A CONVIRON COMPANY

Understanding and Using VPD

Argus Application Note

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INTRODUCTION

This application note is intended as a guide for users of Argus systems in understanding VPD (Vapor Pressure Deficit) and its uses in climate control applications. VPD measurements can provide an indication of the current evaporation potential of the air, and as such can be useful in environmental control applications for horticulture.

The Argus system can calculate VPD on any temperature sensor screen with the addition of a representative humidity sensor reading. VPD readings can be used in applications where indications of the current or accumulated plant evaporation potential are required. It is particularly useful:

- As an indicator of crop stress that can be used to drive control decisions to shade, cool, or heat the crop in order to ***modify*** this stress
- As a component of irrigation management to ***satisfy*** the water loss that is predicted by this stress indicator

VPD measurements can also be used for other purposes such as:

- Predicting the evaporation rate for other processes such as crop drying
- Regulating fog or mist delivery. For example: when the VPD is high, a fog nozzle can be left on for longer pulses without wetting the crop or the ground since the fog will evaporate before it has time to contact solid surfaces. The fog pulse can be initiated by some other threshold value, and then ***moderated*** with VPD to compensate for the ability of the air to absorb the moisture evaporating from the fog particles.

VPD alone does not provide a perfect model of plant water stress, and there has been a tendency in the past to rely too heavily upon calculated VPD alone for irrigation and environmental control purposes. However, if the measurements for calculation of VPD are taken in a manner that provides an accurate representation of the current crop conditions, and this information is then applied in an equally careful manner, it can be used to influence key environmental control management decisions.

VPD is only one method of approximating plant water stress. The Argus system offers a range of measurement and control options to meet the demands of our customers including a complete Evapotranspiration Model for use in outdoor crop applications. Other irrigation and climate decision strategies or a combination of strategies may be more suitable for many crops. If you require more information on using VPD calculations with your control system please contact Argus. Our contact information is listed on the back page of this document.

What is VPD?

VPD stands for **Vapor Pressure Deficit**. To understand VPD we must first understand the concept of **vapor pressure** and how it relates to humidity. Most of us are familiar with the concept of **relative humidity**. It is the ratio of actual water in the air to the theoretical saturation point at the current air temperature, expressed as a percentage. The **saturation point** is the maximum amount of water vapor that an air mass can hold at a given temperature and pressure. Anything in excess of the saturation point will condense out as liquid water. Therefore, whenever you see condensation or 'dew' on the surface of an object, it indicates that the air immediately surrounding that surface has become cooled to below its saturation point, causing some of the water vapor to condense into its liquid form. The saturation point is also called 'dew point'.

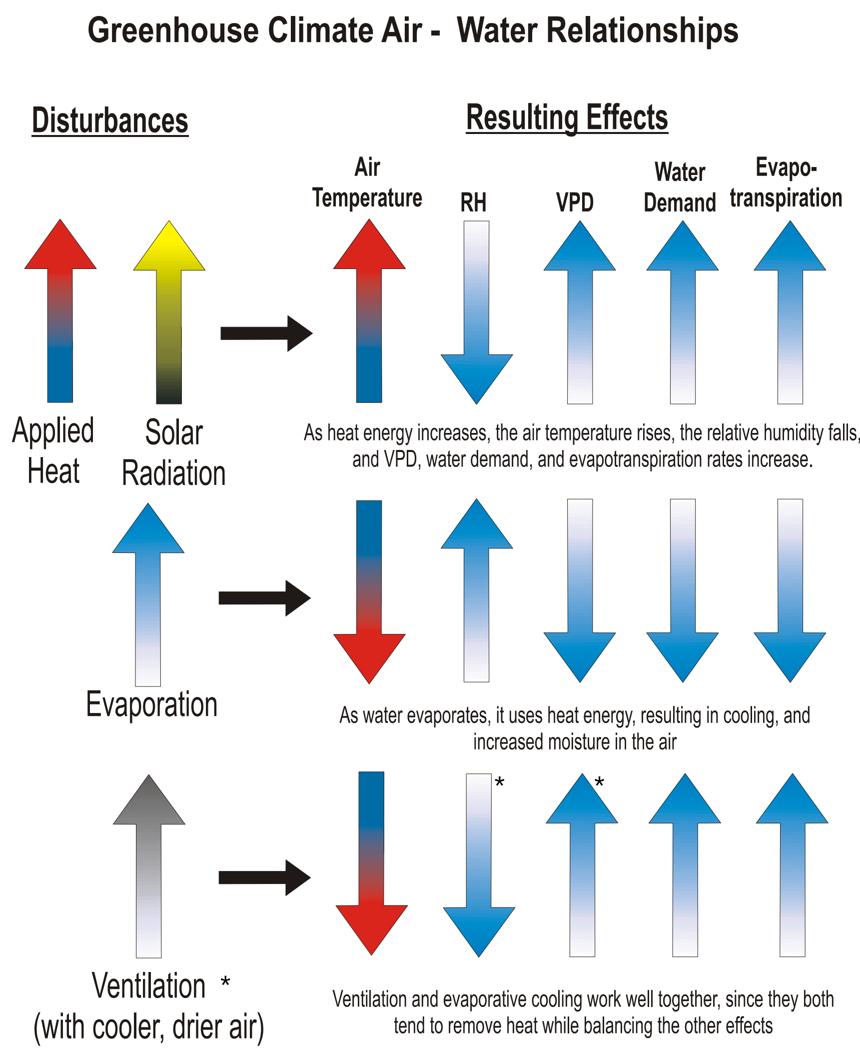
What does pressure have to do with humidity? Vapor pressure is a different way of thinking about humidity. Air typically contains about 1-4% water vapor. All gasses in the air exert a pressure. The combination of theses gasses including water vapor produce a pressure at sea level of about 1013 mb (14.7 psi). Within this total, water vapor pressure accounts for about 2 mb (millibars) under extremely dry and cold conditions to about 42 mb of pressure at 30ºC and 100% relative humidity.

Vapor Pressure Deficit or **VPD** is a measure of the *difference* (or deficit) between the pressure exerted by the moisture currently in the air and the pressure at saturation. VPD units are most often expressed in standard pressure units such as millibars, kilopascals, or pounds per square inch. VPD is sometimes expressed in mass deficit concentration units such as grams of water per cubic meter of dry air, or grams of water per kilogram of dry air. The Argus system uses millibars as the default measurement unit although other measurement units can be configured.

Why not just use Relative Humidity? In many situations you can. At any fixed air temperature and pressure, there is an excellent inverse relationship between RH and VPD. For this reason, many growers simply use RH values for the same purposes with good results. However, if the air temperatures change significantly, VPD can provide a more accurate indication of the current evaporation potential since it combines the effects of both temperature and humidity into a single value.

Greenhouse Air-Water Relationships

A full explanation of the complex relationships between solar radiation, plants, air, and water vapor would require examination of thermodynamics, the gas laws, and the properties of the psychrometric chart, not to mention the biochemical and morphological properties of the plant. Without resorting to that, the following diagram attempts to illustrate the general effects disturbances such as applied heat, solar radiation, evaporation, and ventilation will have on other climate parameters.



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* **Note:** Ventilation alone may not always decrease the ***relative*** climate humidity, depending on the amount of moisture in the incoming air, and how much the climate air temperature is decreased. However, in greenhouses, ventilation for humidity control is usually combined with reheating to the target setpoint, resulting in a net reduction in the relative humidity

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Whenever the relative humidity increases the VPD value decreases. Although the two are related, VPD measurement is somewhat superior to relative humidity measurement in certain applications since it ***combines*** the effects of temperature and pressure into a single value. For example, under certain conditions, a plant may experience ***more*** water loss on a warm day with High RH than on a cool day with low RH.

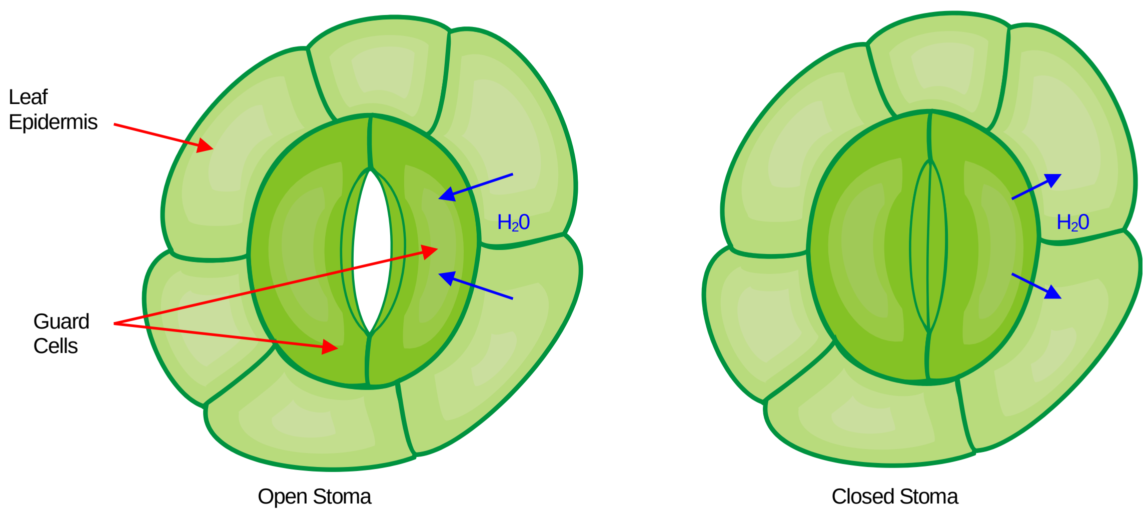
VPD is a good indicator of plant stress brought about by either excessive transpiration (high VPD values) or the inability to transpire adequately (low VPD values).

While plants are affected by changes in the surrounding air mass, they can also actively affect this same air mass. Whenever plants increase their own rate of transpiration a local decrease in the VPD will occur as the surrounding air absorbs this evaporated moisture. There is also an associated cooling effect as the process of water evaporation absorbs a lot of heat. This cooling will further reduce the water holding capacity of the air mass and thus lower the VPD value.

A mature crop with a full leaf canopy can handle most of the cooling load in a greenhouse. To witness this, just stand in an empty greenhouse on a hot sunny day (under full venting) and then stand in one filled with plants. The one filled with plants will be several degrees cooler and the VPD will be lower. In this situation, the primary purpose of the ventilation system is to bring in ***dryer*** air to allow the evaporation process to continue; not to bring in ***cooler*** air to cool the greenhouse through sensible heat transfer.
This is the main cooling mechanism used in 'semi-closed' greenhouse designs. The reduction in ventilation requirements saves operating costs and also facilitates insect exclusion (less insect screen required) and improves CO2 enrichment efficiency (less CO2 losses)

VPD and Plant Stress

Plants absorb CO_2 and evaporate water into the atmosphere via the leaf stomata. Guard cells surrounding each stoma open and close to regulate the amount of water evaporation and gas exchange.



In the above diagram, as water moves into the guard cells the stomata open allowing gas exchange and transpiration. Whenever water moves out of the guard cells, they collapse, closing the opening.

The opening and closing mechanism is controlled by water pressure within the guard cells. Pairs of guard cells are joined at the ends and when they inflate with water, they bow outward leaving a hole like the middle of an inflated inner tube. When the guard cells lose water, they collapse together, closing the opening. In this manner, the stomata will naturally tend to be closed whenever the plant is under water stress due to drought, heat, or low humidity.

The stomata will also close in the daytime whenever the plant is losing too much water to maintain the turgidity of the guard cells. This action helps the plant reach its primary objective of reducing water loss. However, it consequently reduces or stops photosynthesis and allows leaf temperatures to rise as the plant tries to preserve its water balance and prevent permanent wilting.

CO_2 also affects the opening amount. High CO_2 levels will cause the stomata to close. The stomata are normally opened in the daytime during photosynthesis since the leaf air spaces tend to be starved of CO_2.

This enables CO_2 to be absorbed from the surrounding air. The stomata typically close at night due to high levels of CO_2 in the leaf air spaces, since photosynthesis has stopped while respiration continues, flooding these spaces with internally produced CO_2.

VPD Does Not Measure Plant Stress!

Remember, **VPD is not an actual measurement of plant stress or water loss**, it is only an indirect indicator. VPD alone can't tell you if your crop is currently 'happy' or wilting due to underlying problems such as root disease or acclimatization issues.

VPD Does Not Measure Plant Water Use!

VPD can only tell you about the ***potential*** for water to evaporate from the leaves. There are several other factors that affect water transport including salinity in the rooting media, root health, and whether the leaf stomata are opened or closed. Although the actual rate of water loss is not directly proportional to VPD, there is a general relationship.

It ***can*** tell you whether the crop is experiencing drying conditions and you can then make some assumptions based on this. However, the actual rate of water movement through the plant is controlled by three major contributing factors, and VPD has a role in only the first one:

1. **Transpiration losses** caused by the leaf (stomata) responses to the immediate surrounding environment. Contributing factors include: VPD, temperature, solar radiation, wind speed, and CO_2 levels.
2. **Water availability and water uptake**. This is affected by soil water availability, salinity (osmotic pressure) and root system structure and health.
3. **Transport mechanisms** between the "root and the shoot" including the structure and health of the vascular system.

VPD Too Low

- When the VPD is too low (humidity too high) plants are unable to evaporate enough water to enable the transport of minerals (such as calcium) to growing plant cells, even though the stomata may be fully open. Therefore, a VPD target threshold can be used to influence ventilation and/or heating equipment used to increase the VPD by reducing the air moisture level.
- In cases where the VPD is extremely low, water may condense out of the air onto leaves, fruit, and other plant parts. This can provide a medium for fungal growth and disease.
- Under low VPD conditions, some plants may even exude water from their leaf cells in a process called guttation.
- When plants are unable to evaporate water, excessive turgor pressure within the cells can cause splitting and cracking of fruits such as tomatoes.
- In cases where the VPD alternates between too high and too low, fruit quality can be adversely affected by 'shrink cracks' in the skin as the turgor pressure alternately expands and contracts the water-filled cells in the fruit.

Most of these conditions are detrimental.

VPD Too High

When the VPD is too high (humidity too low) the rate of evaporation from the leaves can exceed the supply of water into the roots. This in turn will cause the stomata to close, and photosynthesis to slow or stop. Once the stomata close, the leaves are at risk of high temperature injury since evaporative cooling is reduced due to the lack of water to evaporate

To avoid injury and death from wilting, many plant species will either curl their leaves or orient them downward in an attempt to expose less surface area to the sun. This can significantly downgrade the quality of potted and foliage plants and can also reduce the growth rate and quality of vegetable crops.

What is the Ideal VPD Range?

The ideal VPD range varies with the crop species and the stage of growth. The table below indicates VPD values in millibars at various temperatures and humidity levels. Although the values do not change, the ***interpretation*** of the numbers will vary for each crop species, the stage of growth, cultivation methods, crop acclimatization, and local conditions. We have arbitrarily selected the green shaded area (approximately 5.0 to 12.0 mb) as being ideal for an imaginary crop. The yellow areas indicate an acceptable but marginal VPD range and the red areas are either too high or too low. Again, you need to make your own interpretations for your crops.

		Relative Humidity													
ºC	ºF	100%	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%	45%	40%	35%
15	59	0.0	0.8	1.7	2.5	3.4	4.2	5.1	5.9	6.8	7.6	8.5	9.4	10.2	11.1
16	60.8	0.0	0.9	1.8	2.8	3.7	4.6	5.5	6.4	7.3	8.2	9.1	10.0	10.9	11.8
17	62.6	0.0	1.0	2.0	2.9	3.9	4.9	5.8	6.8	7.8	8.8	9.7	10.6	11.6	12.6
18	64.4	0.0	1.0	2.0	3.1	4.1	5.1	6.2	7.2	8.2	9.3	10.3	11.3	12.4	13.4
19	66.2	0.0	1.1	2.2	3.3	4.4	5.5	6.6	7.7	8.8	9.9	11.0	12.1	13.2	14.3
20	68	0.0	1.2	2.4	3.5	4.7	5.9	7.0	8.2	9.4	10.6	11.7	12.8	14.0	15.2
21	69.8	0.0	1.2	2.4	3.7	4.9	6.2	7.4	8.6	9.9	11.1	12.4	13.7	14.9	16.1
22	71.6	0.0	1.3	2.6	3.9	5.3	6.6	7.9	9.2	10.5	11.9	13.2	14.5	15.8	17.2
23	73.4	0.0	1.4	2.8	4.2	5.6	7.0	8.5	9.9	11.3	12.7	14.1	15.4	16.8	18.2
24	75.2	0.0	1.5	3.0	4.5	5.9	7.4	8.9	10.4	11.9	13.4	14.9	16.4	17.9	19.4
25	77	0.0	1.6	3.2	4.8	6.4	8.0	9.5	11.1	12.7	14.3	15.9	17.4	19.0	20.5
26	78.8	0.0	1.7	3.4	5.1	6.7	8.4	10.1	11.8	13.4	15.1	16.8	18.4	20.1	21.8
27	80.6	0.0	1.8	3.5	5.3	7.1	8.9	10.7	12.4	14.2	16.0	17.8	19.6	21.3	23.1
28	82.4	0.0	1.9	3.8	5.7	7.6	9.5	11.4	13.3	15.1	17.0	18.9	20.7	22.6	24.5
29	84.2	0.0	2.0	4.0	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0	22.1	24.1	26.1
30	86	0.0	2.1	4.2	6.4	8.5	10.6	12.7	14.8	17.0	19.1	21.2	23.3	25.4	27.5
31	87.8	0.0	2.2	4.5	6.7	9.0	11.2	13.4	15.7	17.9	20.2	22.4	24.6	26.9	29.1
32	89.6	0.0	2.4	4.7	7.1	9.5	11.9	14.2	16.6	19.0	21.3	23.7	26.1	28.4	30.8
33	91.4	0.0	2.5	5.0	7.5	10.0	12.5	15.0	17.6	20.1	22.6	25.1	27.6	30.1	32.6
34	93.2	0.0	2.7	5.3	8.0	10.6	13.3	15.9	18.6	21.2	23.9	26.5	29.2	31.8	34.5
35	95	0.0	2.8	5.6	8.4	11.2	14.0	16.8	19.6	22.4	25.2	28.0	30.8	33.61	36.4

You can think of these VPD numbers as an indication of the current **evaporation potential**. As the number increases so does the evaporation potential. Remember, this may not correspond exactly to the actual rate of water loss, particularly in extremely high VPD conditions.

Notice that **VPD can potentially provide a better indication of the evaporation potential than RH**. For example, as the temperature climbs from 15 to 35 ˚C at a constant 75% RH, the VPD will range from a bit on the low side (4.2) to too high (14). Since this digression is much less noticeable when the crop temperature only varies over a few degrees, it allows many growers to produce fairly good results using just RH measurements.

However, even in these cases it may be possible to improve crop performance and/or reduce energy costs through the tighter management that is possible by using VPD measurements directly.

Note: Low VPDs may be acceptable for short periods of time such as the early morning hours when the plant is not actively photosynthesizing ***provided*** there are no problems with condensation on plant or greenhouse surfaces, or guttation on leaves. Likewise, short periods of high VPDs may be OK if the plant is healthy and well supplied with water.

How Argus Measures VPD

The Argus system will calculate the VPD for any temperature sensor linked to a representative humidity sensor reading.

To measure the actual leaf VPD, you would need to accurately measure the temperature of the leaf tissue. While not impossible, this is seldom practical, since leaf temperatures can vary wildly throughout a crop as some leaves are in shade and others in full sunlight. This makes it very hard to find a representative leaf to measure.

Leaf temperature sensors are also more prone to accidents and dislodging. ‘Artificial leaves’ have also been tried, but since they don’t transpire water at the same rate as the leaves, we feel they are not as accurate as simply using a representative air sample from the crop canopy.

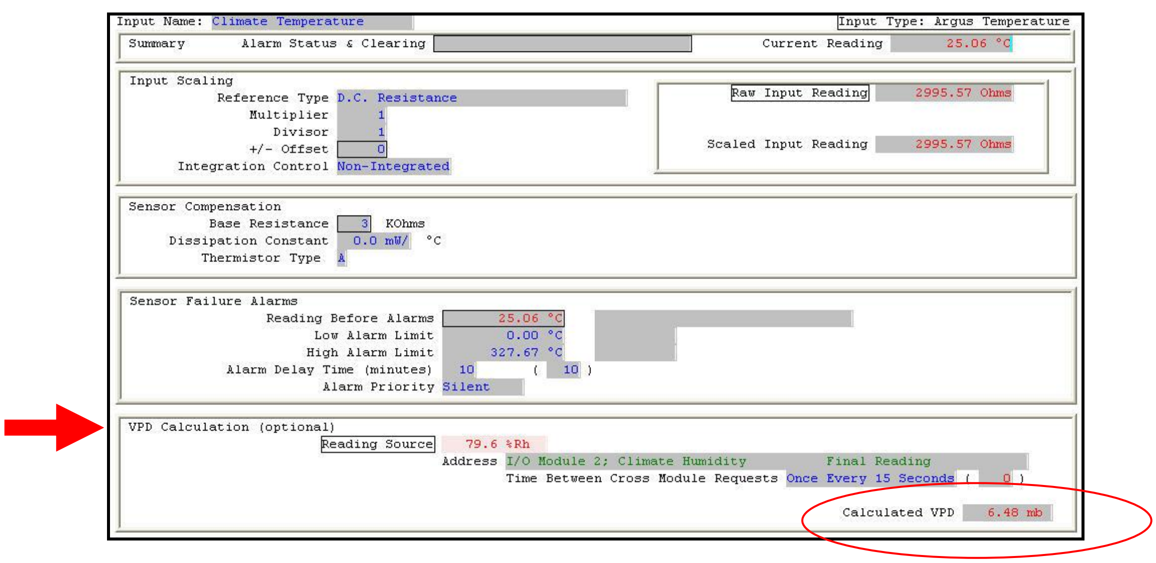
For stress indication and humidity control purposes, the point is not to measure the actual leaf VPD to within strict tolerances, but to gain an insight into how the current temperature and humidity surrounding the crop is affecting the plants. The air temperature and humidity near the leaves, as measured by a properly positioned aspirated sensor module suspended within or as close as possible to the crop canopy is usually sufficient to provide a good indication of the actual leaf VPD.

This is because both the air temperature and humidity in this vicinity are the integrated effects of external influences such as heat loss and gain by the greenhouse structure, evapotranspiration cooling occurring on the leaves and soil surfaces, and the actual temperature of nearby objects such as leaves and other plant surfaces. As such, they can provide a good approximation of the leaf VPD.

To calculate the current VPD, the Argus system normally uses the climate temperature reading and the climate humidity reading from an aspirated sensor module that is **properly positioned in the crop**. Our first choice is to use these sensors since they are already installed in most applications and they can provide reasonable approximations of leaf surface VPDs, saving the cost of purchasing and installing additional sensors.

However, if your application requires an actual leaf or leaf surrogate temperature measurement, this can be easily accomplished since **VPD calculations are available on any temperature sensor screen as well as in the Math Matrix program**. For example, an infra-red remote leaf temperature sensor could be used when coupled with a humidity sensor measuring the air moisture content at the same location.

If you are already measuring temperature and humidity in the zone, then a VPD calculation is available for use on each temperature sensor screen:



By simply designating a suitable humidity sensor as the Reading Source the system automatically calculates the current VPD in millibars (mb) using the air moisture content information provided by the selected humidity sensor.

Note: This calculation relies on the assumption that the air moisture content as measured by the humidity sensor at one location is a reasonable approximation of the air moisture content at *all* temperature sensors that use its reading to calculate local VPD values. Be aware that local influences such as the proximity to heavily transpiring leaves, mist or fog nozzles, or outdoor vents may produce significant differences to the local air moisture content, contributing substantial errors to this calculation. The best solution is to always use a nearby RH sensor that is truly measuring local conditions.

Using VPD Values

The successful use of VPD calculations depends upon good representative measurements, careful application of this information in control programs, and tuning the control response based on your observations. There are several things you can do with this information. Here are some ideas:

Data Recording

You can record and view the VPD values in the Argus Graph. This will give you a good day-to-day indication of the relative rates of evaporation. This data informs many growing decisions and may help when diagnosing crop problems. Decisions on crop spacing, pruning or de-leafing might in part be based on recorded VPD information.

Accumulation/Event Recording

Daily VPD totals can also provide a good summary of the total ‘evaporation potential’ from day to day.

Alarms

You can establish high and low management alarm thresholds to warn you whenever the VPD is beyond the limits you set. This may indicate that adjustments are needed to irrigation, heating, cooling, humidification, or dehumidification equipment.

VPD Control

Although VPD can indicate whether the current evaporation stress on the plants appears to be too high or low, it can’t tell you the reason, since the effect is a combination of temperature and humidity.

Therefore**, using VPD for direct feedback control of temperature or humidity is not usually practical.** However, you can still use VPD to **influence** climate management strategies, and as the basis for operating humidification equipment such as fog and mist systems. On Argus Titan control systems, you can enter a range of VPD setpoints in either the Diurnal Setpoints or the Multi-Day Setpoint Schedules to adjust the control points for VPD throughout the day or the crop cycle.

Controlling High VPD

In high VPD situations, you can use the current VPD reading to directly operate sprinklers, fog, or misting equipment to add water vapor to the air while simultaneously cooling the air through evaporation. Both these effects will reduce VPD values and evaporation stress in the crop. Any consequential air temperature or relative humidity changes will be looked after by your standard temperature and humidity climate control strategies.

A misting program based on VPD is capable of regulating the on time of the fog or mist nozzles to provide the maximum amount of water for evaporative cooling and VPD setpoint control while minimizing plant and soil wetting.

Controlling Low VPD

In situations where the VPD is too low, moisture must be removed from the air or the air moisture holding capacity must be increased through a rise in temperature. Moisture removal can be accomplished directly through the use of de-humidifiers (not common) or by replacing the moist air with drier air (typically through ventilation). The need for this is normally established using relative humidity measurements alone, and it is the standard practice for avoiding direct condensation onto crop or greenhouse surfaces.

However, to alert you to possible problems with guttation or low water transpiration rates, VPD is an excellent ***additional*** indicator. Notice from the table on page 10 that at a constant 75% RH, it is possible for the VPD to be high, ideal, or low depending on the current temperature!

SUMMARY

In conclusion, VPD can be a useful tool for assessing the evaporation potential in the crop and for monitoring conditions that produce evaporation stress. With careful observation and application, it can also be used to drive automatic equipment control processes.

However, ***VPD is just an indicator. It is not a direct measurement of plant water transport or the current evaporation rate.***

When implementing any equipment control strategy based on VPD:

1. Evaluate how effective it will be in the given application.
2. Make sure that the measured temperature and humidity readings used to calculate VPD are representative of the crop conditions.
3. Use data recording and alarms to monitor VPD readings and any resulting control actions. Use this information to inform crop production decisions. Make sure you are getting the expected results.
4. Carefully observe the crop over time and tune the control response as necessary.

USEFUL MEASUREMENTS AND CONVERSIONS

1 atmosphere	= the standard value for air pressure at sea level
	= 14.696 psi (sea level)
	= 1.033 kilograms per square centimeter (kg/m2)
	= 1013 millibars (mb)
	= 101.3 kilopascals (kpa)
	= 760 millimeters of mercury (mm Hg)
	= 29.92 inches of mercury (in. Hg)
1 millibar	= .001 bar
	= 100 Pascals
	= .1 kilopascals
	= 0.750 mm Hg
	= 0.750 torr
	= 1000 Newtons/square meter
	= 1000 Pascal
	= 0.0145 psi

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