# Air Humidity, Stomata & Transpiration

Condensation on rose plant.

**The plant's water status is the balance of water uptake and water loss. Transpiration (water loss) is influenced by sun, wind, humidity, leaf area, and opening of stomatal pores in the leaves.**

**By ELLY NEDERHOFF**

Most greenhouse crops consist of 85 to 95% of water, with the remaining part being dry matter. Some plant parts (e.g. cucumber fruit) are only 3% dry matter. Water is absolutely vital for plants and has many functions. The more we understand the role of water, the better we can control plant growth. Water provides building blocks for plant tissue, fills plant cells, acts as a transport medium, provides firmness to leaves and cools the plant. Plant water status is the balance of water uptake and water loss. In a greenhouse crop, these are controlled by the grower through irrigation and climate control. Water loss, or transpiration, depends on the weather (sun, humidity, wind), as well as on leaf area and opening of the pores in the leaves (stomata). These stomata open and close very dynamically to regulate the transpiration. After radiation is air humidity, the most important factor that influences transpiration. Humidity is complicated because it has various 'appearances' (relative humidity, vapour pressure, VPD, dew point) and is expressed in various units (%, g/m$^3$, kPa). This article discusses the working of stomata and the effect of air humidity on transpiration. It explains the terminology around air humidity (see *Table 1*), and shows the unit conversion (*Table 2*). In a future article we will discuss how to control air humidity in greenhouses.

**Transpiration**

Leaves exposed to the sun would get overheated if they were not cooled by water evaporating from the leaves. This is transpiration and its main function is cooling the leaves. Transpiration is a passive process, similar to what happens to a layer of water on a concrete floor: when the sun shines the water evaporates. It is actually the sun's energy and not the plant's energy that drives transpiration of plants. It is important that the water transpired from the leaves is replaced immediately by new water to avoid wilting. The replacement water has to come from the root-zone, via root hairs, into the roots, through the vessels and up into the leaves. This stream of water is called the transpiration stream or the xylem flow. This stream also transports nutrients from the roots to the leaves.

**Stomata**

If the roots are not able to supply enough water to the shoot, the leaves dry out. But before the plant shows any visible sign of wilting, the pores in the leaves gradually close. This is an attempt to block the water loss, and protect the plant from wilting. These pores, called stomata, are very dynamic. They can be open or closed or anything in between, and their opening changes continuously. Stomata control the flows of $CO_2$ and water vapour, but they themselves are also controlled by $CO_2$ and water. For example, during drought stress, the pores are fairly closed. This reduces the transpiration. As a consequence these leaves are not cooled so well anymore. If the lack of water uptake continues, the stomata close further, block the transpiration further; the leaves get warmer, and ultimately get 'cooked' and die. With sufficient water uptake, however, plants do perfectly well in high radiation. How much radiation a plant can handle depends on the amount of water that runs through the plant and on other conditions. Plants exposed to high humidity for a long time, get more and bigger stomata.

Stomata respond not only to humidity, but also to light and $CO_2$. A low $CO_2$ level in the greenhouse creates a hunger for $CO_2$. This stimulates the stomata to open wider in order to let more $CO_2$ come in. Light triggers photosynthesis. This consumes $CO_2$ from the space under the stomata. Due to $CO_2$ hunger the stomata open further. Other factors that affect the stomata are light colour, hormonal effects, potassium.

**Water as transport medium**

Water is the vehicle for transport in the plant. Plants are built out of the chemical elements carbon (C), hydrogen (H), oxygen (O) and many mineral elements (N, P, K, S, K, Ca, Mg, Fe, etc.). Water ($H_2O$) taken up by the roots provides the elements H and O, while carbon dioxide ($CO_2$) taken up by the leaves provides C. These building blocks are combined to form assimilates (sugars and other carbohydrates) in the assimilation or photosynthesis process in the leaves. The sugars are carried from the leaves towards the growing organs by the sap flow or 'phloem flow', which is based on water. The minerals taken up by the roots (N, P, K, S, K, Ca, Mg, Fe, etc.) are carried upwards by the transpiration stream or xylem flow, which is also based on water. Furthermore, water delivers amino acids and plant hormones in the plant. So water facilitates all internal transport within the plant.

**Water for growth**

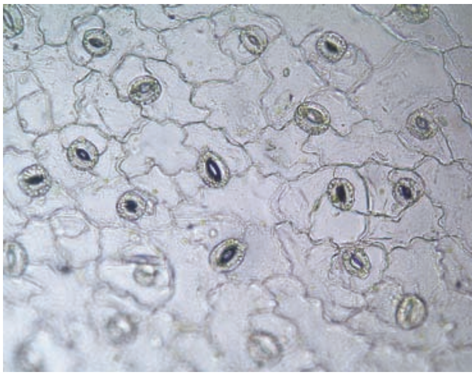
In daytime, water uptake is needed to compensate the water that is lost by transpiration. Also a bit of water is needed for assimilation or photosynthesis, as described earlier. In daytime, tomato fruit don't grow a lot, in fact they can even loose some weight, temporarily, due to water retraction when transpiration is high. At night, however, transpiration is limited because there is no sunshine. Then water is used to replenish and fill new plant cells and to pump up young fruit, such as tomatoes. Thus, at night fruit gain weight. The fact that fruit actually grow at night is not a reason to give a lot of water at night. The fruit only take up what they need, and usually enough water is available in the root-zone.

**Water for turgor**

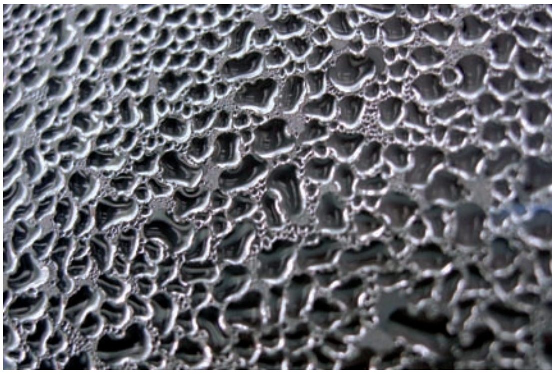
Another function of water is providing firmness to plant cells by putting an outward pressure on the cell walls. This pressure and the firmness are called 'turgor'. Turgid plant cells are pumped full with water and cannot be compressed, like a balloon filled with water. Plant cells that have lost a (small) part of their moisture don't have this turgor anymore and get floppy. This is the case when leaves suffer from water stress (actually 'drought stress' would be a better name). In young cells, turgor stimulates the cells to expand and grow (older cells are not able to grow anymore). If young cells do not experience sufficient turgor pressure, they don't expand very much. Therefore leaves that experience water stress (lack of water) during their growth period generally stay smaller than leaves with normal water uptake and normal turgor.

**Air humidity and water economy**

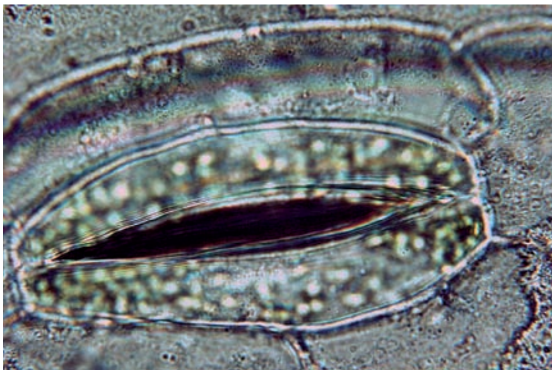
Humidity has a strong effect on the plant water status, in various ways. High humidity restricts the transpiration,



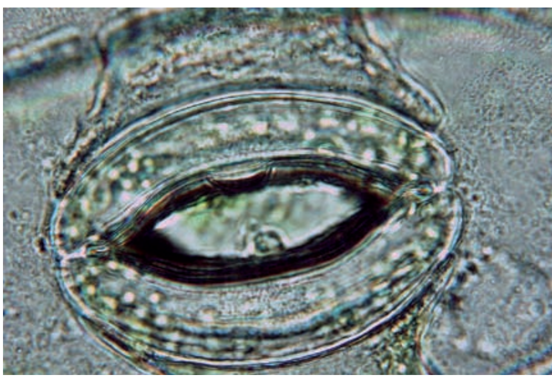
*Stoma open on broad bean leaf. (Image Stephen G. Saupe, Biology Dept, College of St. Benedict/St. John's University; Collegeville, MN.)*



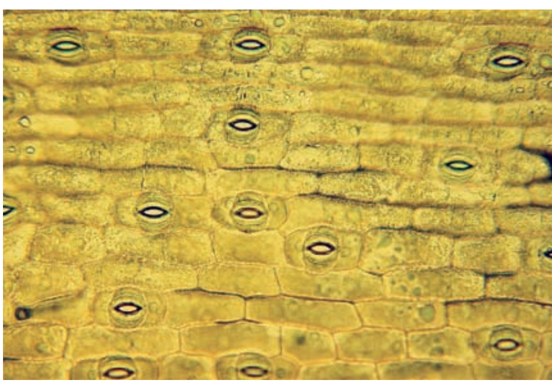
*Close up view of leaf stomata.*



*Stoma closed (image B. Van Meeteren)*



*Stoma open (Image B. Van Meeteren).*



*Many stomata (Image B. Van Meeteren).*

*Fungal disease on capsicum caused by excessive humidity.*


*Water is used to replenish and fill new plant cells to pump up young fruit.*

because very humid air is almost saturated with water vapour and cannot absorb much more. Low humidity stimulates plant transpiration, because dry air draws water from the leaves. If the transpiration increases enough, it may gradually increase the humidity of the greenhouse air too. So, after some time the humidity gets higher, and the rate of transpiration slowly declines. Thus the circle is closed. Air humidity also affects opening of stomata: in low humidity, transpiration increases, which stimulates the stomata to close to prevent water stress.

When transpiration is restricted (e.g. due to high air humidity), the water uptake is low. Therefore transport of nutrients from roots to shoots is restricted too. If the high humidity conditions last for a longer period of time (e.g. a week) then the plants may suffer deficiencies. Especially shortage of calcium in the youngest leaves is very common in those conditions. It is obvious that low humidity stimulates the transpiration. This is good up to a point. At very low humidity the leaves loose so much water that the xylem cannot completely replace the water losses, and thus plants can not maintain turgor in the plant cells. Then the cell walls are not pressed outwards, and the plant cells not stimulated to grow. Therefore, a low humidity for a long period of time generally results in shorter plants and smaller leaf area.

**Relative and absolute humidity**

The most common way of describing air humidity is by 'relative humidity', or RH, expressed on a scale of 0 to 100%. RH of 100% obviously is extremely humid conditions, while for instance RH of 60% or lower indicates dry conditions. RH is a handy measure and growers are used to it, but RH does not say anything about the amount of water in the air, unless the temperature is given. The 'absolute humidity' in g/m3 is a much more informative measure. Some examples may illustrate this.

If in an enclosed space a steamer produces water vapour, the moisture is absorbed by the air (it becomes invisible). This goes well until 'saturation' occurs (i.e. until the air contains the maximum amount of water vapour it can hold). If the steamer then continues to produce water vapour, we see condensation occur (i.e. formation of water droplets on windows and walls). This indicates that the maximum water content, or the 100% RH level was reached.

It is a fact that cold air can hold far less water vapour than warm air, as shown in *Table 1*. For example, air of 30°C can hold 30.4 gram of water vapour per $m^3$ of air ($g/m^3$); air of 20°C can hold not more than 17.3 $g/m^3$, and air of 10°C can hold only 9.4 $g/m^3$. This maximum amount is lower at lower temperature.

Relative humidity (RH) is the percentage of maximum water content at a given temperature. If air of 20°C holds 13 $g/m^3$ (whereas it can hold 17.3 $g/m^3$), the relative humidity is 75% (13/17.3 = 75%). In contrast, if air of 30°C holds 13 $g/m^3$ of water vapour (whereas it can hold a maximum of 30.4 $g/m^3$), it's relative humidity is 43% (13/30.4 = 43%). Note that absolute humidity, RH and temperature go hand-in-hand.

**Dewpoint**

If the absolute humidity (in $g/m^3$) remains equal, but the temperature goes down, the relative humidity goes up. For example, air of 30°C with 13 $g/m^3$ water content has an RH of 43%. If the temperature then drops to 16°C, while the absolute humidity remains 13 $g/m^3$, the RH becomes 100%. This can be seen in *Table 1*. If the temperature drops even further, condensation will occur (i.e. droplets will form). The absolute humidity will decrease and the RH will stay 100%. RH can never be more than 100%. The temperature where condensation occurs is called the 'dewpoint'. It is expressed in °C and is an accurate measure of the water content of the air.

## *Table 1. For conversion of units for air humidity*

RH = relative humidity (%). ABS = absolute humidity ($g/m^3$). VD = Vapour Deficit ($g/m^3$) VPD = Vapour Pressure Deficit (kPa).
1 kPa (kilo-Pascal) = 10 mbar (10 millibar). kPa en mbar are units for Vapour Pressure Deficit.

| temp: | 10°C | 10°C | 10°C | 15°C | 15°C | 15°C | 20°C | 20°C | 20°C | 25°C | 25°C | 25°C | 30°C | 30°C | 30°C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RH | ABS | VD | VPD | ABS | VD | VPD | ABS | VD | VPD | ABS | VD | VPD | ABS | VD | VPD |
| % | $g/m^3$ | $g/m^3$ | kPa | $g/m^3$ | $g/m^3$ | kPa | $g/m^3$ | $g/m^3$ | kPa | $g/m^3$ | $g/m^3$ | kPa | $g/m^3$ | $g/m^3$ | kPa |
| **100%** | 9.42 | 0.00 | 0.00 | 12.86 | 0.00 | 0.00 | 17.33 | 0.00 | 0.00 | 23.09 | 0.00 | 0.00 | 30.43 | 0.00 | 0.00 |
| **95%** | 8.94 | 0.48 | 0.06 | 12.21 | 0.65 | 0.09 | 16.47 | 0.86 | 0.12 | 21.94 | 1.15 | 0.16 | 28.91 | 1.52 | 0.21 |
| **90%** | 8.47 | 0.95 | 0.12 | 11.57 | 1.29 | 0.19 | 15.60 | 1.73 | 0.23 | 20.79 | 2.30 | 0.32 | 27.39 | 3.04 | 0.42 |
| **85%** | 8.00 | 1.42 | 0.18 | 10.93 | 1.93 | 0.26 | 14.73 | 2.60 | 0.35 | 19.63 | 3.46 | 0.48 | 25.87 | 4.56 | 0.64 |
| **80%** | 7.53 | 1.89 | 0.25 | 10.28 | 2.58 | 0.34 | 13.87 | 3.46 | 0.47 | 18.84 | 4.25 | 0.63 | 24.34 | 6.09 | 0.85 |
| **75%** | 7.06 | 2.36 | 0.31 | 9.64 | 3.22 | 0.43 | 13.00 | 4.33 | 0.59 | 17.32 | 5.77 | 0.79 | 22.82 | 7.61 | 1.06 |
| **70%** | 6.59 | 2.83 | 0.37 | 9.00 | 3.86 | 0.51 | 12.13 | 5.20 | 0.70 | 16.17 | 6.92 | 0.95 | 21.30 | 9.13 | 1.27 |
| **60%** | 5.65 | 3.77 | 0.49 | 7.71 | 5.15 | 0.68 | 10.40 | 6.93 | 0.94 | 13.86 | 9.23 | 1.27 | 18.26 | 12.17 | 1.70 |
| **50%** | 4.71 | 4.71 | 0.61 | 6.43 | 6.43 | 0.85 | 8.67 | 8.66 | 1.17 | 11.55 | 11.54 | 1.59 | 15.22 | 15.21 | 2.12 |
| **40%** | 3.77 | 5.65 | 0.74 | 5.14 | 7.72 | 1.02 | 6.93 | 10.40 | 1.41 | 9.24 | 13.85 | 1.90 | 12.17 | 18.26 | 2.55 |
| **30%** | 2.82 | 6.60 | 0.86 | 3.86 | 9.00 | 1.20 | 5.20 | 12.13 | 1.64 | 6.93 | 16.16 | 2.22 | 9.13 | 21.30 | 2.97 |

Fogging can be used to increase humidity.

Condensation indicates the maximum water content, or 100% RH level has been reached.

Plant cells that have lost moisture don't have turgor and become floppy.

Excessive humidity can cause fungal diseases.

Condensation clearly visible on the leaf surface.

Plant damage caused by guttation or water leaking from leaves, mostly at night.

Water uptake is needed to compensate water lost by transpiration.

## Vapour Pressure Deficit (VPD)

Vapour Deficit (VD) and Vapour Pressure Deficit (VPD) are the most suitable units in relation to transpiration control. They both indicate the 'vacant space' (deficit) for water vapour, and also the 'drying effect' of the air, or the driving force on transpiration. A high deficit means there is more vacant space before saturation occurs. Vapour Deficit (VD) can be expressed in g/m$^3$.

Vapour pressure (VP) is the pressure caused by a gas or a vapour. All gases, including water vapour, have a certain pressure. All gases together make up the total air pressure. Vapour pressure of water normally ranges from 1 to 5 kPa (kilo-Pascal), which is the same as 10 to 50 mbar (millibar). Each temperature has a maximum VP of water. If more water is added, condensation occurs (as described for relative humidity). Vapour pressure deficit (VPD) is the difference between the actual and the maximum vapour pressure. For water vapour, VPD is normally in the range 0.1 kPa (very humid) to 1.7 kPa (dry air), or 1 to 17 mbar. Note that a low VPD means a high air humidity, and vice-versa. The higher the VPD the stronger the driving force on transpiration.

## Conversion of units

Relative humidity (RH), absolute humidity (abs.) and Vapour Pressure Deficit (VPD) are important units in horticulture. The table shows the various units at prevailing temperature. For instance at 20°C, 80% RH equals 13.87 g/m$^3$ absolute humidity, and 0.47 kPa VPD. This table can be used for unit conversion.

## Greenhouse air humidity

The starting point of the humidity inside the greenhouse is the humidity of the outside air. On top of that comes the water transpired by the plants. In a greenhouse with an active crop, the absolute humidity is higher than outside, due to this transpiration. But the RH is a different story, because this depends strongly on the temperature. The air temperature is usually (although not always) higher inside the greenhouse than outside. The relative humidity (RH) in the greenhouse can be higher or lower than outside, depending on the temperature. Important is that greenhouse air has a higher absolute humidity, so a higher water vapour content than the outside air.

## Humidity control

Nothing in greenhouse climate control is so complicated as controlling air humidity. Transpiration influences air humidity, but in turn, air humidity influences transpiration. Thus, controlling air humidity is a battle, and sometimes it's virtually impossible to achieve the desirable air humidity. All a greenhouse operator can do is adjust air humidity and try to avoid extremes. Even when a grower really understands everything about humidity, it is still not easy to decide which humidity level should be targeted in the control. That depends on what the grower wants, plant requirements, weather, availability of equipment for heating, venting, fogging, and energy input. This will be discussed in a future article.


***About the author***

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## *Table 2.*

**Absolute (air) humidity:** humidity in gram water vapour per m$^3$ air. Conversion to relative humidity (RH) can only be made when the temperature is known. For instance 9.4 g/m$^3$ at 10°C equals 100% RH, while at 20°C it equals 54% RH, and at 30°C it equals 32% RH (see *Table 1*).
**Boundary layer:** thin layer of air and water vapour close to the leaf surface.
The boundary layer resistance is a barrier for transpiration. It's effect is reduced by air movement (wind).
**Condensation:** transition of water vapour to liquid water.
Water vapour condensates on glass or leaves that are cold (below the dew point).
**Conductance (opposite of resistance):** 'ease' with which water flows through a barrier. When leaf pores are wide open, the resistance for water vapour to go out is low and the conductance is high.
**Conductivity, conductivity factor (CF):** concentration of mineral salts in water (in hydroponics).
**Deficit:** shortfall, gap between actual and maximum of something.
**Dew point:** indication for air humidity, but it is expressed as temperature. Below this temperature, water vapour will condensate (e.g. air with 17.33 g/m$^3$ has a dew point of 20°C, thus below 20°C, water would condensate).
**Evaporation:** transfer of water vapour from a wet surface or from the soil to the air.
**Evapotranspiration:** transfer of water vapour from soil and plants to the air.
**Guttation:** water leaking from leaves, caused by high root pressure, mostly at night.
**Humidity:** dampness, amount of water vapour in the air, can be expressed in many ways and various units.
**Osmosis, osmotic potential:** pressure in water (or in plant sap) caused by salts.
The more salts in the plant sap, the higher the water pressure in that plant.
**Resistance:** strength of hindrance for water flowing through a barrier. For instance, when leaf pores are closed they are a strong resistance for transpiration.
**Transpiration:** transfer of water vapour from a plant to the air. Transpiration has two effects: cooling the leaves during sunshine and internal transport of nutrients.
**Relative humidity (RH):** humidity in % of maximum humidity at a given temperature.
At 20°C air can hold 17.3g of water vapour per m$^3$ at maximum. If it holds only 13 g/m$^3$ at 20°C, the relative humidity is 75 %.
**Relative water content (RWC):** water content in % of maximum water content.
**Root pressure:** strength with which the roots press water upwards to the shoots. This mechanism cause water uptake at night, while at daytime transpiration is the driving force.
**Saturation:** situation of being completely filled: filled to the maximum (with water).
**Saturation deficit:** a measure of air humidity: difference between actual and maximum vapour content (e.g. in gram water per m$^3$ air).
**Specific humidity:** water content of air in kg water vapour per kg dry air.
**Stoma (stomata):** pore (pores) in the leaf surface that let water vapour out and $CO_2$ gas (carbon dioxide) in, and thus influence the transpiration and photosynthesis.
**Stomatal conductance:** ease with which water vapour can pass the leaf pores.
**Stomatal resistance:** strength of hindrance to water vapour by the leaf pores.
**Transpiration:** loss of water (vapour) from plants (leaves), driven by sunshine, wind, humidity.
**Turgor:** pressure of plant cell walls to hold water.
**Vapour deficit:** saturation deficit, or vapour pressure deficit (VPD). Deficit is gap between actual and maximum.
**Vapour pressure:** pressure caused by a gas or a vapour. It normally ranges from or 1 to 5 kPa or from 10 to 50 mbar.
**Vapour pressure deficit (VPD):** difference between actual and maximum vapour pressure, normally in the range 0.1 kPa (very humid) to 3 kPa (very dry air), or 10 to 30 mbar.
**Water potential of a plant:** water content expressed in units of energy or pressure.
**Water uptake:** the amount of water taken up by the plants for transpiration and for plant growth.
**Water stress (drought stress):** shortage of water in the plant, leading to wilting.
**Water status:** condition of the plant in terms of water content.