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I. BASIC PROBLEMS OF WATER RELATIONSHIP

ENERGY BALANCE AND WATER SUPPLY IN GLASSHOUSES IN THE WEST-NETHERLANDS

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Abstract. - Research was carried out to define the relation between evapotranspiration and global radiation. A good correlation was proved to exist between evapotranspiration in a glasshouse and total incoming solar radiation, so the energy balance of the year was drafted based on data of the mean meteorological situation over 24 hours.

Approximately 50% of the global radiation inside non-heated glasshouses appeared to be used to evaporate water. The energy supplied by artificial heating in heated glasshouses is to a lower percentage used for this purpose. As an exact calculation of the energy balance components is not yet possible it is estimated that 25 to 30% of the heating energy was used for evapotranspiration.

Data on water supply to tomatoes, cucumbers, roses and carnations in heated glasshouses from a large number of holdings were in a good agreement with the calculated requirements. Solar radiation was the most important factor when calculating the needed water supply.

Some limitations were made to the use of the found relationship between the to be given additional water supply and global radiation in heated glasshouses. Account should be taken of soil and glasshouse type as well as ventilation frequency and heating intensity. Checks on moisture content of the soil and evaluation of crop growth remain necessary.

Introduction. - Crops cultivated under glass need artificial water supply, which means that in principle the water requirements of such crops should be known. That up to fairly recently not many growers in the West-Netherlands were aiming with scientific means at an optimum water supply was caused by a number of factors inherent to this area. Water is used from canals and ditches abundantly present, so the quantities available are almost unlimited. Nearly all holdings have an intensive drainage system, so an excess supply is quickly drained away. As the groundwater table is mostly within 1 metre depth, a deficient supply is easily compensated for by capillary rise.

During the last decade, however, the quality of open water, especially as regards salinity, gradually declined. This became the more serious as the area of very susceptible flower crops increased. This leads to the use of rainwater storage basins or the additional use of drinking water. Furthermore the technical improvements in managing glasshouse climates needed a similar improvement of water and soil management, to be able to obtain maximum results.

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In this context a better knowledge of the water requirements of crops grown under glass and of the influence of additional water supply on the energy balance inside glasshouses is a prerequisition for advanced growing. Assessments of evapotranspiration in heated as well as unheated glasshouses will be derived via an energy balance approach and will be compared with measured data.

Energy balance in unheated glasshouses. - The influence of the climate factors on evapotranspiration was formulated by Penman (1956) for open field conditions. Glasshouse climate differ that much from outdoor conditions, however, that the method will have to be adapted. The most important climate factor for evapotranspiration, also under glass, is radiation (Morris et al., 1957), while the factor wind will be of a much smaller influence. An analysis of the energy balance in glasshouses seemed to be indicated.

To simplify the approach the calculations are based on the conditions in a large 'Venlo' glasshouse. In this case the approximation is allowed that only the vertical energy exchange is important and the horizontal exchange at the walls may be neglected. The heat exchange of the soil can be omitted by using balances for the whole year round.

The energy balance of an unheated glasshouse, as pictured in fig. 1, can be written as:

$$H_{sh}^{out} - {}^{r}H_{sh}^{out} = H_{sh}^{in} = {}^{r}H_{sh}^{in} + {}^{net}H_{lo} + LE + H_{se} \qquad (1)$$

The shortwave radiation falling on the glasshouse H_{sh}^{out} will be partly reflected by the roof surface: ${}^{r}H_{sh}^{out}$, the rest H_{sh}^{in} will enter the glasshouse. Some of this radiation is reflected to the roof again and part of it ${}^{r}H_{sh}^{in}$ passes to the outside. Another part of it is changed in long wave radiation and leaves the glasshouse as net long wave radiation ${}^{net}H_{lo}$. The remainder is changed into latent energy LE and sensible heat H_{se}. A small, here neglected part is fixed in the crop by biochemical processes.

Quantifying the energy balance. - In The Netherlands the yearly received sun-energy H_{sh}^{out} amounts to approximately 85,000 cal. cm^{-2}. This radiation is available at the glasshouse roof. Depending on orientation and slope of the glass cover and the area of non-transparant parts of the glasshouse construction, some of the short wave radiation will be reflected and absorbed. In a modern glasshouse about 70% enters, consequently $H_{sh}^{in} = 0.7 \times 85,000$ cal. $cm^{-2}.yr^{-1} = 59,500$ cal. $cm^{-2}.yr^{-1}$.

The losses by reflection at the soil and the crop surface ${}^{r}H_{sh}^{in}$ depend on soil type and fraction of soil covered by the crop (Feddes, 1971), which in its turn depends on the yearly rotation of crops. Taking this into account as well as the fact that the soil is rather humid and frequent moistened, the reflection taken to be 20%.

Of this amount 70% will escape from the glasshouse. Neglecting any reflections of a higher degree one may therefore put ${}^{r}H_{sh}^{in}$ at 14% of H_{sh}^{in}, so ${}^{r}H_{sh}^{in} = 0.14 \times 59,000$ cal. $cm^{-2}.yr^{-1} = 8330$ cal. $cm^{-2}.yr^{-1}$.

For long wave radiation the glass cover can be regarded as a heavy cloud cover ($n/N = 0$). Of further importance is the temperature (T) and the air humidity (e). An unheated glasshouse can be taken to have an average year temperature of 15°C and a relative humidity of 85%. The net long wave back radiation can be calculated with $^{net}H_{lo} = f(^{n}/N).\ f(e).\ f(T)$ and the tables given by Wesseling (1960). Per 24 hours we get $^{net}H_{lo} = 0.10 \times 0.26 \times 811.5$ cal. cm^{-2} = 21 cal. cm^{-2} and consequently per year: 365 x 21 cal. cm^{-2} = 7665 cal. cm^{-2}.

The radiation finally available per year for $LE + H_{se} = H^{in}_{sh} - (^{r}H^{in}_{se} + {}^{net}H_{lo}) = 59,500 - (8330 + 7665) = 43,500$ cal. cm^{-2}. yr^{-1}.

This energy is used by approximation (Penman) for $\frac{\Delta}{\Delta+\gamma}$ as latent energy and for $\frac{\gamma}{\Delta+\gamma}$ as sensible heat. At a temperature of 15°C $\Delta = 0.81$ and the psychrometer constant $\gamma = 0.485$. Thus $\frac{0.81}{0.81+0.485} = 63\%$ will be LE and the rest 0.37 x 43,500 cal. cm^{-2}. yr^{-1} = 18,100 cal. cm^{-2}. yr^{-1} as sensible heat. This means that in a glasshouse with a height of 2.5 m, a yearly average air temperature of 15°C and a yearly relative humidity of 85%, against 9.4°C and 85% as year averages for outdoor conditions, the air has to be changed approximately 4.5 times per hour to exchange the sensible heat to keep the temperature constant. Latent heat used for evapotranspiration will amount to 0.63 x 43,500 cal. cm^{-2}. yr^{-1}. With a latent heat of vaporization at 15°C of 588 cal. cm^{-3}, this corresponds with an evaporation of 466 mm per year.

Although under glass wind is of much less importance than it is out of doors, its influence cannot be wholly neglected because just in the periods of a high evaporating level (summer) the vents are often opened wide. Koppe and Bokhorst (1967) measured in the top of a tall crop (tomatoes) in a glasshouse wind velocities of the order of 0.1 m. s^{-1}. Under outdoor conditions this would involve a 'Penman-evaporation' of 51 mm. yr^{-1}. The evapotranspiration due to wind velocity may therefore be estimated at 25 to 50 mm. yr^{-1}. This brings the total evapotranspiration in the unheated glasshouse at the level of at least a 500 mm per year.

Influence of artificial heating on evapotranspiration. - In heated glasshouses the artificial heating H^{ah}_{lo} is responsable for a certain additional evapotranspiration. According Kostelijk and Withagen (1966) holdings with a crop rotation of early hothouse tomatoes and autumn lettuce use about 40,000 cal. cm^{-2}. yr^{-1} as heating energy. Although during winter this energy is mainly used to keep the air temperature in the glasshouse at the desired level, this energy has to be divided over three components: sensible heat, longwave radiation and latent heat:

$$H^{ah}_{lo} = H^{ah}_{se} + {}^{net}H^{ah}_{lo} + LE^{ah}$$

In heated glasshouses there is more convection than in unheated ones, because of the larger difference between inside and outside temperature. Besides that, the growing period and consequently the ventilation period over the year is longer and during artificial heating the vents will sometimes be opened to increase vapour discharge. Therefore the air changes per hour must be set at a higher level than was calculated for the unheated glasshouse. For the present calculation an estimated air change of six times per hour has been taken for the heated glasshouse. With an average air temperature in the heated glasshouse of 20°C and a relative humidity of 80%, the additional sensible heat discharge amounts to approximately 23,000 cal. cm^{-2}. yr^{-1}.

As a result of a higher glass temperature of the heated glasshouse the amount of long wave radiation is also higher than in an unheated one. Not much is known about temperatures of glass compared with outside air. From researches of Hiller (1956) it seems that glass temperatures of a heated glasshouse are on the average some 1 to 2°C above the outside air temperatures, while in the unheated glasshouse the difference in temperature between outside air and glass is on the average neglibeably small.

The above considerations give rise to the following rough estimation of the net long radiation loss in heated glasshouses:

$$^{net}H_{lo}^{ah} \text{ of } 6000 \text{ cal. cm}^{-2}.\text{yr}^{-1}.$$

It is to be expected that from the added artificial heat a far higher percentage is available as sensible heat and long wave radiation than is the case from global radiation. This means that less of this energy is available for latent heat flow (say 25% instead of 50%). With these approximations evapotranspiration: $LE^{ah} = 40,000 - (23,000 + 6000)$ cal. $cm^{-2}.yr^{-1}$ $= 11,000$ cal. $cm^{-2}.yr^{-1}$, agreeing with an additional 188 mm of water. The total evaporation in a heated glasshouse then will be 500 + 188 = 688 or about 700 mm. yr^{-1}.

Measurements of water consumption. - The available information on water use of plants and the application of water in glasshouses is comparable to only a limited extent. As a rule the growing circumstances are insufficiently described. Seldom it is known whether the applied water is completely used by the crop or is partly drained away. Some available information is given in Table 1.

During the last six years data on water supply in glasshouses were collected by the Research Station at Naaldwijk, mainly derived from observations on holdings in the West-Netherlands' glasshouse areas and partly from experiments at the Research Station itself.

Starting in 1966, during three years data were collected on the amount of water applied by irrigation and discharged by the drainage system on 10 holdings having hothouse tomatoes or cucumbers as main crop. To this purpose the weekly number of turning hours of the irrigation as well as the discharge pumps were registered and the pumping capacities measured (Van Schie, Van der Post, 1969). On holdings with early tomatoes followed by autumn lettuce the water consumption by the crops was 707 mm. yr^{-1} on the average and for cucumbers 880 mm. yr^{-1}. The water supply was far higher since part of the water applied was discharged via the draining system.

To obtain a better idea concerning the influence of global energy and additional heating energy, the calculated 'Penman evaporation' is introduced as demonstrated in Fig. 2. Based on a light transmission of the glasshouse of 70%, the potential evapotranspiration under glass has been taken to be 70% of the 'Penman evaporation' (740 mm) for the periods under consideration. In this way, of the total water consumption of 707 mm the Penman evaporation is responsable for 517 mm and the heating energy for 190 mm. This is in good agreement with the calculations given above.

In 1968 and 1969 water supply data were collected at a large number of holdings where early tomatoes, cucumbers, roses and carnations were grown. The data from 1969 for some 20 holdings per crop are given in Fig. 3. The total amount for a certain period in 1968 and 1969 is listed in Table 2, together with the calculated evapotranspiration of hothouse tomatoes. Added are data of crops grown under irrigation at the Research Station in 1971 and 1972.

Although, as already mentioned, water supply does not always run parallel with water consumption by the crop, the agreement between actual water supply and calculated evapotranspiration is rather good. The water gift during the early summer months is generally somewhat higher than evapotranspiration so during that time some drainage discharge occurs. Futhermore it is quite common to give particularly cucumbers in an area where the salt content of the irrigation water is rather high an excess amount of fresh water. Near the end of a culture on the other hand, the amount of water added is a rule lower than the evapotranspiration amount. Growers then let the topsoil dry out to a certain extent.

The dominant influence of the radiation on the water requirement of the crop can be shown by Fig. 4 (De Graaf, 1972). The data on total water use given in fig. 2 have been split-up into winter plus spring, and summer plus autumn data. During winter and spring when artificial heating is fairly continuously practiced, relatively more water is applied than during summer and autumn when global radiation is often the only source of energy. Irrigating early tomatoes in 1971 water gifts were based on a lysimeter evaporation during the same period. A close relationship was shown between water gifts and radiation level (Fig. 5). The curve shows a steeper slope at low radiation levels when much artificial heating is applied and the plants are growing up than at higher radiation levels during spring and summer.

The water to be added on a certain day can therefore be determined from the radiation received on the preceding day. During 1972 this procedure was followed with good results.

Some limitations of this method have to be considered:

- The needed water supply will depend on soil type and groundwater level, as on soils with a high capillary rise the less water is to be applied.
- In modern glasshouses with a highly transparent glass cover a higher water requirement will occur.
- Finally, the ventilation frequency and heating intensity will influence the evapotranspiration level.

It is therefore to be recommended to take the specific growth conditions in the glasshouse into account and to check frequently soil moisture content and crop growth.

Discussion. - In experiments in the United Kingdom between 1950 and 1960 Morris et al. (1957, 1962) and Rothwell and Jones (1961) indicated the close correlation between evapotranspiration under glass and solar radiation. They calculated that a mature crop in a single span glasshouse took 70 to 80% of the incoming radiation to evaporate water. Lake (1966) decreased this to approximately 60% for crops in glasshouses of large extension. This was more in agreement with the measurements of Bierhuizen (1963), who found a mean evaporating efficiency of evaporation pans of 60%. From fig. 4, derived from experiments in large 'Venlo-type' glasshouses, an evaporating efficiency of 65 to 80% of the incoming radiation is found during periods with considerable artificial heating. During periods with less of no artificial heating the evaporating efficiency seems to be some 60%.

Calculation of the evaporation based on the energy balance gives an evaporating efficiency of about 50% for non-heated glasshouses. Evapotranspiration in the heated ones is some 40% higher. For the main growing period of the mature tomato crop in spring and early summer in heated glasshouses the water consumption is 20 to 50% higher than in non-heated ones. Evapotranspiration efficiency is then in a range of 60 to 75%.

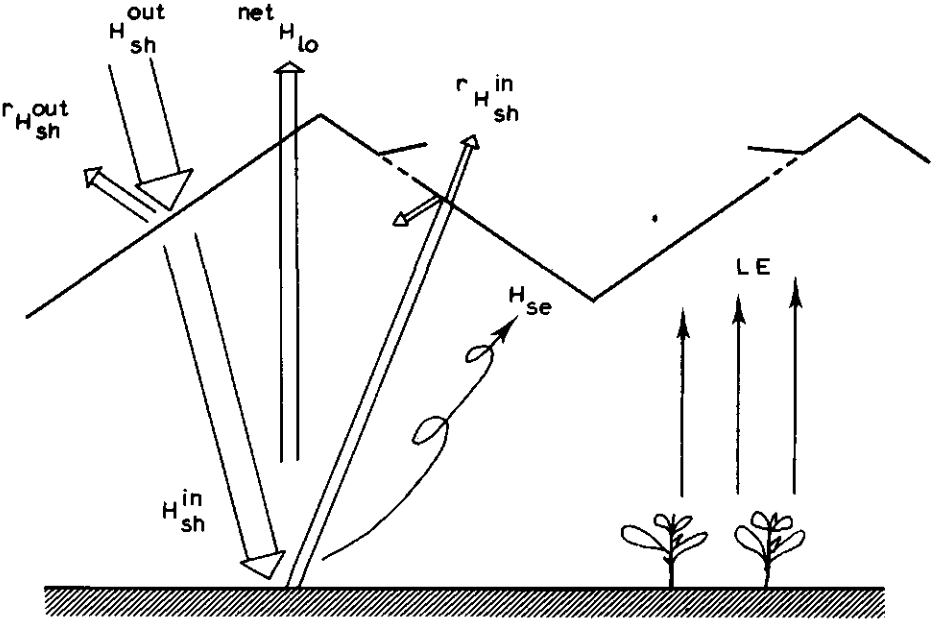
Although good agreement was reached between calculations and measurements in The Netherlands and the United Kingdom a better basis for calculations on needed water supply in glasshouses could be obtained if more information was available on glass temperatures, as then differentiated energy balances could be set up for different growth periods.

Table 1 - Water use of crops.

Author	Crop	Period	Amount in mm
Fröhlich (1959)	early cucumbers summer cucumbers	Jan. -Aug. Apr. -Sept.	600-650 500
Ploegman (1964)	hothouse tomatoes	6-7 months	500
Salter (1957)	" "	"	400-500
Spender (1964)	" "	6 months	400-500
Dunkel (1967)	" "	7 months	600-700
Van der Post and Van Leeuwen (1961)	hothouse tomatoes + autumn lettuce	Jan. -Nov.	550-600

Table 2 - Actual water supply and calculated water consumption in mm.

Period	Actual water supply				Evapotranspiration of hothouse tomatoes according	
	tomato	cucumber	rose	carnation	energy balance	measurements 1966-68 (fig. 2)
May -Sept. 1968	380	450	490	470	380	390
Febr. -Sept. 1969	620	750	770	710	620	610
12/I-13/VIII 1972	600				560	530
17/I- 6/VIII 1972	530				510	510



$$H_{sh}^{out} - {}^{r}H_{sh}^{out} = H_{sh}^{in} = {}^{r}H_{sh}^{in} + {}^{net}H_{lo} + LE + H_{se}$$

Figure 1 - Scheme of the energy balance in an unheated glasshouse of the 'Venlo' type.

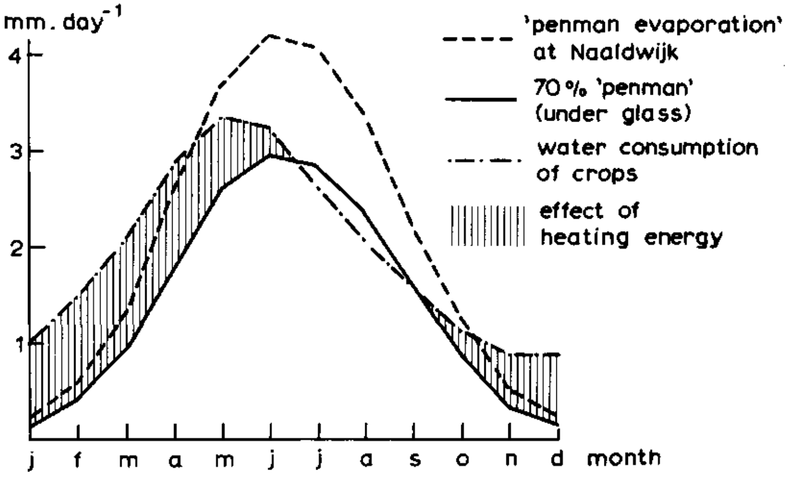


Figure 2 - Influence of global energy and additional heating energy on water consumption of tomatoes followed by autumn lettuce in heated glasshouses (mean 1966 through 1968).

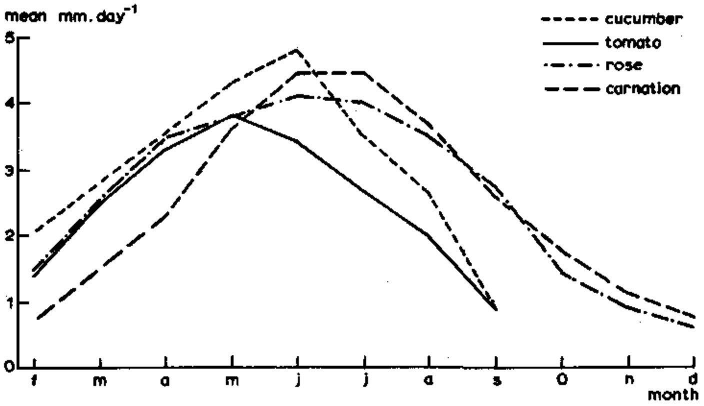


Figure 3 - Additional water supply to several crops in heated glasshouses (1969).

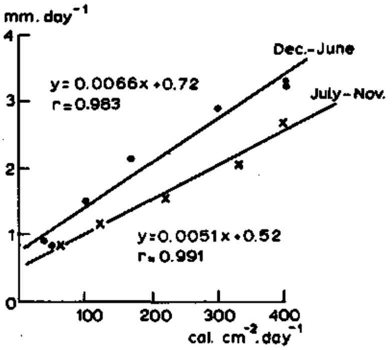


Figure 4 - Relation between global radiation at Naaldwijk (The Netherlands) and additional water supply to tomatoes in heated glasshouses (1966 through 1968).
After De Graaf, 1972.

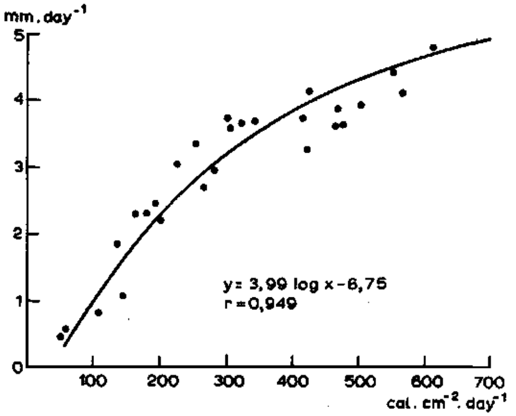


Figure 5 - Relation between global radiation at Naaldwijk (The Netherlands) and total water use of tomatoes in a heated glasshouse in 1971.
After De Graaf, 1972.

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