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VPD_{leaf} vs. VPD_{air} - Two different ways to determine VPD

Moisture content in the air is an important environmental variable for plant production systems. There are different variables to express the moisture content in air, including relative humidity (RH) and dewpoint temperature. In addition, we use "VPD" to evaluate the moist air when the plant response is the concern. However, there are some confusions about the definitions and calculation methods of VPD.

VPD is often spelled out as (water) **v**apor **p**ressure **d**eficit, which represents the difference (deficit) between the amount of moisture in the air and how much moisture the air can hold when it is saturated. For this reason, it is also referred to as the water vapor pressure saturation deficit. Levels of moisture in the air are often measured using partial pressure of water vapor (i.e., water vapor pressure). VPD is recommended for use in climatology and ecology because it has a linear relationship with evapotranspiration under otherwise identical conditions (e.g., Anderson, 1936). Anderson (1936) recommended reporting VPD instead of relative humidity in ecology studies. In these literatures, VPD is clearly defined as the physical absolute quantity of moist air, independent from the status of the plant (for example its leaf temperature).

Using the leaf temperature, instead of air temperature, to determine the saturation water vapor pressure has been also used widely as another method to calculate the VPD (e.g., Faust, 2017). I do not know who first defined VPD with leaf temperature. But it is an extended definition of VPD to solely consider the transpiration from plant leaves. This approach makes sense for CEA (controlled environment agriculture), but when the VPD can be calculated in two different ways, it can be confusing. Leaf temperature can be different by several degrees from air temperature, and consequently, VPD values can be largely different depending on temperatures used for computing VPD. For example, when the air temperature is 20 °C (68 °F) with a relative humidity of 60%, and the leaf temperature is 18 °C (64 °F), VPD is 0.94 kPa using the air temperature for the calculation, and 0.66 kPa using the leaf temperature (Table 1).

Table 1. Example vapor pressure deficit calculated based on the air temperature (VPD_{air}) or on the leaf temperature (VPD_{leaf}) for saturation water vapor pressure.

Air temperature	Relative humidity	Leaf temperature	VPD_{air}	VPD_{leaf}
20 °C (68 °F)	60%	18 °C (64 °F)	0.94 kPa	0.66 kPa
20 °C (68 °F)	60%	22 °C (72 °F)	0.94 kPa	1.24 kPa

Vapor pressure difference - VPD_{leaf}

For single leaves, the transpiration rate is proportional to the difference between moisture concentration (water vapor pressure) in the leaf's internal airspace (i.e., stomatal cavities) and the surrounding air. This is because moisture moves by diffusion. These internal airspaces of the leaf are considered as nearly 100 % saturated with moisture (i.e., 100 % relative humidity). Therefore, in VPD calculation by using leaf temperature to determine the saturation water vapor pressure, the driving force of transpiration (diffusion of water from the leaf to the surrounding air) can be well represented. However, these values are "difference" in water vapor pressure between two points (leaf and air) rather than "deficit" in water vapor pressure to its saturation status. For this reason, some researchers recommend using a terminology **"vapor pressure difference"** when leaf temperature is used for calculating saturation point. However, the issue of this approach is that it is still abbreviated with the same three letters (VPD). For this reason, it is recommendable to annotate with "leaf" (**VPD_{leaf}** or **VPD_{l}**) for vapor pressure difference to avoid this confusion (Table 2).

One of the problems for actual usage of **VPD_{leaf}** is that leaf temperature is largely different between locations of leaves (e.g., upper vs. lower leaves in the canopy), while all leaves contribute to the plant and canopy transpiration. This is because leaf temperatures are significantly affected by many different environmental variables including net radiation (shortwave and longwave radiation) and air current speed as well as plant physiological variables including stomatal conductance. Transpiration rate itself is also a significant variable affecting leaf temperature. Therefore, "which leaf temperature to measure?" is a practical issue of finding **VPD_{leaf}**.

Table 2. VPD definitions and calculation methods.

Measure-ment	Abbreviation	Definition and calculation*
Vapor pressure deficit (kPa)	VPD_{air} or VPD_{a}	Difference between the saturation water vapor pressure (SVP_{air}) and the current water vapor pressure of the air (VP_{air}). **$VPD_{air} = SVP_{air} – VP_{air}$** where $VP_{air} = SVP_{air} \times RH/100$
Vapor pressure difference (kPa)	VPD_{leaf} or VPD_{l}	Difference between the water saturation vapor pressure at the leaf temperature (SVP_{leaf}) and the current water vapor pressure of the surrounding air (VP_{air}). **$VPD_{leaf} = SVP_{leaf} – VP_{air}$** where $VP_{air} = SVP_{air} \times RH/100$

**Equations to calculate the saturation water vapor pressure (SVP) at a given temperature can be found in various literature sources, for example Lowe (1977).*

Vapor pressure deficit - VPD_{air}

When VPD is calculated as the numerical difference between saturation water vapor pressure and the current water vapor pressure, the resulting value should be referred to as the "vapor pressure deficit", as it is truly the "deficit" relative to the saturation point. To distinguish the value, VPD for the air is recommended annotating with "air" (**VPD_{air}** or **VPD_a**) to avoid the confusion with **VPD_{leaf}**.

Measurement unit for VPD_{leaf} and VPD_{air}

The most common measurement unit for the water vapor pressure difference or deficit is kPa (kilo pascal). If preferred, other units used for partial pressure such as mmHg, bar, or psi, can be used for VPDs. When various units are used, always including unit with values used is the only way to avoid confusion.

To a limited extent, **VPD_{air}** is expressed using mass per volume concentrations (g/m^3). Using a pressure-based terminology (VPD) for the measurement expressed with a mass-based unit is very confusing and rather wrong. Instead, the mass-based measurement should be called **humidity deficit** (HD). HD (g/m^3) of the air can be converted to **VPD_{air}** (kPa) using a conversion factor specific to the water vapor density at given temperature.

Useful tools for VPD

Most humidity sensors used for plant production systems unfortunately do not measure **VPD_{air}**, unless users introduce additional processing of the relative humidity and temperature to find **VPD_{air}**. Some climate controllers or dataloggers have a built-in function to determine **VPD_{air}** based on the relative humidity and temperature measurement. Otherwise, a tool to compute **VPD_{air}** and/or **VPD_{leaf}** is handy for researchers and growers, as computation processes, especially the one for saturation water vapor pressure, is cumbersome. Such a tool is available from University of Arizona (Figure 1) and it calculates the saturation water vapor pressure (kPa), water vapor pressure (kPa), **VPD_{air}** (kPa) and HD (g/m^3) based on the relative humidity (%) and the air temperature (°C). Although this tool is not designed to find **VPD_{leaf}** directly, by using leaf temperature to find SVP and air temperature to find VP, the **VPD_{leaf}** can be calculated by subtracting two values (SVP_{leaf} - VP_{air}) (Table 2).

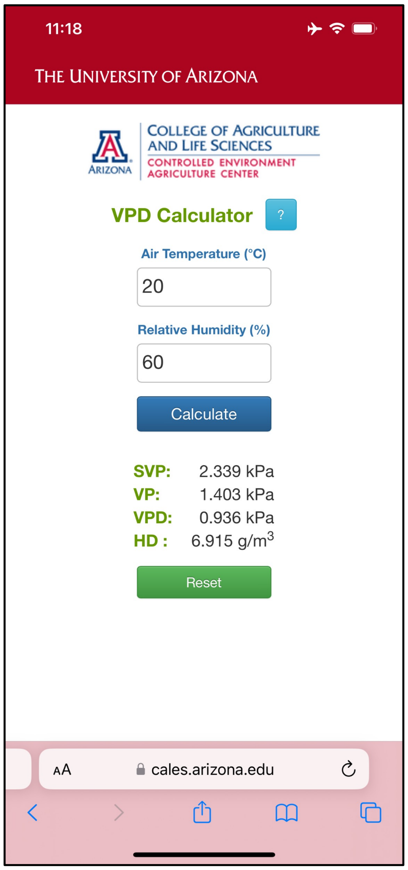

Figure 1. A VPD_{air} calculator (available at University of Arizona Controlled Environment Agriculture Center (https://cales.arizona.edu/vpdcalc). This tool calculates the saturation water vapor pressure (SVP) and water vapor pressure (VP) and therefore it can be used for finding VPD_{leaf} by using both leaf and air temperatures as described in this article.

Terminology confusion is not a unique issue in science and engineering, especially interdisciplinary area like CEA where researchers and professionals with different training background communicate. In such situations, we should try to understand principles and background rather than conventions recommended by others. Terminologies and units used for measurements are considered as language in scientific and technical communication. I hope this article is helpful to solve some issues that we often encounter to discuss humidity and VPD in CEA.

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