THEORY OF DEVELOPING A MATHEMATICAL MODEL OF THE DYNAMICS AND EMISSION OF GREENHOUSE MICROCLIMATE INDICATORS

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https://doi.org/10.5281/zenodo.20080522

Abstract. *This article analyzes the theoretical foundations of mathematical modeling of the dynamics and emission of greenhouse microclimate indicators. In the course of the study, deviations from the standard values of relative air humidity and temperature in greenhouses were identified, and it was substantiated that these deviations negatively affect both workers' labor conditions and plant development. In order to ensure effective microclimate control, a mathematical model was developed on the basis of the theory of dew formation. In the modeling process, the Clausius-Clapeyron equation and the Magnus approximation were applied, and the relationships between dew point temperature, air temperature, and relative humidity were determined. Based on the obtained results, the possibility of regulating excess moisture in greenhouse air through the condensation method was demonstrated, and an innovative ventilation-condensation device was proposed. The research findings contribute to improving occupational safety in greenhouses, ensuring energy efficiency, and increasing the efficiency of agricultural production.*

Keywords: *greenhouse, microclimate, relative humidity, dew point, mathematical modeling, condensation, ventilation, emission.*

Introduction. The results of the preliminary experimental studies showed that greenhouse microclimate indicators, particularly the amount of relative air humidity, significantly exceeded the optimal permissible standards [1]. The obtained results clearly demonstrated that labor conditions in greenhouses do not meet the requirements of international standards or national sanitary and hygienic norms and regulations. In addition, these conditions are not suitable for the proper development of cultivated plants and may cause the emergence of various pests. During a day, the relative humidity of greenhouse air varies from 25% to 90%, while the air temperature rises from 15°C to 40°C. Such microclimatic conditions have a considerable impact on the body of greenhouse workers and sharply increase the probability of occupational diseases [1].

Under the conditions of family greenhouses, improvement of the air environment should be aimed simultaneously at creating healthy labor conditions for workers and optimal conditions for plants. Therefore, the mechanical ventilation systems used in such greenhouses should represent a compact integrated system of innovative technical solutions that simultaneously normalize microclimate indicators, purify the air from toxic pesticide residues, and ensure heat and energy saving. Based on the scientific research results and considerations presented above, it is advisable to develop a mechanical ventilation system that meets these requirements. Through this system, it becomes possible to maintain the concentration of harmful substances in greenhouse air within permissible limits and to prevent harmful substances from entering the greenhouse air

from outside. On this basis, favorable conditions can be created for improving workers' labor conditions and for cultivating fruit and vegetable crops under conditions suitable for plant development. The system to be developed should normalize microclimate indicators, purify the air from toxic pesticide residues, and consist of a compact set of innovative technological and technical solutions that ensure heat and energy saving.

Materials and Methods. One of the most reliable and cost-effective methods for regulating the relative humidity of air inside a greenhouse is dew formation from humid air, which occurs when moist air is cooled to the saturation temperature. This process is based on the equilibrium between water vapor and liquid water; as air cools, its capacity to retain water vapor decreases, and the moisture content of the air sharply declines.

The theoretical substantiation of the system to be developed, which should normalize microclimate indicators, purify the air from toxic pesticide residues, and constitute a compact set of innovative technological and technical solutions ensuring heat and energy saving, requires the development of a mathematical model of the dynamics and emission of greenhouse microclimate indicators. In developing this mathematical model, the regularities of the theory of dew formation in air were used.

According to the theory and physical nature of dew formation, dew is the result of the phase transition of water vapor from the gaseous state to the liquid state. This occurs when humid air is cooled to the saturation temperature. The process is based on the equilibrium between water vapor and liquid water; as air cools, its ability to retain water vapor decreases. When the process reaches a limiting state, condensation occurs. According to the theory of dew formation, the phase transition of water vapor from the gaseous state to the liquid state is associated with the following physical indicators:

- absolute humidity of air, $d=\frac{m_b}{V}\ kg/m^3$, where d, m_b, V denote, respectively, absolute humidity, the mass of water vapor, and volume.

- relative humidity, $\varphi=\frac{p_b}{p_t}\cdot 100\%$, where φ, p_b, p_t denote, respectively, relative humidity in air, the partial pressure of water vapor, and the partial pressure of saturated vapor. The saturation pressure depends only on the dew point temperature *(Tsh).* The dew point is the temperature to which air at constant moisture content must be cooled until $\varphi=100\%$. Dew formation depends on the relationship between surface temperature and dew point temperature; dew forms under the condition $T_{surf} \leq T_{sh}$, where T_{surf} is the surface temperature and T_{sh} is the dew point temperature. The mechanism of dew formation consists of several stages. The first stage is air cooling, when the earth's surface releases heat at night and cools. The second stage is the attainment of saturation, when the air temperature near the surface decreases and the partial vapor pressure becomes equal to the saturation pressure. The third stage is condensation, when excess vapor turns into water and dew droplets are formed [2,3,4,5,6,7,8].

The Clausius-Clapeyron equation is applied in the thermodynamic modeling of the process [9]:

$$\ln p_t = A - \frac{B}{T} \dots, \quad (2.1)$$

where A and B are empirical constants selected in such a way that, when temperature T is substituted into the equation in degrees Celsius, the calculated result gives the value of the saturation pressure p_t in millimeters of mercury.

There are a number of factors affecting dew formation. The main factors are as follows:

- the higher the relative humidity in the air, the higher the dew formation temperature;
- an increase in wind speed reduces the probability of dew formation;
- cloud cover reduces air cooling and decreases the probability of dew formation;
- the surface material may accelerate dew formation, as metal cools more rapidly, or slow it down, as in the case of wood, that is:

$$T_{surf} > T_{sh} + \Delta T_{zas} \quad (2.2)$$

- the relief of the area may accelerate or slow down dew formation; in lowland areas, dew forms more frequently.

In ventilation and air-conditioning technical systems, dew formation is often observed in cold air ducts, heat exchangers, and poorly insulated structures. Dew formation has a significant effect on the ecological, climatic, and microclimatic balance of an area, including greenhouse environments: the water balance of plants changes, the formation of the microclimate is affected, and aerosol transport is modified.

The dew point temperature (T_{sh}) depends only on the amount of water vapor in the air, that is, on the level of absolute humidity. If the moisture content does not change, it is not directly dependent on air temperature. The dew point temperature (Tsh)

Formally, Tsh is determined by the values of the following physical quantities:

1. The partial pressure of water vapor (p_v) is the main indicator, and partial pressure directly affects the dew formation temperature, that is [10,12,13,14,15]:

$$T_{sh} = f(p_p),$$

that is, the higher the partial pressure of water vapor in the air, the higher the dew formation temperature. This relationship is expressed through the following equations:

$$\varphi = \frac{p_p}{p_{tyb}(T_{sh})} \cdot 100\% \quad (2.3)$$

where the partial pressure of water vapor is:

$$p_p = \varphi \cdot \frac{p_{tyb}(T_{sh})}{100} \; yani \rightarrow T_{sh} = f(p_p) \quad (2.4)$$

2. In addition, as noted above, according to the theory of dew formation, the phase transition of water vapor from the gaseous state to the liquid state is associated with the values of the following physical indicators: the absolute humidity of air and the relative humidity of air.

3. Air composition and total pressure exert a partial influence. In engineering calculations, atmospheric pressure and gas mixtures are usually treated under the assumption of normal pressure only.

On the basis of the information presented above, it may be stated that the dew point is the “passport” of the moisture content of air. If the air contains the same amount of moisture, the dew point remains the same even when the air itself is heated or cooled.

The dew point is determined by the relative humidity of air. The higher the relative humidity, the higher the dew point, and the closer it approaches the actual air temperature. The lower the relative humidity, the lower the dew point relative to the actual temperature. If the relative humidity is 100%, the dew point is equal to the actual temperature.

In developing the mathematical model of the dynamics and emission of greenhouse microclimate indicators depending on dew point temperature, air temperature, and relative humidity, the Magnus approximation was applied, that is [16,17,18,19,20,21,22]:

$$T_{sh} = \frac{b \cdot f(T_h, \varphi)}{a - f(T_h, \varphi)} \quad (2.5)$$

where φ is the relative humidity of air; T is the air temperature; and a and b are intermediate coefficients, the values of which are calculated as follows:

$$f(T_b,\varphi)=\ln\frac{\varphi}{100}+\frac{a\,T_b}{b+T_b} \quad (2.6)$$

For air: a = 17.27, b = 237.7°C.

Below, on the basis of the developed mathematical model of the dynamics and emission of greenhouse microclimate indicators depending on dew point temperature, air temperature, and relative humidity, the graphs of the Magnus approximation were constructed (Figure 2.1).

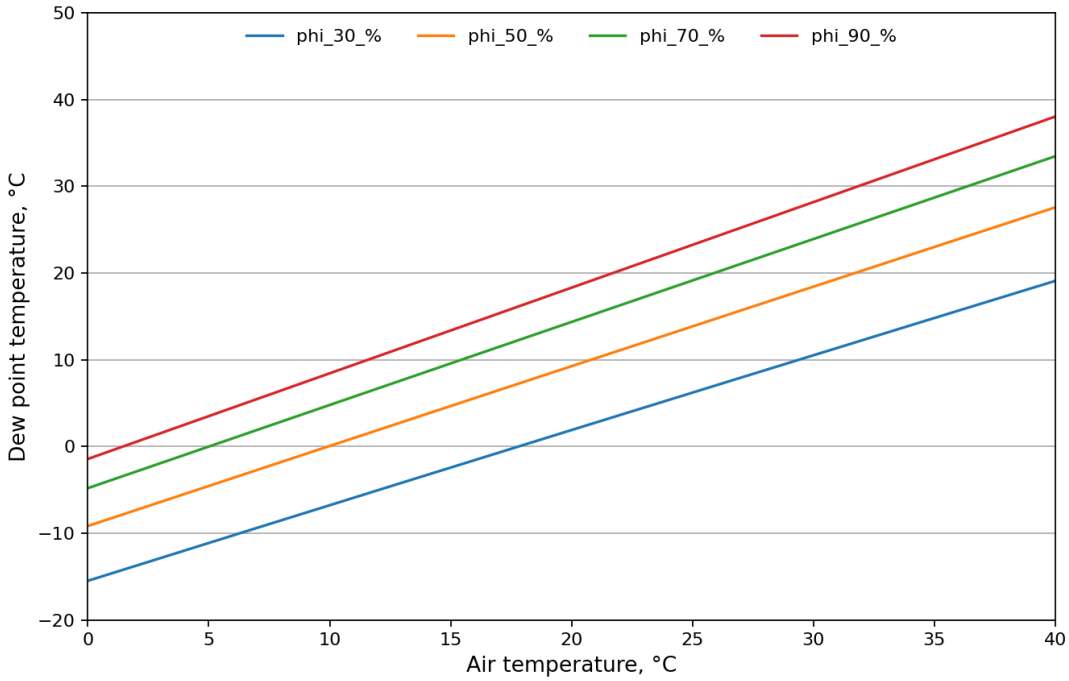


Figure 2.1. Dynamics and emission of microclimate indicators (dew point temperature, air temperature, and relative humidity)

A family of dependence curves between dew point temperature T_{sh} and air temperature T is presented for relative humidity values of 30%, 50%, 70%, and 90%, where each curve corresponds to its own value of relative humidity φ. The graph shows the dependence of greenhouse microclimate indicator dynamics and emission (dew point temperature, air temperature, and relative humidity) on the maximum amount of water vapor in air and on temperature. By using this model, it is possible to control the dynamics and emission of greenhouse microclimate indicators; specifically, excess vapor can be converted into water through condensation of greenhouse air by means of a surface on which dew formation occurs.

Results. On the basis of the developed mathematical model of the dynamics and emission of greenhouse microclimate indicators, a device was developed that makes it possible to control the value of relative humidity in greenhouse air, and an experimental prototype of this device was created. The device drives warm, humid air toward a cold pipe by means of a fan. The humid air comes into contact with the cold pipe; the air near the surface cools below the dew point; water vapor passes into the liquid phase; water droplets appear on the pipe and then flow through the pipe openings and are absorbed into the soil in which the pipe is buried. Condensate formation occurs as a result of the phase transition of water vapor from the gaseous state to the liquid state when moist air is cooled to the saturation temperature. The main parameter determining the onset

of condensation is the dew point temperature *Tsh*, which depends only on the moisture content of the air and characterizes its saturation state.

The family of dependence curves between dew point temperature *Tsh* and air temperature *T* at relative humidity levels of 30%, 50%, 70%, and 90% demonstrated the dependence of greenhouse microclimate indicator dynamics and emission (dew point temperature, air temperature, and relative humidity) on the maximum amount of water vapor in air and on temperature. Using this model, the dynamics and emission of greenhouse microclimate indicators can be controlled. On the basis of the mathematical model of the dynamics and emission of greenhouse microclimate indicators, a device was developed that enables regulation of the relative humidity of greenhouse air.

Discussion. The obtained results indicate that one of the most effective methods for controlling the microclimate in greenhouses is the application of technologies based on condensation.

The process of dew formation is not only a physical phenomenon but also has important practical significance:

it affects the water balance of plants

it stabilizes the internal environment of the greenhouse

it reduces the movement of aerosols and harmful substances

The research results are also consistent with other scientific studies [3,5,7]. In particular, the study of condensation processes from the standpoint of heat exchange [10-13] confirms the reliability of this model. The device created on the basis of the proposed model is suitable for small greenhouses, energy-efficient, and environmentally safe.

These characteristics expand the possibilities for its practical implementation.

Conclusion. As a result of the study, a mathematical model of the dynamics of greenhouse microclimate indicators was developed; a method for humidity control based on the theory of dew formation was proposed; an accurate calculation model was created using the Magnus approximation; and an innovative condensation device was developed.

These results have important scientific and practical significance for increasing occupational safety in greenhouses, improving plant productivity, and ensuring energy efficiency.

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