VENTILATION-COOLING

Department of Agriculture

Co-funded by the Erasmus+ Programme of the European Union

Ventilation

- The general term "greenhouse ventilation" describes two different techniques :
  - stirring / mixing of the indoor greenhouse air,
  - and the exchange of greenhouse hot air with outside air, specifically called ventilation

Ventilation

- Stirring / mixing the indoor air aims to:
  - create uniform environmental conditions throughout the greenhouse
  - avoid temperature stratification
- Ventilation aims to:
  - limit temperature rise inside the greenhouse beyond the desired level
  - correct the ratio of the various air components (water vapor, CO_2 and other gases)

Ventilation

- In Mediterranean climates the needs for ventilation become very high from early spring to late autumn
- The pace and way of ventilating a greenhouse depends on the season
- Therefore, we distinguish between winter, summer and spring-autumn ventilation

Winter Ventilation

- During winter the main goal of ventilation is the uniform distribution of temperature in the plant area (avoiding temperature stratification), by stirring the greenhouse air
- Often, during the noon hours, ventilation is required to reduce the temperature
- The ventilation system must introduce small amounts of air, much less than its maximum capacity, 10 to 20% of the maximum flow
- The cold air that enters the greenhouse in winter must be mixed with the warmer air inside before it comes in contact with the plants, to avoid problems of uneven growth.

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Winter Ventilation

- In greenhouses operating with passive systems, only the roof windows should work during winter
- In greenhouses with dynamic systems, outside air must enter the greenhouse through the openings located at the highest points of the greenhouse.

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Summer Ventilation

- In summer, the main goal is to reduce the high temperature developing in the greenhouse due to the increased incoming sunlight
- The air velocity in the plant canopy should not be high, as it may cause excessive perspiration, resulting in temporary wilting
- The air must move through the plants in order to cool them

Summer Ventilation

- Passive ventilation systems use roof and side windows for ventilation
- Dynamic systems use the continuous opening located on the side opposite the fans

Spring and autumn ventilation

- Spring and autumn are characterized by:
  - continuous alternation of periods with high temperatures (and consequently high ventilation requirements) and
  - periods with relatively low temperatures (and consequently with requirements mainly for stirring / mixing of air in the greenhouse and less ventilation)

Spring and Autumn Ventilation

- In passive ventilation at the beginning of the day the roof windows are used and later, when they no longer suffice, the side windows are added.
- In dynamic ventilation at the beginning of the day, only a part of the ventilators operate in low level of operation and the air inlet is from above

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Air Circulation in the Greenhouse

- In order to maximize crop production in the greenhouse, suitable conditions must be achieved, and maintained as close as possible to the optimum level:
  - Temperature
  - Humidity
  - CO_2 concentration

Air Circulation in the Greenhouse

- Conditions in the plant canopy are influenced by several factors during the day:
  - from the incoming solar radiation, the plant canopy acquires a temperature higher than that of the air
  - the perspiration of plants adds moisture, and the relative humidity increases
  - CO_2 is consumed by photosynthesis, thus reducing the CO_2 concentration

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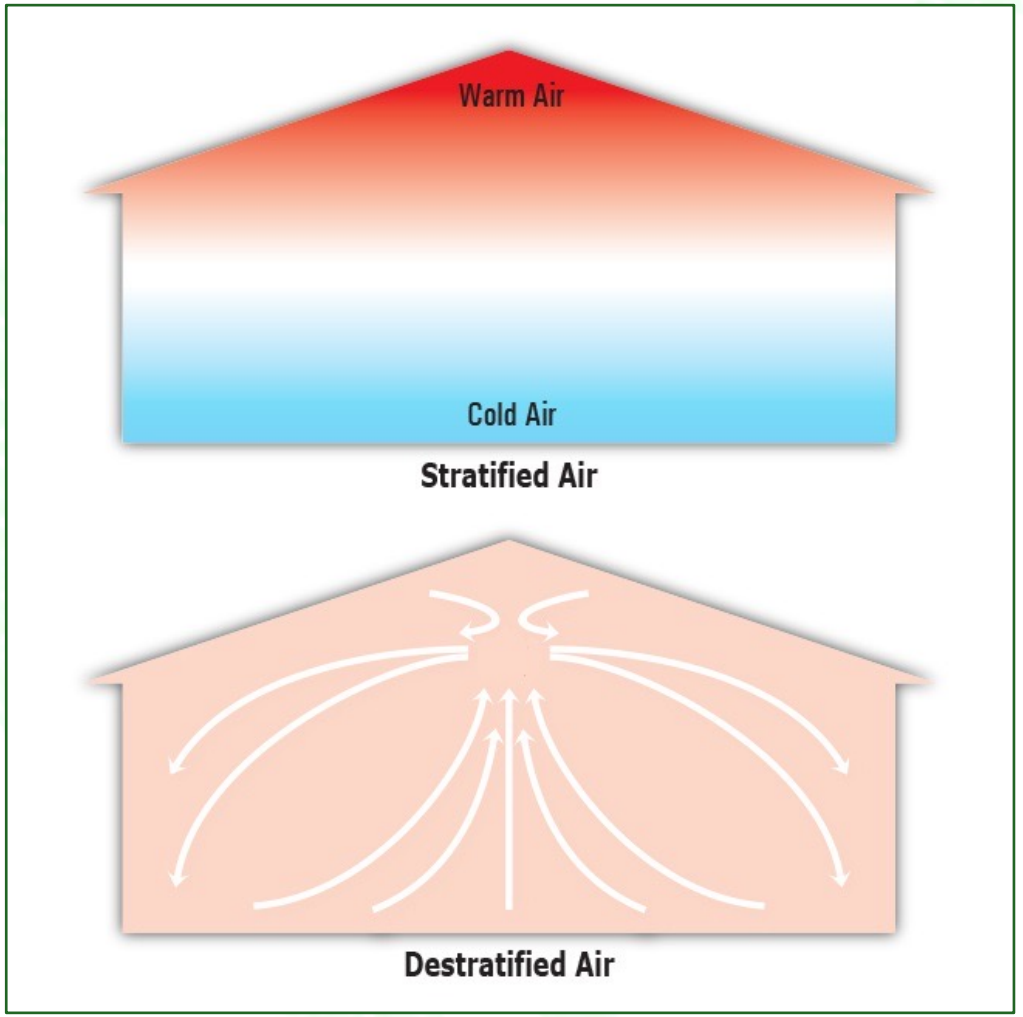
Air Circulation in the Greenhouse

- During the night
  - the heat loss of the plant canopy through radiation, causes a decrease in its temperature to a level lower than that of the ambient air
  - stratification of the temperature inside the greenhouse, due to the lower density of hot air rising to the roof and the higher density of cold air descending to the lower levels



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Air Circulation in the Greenhouse

- Inside the greenhouse, air circulation occurs because hot-humid air is lighter than cold dry air.
- The greater the temperature difference, the greater the flow. But for normal greenhouse temperatures this rate is relatively low
- From experimental studies we know that in a greenhouse that is heated with a heating system, and at the same time its air is stirred with dynamic means, temperatures are kept more uniform at the level of the plant canopy.

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Air Circulation in the Greenhouse

- Also, the relative humidity of a greenhouse with dynamic movement of air is lower than in a greenhouse that is only heated
- At low outdoor temperatures the forced air circulation inside the greenhouse increases the condensation of moisture on the cold surfaces resulting in the reduction of the relative humidity of the room

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Air Density as a Function of Temperature

Temperature (°C)	Air's Specific Weight (kg/m³)
0	1,29
5	1,27
10	1,25
15	1,23
20	1,20
25	1,18
30	1,16
35	1,14
40	1,13

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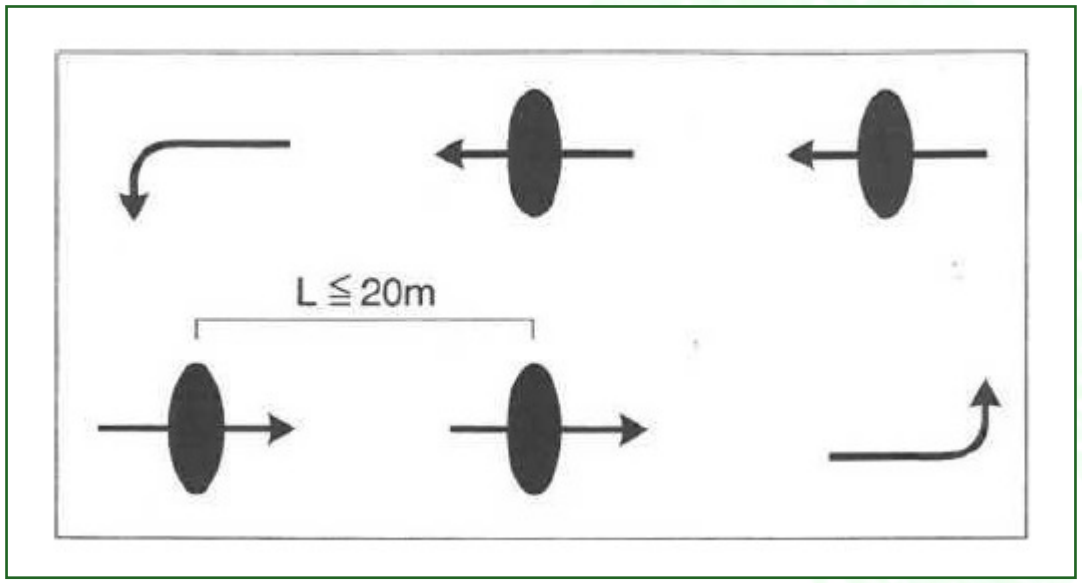
Air Circulation in the Greenhouse

Axial fans for stirring / mixing the air inside the greenhouse

Air circulation systems in the greenhouse - axial fans

- For the horizontal movement of air into the greenhouse space, it is considered sufficient to install fans with a total flow of 1/4 of the volume of the greenhouse / min
- Studies suggest that the most efficient diameter of the fans is about 30 cm, and they should be placed close to the ceiling with a slope of 10 ° -15 ° to the inside of the greenhouse

Air circulation systems in the greenhouse - axial fans



Distribution of fans for horizontal movement of air inside the greenhouse

Air Circulation Systems Inside the Greenhouse

- Axial air movement with perforated transparent PE pipe which favors air circulation along the entire length of the greenhouse
- The system consists of one or more fans that are placed at the end of the greenhouse and push the air through perforated pipes, which hang along the entire length of the greenhouse.
- Each pipe has holes of equal diameter, surface 5 cm2 each and at equal distances (two / 30 cm) along, from which air is extracted into the greenhouse.

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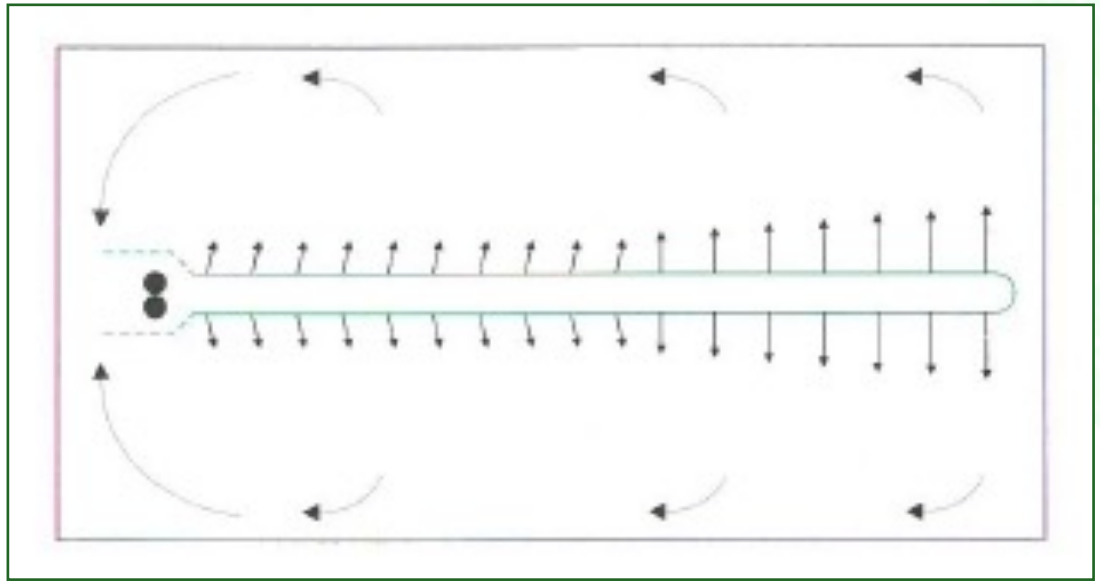
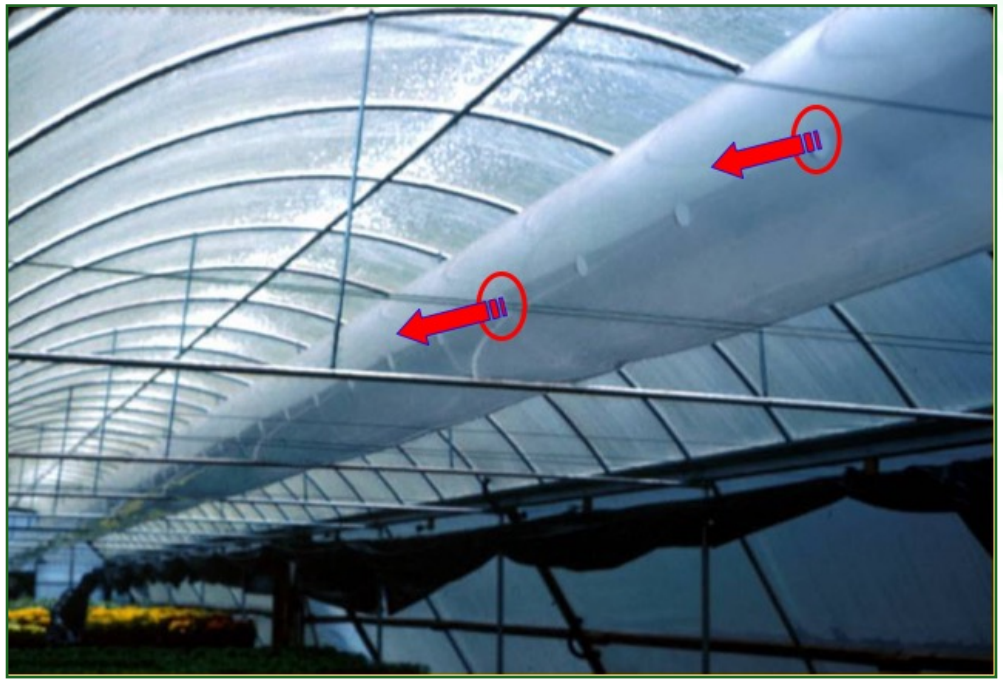
Distribution of air in a greenhouse through a perforated PE pipe



Distribution of air in a greenhouse through a perforated PE pipe



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Distribution of air in a greenhouse through a perforated PE pipe

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Ventilation

- The greenhouse, due to the transparent cover, receives most of the incident sunlight in its interior
- Therefore, on sunny days the indoor air temperature rises to high levels (overheating)
- From the incident radiation outside the greenhouse 50% -80% enters the greenhouse depending on the permeability of the cover material and the time of year
- Plants use about 23% -85% for evapotranspiration, depending on the leaf area index (LAI)

Ventilation

- The ratio between the energy consumed for evapotranspiration and the energy received by plants varies, with a high frequency of 0.50-0.60
- In the warm season of the year, evapotranspiration alone is not enough to significantly reduce the greenhouse temperature, because the incident and incoming solar energy is too great
- Therefore, it is necessary to ventilate the greenhouse

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Ventilation

- Ventilation is essential in order to:
  - Reduce the high temperature of the greenhouse area,
  - Extract water vapor exuded by plants and
  - Replace $C0_2$ used in photosynthesis

Ventilation

- Temperature regulation is the most demanding factor in ventilation and determines the design of the greenhouse ventilation system
- The factors that affect the size of the ventilation to control the temperature are:
  - Intensity of solar radiation
  - the temperature of the outside air
  - the maximum tolerable temperature inside the greenhouse (critical temperature, depending on the plant species)
  - The size of the greenhouse
  - the characteristics (optical and thermal) of the greenhouse cover materials
  - The rate of evapotranspiration in the greenhouse (size of leaf area, relative humidity)

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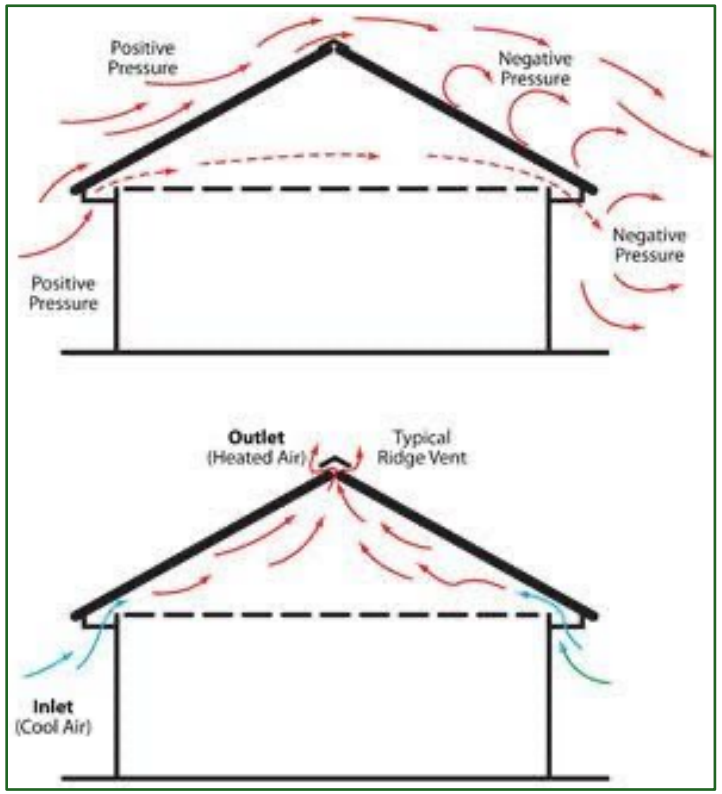
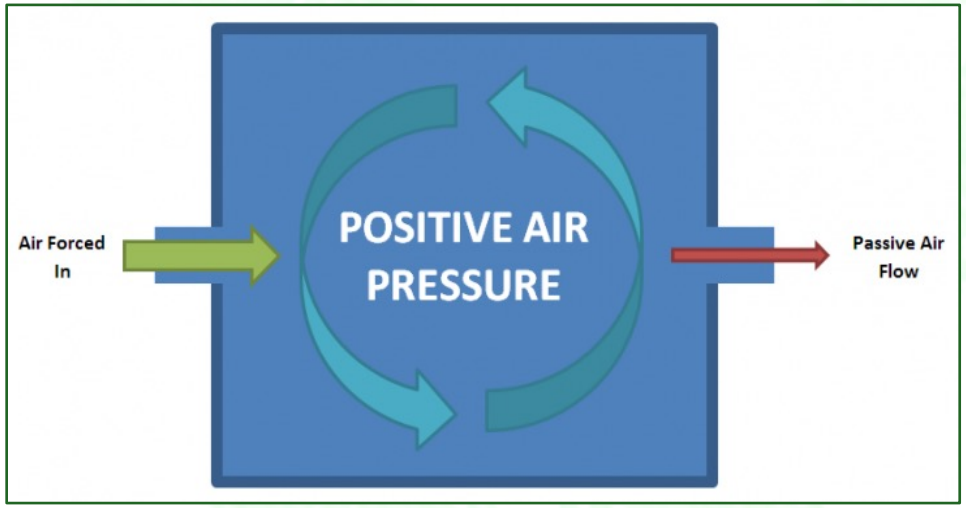
Ventilation

- The ventilation of a greenhouse is:
  - Physical / passive, caused by pressure differences between indoor and outdoor, developed by natural causes
  - Pressure differences are caused by the wind and the difference in air temperature inside and outside the greenhouse.
  - Dynamic, when the pressure differences between the indoor and outdoor space of the greenhouse are created by mechanical means

Ventilation





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Ventilation - Number of Air Changes

- The number of air changes (N) of the greenhouse in the unit of time, in order to keep the room temperature constant, is equal to the ratio of the ventilation needs to the volume of the greenhouse
- The temperature difference between inside and outside, which is achieved in the greenhouse area, is related to the rate of rotation of the greenhouse air.
- During the operation of the greenhouse in summer and using natural ventilation, ¾ to 1 *changes/min* gives satisfactory results
- Higher values can only be achieved with dynamic ventilation

Natural Ventilation

- The forces acting on the operation of natural / passive ventilation are:
  - the difference in static pressure created by the wind on the sides of the greenhouse,
  - the constant change in pressure created by the change in the instantaneous wind speed and
  - the pressure difference created by the temperature difference between the air inside and outside the greenhouse

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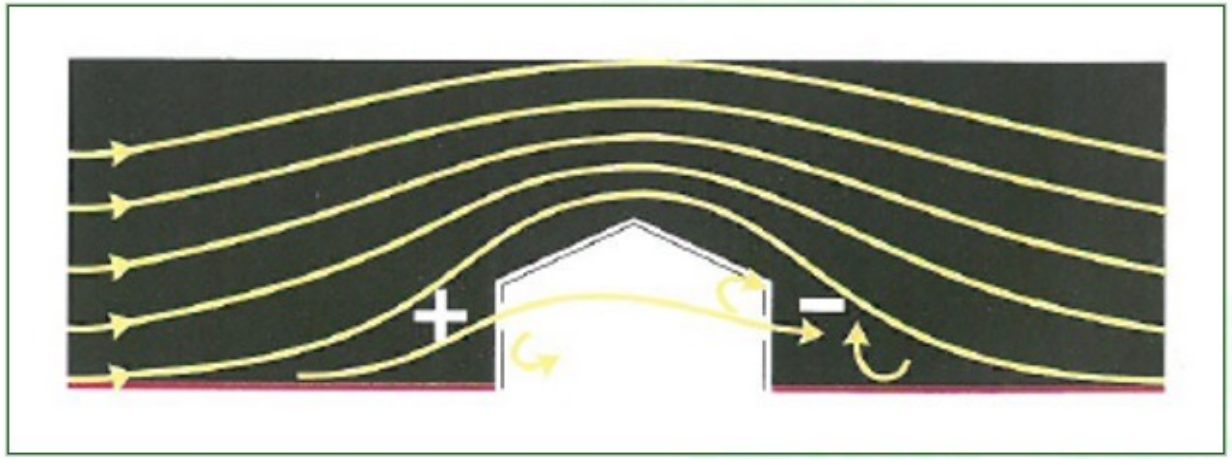
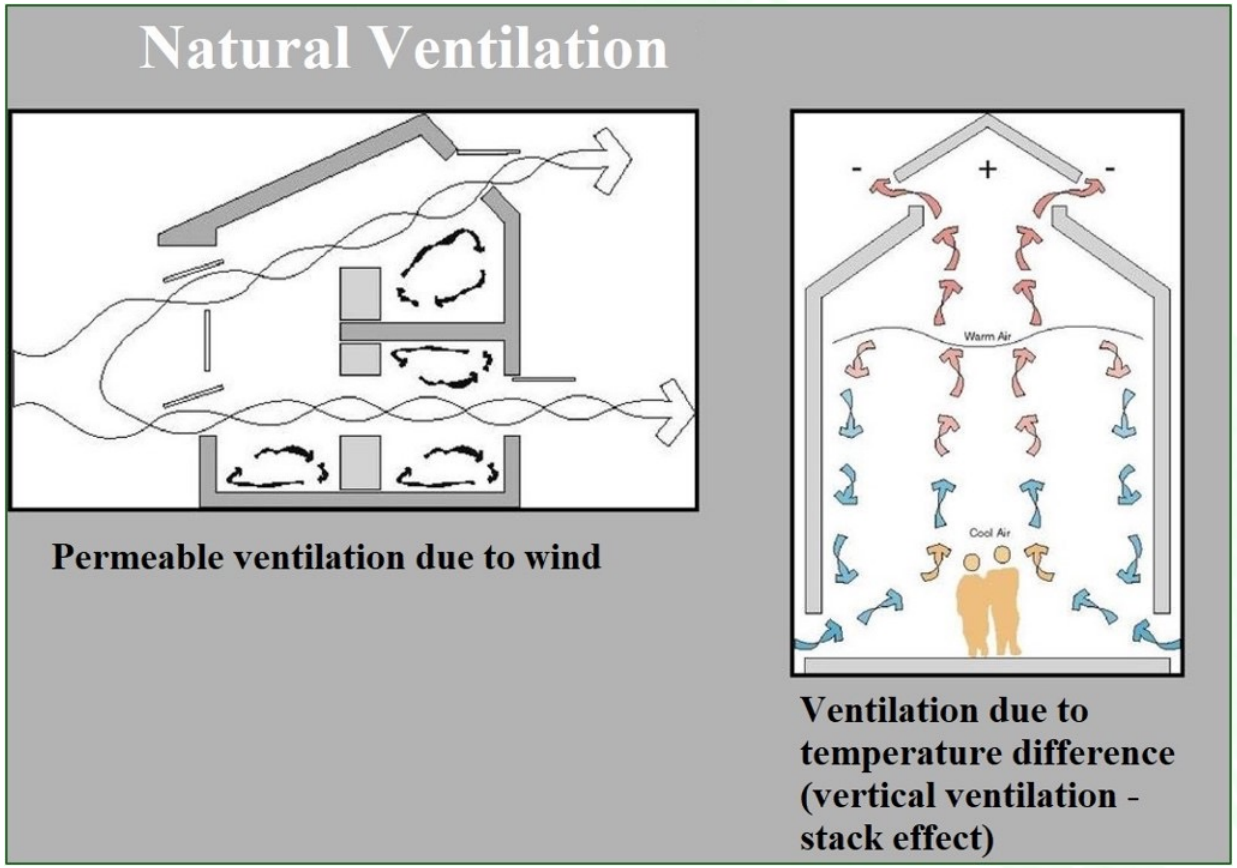
Natural Ventilation



The difference in static pressure created by the wind on different sides of the greenhouse, as a driving force for ventilation

Natural Ventilation



Natural Ventilation by the speed of the wind

- The difference in static pressure created on the various sides of the greenhouse by the speed of the wind
- In a greenhouse on the windward side, static pressure is created that is higher than the barometric pressure
- On the contrary, on the leeward side the pressure created is lower than the barometric pressure
- Thus, positive and negative pressure (relative to barometric) is created on the sides of the greenhouse, the magnitude of which depends on the wind speed.

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Natural Ventilation by the speed of the wind

- External air enters the greenhouse space through the openings on the sides which have a positive static pressure and
- Indoor air comes out of the greenhouse through openings on the sides where there is negative static pressure
- This is the predominant cause of ventilation in most greenhouses when the wind blows

Natural Ventilation due to the temperature difference

- The pressure difference due to the difference in air temperature inside and outside the greenhouse
- At the same level, the hydrostatic pressure differs inside and out, due to the different density of air
- Therefore, in a greenhouse opening, this difference in hydrostatic pressure causes ventilation
- The cause of air flow at each level of the opening is the difference between internal and external pressure

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Natural Ventilation due to the Temperature Difference

- In cases where side windows and roof windows are open at the same time, as is the case with natural / passive ventilation
  - cold air enters through the lower side windows and indoor heat exits through the higher roof windows (chimney effect)
  - The larger the height difference, the greater the in-out pressure difference and therefore the ventilation rate.

Modified Arched Greenhouse with Continuous Side and Roof Windows

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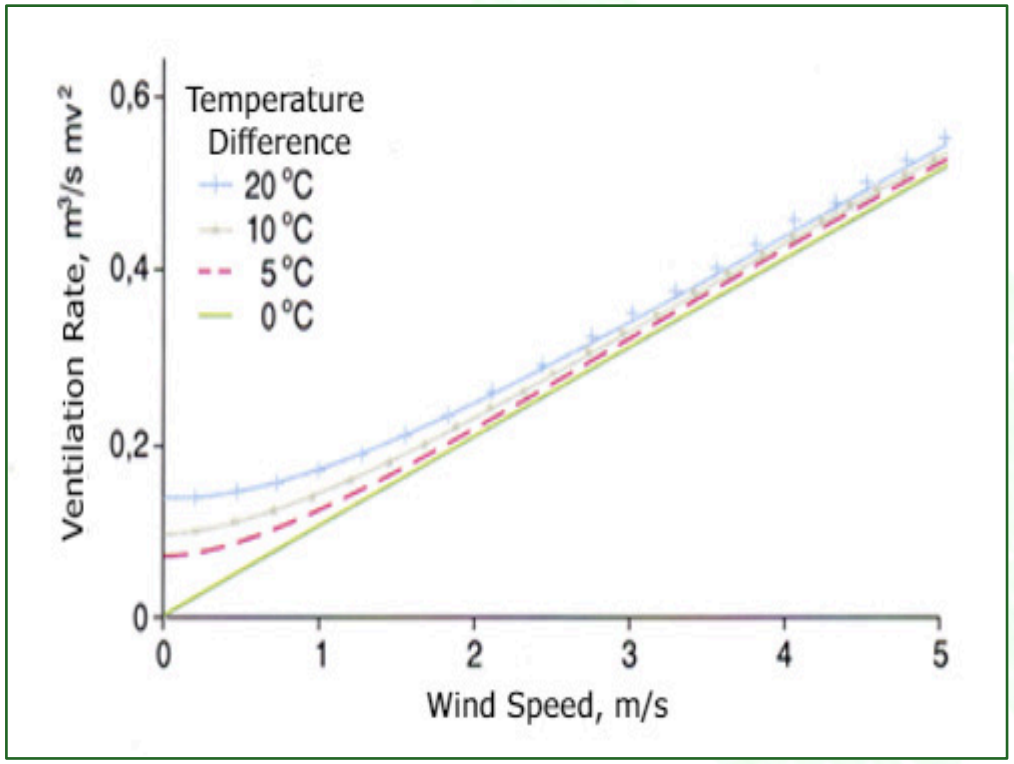
Greenhouse with Continuous Roof Windows

Natural Ventilation



Ventilation rate is affected by wind speed and the temperature difference between the inside and outside air

Distribution of Natural Ventilation Vents

- The aim of all research is to optimize the design of Natural / passive ventilation in the greenhouse
- An efficient natural ventilation system is particularly critical especially in Mediterranean conditions, in order to control air temperature, relative humidity and crop perspiration.

Distribution of Natural Ventilation Vents

- Vents must provide the required ventilation and distribute air evenly throughout the greenhouse
- This is achieved with the right size and the right position of the vents so that they are evenly and symmetrically distributed along the greenhouse.
- The minimum relative area of vents that a greenhouse should have is a function of the climatic conditions of the area and the type of plants to be grown.
- It is estimated that in Mediterranean conditions, for ventilation during spring and autumn, the extent of the openings should allow at least 40 changes / hour

Distribution of Natural Ventilation Vents

- The ventilation area of the greenhouse is given by the relation:

$$S = N * L * h \quad (m^2)$$

  - S = the maximum area of ventilation openings [m^2]
  - N = number of vents
  - L = length of the vents [m]
  - h = its maximum actual width [m]

Distribution of Natural Ventilation Vents

- The ventilation area of the greenhouse is given by the relation:

$$\Sigma A = \left(\frac{S}{A_g}\right) * 100$$

  - ΣA = the relative area of the vents
  - A_g = the ground surface of the greenhouse

Distribution of Natural Ventilation Vents

- The temperature difference between outside and inside air in natural ventilation decreases as the surface area of the vents increases, until the surface area of the vents becomes about 30% of the ground surface.
- Above this percentage, the extra surface of the vents has very little effect on further reducing the temperature difference

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Dynamic Ventilation

- Dynamic Ventilation reduces overheating of the greenhouse compared to that of the outside air and is an effective tool for reducing the thermal solar load thus improving the microclimate of the greenhouse
- Air renewal rates greater than $40/h$ are achieved, something that is not achieved with Natural ventilation systems
- In hot periods, when the sun radiation is high, in order to achieve a temperature difference inside-out (T_{in} - T_{out}) 4-6 °C, about $60\ {}^{air\ changes}/_{h}$ are required
- While with natural ventilation these changes can be reached only with sufficiently high wind speeds, there is also the solution of mechanical air circulators, also known as dynamic ventilation.

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Dynamic Ventilation

- With sufficiently effective fans, the ambient temperature of the greenhouse, even in case of apnea, can easily be kept only 4 °C to 6 °C above the outside air temperature.
- Dynamic ventilation is used:
  - In greenhouse constructions, where it is not possible to install a reliable natural ventilation system, or its installation greatly increases the total construction cost.
  - When lowering the greenhouse temperature is required, in areas where apnea is usually prevalent during the warm season

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Dynamic Ventilation

Dynamic Ventilation

- The yearly required ventilation time depends on:
  - the desired temperature for cultivation
  - the average maximum temperature of the outside air
  - the intensity of solar radiation
  - the leaf area index during the warm season

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Dynamic Ventilation Mechanism

- Dynamic ventilation is achieved using fans mounted on the wall of the greenhouse
- With the installation of electric fans, the greenhouse air is renewed regardless of the conditions of the external environment.
- The vents suck in and out the indoor air, which is replenished with outside air entering through vents on the opposite side.
- The air that enters, on its way into the greenhouse is heated and so there is a gradual rise in temperature from the entrance to the fans, from where it exits

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Dynamic Ventilation Mechanism

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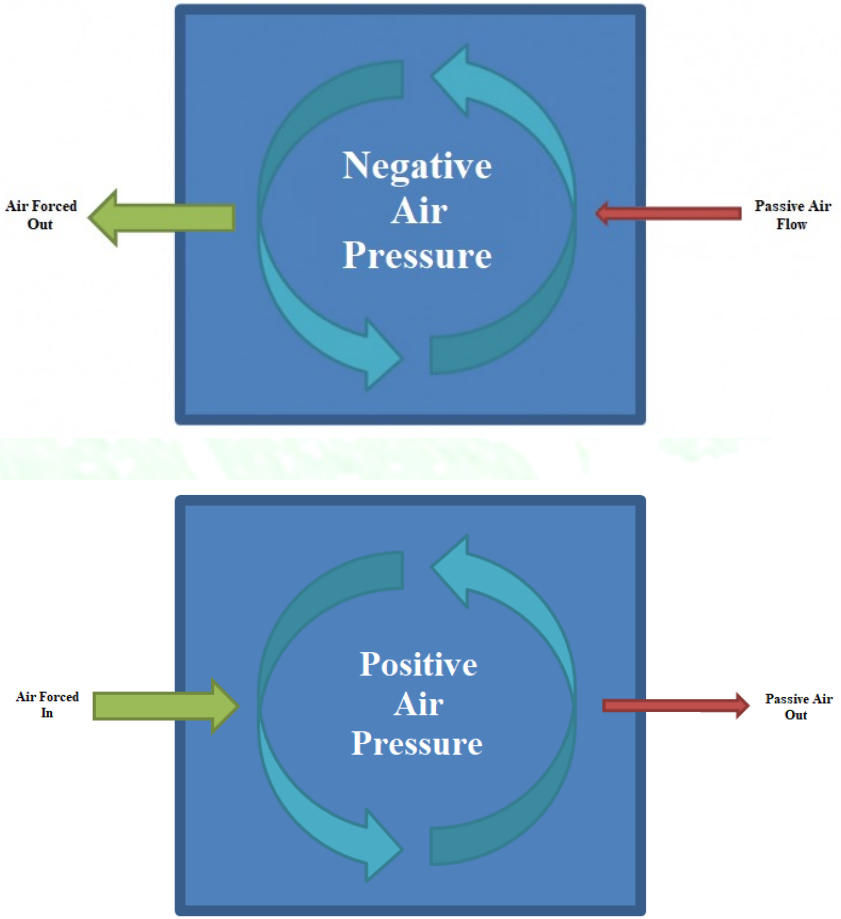
Dynamic Ventilation Mechanism

- Ventilators absorb air from the outside environment of the greenhouse and channel it inside, repelling the air that needs to be renewed (positive pressure ventilation).
- Usually, however, they remove the air from the inside of the greenhouse to the outside, creating a vacuum, so fresh air enters through the windows on the opposite side (negative pressure ventilation)



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Dynamic Ventilation Mechanism

- During the winter the air inlet opening is smaller and is located at the highest points of the opposite side (on the gable)
- or use a perforated plastic air distribution pipe high so that the cold air mixes with the greenhouse heat before it reaches the plants.
- During the warm season the air inlet opening is continuous across the width of the greenhouse, about halfway up the side.

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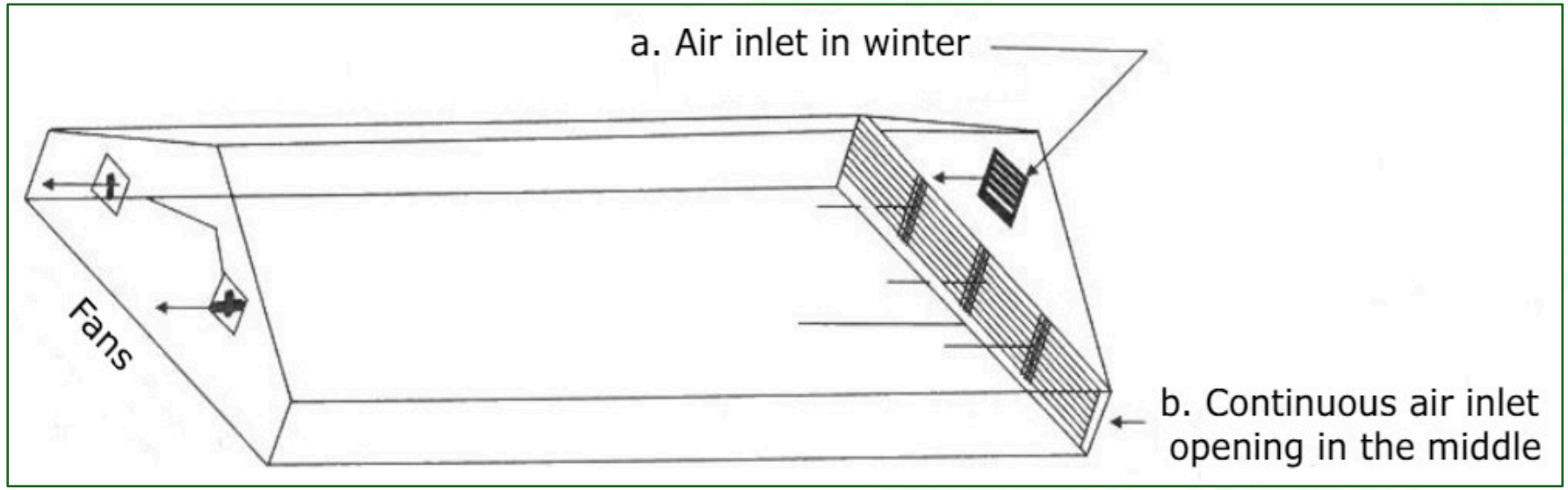
Dynamic Ventilation



Dynamic greenhouse ventilation, with fans on the small side and air inlet from the opposite side

Dynamic Ventilation – Negative Pressure Ventilation

- **Negative pressure ventilation** with fans on the **small side** of the greenhouse
- The fans are placed on the small side of the greenhouse, while the air inlet is from the opposite side
- The air runs through the long side of the greenhouse
- It is considered the most effective system for tall crops
- For uniform ventilation the maximum distance between the fans on the side is L_{max} = 6.50 m
- To limit the increase in temperature along the greenhouse, the length of the path should be limited to 30 to 40 m

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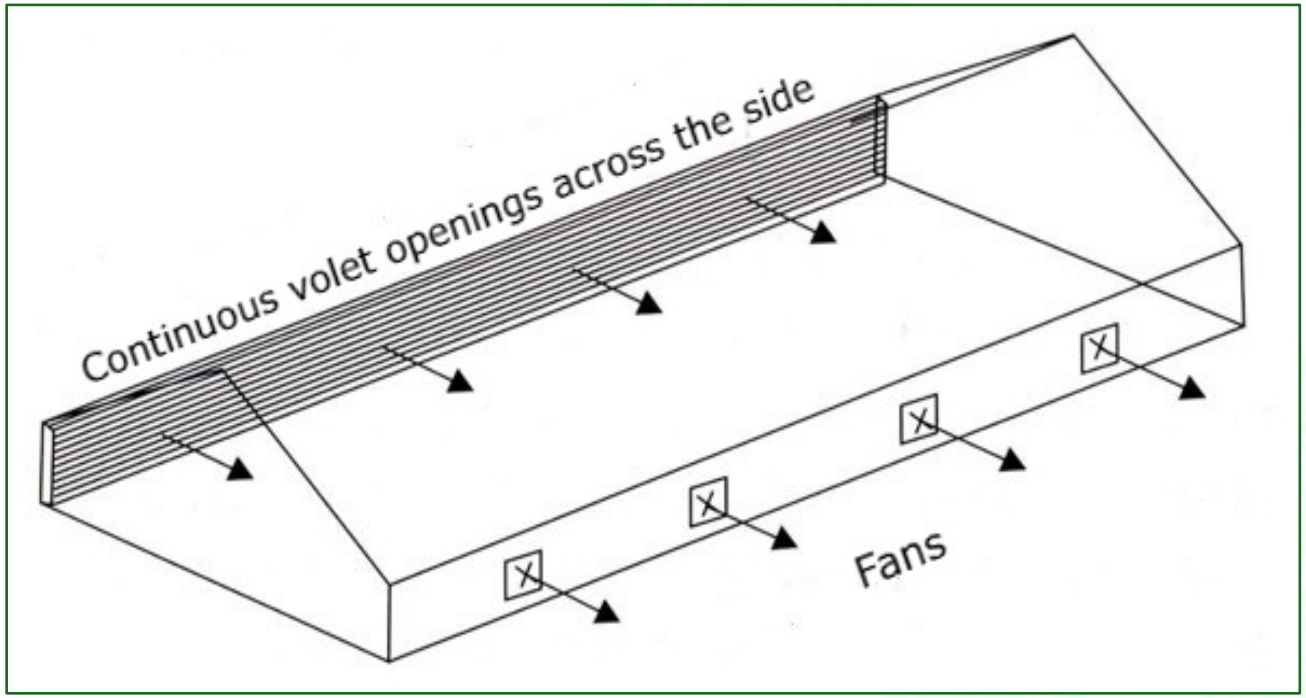
Dynamic Ventilation – Negative Pressure Ventilation

- **Negative pressure ventilation** with fans on the **large side** of the greenhouse
- When different temperatures are required along a greenhouse, transverse to the greenhouse axis ventilation is essential, with ventilators of different flow
- If the distance between the ventilators is too large, dead ventilation zones are created between the adjacent currents
- If the air vent is high on the opposite side and the air is reflected back to the roof and then is pushed out by the fans, no significant reduction in temperature in the plant area is achieved

Ventilators on the large side of a greenhouse

Ventilators on the large side of a greenhouse



Dynamic Ventilation – Positive Pressure Ventilation

- Ventilators absorb air from the outside environment of the greenhouse and channel it inside, repelling the air that needs to be renewed.
- It is mainly used when negative pressure systems cannot be used, because there are mandatory openings in the greenhouse cover.

Dynamic Ventilation – Fans

- Any rate of greenhouse ventilation is easy to achieve by determining the appropriate number and size of fans.
- In practice, their number can be calculated, knowing that for a good result (Tin - Tout = 4-6 °C) the greenhouse air must be changed once / min
- This change can also be done at 75% of the greenhouse air / min, thus saving a lot of energy

Dynamic Ventilation – Fans

- The fans used are characterized by the volume of air (V) they can move in the unit of time (sec) and the speed of rotation (ω)
- The efficiency of the fan depends on the total efficiency, which is estimated / derived from the volume of air (V) that the fan can move / power unit (P)
- Dividing the total volume of air V that must be changed / min by the supply of the fan / min, the number of fans required is found.
- The desired air speed at the entrance of the greenhouse is 230 m/min.
- This speed allows good mixing of the outside with the indoor air and prevents damage on the plants from excessive perspiration.

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Dynamic Ventilation Conditions

- Ensure at least 50-60 $^{air}/_{hour}$ changes.
- The air speed in the plant area should be max 1.5 $^{m}/_{sec}$.
- The distance of the fans from the opposite air vents should be 30-50 m.
- The vents and fans should be placed at the same height and opposite to ensure even distribution of cold air.
- The distance of fans on the side should not be more than 6 m and from the corner of the greenhouses less than 3 m.
- There should also be a backup generator (or natural ventilation openings provided).

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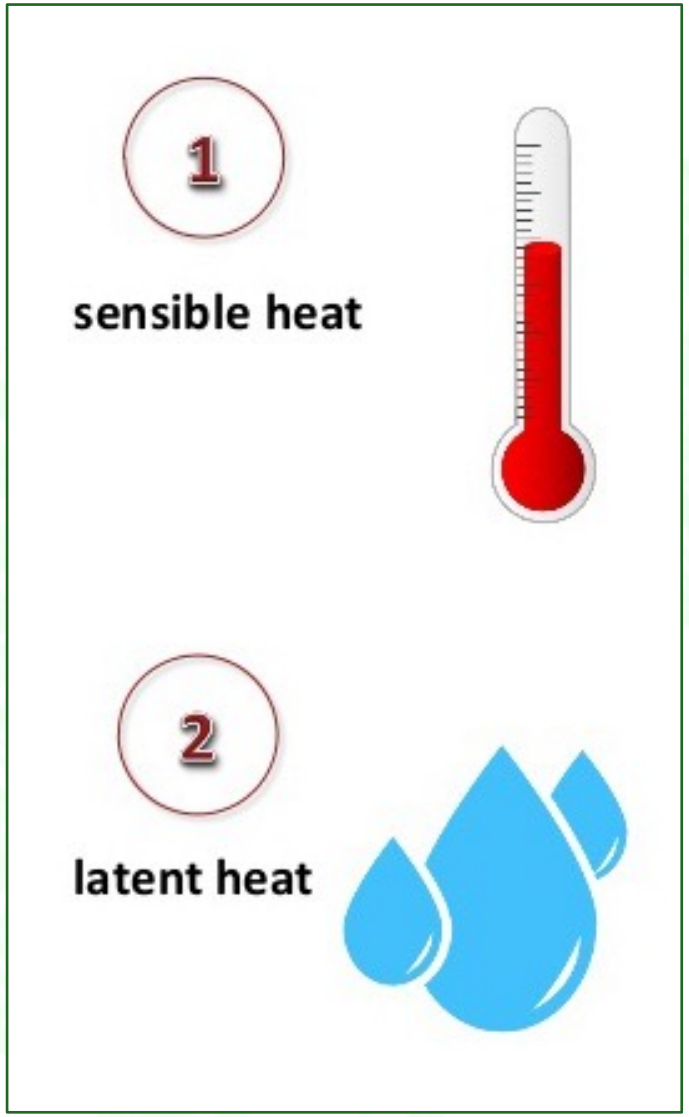
Cooling

- Ventilation of the greenhouse, even by dynamic means, cannot adequately reduce the temperature during the hot period of the year
- High air velocities inside the greenhouse, aiming to reduce temperature, result in excessive increase of perspiration, with negative effects to the plants growth
- Cooling the greenhouse with standard refrigeration equipment (freon, air condition) is excluded due to the large amounts of heat that has to be removed from the greenhouse and the additional installation of systems to avoid air dehumidification.
- Therefore, installation, operation and maintenance costs get too high

Cooling Mechanism

- The cooling mechanism for reducing the temperature and at the same time increasing the relative humidity of the greenhouse is based on the phase transition of water
- Is achieved by evaporating water in the greenhouse and converting a large part of the sensible heat of air into latent heat
- In a greenhouse full of grown plants, this conversion is initially done naturally through evapotranspiration



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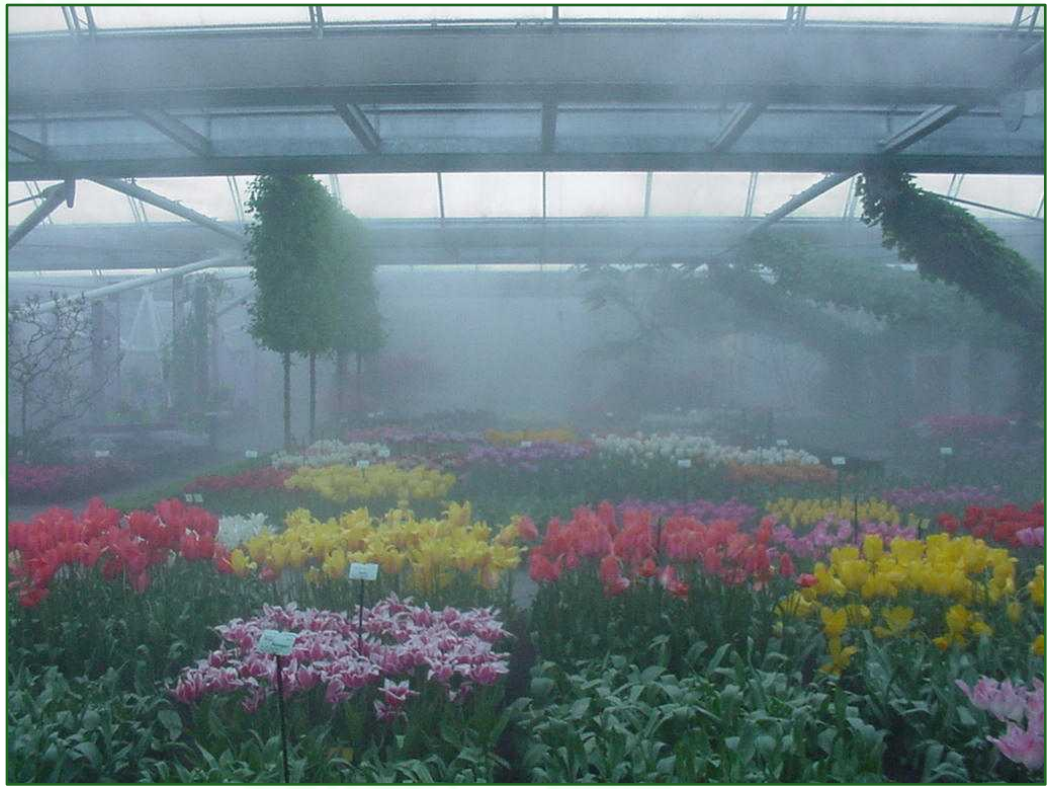
Cooling Systems

- In practice the means used to reduce the temperature inside the greenhouse by water evaporation are:
  - wetting of plants and soil. This method only gives temporary results
  - spraying water in the form of very fine drops in the greenhouse (fog) and at the same time natural ventilation
  - dynamic air flow through wet wall (fan and pad)

Fog Cooling System

- In the fog system, cooling and more air humidity are achieved by spraying water in the form of thin water droplets.
- It is used in small and large greenhouses and is considered the most economical of the automated cooling systems
- It is applied in greenhouses equipped with natural ventilation



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Fog Cooling System

- The water is sprayed in the air above the plant canopy, with high pressures and with sprinklers of usually low flow, 2-3 $^{lit}/_{h}$, one for every 25 m^2 of greenhouse
- They create drops of 5 μm in diameter that evaporate before reaching the surface of the plants
- Constant pressure pumps or turbines are used for the pressure

Fog Cooling System

- This system operates and is efficient, as long as there is low relative humidity, so the windows of the greenhouse should be open.
- The automation system activates the spray when the room temperature exceeds the desired level and stops it when the relative humidity exceeds the specified / desired limit
- Temperature differences of 5-14 °C can be ensured compared to a greenhouse using solely ventilation

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Fog Cooling System

- The water must be of very good quality in order to avoid clogging of the sprayers due to the accumulation of salts.
- Simultaneous operation of the natural ventilation system is necessary during spraying
- In very large greenhouses this system, when properly designed, provides better spatial uniformity of conditions, than those achieved with the system "dynamic ventilation and wet wall" (fan and pad), during the hottest hours of the day.

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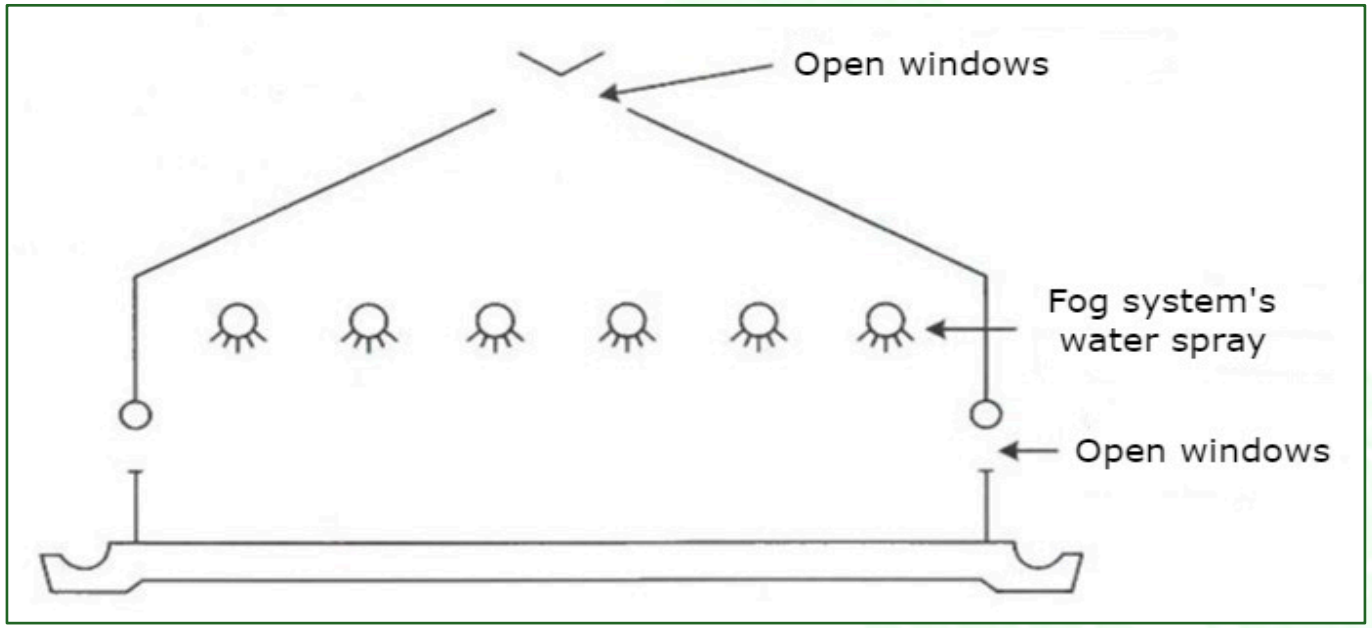
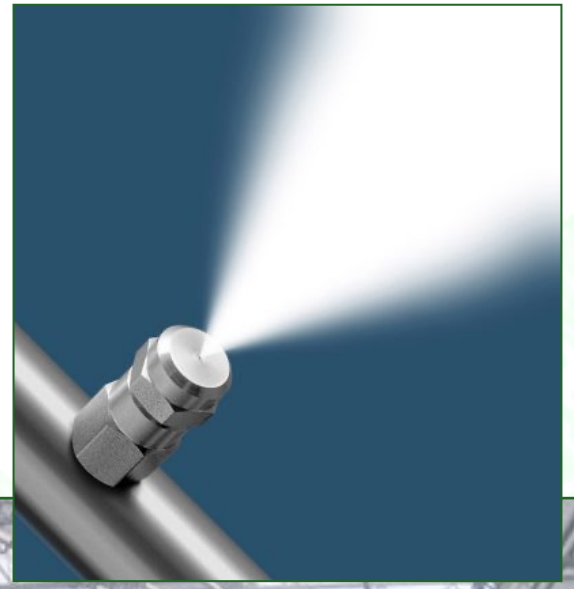
Fog Cooling System



Cooling the greenhouse with fog cooling system

Fog Cooling System



Fog Cooling System

Radiation Intensity Watt * m^{-2}	Outside		Inside Temperature and Relative Humidity		
	Temperature °C	Rel. Humidity %	Natural Ventilation and Shading, T in °C	High-pressure fog system, T in °C	Rel. Humidity in fog system Hr %
146	27,8	71	33,3	24,4	90
324	27,8	85	33,9	27,2	98
360	35,0	40	43,3	29,4	82

Temperatures in a greenhouse with high pressure mist and in a naturally ventilated greenhouse with shading

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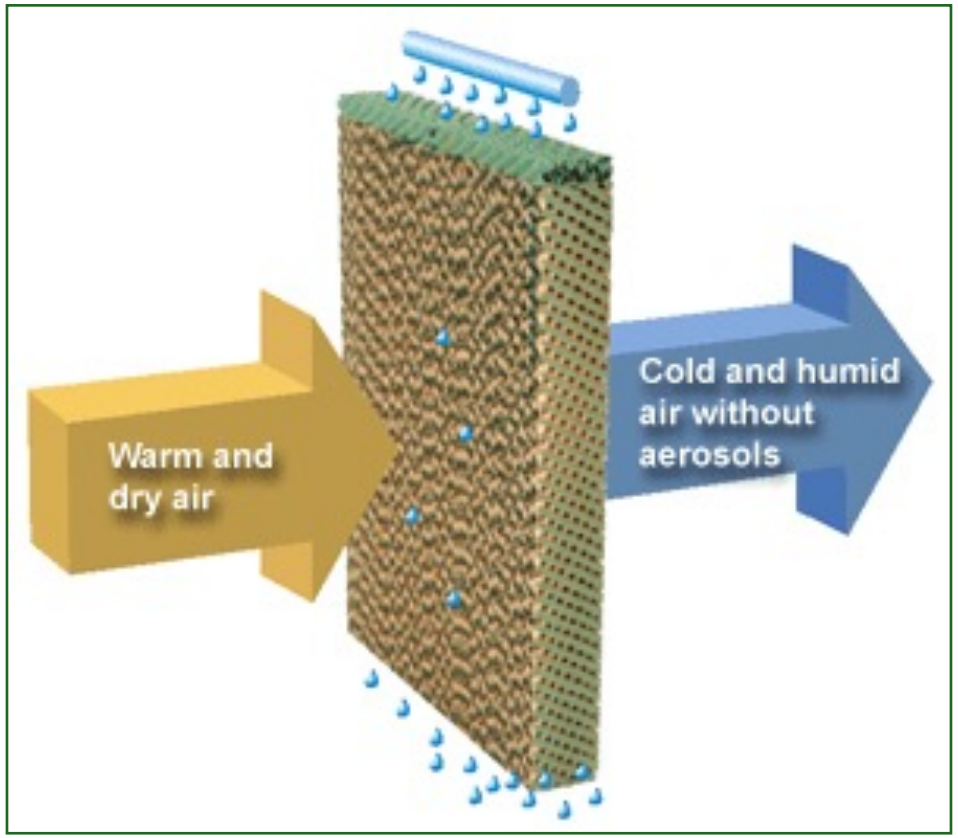
Dynamic Ventilation and “Fan And Pad”

- Low-speed, high-volume fans are used, which absorb the greenhouse air and blow it out.
- The negative pressure created in the greenhouse space forces the outside air to pass through a porous and wet wall, located on the opposite side of the greenhouse.
- This wall is distinguished for its large surface area

Dynamic Ventilation and “Fan And Pad”



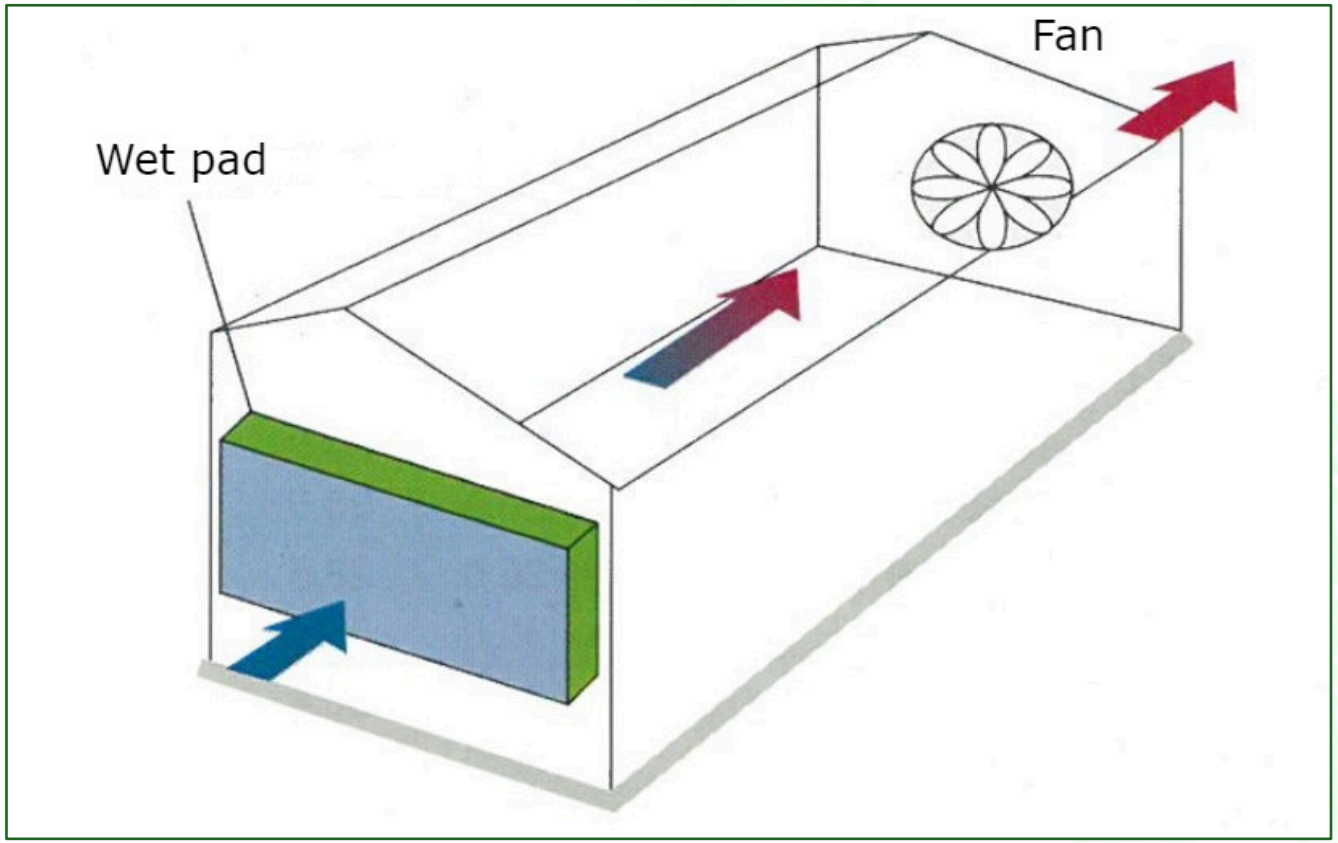
Dynamic Ventilation and “Fan And Pad”

Dynamic Ventilation and “Fan And Pad”

Dynamic Ventilation and “Fan And Pad”

- The outside air, passing through the wet wall, is enriched with moisture and at the same time is cooled by the evaporation of water located on the porous surface (latent heat mechanism)
- Cold air, as it passes along the greenhouse, removes heat from the area of the plant canopy, thus reducing the room temperature by 3-12 °C (inversely depending on the relative humidity of the outside air) compared to a greenhouse with ventilation system only

Dynamic Ventilation and “Fan And Pad”



Dynamic Ventilation and “Fan And Pad”

- During operation of the system there should be no open windows on the walls of the greenhouse, except for the wet wall
- We distinguish systems with placement of fans on the small side (usual case), and systems with placement of fans on the large side The wet sides are always on opposite sides of those of the fans
- Care must be taken to ensure that the wall is evenly moistened throughout the surface and that no dry surfaces or holes are created in the wet wall.

Evaluation of Cooling Systems

Outside Temperature in °C	Cooling system	Inside Temperature °C			
		9 am	11 am	2 pm	4 pm
26,5 – 31,5	Ventilation + wet pad	23,5	25,0	27,0	25,5
	Ventilation	26,5	30,5	35,0	33,5
32,0 – 37,0	Ventilation + wet pad	26,0	28,5	29,5	28,5
	Ventilation	30,0	35,0	38,5	38,0
37,0 – 42,0	Ventilation + wet pad	27,0	30,0	30,8	29,5
	Ventilation	33,0	38,0	45,0	41,0

Average temperatures achieved in greenhouses with dynamic ventilation and “fan and pad” and solely ventilation

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Evaluation of Cooling Systems

Cooling system at mean outside temperature T_e = 25,3°C and Rel. Humidity = 58,4%	Mean greenhouse temperature from 8am – 5pm [°C]	Difference between inside and outside temperature [°C]
Fog system under perforated roof	29,0	+ 4,0
Ventilation and wet pad	23,5	- 2,0
Ventilation and low-pressure fog system	25,5	+ 0,0
High-pressure fog system	25,8	+ 0,5
Ventilation and high-pressure fog system	24,5	- 0,8

Comparison of the different cooling systems efficiency in lowering internal temperature

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