The Automation of the Mathematical Model of Heated Glasshouses

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Abstract. The analysis of technical operations associated with growing vegetables in glasshouses shows that it is possible to reduce labor inputs and improve the efficiency of indoor growing structures through a specific set of technical solutions. The facilitation of the fundamental improvement of the glasshouse vegetable production technology requires stationary transportation systems and robot hardware. The glasshouses can be classified according to their functional and structural properties: intent, seasonality, growing practices, the type of transparent cover, the type of frame, and heating method. In this case, detailed thermophysical models should not be used. The lack of properly rationalized mathematical models for heated glasshouses holds back their development and improvement. When creating such models, it is necessary to consider heat and mass transfer processes taking place in the glasshouse, the distribution of their parameters, and the accidentality of external impacts. Additional problems arise because the requirements set for models rarely comply with the research goals set or do not reflect the conditions, under which it is used. The suggested balanced dynamic models allow for the extensive use of computers to research heat consumption patterns in glasshouses and synthesize temperature regulators. The mathematic methods for such calculations comprise vector-matrix algebra, for the respective software is widely available on various computers. Growing plants indoors during winters and springs requires the maintenance of climatic factors influencing the growth and development of plants. Due to this, automated control of such factors in compliance with agricultural practices receives great importance. To maintain temperatures automatically in hotbeds, two-position control systems are used. Large glasshouse businesses are currently introducing intensive vegetable growing technologies, and automated workflow control systems based on micro- and minicomputers. Key production activities include the watering and mineral fertilizer dressing of plants. These processes must be automated because they require large labor inputs during the preparation of the solution, the maintenance of the required content proportions, timely feed, and even distribution across all of the glasshouse under various external impacts.

1. Introduction

The temperature sensors used include contact mercury-filled thermometers, bimetal, and manometric temperature gauges, while the controls often comprise starter switches or contactors. To ensure safe
operation of electricity-heated glasshouses, temperature sensors are connected to a low-voltage grid of 6-12 V. The experience of glasshouse operation shows that growing plants in artificial environments allows to significantly increase the vegetable yield, as well as reduce the vegetation period, labor inputs associated with plant care, eliminate such straining operations as glasshouse soil treatment and replacement, and simplify the process of growing medium disinfection. The use of artificial growing media provides extensive opportunities to efficiently use the business process automation means, especially in large glasshouse businesses. The main glasshouse vegetable growing operations to be automated include the regular feed of culture solution to the racks and its discharge to the accumulating reservoir, as well as the supply of water to the solution with a regular or on-going admixture of required salts. The need for solution replenishment is due to its partial absorption when it goes through the mineral medium. Regular glasshouses feature significant heat losses due to the large areas of transparent surfaces. To compensate for those, some fuel must be consumed by the heating system. Glasshouses can be heated by hot water, water steam, hot air, infrared radiation, or fuel burning products. When building a solar glasshouse, it is necessary to reduce heat losses by thermal insulation. Besides, it is vital to catch as much solar energy as possible and accumulate the extensive heat [3,p.62; 4,p.20; 8,p.10]. A key difference between glasshouses and other sheltered ground structures is the possibility of creating favorable conditions not only for the plants but also for the personnel and the equipment. As a result, glasshouses have high labor productivity and better production standards, and the seasonality typical of agricultural works disappears [1,p.152; 7,p.2]. Unlike small shelters and hot frames, glasshouses allow for performing all and any agrotechnical operations without dismantling the mainframe and use various machinery to treat plants. In heated glasshouses, various automation means and structure upgrades are used to improve their energy efficiency. The glasshouses are viewed as an object with concentrated thermal condition parameters averaged across the volume and area of the frame enclosure.

2. Research methods
The lack of properly rationalized mathematical models for heated glasshouses holds back their development and improvement. When creating such models, it is necessary to consider heat and mass transfer processes taking place in the glasshouse, the distribution of their parameters, and the accidentality of external impacts. Additional problems arise because the requirements set for models rarely comply with the research goals set or do not reflect the conditions, under which it is used. The glasshouse must be exposed to about half of the southern section of the sky. Alternatively, the sunlight falling on the glasshouse at 45° must reach the lower edge of its back wall. The end walls must be fully or partially transparent if the glasshouse is oriented towards the South or its divergence from this direction is insignificant. If these conditions are observed, the glasshouse receives the best possible and the evenest illumination. The multi-stage nature of heat exchange on the dividing surfaces can be accounted for by the selection of a general order of the model. When building models reflecting the significant energy properties of the glasshouse, the functional identification approach proves to be the most efficient [2,p.2; 5,p.5]. Table 1 shows indicators influencing the microclimate of the glasshouse.

| No. | Criterion |
|-----|-----------|
| 1   | The interior temperature is usually higher than the exterior (it gets excessive if the glasshouse is exposed to the sun) |
| 2   | The soil temperature increases properly, sometimes excessively (some of the plants stop germinating). The soil in the glasshouse does not freeze |
| 3   | The amount of light entering the glasshouse is almost 50% lower than outside. |
| 4   | The wind impact is almost eliminated, which is comfortable for people but not so much so for the plants. |
| 5   | Specific smells can appear |
| 6   | Air exchange reduces, and plants might lack CO2 |
The humidity inside the glasshouse is higher than necessary for the plants, and prolonged high humidity levels lead to the growth of molds and fungi.

The intrusion of insect pests into the glasshouse is complicated, but if they get in the glasshouse, they start multiplying in its conditions, which can make a very bad impression on some people.

The access of useful insects to the plants is complicated because they can only enter the glasshouse through doors, windows, or vents.

The glasshouse protects the plants from natural rains, so their watering completely depends on the people who tend them.

The excessive humidity in unheated glasshouses usually does not present any extra problems for people.

When the glasshouse is exposed to the sun, the conditions inside it are normally good for people.

Due to the plants, the air inside the glasshouse has more oxygen than the air at home.

Figure 1 shows a process flow chart for a simple heated glasshouse. The model obtained for this chart can be transformed for more complex layouts using the suggested methods [6,p.204; 9,p.23].

![Figure 1: Process flow chart for heated glasshouse](image)

The three key model forms in the conditioned space:

**Uninterrupted**

\[ X = AX + BU(t) + CF(t), \quad X(t_0) = X_0; \quad (1) \]

**Discrete**

\[ X[k + 1] = FX[k] + BU[k] + CF[k], \quad X[0] = X_0; \quad (2) \]

**Operator**

\[ X(p) = W_U(p)U(p) + W_F(p)F(p), \quad (3) \]

where \( A = [n \times n] \) is the measured dynamic matrix; \( n \) is the dynamic order of the model; \( X = [n \times 1] \) is the measured condition vector; \( B = [n \times m] \) is the measured control matrix; \( m \) is the number of independent controls; \( U = [m \times 1] \) is the control vector; \( t \) is time; \( C = [n \times r] \) is the measured impact matrix; \( r \) is the number of independent impacts; \( F = [r \times 1] \) is the measured impact vector; \( k \) is the increment number; \( F = [n \times n] \) is the measured one increment shift matrix; \( W_U(p) = F(p)B \) and \( W_F(p) = F(p)C \) are the transfer matrices for controls and impacts determined through the operator image of the shift matrix.
For the glasshouse layout given, the temperature of the return heat carrier \( x_1 = \theta_2 \); the average temperature of heating units \( x_2 = \theta_{hu} \); the average air temperature inside the glasshouse \( x_3 = \theta_{in} \); the average frame temperature \( x_4 = \theta_{ft} \); the heat carrier temperature at the output of the heat exchange unit \( u = \theta_1 \); and the outside temperature \( f = \theta_{out} \). For this model, \( n = 4 \), \( m = 1 \), \( r = 1 \).

The identification resulted in the parameters of the discrete form of the model

\[
\Phi = \begin{pmatrix}
0.0996 & 0.0943 & 0 & 0 \\
0.3585 & 0.2573 & -0.017 & 0.2705 \\
0 & 0.0103 & 0.0255 & -0.1715 \\
0 & 0.0058 & 0.2122 & 0.0661
\end{pmatrix}; \\
B = \begin{pmatrix}
0.1371 \\
0 \\
0 \\
0
\end{pmatrix}; \\
C = \begin{pmatrix}
0.0044 \\
0.0044 \\
0.089
\end{pmatrix}.
\]

Using the matrix constrain equation for the discrete and the uninterrupted forms of the condition space models (1), (2)

\[
F = e^{At}, \quad B = A^{-1}(e^{At} - I)B, \quad C = A^{-1}(e^{At} - I)C,
\]

where \( \tau \) is the sampling period; \( I = [n \times n] \) is the measured identity matrix. Thus, we get the parameters of the model (1) for the timescale \( K_M = 1200 \):

\[
A = \begin{pmatrix}
-3.007 & 0.315 & 0 & 0 \\
1.197 & -2.481 & 0.057 & 0.903 \\
0 & 0.0344 & -3.255 & -0.573 \\
0 & 0.019 & 0.709 & -3.119
\end{pmatrix}; \\
B = \begin{pmatrix}
0.4579 \\
0 \\
0
\end{pmatrix}; \\
C = \begin{pmatrix}
0 & 0 \\
0 & 0.13 \\
0 & 0.0147
\end{pmatrix}.
\]

Using the expression for transfer matrices \( W_U(p) \) \( W_F(p) \) and the shift matrix \( F(p) \), we get transfer function for the temperature of indoor air, \( X_4 \) component of the condition vector (for the comfort of further calculations we swapped the components \( \bar{\theta}_{in}, \bar{\theta}_{ft} \))

\[
W_U^{X_4}(p) = \frac{1.218p + 1}{3.79p^4 + 5.79p^3 + 7.753p^2 + 4.574p + 1};
\]

\[
W_F^{X_4}(p) = \frac{2.535p^3 + 6.693p^2 + 5.782p + 1}{3.79p^4 + 5.79p^3 + 7.753p^2 + 4.574p + 1}.
\]

Thus, we have reviewed the methods of building balanced models for heated glasshouses. Before describing their usage, let us show the sequence of accuracy calculations for these models [10,p.16].

Let us compare the modeling results with the real conditions in the glasshouse. Based on the results of this comparison, we can calculate the accuracy matrix

\[
\Omega = \{M[(X[k] - X_m[k])(X[k] - X_m[k])^T]\}.
\]
Assuming that the modeling error vector is subject to Gauss’ law, let us write down an expression for the joint density of error probability distribution based on parameters F, B, and C of the model and the Ω accuracy matrix:

\[
\pi(ε|F, B, C, Ω) = (2π)^{-2} |Ω|^{-\frac{1}{2}} \times \exp\left\{-\frac{1}{2} (X[k + 1] - FX[k] - BU[k] - CF[k])^T \times Ω (X[k + 1] - FX[k] - BU[k] - CF[k])\right\}.
\]

Expressions (9) and (10) allow us to calculate the trustworthy identification for the results obtained, taking into account the acceptable modeling error vector \(ε_d^t = [|ε_{d1}|, |ε_{d2}|, |ε_{d3}|, |ε_{d4}|]\)

\[
P(ε) = 2F(ε^TΩε),
\]

where \(F(\cdot)\) is Laplace’s function, employing special tables [10, p.18].

In our case, if the acceptable error vector \(ε^t = [2, 2, 4, 1]^T\C\), the trustworthy probability \(P(ε) = 0.96\).

Let us show some examples of using heated glasshouse models to synthesize temperature regulators on computers.

Having transformed expressions (8), (9), we receive the following matrix structure:

\[
\tilde{F} = \begin{pmatrix}
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
−\tilde{φ}_4 & −\tilde{φ}_3 & −\tilde{φ}_2 & −\tilde{φ}_1
\end{pmatrix};
\tilde{B} = \begin{pmatrix}
\tilde{β}_1 \\
\tilde{β}_2 \\
\tilde{β}_3 \\
\tilde{β}_4
\end{pmatrix};
C = \begin{pmatrix}
\tilde{c}_1 \\
\tilde{c}_2 \\
\tilde{c}_3 \\
\tilde{c}_4
\end{pmatrix}.
\]

It is easy to determine the stabilizing digital regulator coefficients on the basis of the transformed system (9):

\[
k_{p,i} = d_i^* - \tilde{φ}_i,
\]

Where \(d_i^*\) is the required values of the characteristic polynomial of matrix F.

Assuming \(d_1^* = 0.08\), \(d_2^* = 0.12\), \(d_3^* = 0.18\), \(d_4^* = 0.24\) for the system (22), (23), we have

\(k_{p,1} = 0.0796, k_{p,2} = 0.107, k_{p,3} = 0.238, k_{p,4} = -0.206\).

The combined digital regulator equation can be calculated if the current regulation error equals zero:

\[
u[k] = β^{-1}_1 \left\{\sum_{i=2}^{4} u[k - i] β_i - \sum_{i=1}^{5} (φ_i ν[k - i] - γ_i f[k - i])\right\}.
\]

Through the calculations using formulae (21), (22), (24, 27), we receive the following parameters of the combined digital regulator:

\[
β^T = [-2.058; 1.724; 1.311; -0.093];
γ^T = [10.623; -12.113; -31.77; 5.674].
\]

Let us note that the digital regulator parameters were synthesized in a transformed basis, i.e. for \(X\). Thus, switching to the true vector requires the reverse transformation \(X = S^{-1} X\).

3. Conclusion

In sheltered ground vegetable production, over half of operating costs are associated with the heating of the growing premises. Apart from the biological fuels, residual heat from industrial enterprises, hot
water, or steam from boiler houses and electricity can be used to heat glasshouses. Electricity is used to heat glasshouses when residual heat or local fuel resources are inaccessible or their use is economically unfeasible. Glasshouses differ by their operation period (spring-and-summer and year-around ones) and structural design. The design of a glasshouse does not depend on the owner’s budget and imagination only but also on the plant they are going to grow. Some glasshouses are best for specific plant varieties, while others are more flexible. The presented glasshouse model with microclimate control features was developed for computerized yield management systems to determine the best modes of operation. The simplicity of parameter adjustment makes it easy to use for various glasshouse types and various ambiance behavior scenarios. The suggested balanced dynamic models allow for the extensive use of computers to research heat consumption patterns in glasshouses and synthesize temperature regulators. The mathematic methods for such calculations comprise vector-matrix algebra, for the respective software is widely available on various computers. The suggested balanced dynamic models allow for the extensive use of computers to research heat consumption patterns in glasshouses and synthesize temperature regulators. The mathematic methods for such calculations comprise vector-matrix algebra, for the respective software is widely available on various computers.

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