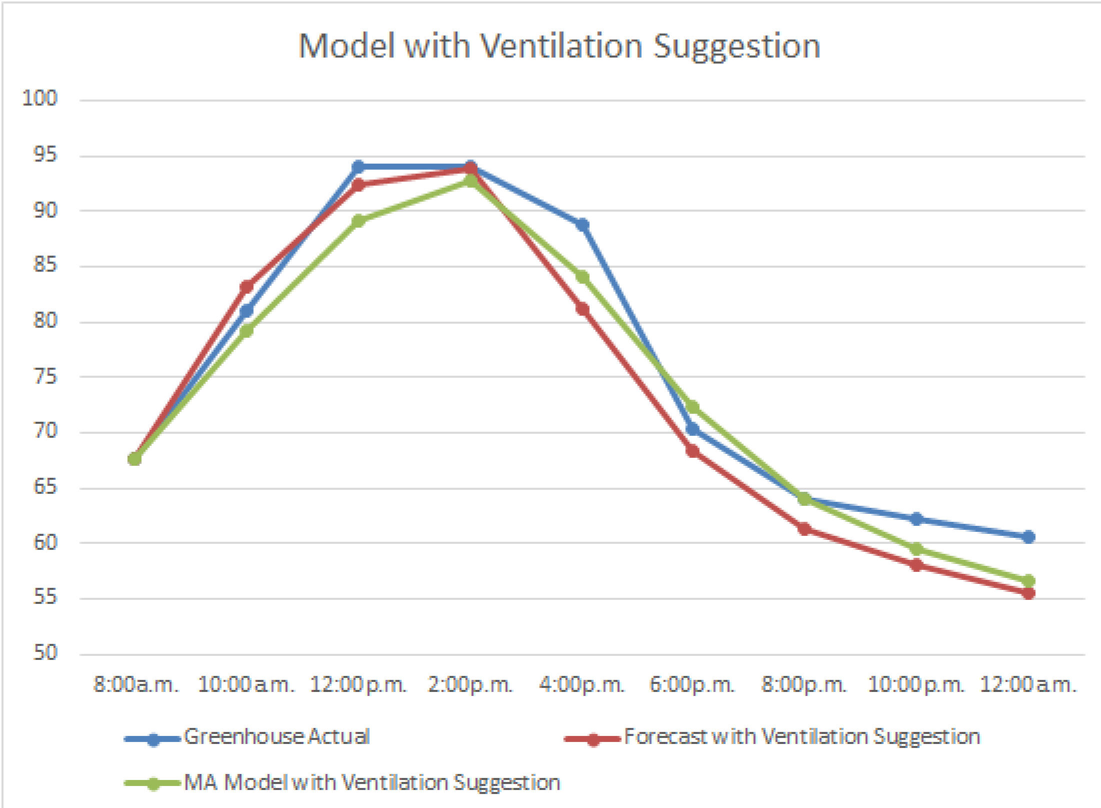

Figure 3: Actual vs. predicted temperatures of greenhouse with ventilation suggestion

Discussion & Future Applications of the Model

Our temperature predictions are the result of a system of heat-flow equations. To improve our predictions we would certainly need to test our model against more temperature data. In addition, there are numerous other factors that need to be examined in order to make our model more effective.

With more time we could first consider the effects of the plants themselves on the greenhouse's internal temperature. Different species of plants have different rates of photosynthesis, which affect the gaseous makeup of the climate inside the greenhouse. Furthermore, some plants retain more water than others; this affects the humidity and perhaps the temperature within the greenhouse. Knowing more about the number, size, and the type of plants being grown in the greenhouse would give us more information on the composition of the greenhouse's internal climate.

Also, our model does not do much to consider the humidity within the greenhouse as we assumed that it was constant. However, collection of our own data and further examination of past literature would be needed to justify this assumption. We observed that the irrigation was effectively being used to cool off the plants during the heat of the day, so it is not unreasonable to hypothesize that humidity and water levels in the greenhouse are significant determinants of temperature. Furthermore, accounting for the frequency and the amount of water that the irrigation system dispenses would serve to increase the accuracy of our model of the greenhouse climate.

In constructing our system of equations we assumed that there was no temperature gradient within the greenhouse, i.e. the temperature within the greenhouse was the same at all heights. This assumption was made for the sake of simplicity, however with the plants a few feet off the ground, the irrigation system a few feet above the plants, and the majority of the solar energy being absorbed through the roof, this could potentially be a source of inaccuracy. The greenhouse examined by C. Chen et al. (2011) was much larger and it contained internal shading nets. They found it useful to compartmentalize the greenhouse above and below the internal nets. By comparison, the Pomona greenhouse is much smaller and is not equipped with internal shading nets, however partitioning it into layers and including a gradient term to account for the change in temperature between these compartments could yield more useful predictions. It may be possible to obtain a temperature prediction specific to the height level in the greenhouse, as opposed to a generalized prediction for the overall internal temperature.

One improvement to our model would be to see what effects internal and external shading nets would have on the greenhouse temperatures. Another improvement to our model would be to find a way to account for the inclusion of more than one ventilation method. For example, if a greenhouse had shading nets and an electrical fan, how would we accurately predict their combined effects? An answer to this would allow us to accurately optimize more complex ventilation systems.

Our model agrees with this small collection of data, however it is clear there is still much to be considered in order to accurately represent the internal climate and temperature of the greenhouse. After further investigation of this model's assumptions and other factors that may be necessary to include, our task would be to generalize the computational steps we took to attain our temperature predictions. We could develop a Graphical User Interface (GUI) that would allow users to find the optimal greenhouse architecture with respect to their specific parameters. The GUI applet could take the following as possible parameters: type of material available, projected dimensions of the greenhouse, geographical location of the greenhouse, specifics about projected irrigation system, projected ventilation configuration, number and species of plants, orientation with respect to the sun, etc. Based on the values of these inputs the applet would provide temperature predictions to the user so that he or she may adjust the parameters until satisfied.

Conclusion

A model of temperature in the Pomona College Organic Farm greenhouse was created. The model was validated by collected sample data, and was found to be highly accurate, with a prediction accuracy of 1.8°F mean absolute deviation from actual greenhouse temperature. The model was then modified to account for the effects of natural ventilation from 9:00am to 5:00pm. This model shows that temperature does decrease, but not to the optimal temperature of <83°F at all times throughout the day. Thus, we recommend the greenhouse take further measures to cool the internal temperature. We offer suggestions to improve the model and for further applications.

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