GREENHOUSE CLIMATE FACTORS

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INTRODUCTION

There are many examples of geothermally heated greenhouses throughout the world, even in warmer climates. The main reason for using geothermal heating systems is that greenhouses are one of the largest energy consumer in agriculture. This concentrated demand for energy can be satisfied, in the case of geothermal, by siting facilities near wells even though they are located far from urban areas and industrial concentrations.

The reasons for this high energy requirement are in the nature of the greenhouse construction itself:

- Greenhouses are typically constructed of light materials that have very poor insulating qualities, and
- The "internal" climate of the greenhouse are usually significantly different than the external one, especially during the colder seasons.

GREENHOUSE CLIMATE

One of the main tasks in greenhouse construction is to optimize the conditions for plant development, generally during the off-season from normal outside field production. The "internal" or greenhouse climate factors required for the optimal plant development involve photosynthesis and respiration.

Photosynthesis, or the active process, is the formation of carbon dioxide through solar radiation and can be expressed by the following simplified balance equation:

$$6CO_2 + 6H_2O + 2{,}810\ kJ = C_6H_{12}O_6 + 6O_2 \qquad (1)$$

On the contrary, respiration is expressed as:

$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O + 2{,}810\ kJ \qquad (2)$$

These equations do not represent the real situation, which is more complicated, but can be used to define the energy aspect of greenhouse climate: the water transport, CO_2 separation and energy intake, along with the creation of chlorophyll and O_2 that result from the natural or artificial application of light.

It is not possible to understand greenhouse energy demands in order to calculate heat (or coldness) requirements, without the essential knowledge of the "greenhouse climate." This climate is composed of parameters that are variable and interdepedndent, and are influenced by external climate changes, the stage of the plant development and other factors.

In principal, four physical phenomena are responsible for the differences between greenhouse and external climatic conditions:

1. Solar radiation, in particular the short waves, penetrates the glass or plastic covering of the greenhouse practically without any loss. On reaching the soil surface, plant canopy, heating installation, etc., the radiation changes to long-wave, and can no longer pass through the covering, or with difficulty. Most of the radiation is trapped within the greenhouse space, raising the inside temperature;

2. The enclosed air within the greenhouse is stagnant: local air velocity is much smaller than it is outside and the effects of temperature transfer are entirely different;

3. The concentration of plant mass in the greenhouse space is much higher than outside. Artificial control of humidity and condensation clearly creates a different mass transfer from outside the greenhouse, and

4. The presence of heating and other installations changes some of the energy characteristics of greenhouse climate.

Taking into account the real meaning of the equation (1) and (2), and the associated physical phenomena, it is possible to simplify the definition of greenhouse climate and to state that it is a physical process of predominantly energy related character. The main processes are the water transport between the plant canopy, air and soil in the greenhouse, the chlorophyll composition and degradation under the influence of solar light, energy transfer, and CO_2 and O_2 flow.

The values of these parameters, their interdependencies and changes determine the limiting conditions and character of greenhouse climate.

LIGHT

Light is the most significant parameter for the plant development and life. All the active life process in it can be achieved only in the presence and active influence of light.

When speaking about natural light, meaning solar light, it is necessary to distinguish:

- Solar radiation with specific influence to the life processes of the plants, and
- Solar radiation with energy related influence to the plants, directly or indirectly through the influence of the environment.

By the use of different scientific methodologies and investigations of changes in photosynthetical, phototropical, photomorphogenical and other plant activities, it is found that only the part of total solar spectrum between 400 and 700 nm influences significantly plants life processes (Figure 1). That determines the quality of transparent materials for greenhouse cover– it must be maximally transparent to this part of the solar spectrum.

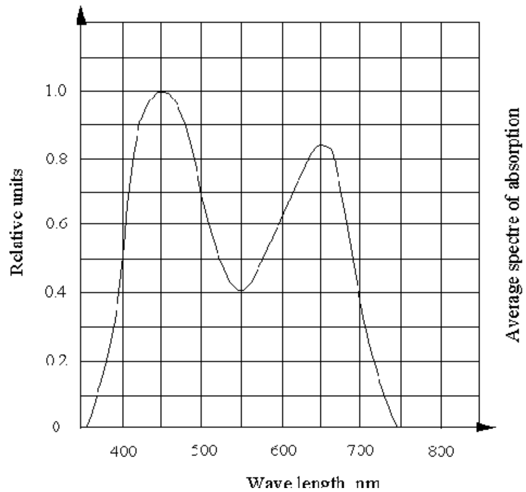

Figure 1. Average specter of absorption "in vitro" of chlorophyll pigments (Dogniaux & Nisen, 1975).

The intensity of the energy related part of the total spectrum of solar radiation (i.e., the infra-red one) offers the necessary energy to the plant (Equation 1). Depending on its intensity, life processes are more or less active (Figure 2). Up to some characteristical levels (different for different species) life processes increase their activities; but, after a point, they start to decrease. Below and above these characteristical light intensities, there is no life activity in the plant. Below, because active life processes need light to be activated. Above, because the plant is over- heated and processes of "cooling" are activated.

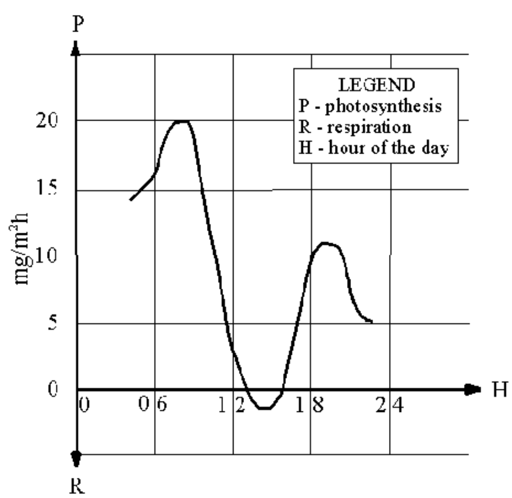

Figure 2. Changes of photosynthetical activity during the summer day (Kamenev, 1975).

To improve light conditions, artificial light is used when the natural one is not available, or shaded when the light intensity is too high.

Light intensity also affects the values of other parameters of greenhouse climate.

AIR TEMPERATURE

Air temperature influences the energy balance of the plant canopy through the convective heat transfer to the plant leaves and bodies. Depending on the character of the air movement in the greenhouse, it is more or less near the temperature of the plant itself.

The optimal level of the air temperature in the greenhouse depends on the photosynthetical activity of the plant in question, under the influence of the intensity of solar radiation on disposal (Figure 3) (i.e., for each light intensity, there is an optimal air [leaf] temperature, enabling maximum photosynthetical activity).

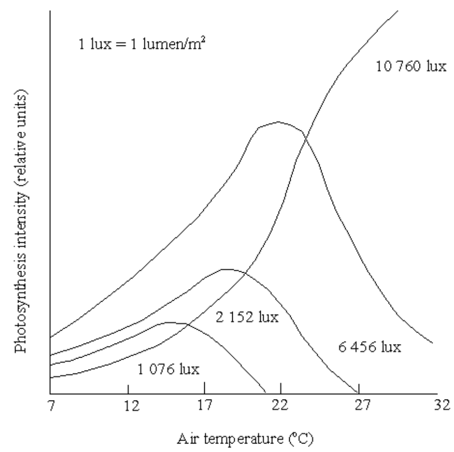

Figure 3. Photosynthesis activity vs. light and air temperature conditions (tomato culture)(Kamenev, 1975).

Due to the changeable character of greenhouse climate, it is not possible to provide the "optimal" air temperature for some plants due to interdependencies of the light intensity and other parameters of greenhouse climate.

Trials to define norms for optimal temperature values or intervals should not be understood as a tool for determination of optimal greenhouse climate (Table 1), but as a basis orientation for the choice of design values for calculation of greenhouse heat requirements and consumption.

SOIL OR PLANT BASE TEMPERATURE

Soil, or plant base temperature influences the energy balance of the plant canopy, too. The influence is by conduction heat transfer directly between the soil structure and through convection between the plant roots and water flow around them.

Through a great number of experiments and investigations, it is proven that:

- Optimal soil (or base) temperature depends on the stage of development of the plant in question (Table 2);

Table 1. USSR Norms for Optimal Values of Air Temperature and Humidity in Greenhouses for Vegetable Cultivation (Source: Kamenev, 1975)

	Inside Air Temperature (ºC)							Relative Humidity of the Air (%)
		Development			Harvesting			
Vegetable	Germination	Day*	Day*	Night	Day	Night	Young Plants	
Cucumbers	17-18	22-25	27-30	17-18	25-30	18-20	13-15	85-95
Watermelon and melons	17-18	22-25	27-30	17-18	25-30	18-20	13-15	65-75
Tomatoes, apple, paprika, and beans	10-12	20-22	25-27	10-13	22-28	15-17	8-10	50-60
Lettuce, celery and garlic	8-9	17-18	20-26	8-12				70-80
Spinach and parsley	8-9	15-16	20-21	8-9				70-80
Radish and cabbage	6-7	12-13	16-18	7-8				65-75

* Inside design temperature ranges for different crops.

- Optimal soil (or base) temperature depends on the light intensity available, and
- Soil (or base) temperature influences the value of the optimal air temperature (i.e., higher soil temperature requires lower air temperature and vice versa).

Table 2. Optimal Soil Temperatures for the Tomato Culture

	Optimal Soil Temperature Intervals	
Phase of Development	Low Intensity of Light (ºC)	Strong Intensity of Light (ºC)
Development before flowering	13-14	17-20
Flowering	15-16	19-22
Harvesting	20-22	23-25

It is necessary to stress that moving away from the optimal values influences the development of the root system of the plant, in the production capacity and the quality of the product. Going to lower values means decreasing production and going to higher values means drying of the root system, and in that way also reducing the production capacity and quality of the products.

Thus, if knowing the nature and requirements of plants, it is possible to influence significantly the heat consumption of a greenhouse through the balance between the air and soil temperatures during the plant cultivation.

CO_2 CONCENTRATION

Normal CO_2 concentration in the atmosphere is about 0.03%. In the case of a closed room under influence of high light intensity and, therefore, high photosynthetical activity (Equation 1), it changes quickly. During a bright day, its concentration can decrease to 0.01% in only a couple of hours for a good tight greenhouse.

As the CO_2 is an active participant of the chlorophyll assimilation, it is a greenhouse parameter of crucial importance. Also through a long process of experimentation and investigation, it is proven that:

- For constant temperature conditions in a greenhouse, CO_2 concentration influences directly the intensity of photosynthetical activity, and

- Optimal concentration of CO_2 in the greenhouse depends directly on the light intensity on disposal (Figure 4).

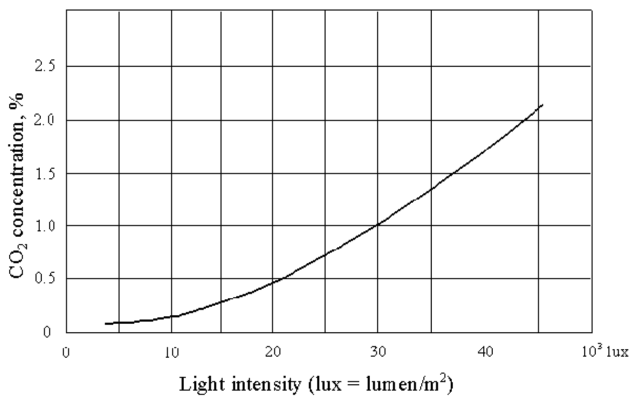

Figure 4. Optimal concentration of CO_2 in the cultivation area of a greenhouse depending on the light intensity (Denis, et al., 1978).

Through the ventilation of greenhouse closed space with 5-6 (vol/h) air exchange, it is possible to keep about a 0.02% CO_2 concentration. It is a compromise, because going to 9-10 (vol/h) exchange enables one to keep about a 0.03% concentration, but this influences significantly the heat consumption of the greenhouse. Middle- and northwest-European climatic conditions require the use of artificial measures to keep the necessary optimal CO_2 concentration; but, in the southern regions, usually controlled ventilation is sufficient.

AIR MOVEMENT IN THE GREENHOUSE

The character and velocity of the air movement in the greenhouse influences:

- The intensity of the heat transfer between the air and plant canopy, and

- The intensity of the water exchange between the air and plant canopy.

At the same time, both processes are directly connected to the energy balance of the plant canopy and, in that way, the intensity of the life processes in it.

It is found that velocities between 0.2 and 0.7 m/s provides the optimal heat exchange if the air stream is vertical (i.e., from bottom to the top of the plant). With some types of heating installations, it is easy to obtain this; but, with most of them, it creates a negative influence in the heat consumption of the greenhouse. Before making the final choice of the heating installation for a greenhouse, it is very important to investigate its positive and negative sides connected to the character of air movement in the greenhouse interior.

WATER TRANSPORT IN A GREENHOUSE

Water transport between the plant canopy and the environment is one of the most important parameters of the photosynthetical activity (Equation 1). It has been proved that it depends mainly on:

- The light intensity on disposal (Figure 5);

- Temperature of the environment (Figure 5), and

- Root characteristics of the plant in question in combination with the "ability" of the cultivation base to offer the necessary water quantity, but also on the air humidity of the plant environment.

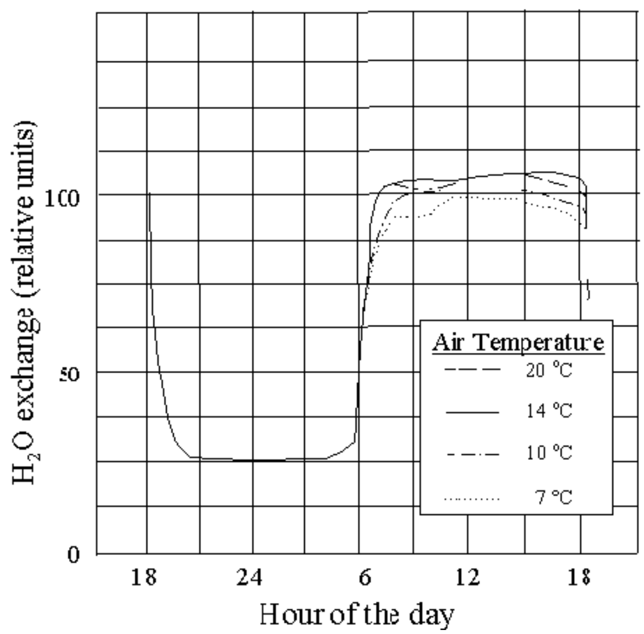

Figure 5. H_2O exchange of tomato plants before flowering.

The last parameters are of particular interest, since they influence the greenhouse climate characteristics. There is a direct relationship between the air humidity and soil moisture (or artificial cultivation base characteristics) in a greenhouse.

Air humidity directly influences transpiration of the plant leaves. Optimal intervals are rather small and difficult to be achieve in a closed room, filled with crops of high transpiration (Table 1). Lower humidity means drying of the plant and reduced production. Higher humidity produces more leaves, lower quality of fruits and sensitive to a number of plant diseases.

The intensity of the water transport of the plants depends directly on the light intensity (Curve ETP outside (light conditions), Figure 6). It is normally smaller in greenhouses and is connected to the light transmittance of their material (Curve ETP inside (light conditions), Figure 6). Depending on the stage of the plant root development and air humidity in the closed room, real water transport is smaller even than the inside one (Curve actual ETP, Figure 6).

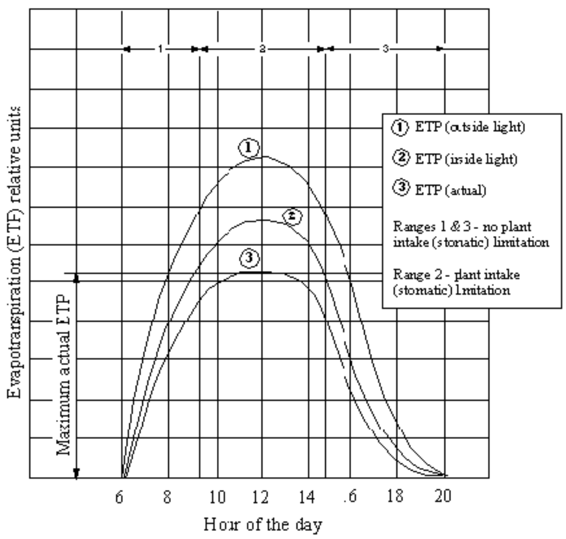

Figure 6. Potential evapo-transpiration (ETP) in a greenhouse (Dogniaux, Nisen, 1975).

HEATING INSTALLATION

Heating installation is an active parameter of the greenhouse climate because it influences:

- The character and velocity of the internal air movement (Figure 7);
- The radiation intercepted by crops by exposure pipe view factor to the heating elements, and in that way, tempera-ture distribution of the plant leaves (Figure 8), and
- Vertical and horizontal distribution of internal air temperatures (Figure 9), and the effect on the plant leaves temperatures.

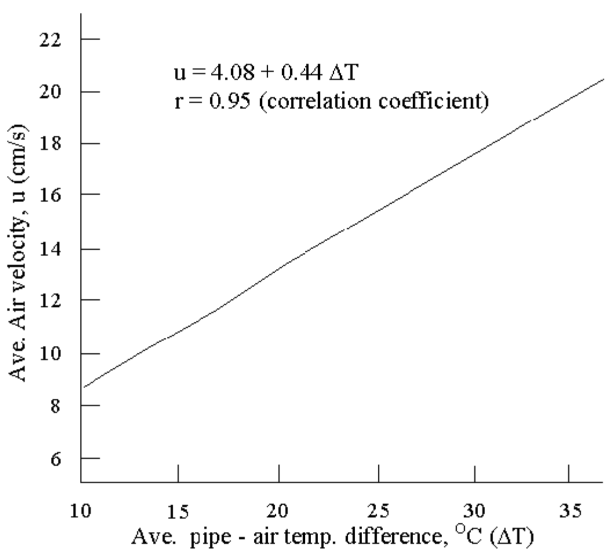

Figure 7. Internal air velocity as a function of temperature difference between the pipe surface and the air (Slanghellni, 1983).

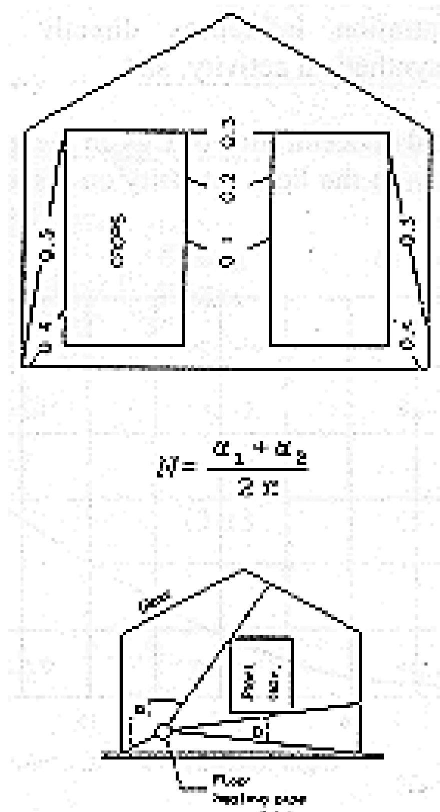

Figure 8. Effect of radiation interception by crops on the pipe view factor of heating pipes (Okada and Takakura, 1978).

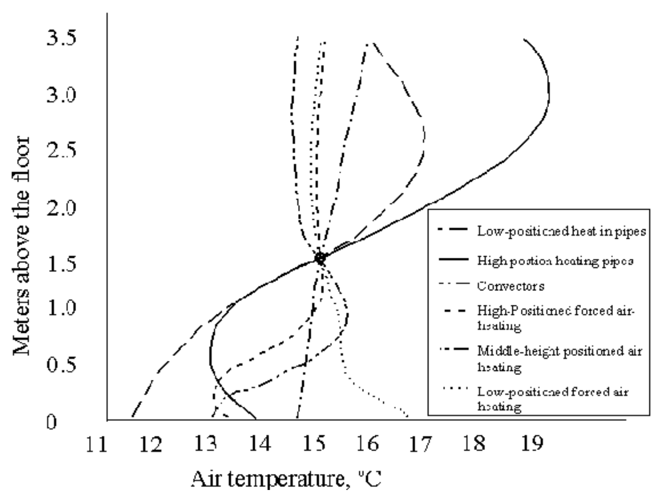

Figure 9. Vertical air temperature profiles in a greenhouse heated by different types of heating installations.

The type and location of the heating installations influences the temperature distribution and internal air movements (i.e., energy distribution and water transport of the plant canopy), which ultimately impacts the intensity and distribution of the photosynthesis.

ENVIRONMENT

The environment of a greenhouse includes the outside air, atmosphere and soil around it. Since the greenhouse climate is enclosed by transparent partitions, it is actively influenced by the outside environment.

A transparent wall has no (or very small) thermal inertia and each change of outside temperature conditions directly influences the ones in the greenhouse. The wall is transparent to a significant part of the solar radiation spectrum, and each change of it means a change of the inside climate conditions. Numerous leaks and the ventilation openings allow the outside air to enter in the greenhouse. Each change in velocity and direction changes directly the temperature distribution in the greenhouse. During the night and cloudy days, the atmosphere radiates "coldness" to the greenhouse interior and changes the temperature distribution of the plant canopy. Exposed parts are always colder than non-exposed ones (Figure 8).

OPTIMAL GREENHOUSE CLIMATE

When taking into account Equation 1 and the known dependence of the plant life processes on the light composition and intensity, the "greenhouse" climate is a rather simple physical quantity:

$$GK = F(I, T_a>, CO_2, H_2O) \qquad (3)$$

where:
I = Light intensity (W/m^2, lumens)
T_a = Plant leaves temperature (K)
CO_2 = CO_2 concentration in the air around the plant canopy (%), and
H_2O = Internal air humidity and soil (plant base) humidity (i.e., moisture) (%).

Temperatures and partly the light are quantities of an energy nature and the others are not.

For each plant and its stage of development, it is possible to define the optimal values of influencing parameters, and then it is necessary to keep them constant. That should result in maximum production results and quality of the fruits and flowers. In a number of laboratories, it has been experimentally proven that this way of thinking is a correct one.

Unfortunately, it has also been proven that it is difficult to make a profit. Even distribution of light with a defined spectrum and intensity means extremely expensive lightening installation and high development costs. The solution is in the use of natural light when available. Even distribution of temperatures in the plant canopy means very expensive insulated partitions between the cultivation room and the environment, and the use of expensive air-conditioning installations. The solution is in the use of natural heat on disposal (solar radiation) and the use of acceptable cheap heating installations.

The general solution using transparent partitions between two climates has been accepted. It allows the capture of the available natural light and particularly the energy part of it.

Unfortunately, such a partition cannot be a real barrier between two different climates. It allows light, heat and air transfer between them and, in that way, makes them interdependent. The outside climate becomes an active participant in the creation of the inside one.

With such pre-conditions, a rather simple physical quantity composed of three parameters (T_a, CO_2 and H_2O) which are depended on the fourth one (I) with known characteristics, becomes extremely complicated. Even nonenergy parameters change the character of energy producing ones. For example, to keep the necessary CO_2 concentration, it is necessary to ventilate the greenhouse (heat loss) or to produce it in an artificial way (heat gain); to keep the necessary air humidity, it is necessary to ventilate the greenhouse (heat loss or gain) or to make artificial humidification (heat loss); etc. Optimal CO_2 concentration depends on the light intensity and temperatures. Higher temperatures--higher CO_2 concentration (i.e., additional ventilation and temperature drop as a consequence of the outside colder air). Higher inside temperatures provoke stronger photosynthesis activity, which means higher plant transpiration (i.e., higher air humidity) then necessary and requiring additional ventilation, which means temperature drop (additional heating is necessary).

These make the greenhouse climate a complicated physical quantity with the following characteristics:

- Composed of the long list of parameters of the inside and outside greenhouse environment. They are interdependent between themselves in very different and often opposite ways;

- All the involved parameters are directly or indirectly of an energy nature. They cause or are the reason for creation of energy transfers in the greenhouse and to its environment, and

- Taking into account that all the parameters which are directly involved in the process of photosynthesis depend on the light characteristics and intensity, greenhouse climate is of a changeable nature:

$$GK = F(t) \qquad (4)$$

Two very important conclusions can be extracted from that:

- The composition of optimal conditions for the plant development ("optimal greenhouse climate") involves a long list of influencing parameters with different influence on the crucial ones and different inertia to the short-time changes of light conditions on disposal. Therefore, one can speak not about "optimal climate," but about "optimal compromise" of influencing factors to the plant life conditions, and

- Even if the nature and interdependencies of the parameters of the greenhouse climate are known, it is not possible to define a final mathematical expression of it because some illogical "estimations" are involved.

  They cause the following consequences:

- One dimensional mathematical expression of "greenhouse climate" and, therefore, "optimal greenhouse climate" doesn't exists. It is always a set of expressions defining different physical quantities of known mutual interdependencies, and

- Composition of the optimal compromises is always connected to a chosen number of influencing parameters, in order to simplify the calculations and the selection of installations and equipment for the greenhouse climate creation. Usually, that is the internal air temperature, CO_2 concentration and air humidity, which depend on the light intensity available. The necessary corrections, connected to the plant, construction, installations and local climate specifics are determined by empirical simulations, based on the previous investigations.

It is very important to always have in mind that even the greenhouse climate is composed of energy parameters and, therefore, it is of an energy nature. Its real nature is biological and complex.

Any mathematical expression of it gives only an approximation. It is never, and cannot be complete and precise.

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