The Path Not Traveled

Rethinking Air Distribution in Canopy-Dominated Environments

Prepared by Walter Stark | Walter Stark Consulting, Division of MSP Technology.com, LLC

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An Engineering Position White Paper on Canopy-Focused Air Distribution in Controlled Environment Agriculture

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Executive Summary

This engineering position white paper argues that HVACD systems for controlled-environment agriculture should be designed around the crop canopy—not the room—because the dominant sensible and latent loads are generated within the canopy and because plant response is governed by canopy-level temperature, humidity, vapor pressure, VPD, and air velocity.

Canopy-Direct™ addresses the question of air distribution. It directly connects the CH&D equipment to the crop canopy, so conditioned air reaches the point where heat and moisture are generated.

Room-mixed systems assume the creation of a stable environment by attempting to fully merge two vastly different climate zones into a dominant third blended climate zone. Room-mixed systems often rely on field adjustment, circulation fans, and observed crop response rather than a clearly defined engineering method for ensuring uniform canopy-entering and canopy-leaving air conditions.

Room-mixed air delivery weakens this connection because dry CH&D supply air is diluted before reaching the canopy, whereas humid canopy-leaving air is diluted before returning to the equipment. Canopy-Direct™ creates a clearer, more measurable air path from equipment to the canopy and back.

In the example analyzed, the Canopy-Direct™ strategy reduces calculated CH&D capacity from 47 tons to 30 tons, a 36% reduction, and reduces required airflow from approximately 12,148 CFM to 6,212 CFM, a 49% reduction, before accounting for additional savings from fan energy, equipment, noise, maintenance, and reduced room-mixing complexity.

Table 1-Summary of air delivery strategies

Room-Mixed		**Canopy-Direct™**	
CH&D → ROOM →	ROOM MIXED → CANOPY	CH&D →	→ CANOPY
CANOPY → ROOM →			
Figure 1, Figure 2, Table 3		Figure 3, Figure 4, Table 4	
Supply air diluted before reaching crop.		Supply air delivered directly to crop.	
Return air diluted before reaching CH&D.		Return air returned directly to CH&D.	
47 Tons, 12,148 CFM		30 Tons, 6,212 CFM	
Baseline		36% Less Capacity, 49% Less Airflow	

Introduction

Vertical farming's narrow margins require disciplined attention to both operating and capital costs. Recent farm closures and the USDA's pause on loan guarantees underscore the financial importance of HVACD design decisions that affect energy use, equipment cost, reliability, and crop performance.

Since vertical farming emerged around the year 2000, engineers have largely adapted comfort-cooling strategies developed for buildings dominated by envelope loads and occupant comfort. Vertical farms are fundamentally different: they are well-insulated, windowless spaces where the dominant sensible and latent loads come from lighting and plant transpiration within the crop canopy.

Dense plant canopies create a distinct HVACD challenge because the primary heat and moisture loads originate within the crop rather than at the building envelope. When existing systems produce marketable crops, their air-distribution assumptions often go unchallenged, reducing the incentive to ask whether the same crop outcome could be achieved with less airflow, less equipment capacity, and more direct canopy control.

CEA design has advanced through improved airflow layouts, zoning, controls, and equipment selection. Yet one assumption remains deeply embedded: that elevated whole-room air movement and mixing are inherently beneficial and sufficient for climate uniformity.

That reliance on whole-room mixing can obscure a more direct strategy: delivering the driest conditioned air to the canopy, where heat, moisture, vapor-pressure, and air velocity most directly affect plant response. It can also hide air-distribution alternatives better suited to concentrated HVACD loads, such as those found in vertical farms and data centers.

Uniformity is central to success in CEA. Growers already recognize the need for uniform delivery of water, nutrients, and lighting. Climate uniformity is different. Current room-mixing strategies cannot ensure uniform canopy conditions because they depend on thoroughly blending two opposing air states: humid canopy-leaving air and dry CH&D supply air. In practice, achieving that level of mixing has no well-defined engineering method and is often left to trial, observation, and adjustment.

This paper compares conventional room-mixed air delivery with a Canopy-Direct™ approach that delivers conditioned air directly to the crop canopy and treats canopy-leaving air as the meaningful reference for design, measurement, and control.

Because room-mixed air delivery remains deeply embedded in CEA practice, its underlying assumptions should be examined before a credible alternative is advanced. The issue is not that every room-mixed system fails. Rather, room-mixed design can misrepresent the canopy psychrometric problem and lead stakeholders to optimize around room-average measurements instead of the air conditions that govern plant performance.

Canopy-Direct™ offers a deliberate alternative by connecting the CH&D equipment more directly to the crop canopy and delivering dry conditioned air where the dominant loads are generated. The goal is not simply to move air differently; it is to make the canopy the primary point of design, measurement, commissioning, and control.

Position of This Paper

This paper does not argue that room-mixed systems cannot grow crops. Many do. The position advanced here is that room-mixed air delivery is an indirect and less measurable strategy for managing canopy-dominated sensible and latent loads. Canopy-Direct™ air distribution provides a more direct engineering framework by delivering conditioned air to the canopy, using canopy-leaving air as the primary reference condition, and aligning equipment selection, airflow design, measurement, commissioning, and control with the actual psychrometric process occurring at the crop.

This analysis is based on a representative psychrometric comparison using stated assumptions for canopy conditions, lighting load, transpiration/irrigation rate, and altitude. Actual performance will depend on crop type, canopy density, rack geometry, outlet design, controls, sensor placement, leakage, bypass airflow, operating mode, and commissioning quality. The results should therefore be understood as a design comparison and proof of engineering principle, not as a universal guarantee of identical savings in every facility.

Concepts and Design Assumptions

Key Terms

For clarity, the term “Grower” refers to the team responsible for managing cultivation operations. The term “CH&D” means a cooling, heating, and dehumidification unit that provides all three functions. “HVACD” refers to the complete climate control system. The term “room-mixed” to describe a system in which the CH&D unit is indirectly connected to the canopy via a blended room-air volume. The term Canopy-Direct™ is used in this paper to describe the canopy-focused air-distribution strategy where the CH&D unit supplies air directly to the canopy; the engineering argument rests on the air-path and psychrometric comparison, not on the trademark itself.

Canopy Air Conditions

This paper distinguishes between two canopy air conditions. **Canopy-entering air** is the conditioned air delivered into the crop canopy before it absorbs heat and moisture from the plants. **Canopy-leaving air** is the air state after that interaction, as it exits the canopy, carrying the heat and water vapor generated by plant lighting and transpiration.

For design and control purposes, canopy-leaving air is the more meaningful reference because it reveals what occurred within the crop zone. It reflects the combined effects of airflow, transpiration, and lighting heat. Therefore, when referring to “canopy air” as a control condition, it means **canopy-leaving air**.

Crop Quality and Uniformity

In vertical farming, uniform delivery of water, nutrients, and lighting has been mastered, but climate is more challenging. Crop quality and uniformity relative to climate are closely related but not the same. **Crop uniformity** happens when the climate is consistent across the growing area. **Crop quality** improves as the climate more closely matches the grower's specifications, resulting in the crop meeting the desired standards for appearance, yield, flavor, shelf life, and marketability. Uniformity alone does not guarantee quality, but consistent high quality is difficult to achieve without uniformity.

Crop quality is optimized when the climate system delivers air to the canopy with a consistent, intentionally selected temperature, vapor-pressure, and velocity, ensuring that each plant experiences the same driving force for transpiration and gas exchange.

Crop Air-Velocity

Canopy air velocity should be treated as a plant-level design variable rather than a generic room-mixing rule. Current canopy-velocity guidance is often derived from conventional room-mixed practice, where air must first be blended throughout the room before it can influence the crop. In a Canopy-Direct™ system, dry conditioned air is delivered intentionally into the canopy air path, so the required velocity should be based on measured canopy response rather than inherited room-air assumptions.

Published and industry recommendations commonly cite broad canopy-velocity ranges—often on the order of 40 to 300 fpm—because the required value depends on crop type, canopy density, lighting load, transpiration rate, outlet geometry, and the selected air-distribution strategy. That range is useful as a reminder that still air is unacceptable, but it is too broad to serve as a final design value. With Canopy-Direct™ delivery, the CH&D airflow itself may provide sufficient vapor removal, temperature control, and VP/VPD management at lower velocities than those typically assumed for room-mixed systems. Supplemental bypass air, shown in Figure 3, should therefore be adjustable and used only as needed to achieve measured canopy uniformity during commissioning and crop trials.

This reframes canopy air velocity as a commissioning variable rather than a fixed rule of thumb. The practical objective is to identify the lowest effective velocity that maintains uniform canopy-leaving temperature, humidity, VP, and VPD while avoiding unnecessary fan energy, turbulence, noise, plant stress, and worker discomfort. Final velocity targets should be established through field measurement at representative canopy locations and reassessed as crop density, growth stage, and operating mode change.

Vapor-Pressure and Vapor-Pressure-Deficit

Vapor pressure (VP) and vapor pressure deficit (VPD) are key grower metrics for assessing how climate conditions drive water movement through the crop. They are typically expressed in kilopascals (kPa). The difference (deficit) in vapor pressure is calculated as the difference between the vapor pressure of the leaf surface temperature (LST), at 100% RH, and that of the canopy air conditions specified by the grower. A chart for calculating VPD is shown in Figure 7 on page 22.

Leaf Surface Temperature

Efficient CEA lighting converts more electrical input into useful photons and less into waste heat. This typically reduces radiant and convective heat at the canopy, which can lower leaf surface temperature (LST), reduce cooling load, and support more stable VPD control. Because lighting conditions are generally fixed for a given crop strategy, bulk VP and VPD values remain useful for comparison, communication, and evaluation when LST is not available.

Leaf surface temperature (LST) strongly influences the leaf vapor-pressure used to calculate VPD. In practice, LST is measured with an infrared thermometer and may range from about 3°F below canopy air temperature in the night-mode to about 8°F above canopy air temperature in the day-mode

When LST is known, actual VPD can be calculated. When the value is unknown, VP and VPD are reported as "bulk" values. Bulk leaf VP is calculated from the grower-specified temperature at 100% RH, without accounting for lighting effects or evaporative cooling.

CH&D Reheat Energy

With most dehumidification systems used in CEA, reheating energy is a free and abundant byproduct of the dehumidification process. Consequently, reheating contributes little to the system's operating expenses.

Measurement and Controls

Canopy-leaving air is the most useful practical reference for measurement and control. It reflects the air state after direct interaction with the crop. It captures the combined effects that determine the vapor-pressure environment near the end of the airflow path, where moisture accumulation is greatest.

The control strategy should include canopy-level verification through distributed temperature and humidity sensing, representative air-velocity mapping, and periodic reassessment as canopy density changes. Measurements should be evaluated during both lights-on and lights-off operation because sensible load, transpiration, airflow demand, and dehumidification requirements vary throughout the crop cycle.

During all modes of operation and stages of growth, the controls must manage canopy-leaving conditions by adjusting supply-air dew point and temperature to maintain design conditions within a close range.

This reframes room condition as a result rather than the primary design variable. If canopy-leaving air is treated as the true design and control reference, CH&D equipment can be selected and operated around the crop's actual psychrometric load rather than an assumed room condition.

Grower-Provided Design Specifications

Growers provide specifications that define the crop's target climate and load assumptions. These inputs typically include the desired temperature and humidity conditions, lighting load, and expected transpiration or irrigation rate. The engineer then uses these values to select the CH&D equipment and design the air-distribution system. Table 2 lists the grower-provided specifications used for the examples throughout this paper.

Table 2-Grower-Provided Data

Canopy Conditions	Value	Units
Altitude	0	ft
Temperature (1)	80°	°F
Relative Humidity (1)	60%	% RH
Transpiration/Irrigation	150	lb./h
Lighting	146,235	Btu/h
Canopy Area	4,286	ft^2

(1) Represents canopy leaving-air condition. (Entering-air conditions should never be used as the grower's specified conditions.)

IMPORTANT: WITH THE ROOM-MIXED STRATEGY, UNLESS THE GROWER IS SPECIFIC, THE ENGINEER MAY MISTAKENLY CONCLUDE THAT THE GROWER'S TEMPERATURE AND HUMIDITY SPECIFICATIONS APPLY TO ROOM-MIXED AIR. THE CONSEQUENCES OF THIS ERROR IN SUBSEQUENT CALCULATIONS ARE COVERED IN THE ADDENDUM ON PAGE 20.

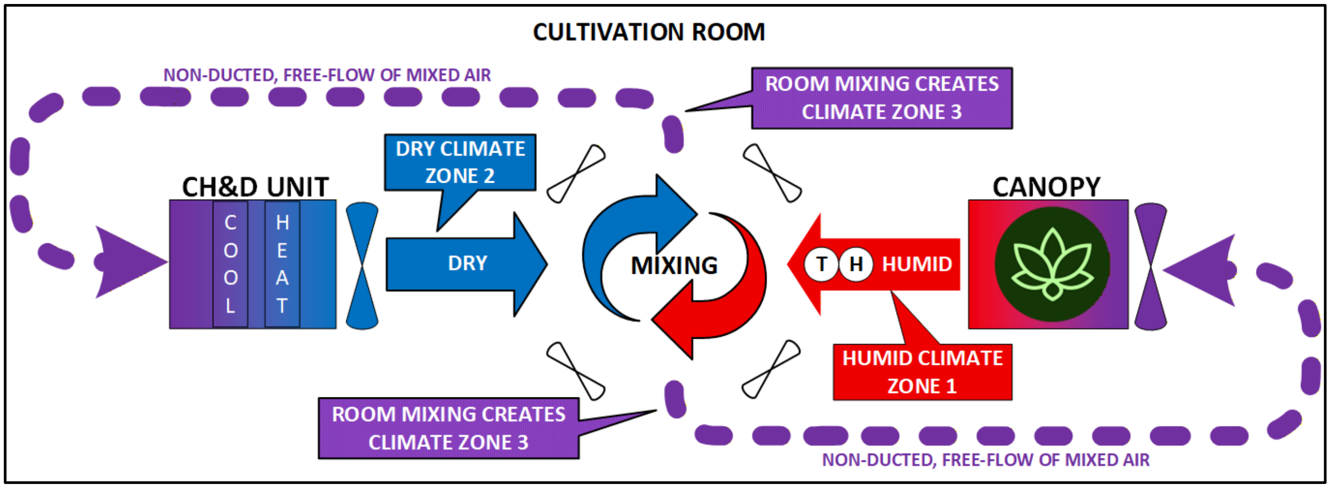
CEA facilities, the dominant sensible and latent loads come from canopy transpiration and lighting rather than the building envelope. Nevertheless, if the engineer identifies significant building envelope gains or losses—such as poor insulation, infiltration, adjacent unconditioned spaces, or unusual outdoor exposure- those loads should be calculated separately and added explicitly to the CH&D capacity. This approach keeps the analysis focused on the crop-driven psychrometric load while still accounting for building-specific conditions.

Room-Mixed Air Delivery

Design Summary: A three-step process cools, dehumidifies, and reheats air in the CH&D unit, then delivers it directly to the cultivation space where it mixes with humid air leaving the canopy. The mixed air then returns to the canopy and the CH&D unit for reprocessing.

Figure 1 illustrates a room-mixed air-delivery strategy in which the CH&D unit is separated from the crop canopy by the room air volume. In this arrangement, the CH&D unit does not deliver conditioned air directly to the canopy. Instead, dry air leaving the CH&D unit is discharged into the room, where it mixes with warmer, more humid air leaving the canopy. The resulting room air mixture then becomes the air entering both the canopy and the CH&D unit. This creates three distinct climate states.

Figure 1-Room-Mixed Air Delivery Schematic with Canopy Leaving Air Control



Room-Mixed Climate Zones

Humid Climate Zone 1 represents the humid air conditions leaving the canopy, as specified by the grower.

Dry Climate Zone 2 represents the dry air conditions leaving the CH&D unit, as calculated by the engineer.

Room-Mixed Climate Zone 3 represents the mixed air entering the canopy and CH&D unit, as calculated by the engineer to achieve the conditions that leave the canopy in Humid Climate Zone 1.

Room-Mixed Psychrometrics

Figure 2-Room-Mixed Psychrometric Chart with Canopy Leaving Air Control

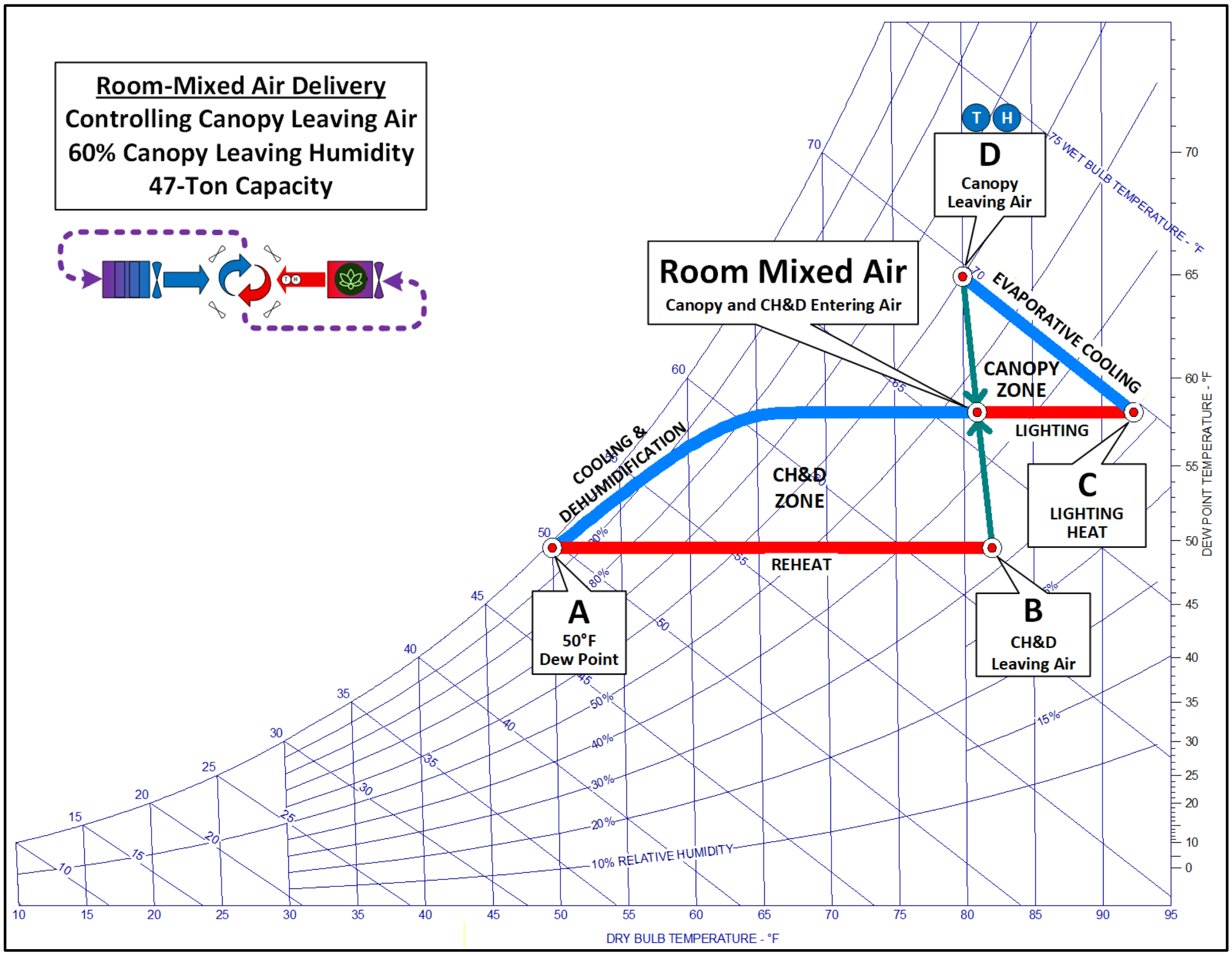


Table 3-Room-Mixed Psychrometric Values with Leaving Air Control

CONDITION	SYMBOL	UNITS	CH&D UNIT		ROOM MIXED AIR	CANOPY	
			A	B		C	D
			COOL & DEHUMID	REHEAT		LIGHTING HEAT	EVAP. COOLING
Dry Bulb	t_db	°f	50.0	82.0	81.0	92.3	80.0
Dew Point	t_dp	°f	49.5	49.5	58.1	58.1	64.9
Relative Humidity	%	%	98%	32%	46%	32%	60%
Sat. Partial Pressure	p_ws	kPa	1.23	3.73	3.61	5.18	3.50
Partial Pressure	p_w	kPa	1.21	1.21	1.65	1.65	2.10
Humidity Ratio	W	grains/lb. (da)	52	52	72	72	92
Enthalpy	h	btu/lb. (da)	20.11	27.90	30.76	33.52	33.63
Specific Volume	v	f^3/lb. (da)	13.00	13.82	13.86	14.15	13.89
Energy	q_s	Btu/h	-564,356	412,708	0	146,235	5,316
Humid/Dehumid	$\dot{m}_w$	lb./hr (H_2O)	-150	0	0	0	150
Air Volume	Q	acfm	11,487	12,174	24,447	12,461	12,273
SUMMARY - Bulk VPD = 1.40 kPa Tons = 47 SHR = -0.09							

The values used to compute airflow and tons are altitude, transpiration/irrigation rate, lighting watts/Btu/h, and the **canopy-leaving air** temperature and humidity.

The key result is that the room-mixed arrangement requires greater airflow and equipment load to produce the same canopy-leaving conditions as the coupled strategy. Because the CH&D unit conditions mixed room air rather than the Canopy-Direct™ stream, a large part of the dehumidification effect is lost to room dilution before reaching the crop.

Why Room-Mixed Air Delivery Falls Short

Room-mixed air delivery falls short because it controls the wrong target. In canopy-dominated cultivation, the critical sensible and latent loads are generated inside the crop canopy. Yet, dry CH&D supply air is diluted before reaching the plants, and humid canopy-leaving air is diluted before returning to the dehumidification equipment. The room average may look acceptable while concealing the canopy microclimate that governs crop performance.

Because canopy air has absorbed moisture from transpiration and heat from lighting, its temperature, vapor-pressure, relative humidity, and VPD can differ materially from bulk room readings. High-volume circulation fans may improve apparent room uniformity, but they do not create a direct, controlled air path through the crop; instead, they add turbulence, noise, fan energy, maintenance, and operating complexity while making sensor readings more dependent on equipment location, rack geometry, bypass airflow, and local recirculation.

The psychrometric penalty is unavoidable: Mixed Climate Zone 3 must serve as both canopy-entering air and CH&D return air, even though it is neither the driest available supply-air nor the true humid canopy-leaving air. To achieve the specified canopy-leaving condition, the system must compensate with more airflow, lower supply-air humidity, larger CH&D capacity, higher fan energy, greater cost, more noise, added maintenance, and increased crop risk.

Figure 2 and Table 3 make this consequence visible: the room-mixed system can be calculated to achieve the desired canopy-leaving condition, but only by conditioning a diluted mixed-room stream rather than the air path that governs plant response. That is why room-mixed delivery can appear reasonable when judged by room conditions yet remain fundamentally weaker as a canopy-control strategy.

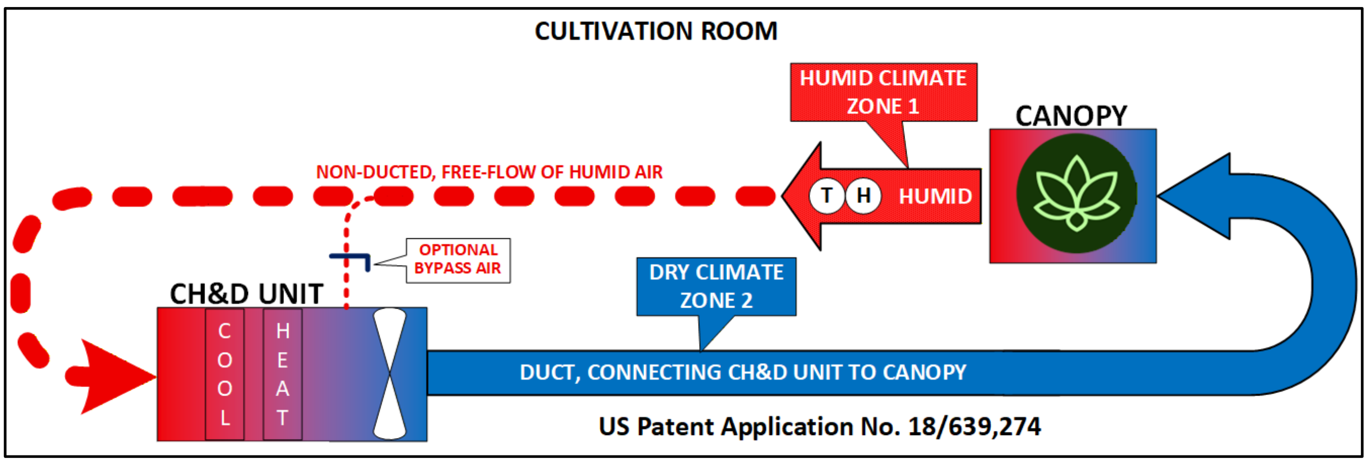
Canopy-Direct™ Air Delivery

Design Summary: A simple two-step process cools, dehumidifies, and reheats air in the CH&D unit, then delivers it directly to the canopy, where it absorbs heat and humidity before returning to the CH&D unit for reprocessing.

Figure 3 illustrates a Canopy-Direct™ air-distribution strategy in which dry, conditioned air is delivered directly from the CH&D unit to the plant canopy rather than first being diluted within the room. This creates a more intentional and measurable air path—CH&D unit → canopy → return—so that conditioned air is applied where heat and moisture are generated. By reducing reliance on whole-room mixing, the Canopy-Direct™ approach makes the canopy, rather than the room, the primary point of design, measurement, and control.

The key advantage is that CH&D unit-leaving air is also the canopy-entering condition, while canopy-leaving air provides the meaningful reference for load calculations, measurement, and control. This creates a clearer connection between equipment performance and the vapor-pressure, humidity, and airflow conditions that govern transpiration in the crop canopy.

Figure 3-Canopy-Direct™ Air Delivery Schematic with Leaving Air Control



Canopy-Direct™ Climate Zones

Humid Climate Zone 1 represents the air condition leaving the canopy, as specified by the grower.

Dry Climate Zone 2 refers to the air condition leaving the CH&D unit and entering the canopy. The engineer calculates this based on the maximum transpiration rate and the lighting watts to achieve the conditions in zone 1, selected by the grower.

Canopy-Direct™ Psychrometrics

Figure 4-Canopy-Direct™ Psychrometric Chart with Canopy Leaving Air Control

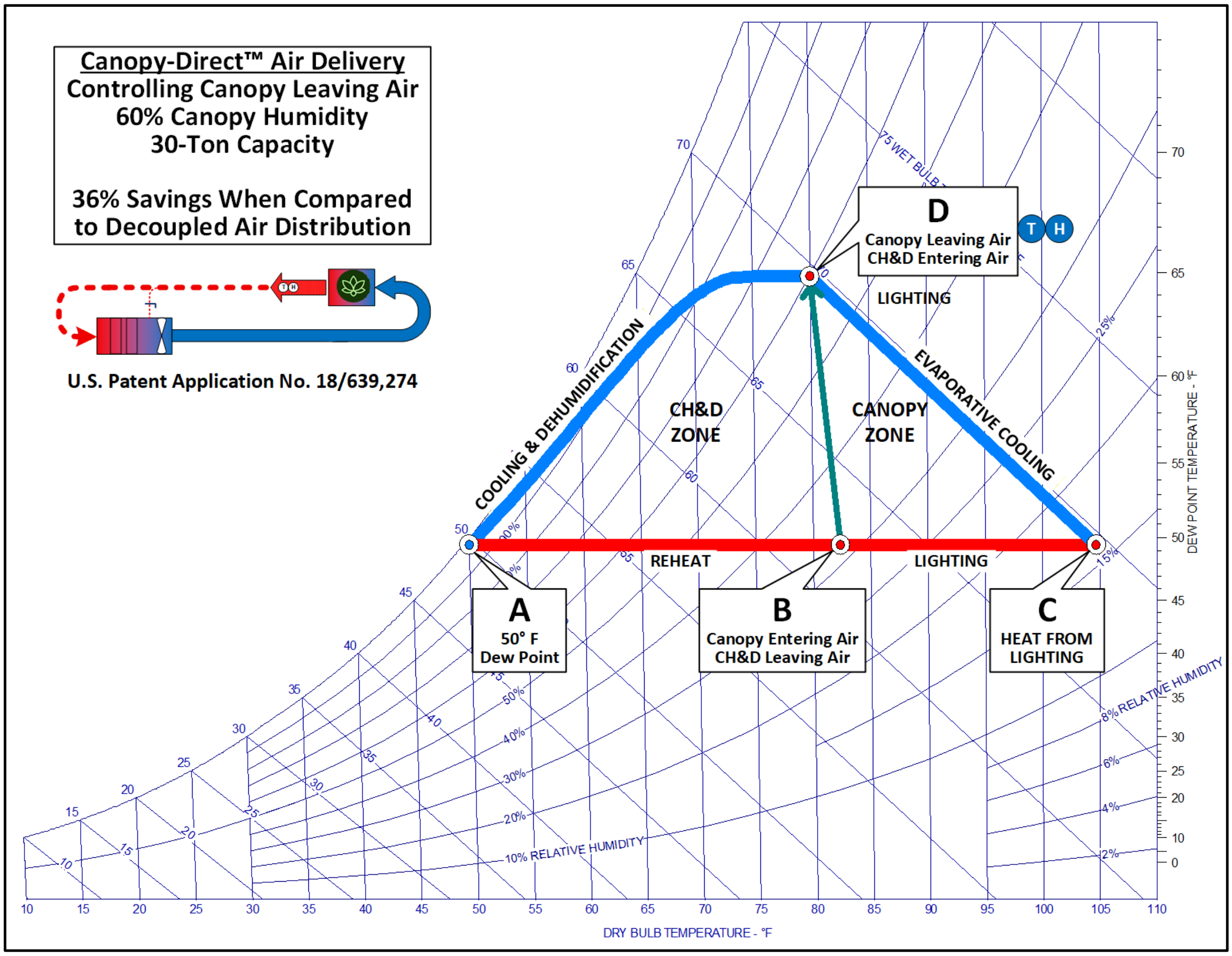


Table 4-Canopy-Direct™ Psychrometric Values with Canopy Leaving Air Control

CONDITION	SYMBOL	UNITS	CH&D UNIT		CANOPY	
			A	B	C	D
			COOL & DEHUMID	REHEAT	LIGHTING HEAT	EVAP. COOLING
Dry Bulb	t_db	°f	50.00	82.42	104.72	80.00
Dew Point	t_dp	°f	49.52	49.52	49.52	64.92
Relative Humidity	%	%	0.98	0.32	0.16	0.60
Sat. Partial Pressure	p_ws	kPa	1.23	3.78	7.54	3.50
Partial Pressure	p_w	kPa	1.21	1.21	1.21	2.10
Humidity Ratio	W	grains/lb. (da)	52.45	52.45	52.45	92.23
Enthalpy	h	btu/lb. (da)	20.12	28.01	33.43	33.65
Specific Volume	v	f^3/lb. (da)	13.00	13.83	14.40	13.89
Energy	q_s	Btu/h	364,640	212,579	146,235	5,826
Humid/Dehumid	$\dot{m}_w$	lb./hr (H_2O)	150			150
Air Volume	Q	acfm	5,840	6,212	6,467	6,275
SUMMARY - Bulk VPD= 1.40 kPa Tons= 30 SHR = -0.11						

The values used to compute airflow and tons are altitude, transpiration/irrigation rate, lighting watts/Btu/h, and the ***canopy-leaving* air** temperature and humidity.

The Practical Canopy-Direct™ Solution

The key result is that the Canopy-Direct™ arrangement requires substantially less airflow and equipment capacity to produce the same canopy-leaving air condition. Because the CH&D unit conditions the canopy directly, rather than conditioning mixed room air, a large part of the dehumidification effect is applied where the load is generated. In this example, the Canopy-Direct™ case requires approximately 6,212 CFM and 30 tons of cooling/dehumidification capacity, compared with the room-mixed case, which requires 12,148 CFM and 47 tons, representing a potential 36% capacity reduction.

Canopy-Direct™ air distribution makes this control strategy more effective because the air path is intentional: conditioned air is delivered to the canopy, and canopy-leaving air serves as the primary feedback for evaluating plant microclimate and CH&D equipment performance. Commissioning is still required, but the control objective is clearer, easier to verify, and directly tied to canopy performance.

The Canopy-Direct™ system also makes sensor placement less arbitrary because the air path is more predictable. This supports tighter canopy humidity control, improved VPD management, reduced risk of mold and mildew, reduced unnecessary turbulence and noise, and lower energy, maintenance, and capital and operating costs.

Canopy-Direct™ air distribution directly connects the CH&D unit to the plant canopy by delivering dry, conditioned air to the point where heat and moisture are generated.

The practical challenge is not whether Canopy-Direct™ delivery is theoretically superior, but how to apply it without compromising access, maintenance, or crop operations. In a theoretical extreme, the crop could be enclosed and uniformly supplied with dry air throughout the enclosure. That arrangement would provide maximum environmental control, but it would also restrict access, complicate everyday operations, and be difficult to apply on a commercial scale.

A more practical approach is to deliver conditioned air through strategically placed outlets at the canopy, allowing the driest air to penetrate the foliage. This shortens the vapor-removal path and makes the canopy—not the room—the primary control target.

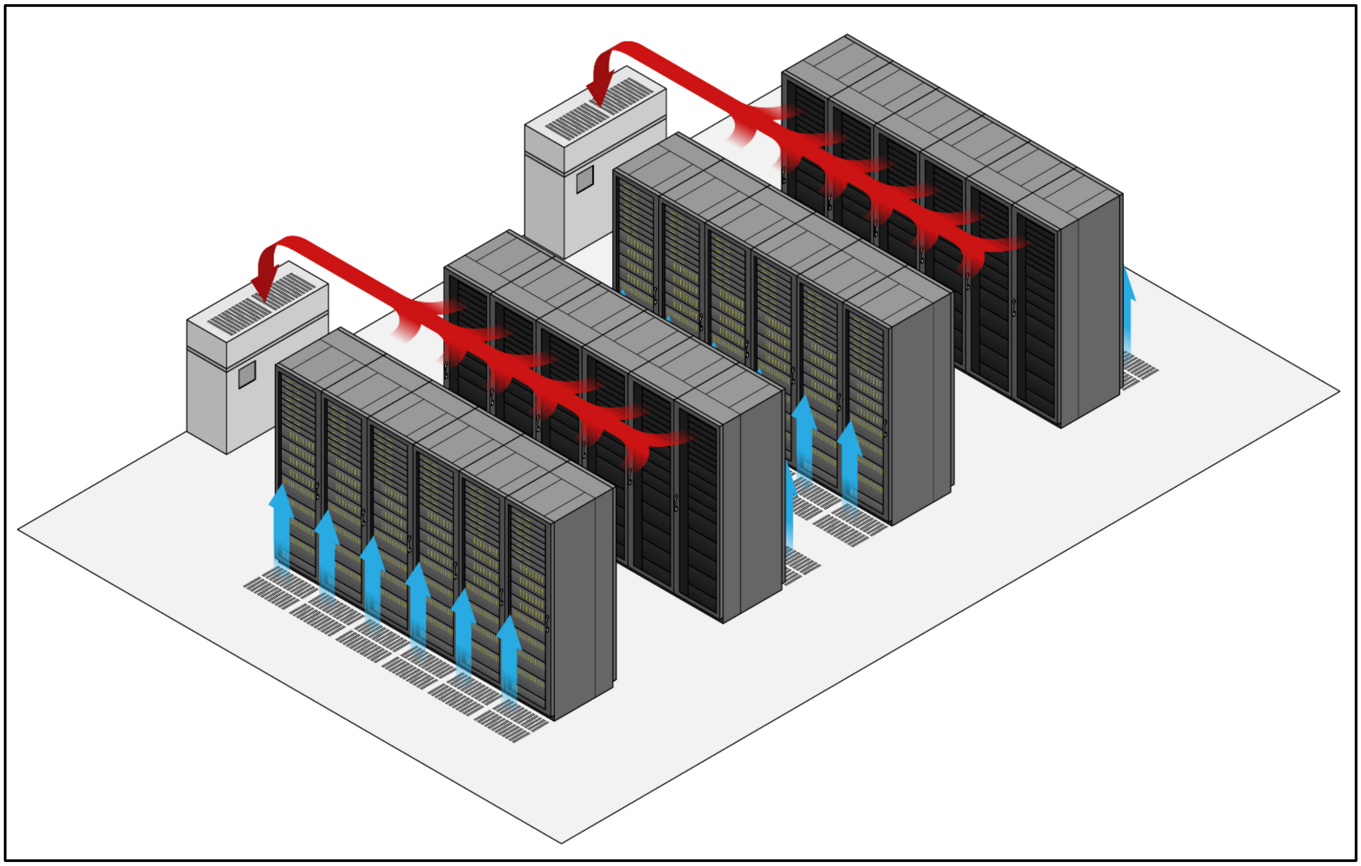
The design goal is to minimize dry-air spillage into the room while providing sufficient, uniform airflow to control canopy temperature, VP, and VPD efficiently. Air volume, outlet location, and throw distance are therefore optimized around canopy performance rather than whole-room mixing.

A Canopy-Direct™ system simplifies the air-distribution problem by reducing it to two meaningful climate states: conditioned air entering the canopy from the CH&D unit, and air leaving the canopy after absorbing heat and moisture from the crop. Eliminating the third, blended mixed-room condition removes much of the ambiguity that complicates measurement, control, and equipment selection in room-mixed systems.

Data Center Analogy

The same principle has already reshaped data-center cooling: when loads are concentrated, generalized room mixing gives way to targeted air delivery and controlled return paths. In vertical farming, the concentrated load is not a server rack but a plant canopy that produces heat, water vapor, and biological response. The engineering principle is the same: deliver conditioned air where the load is generated, measure conditions after the load has been absorbed, and avoid designing around an uncontrolled room average.

Figure 5-Hot / Cold Aisle Strategy for Data Centers



Conclusion

The analysis demonstrates a clear engineering and economic consequence: to achieve the same canopy-leaving condition, the room-mixed case requires approximately 12,148 CFM and 47 tons of CH&D capacity. In comparison, the Canopy-Direct™ strategy requires approximately 6,212 CFM and 30 tons. That represents a 36% reduction in calculated CH&D capacity and a 49% reduction in required air volume, before accounting for additional savings from reduced ancillary fan energy, fan equipment, noise, maintenance, and room-mixing complexity.

Table 5 summarizes the practical engineering implications of the psychrometric comparison.

Table 5-Engineering Comparison of Canopy-Direct™ and Room-Mixed Air Delivery

Performance Outcome	Canopy-Direct™	Room-Mixed	Basis / Reason
Can be engineered to meet a specified canopy-leaving condition	✓	✓	Both strategies can be designed to meet the same canopy-leaving temperature and humidity targets.
Can remove the specified latent load	✓	✓	Both systems can be sized to remove the assumed transpiration or irrigation load.
Supports crop production when properly designed and commissioned	✓	✓	Room-mixed systems can and do produce crops; the distinction is the efficiency and precision of canopy control.
Provides direct VP/VPD control at the canopy	✓		Canopy-Direct™ applies conditioned air directly to the canopy air path and uses canopy-leaving air as the reference condition.
Reduces dilution between CH&D supply-air and the canopy	✓		Room-mixed delivery intentionally blends supply-air with the room before it reaches the crop; Canopy-Direct™ shortens that path.
Can reduce calculated CH&D capacity in this example	✓		The analyzed case shows approximately 30 tons for Canopy-Direct™ versus 47 tons for room-mixed delivery.
Can reduce calculated airflow in this example	✓		The analyzed case shows approximately 6,212 CFM for Canopy-Direct™ versus approximately 12,148 CFM for room-mixed delivery.
Provides a more direct sensor/control relationship to canopy-leaving air	✓		A more defined air path makes measurement and commissioning more directly tied to the crop's psychrometric process.
Checkmarks indicate outcomes each strategy can reasonably support when properly engineered. Blank cells do not mean the outcome is impossible; they indicate that the comparison identifies a stronger or more direct advantage for the other strategy in the example analyzed.			

The central conclusion is that HVACD design for canopy-dominated environments should be based on the air conditions that govern plant response, not on room-average assumptions. In vertical farms, the crop canopy is the primary source of sensible and latent load, the location where vapor transfer occurs, and the point at which temperature, humidity, vapor pressure, VPD, and air velocity determine plant performance. Canopy-Direct™ air distribution provides a more defensible engineering framework because it connects the CH&D unit directly to the canopy load, uses canopy-leaving air as the primary reference condition, and aligns equipment selection, airflow design, sensor placement, commissioning, and controls with the actual psychrometric process occurring at the crop.

The data-center analogy reinforces the broader engineering principle: concentrated loads are best served by targeted air delivery and controlled return paths, not by generalized room mixing.

Room-mixed air delivery can produce crops, but its apparent performance can be misleading when judged mainly by bulk room conditions. Dry supply air is diluted before reaching the canopy, and humid canopy-leaving air is diluted before returning to the CH&D unit. The resulting blended room condition can obscure the actual canopy load, weaken the vapor-pressure driving force at the crop, and increase airflow, equipment capacity, and operating complexity.

For that reason, Canopy-Direct™ air distribution should be evaluated as a primary design strategy for new vertical farms and major retrofits, with final airflow and control targets validated through commissioning and crop-specific measurement.

Design Implications and Future Work

In practical design terms, projects that continue to use a room-mixed strategy should explicitly define whether grower-specified temperature and humidity targets represent canopy-entering air, room-mixed air, or canopy-leaving air.

The remaining question that does not need to delay the implementation of the Canopy-Direct™ strategy is the volume of air needed to serve the local canopy. Ideally, the air volume from the CH&D unit alone may be sufficient, but a strong approach is to include adjustable bypass air, shown in Figure 3 on page 14, allowing commissioning and crop trials to identify the crop-specific velocity “sweet spot” based on measured canopy performance. This value may change based on the crop type and distance of air throw from the air discharge terminal to the canopy.

Future work should convert this proof of concept into an evidence-based design practice through controlled comparisons of room-mixed and Canopy-Direct™ air delivery under representative crop densities, lighting loads, airflow rates, and operating cycles. The most important measurements should include canopy-entering and canopy-leaving temperature. These data will determine the crop-specific velocity requirements, refine commissioning methods, and establish when Canopy-Direct™ delivery provides the strongest technical and economic advantage, just as cold/warm aisle strategy improved data center operations.

Addendum

The Inflection Point: Interpreting the Grower's Climate Specification

The Inflection Point occurs when the engineer assigns the grower's specified temperature and relative humidity to a defined location in the air path—either canopy-entering (room-mixed) or canopy-leaving air. This single decision establishes the psychrometric basis for airflow, CH&D capacity, sensor placement, and control strategy.

The distinction is critical because air gains both sensible heat from lighting and latent moisture from transpiration as it passes through the crop. As a result, the same specification—80°F and 60% RH—yields materially different engineering outcomes depending on whether it is applied to entering, room-mixed, or leaving air.

The key question is not whether a room sensor reads 80°F and 60% RH, but where those conditions are intended to exist within the air path. If the grower's intent is to define the condition of the air after it has passed through the canopy, then the specification must be treated as canopy-leaving—not as room-mixed, or canopy-entering air.

A common error arises when this specification is instead interpreted as canopy-entering (or room-mixed) air. This misinterpretation is understandable, as grower specifications typically state only temperature and relative humidity without identifying their intended location.

As illustrated in Figure 6 and Table 6, the system under this mistaken assumption appears to satisfy the requirement: maintaining 80°F and 60% RH at the entering-air point, removing 150 lb./hr of moisture, and requiring approximately 30 tons of CH&D capacity. However, when the resulting canopy-leaving condition is evaluated, the relative humidity rises to approximately 91%, significantly altering the vapor pressure environment experienced by the crop and inviting the risk of developing mold and mildew. The system satisfies the interpreted condition, but not the grower's actual intent.

When the specification is correctly applied to canopy-leaving air, the required system capacity increases substantially. As shown in Figure 2 and Table 3, the corrected interpretation increases CH&D capacity from 30 tons to 47 tons and airflow from about 6,149 CFM to 12,248 CFM.

This divergence defines the Inflection Point: the grower's specification remains unchanged, but the engineering solution shifts dramatically once the condition is assigned to its correct location in the air path. Because room-mixed systems have been the prevailing design approach in vertical farming, this error is most likely to occur in their application and evaluation.

The implication is straightforward: every CEA design must explicitly define where the temperature and humidity specification applies before finalizing system capacity, airflow, controls, sensor placement, and air distribution strategy. The engineer must then quantify the psychrometric consequences of that choice.

Figure 6-Room-Mixed Psychrometric Chart with Canopy Entering Air Control

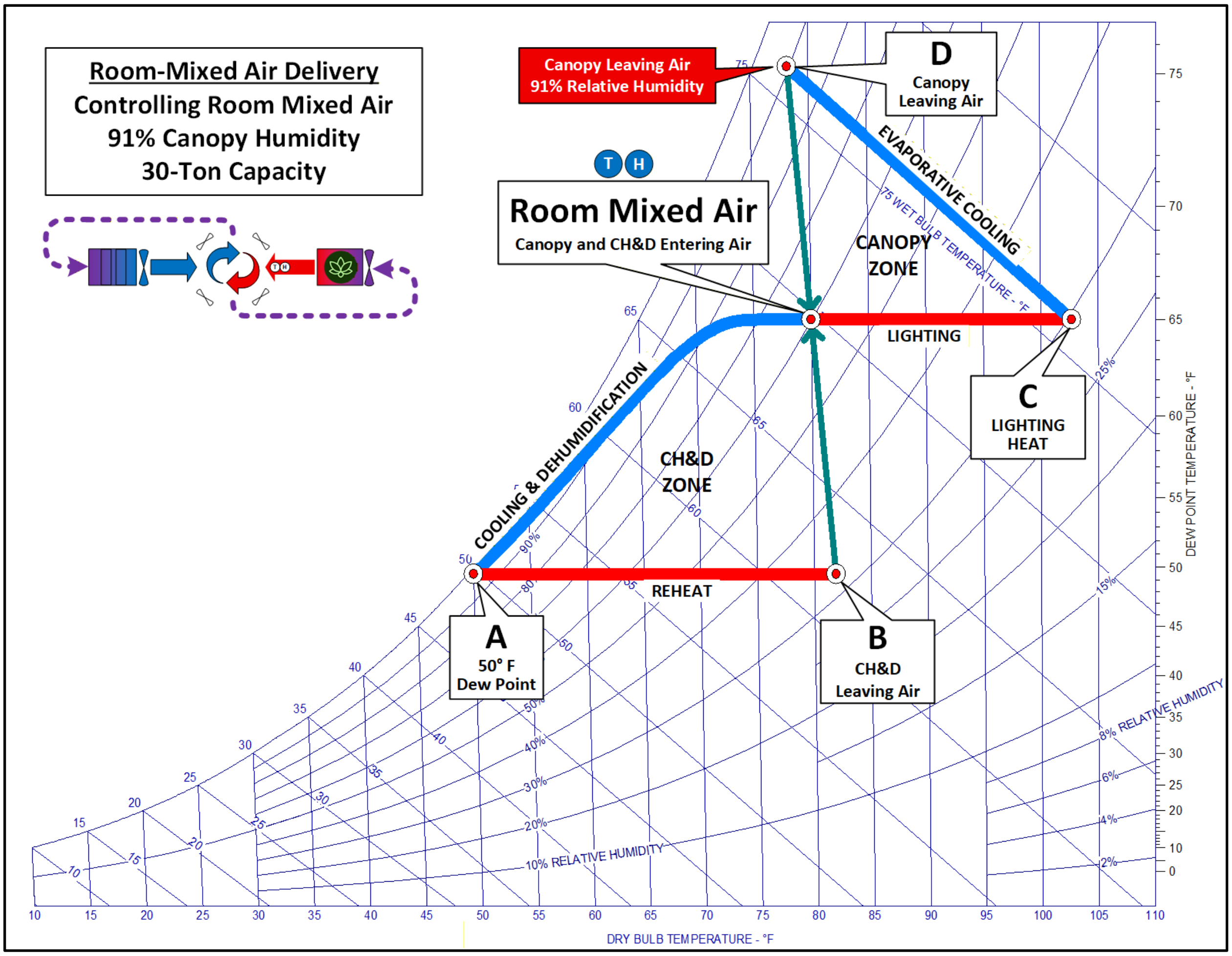


Table 6-Room-Mixed Psychrometric Values with Canopy Entering Air Control

CONDITION	SYMBOL	UNITS	CH&D UNIT		ROOM MIXED AIR	CANOPY	
			A	B		C	D
			COOL & DEHUMID	REHEAT		LIGHTING HEAT	EVAP. COOLING
Dry Bulb	t_db	°f	50.00	81.85	80.00	102.65	78.15
Dew Point	t_dp	°f	49.46	49.46	64.88	64.88	75.18
Relative Humidity	%	%	98.0%	32.4%	60.0%	29.6%	***90.6%***
Sat. Partial Pressure	p_ws	kPa	1.23	3.72	3.50	7.09	3.29
Partial Pressure	p_w	kPa	1.20	1.20	2.10	2.10	2.98
Humidity Ratio	W	grains/lb. (da)	52.33	52.33	92.09	92.09	132.07
Enthalpy	h	btu/lb. (da)	20.10	27.85	33.63	39.19	39.43
Specific Volume	v	f³/lb. (da)	13.00	13.82	13.89	14.48	13.97
Energy	q_s	Btu/h	357,256	204,666	0	146,235	6,172
Humid/Dehumid	$\dot{m}_w$	lb./hr (H_2O)	150	0	0	0	150
Air Volume	Q	acfm	5,723	6,047	12,195	6,336	6,149
SUMMARY - Bulk VPD = 0.31 kPa Tons = 30 SHR = -0.08							

The values used to compute airflow and tons are altitude, transpiration/irrigation rate, lighting watts/Btu/h, and the ***canopy-entering air*** temperature and humidity.

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Figure 7-VPD Calculating Table

Controlled Environment Agriculture (CEA)

By: Walter Stark Consulting

VAPOR PRESSURE TABLE

ROOM OR LEAF °F	ROOM RELATIVE HUMIDITY %																															LEAF %	ROOM OR LEAF °F
	40%	41%	42%	43%	44%	45%	46%	47%	48%	49%	50%	51%	52%	53%	54%	55%	56%	57%	58%	59%	60%	61%	62%	63%	64%	65%	66%	67%	68%	69%	70%	100%	
	VAPOR PRESSURE kPa																																
95	2.25	2.31	2.36	2.42	2.48	2.53	2.59	2.65	2.70	2.76	2.81	2.87	2.93	2.98	3.04	3.10	3.15	3.21	3.26	3.32	3.38	3.43	3.49	3.55	3.60	3.66	3.71	3.77	3.83	3.88	3.94	5.63	95
94	2.18	2.24	2.29	2.35	2.40	2.46	2.51	2.56	2.62	2.67	2.73	2.78	2.84	2.89	2.95	3.00	3.06	3.11	3.17	3.22	3.27	3.33	3.38	3.44	3.49	3.55	3.60	3.66	3.71	3.77	3.82	5.46	94
93	2.12	2.17	2.22	2.28	2.33	2.38	2.43	2.49	2.54	2.59	2.65	2.70	2.75	2.80	2.86	2.91	2.96	3.02	3.07	3.12	3.17	3.23	3.28	3.33	3.39	3.44	3.49	3.54	3.60	3.65	3.70	5.29	93
92	2.05	2.10	2.15	2.21	2.26	2.31	2.36	2.41	2.46	2.51	2.56	2.62	2.67	2.72	2.77	2.82	2.87	2.92	2.97	3.03	3.08	3.13	3.18	3.23	3.28	3.33	3.39	3.44	3.49	3.54	3.59	5.13	92
91	1.99	2.04	2.09	2.14	2.19	2.24	2.29	2.34	2.39	2.44	2.49	2.54	2.59	2.64	2.68	2.73	2.78	2.83	2.88	2.93	2.98	3.03	3.08	3.13	3.18	3.23	3.28	3.33	3.38	3.43	3.48	4.97	91
90	1.93	1.98	2.02	2.07	2.12	2.17	2.22	2.26	2.31	2.36	2.41	2.46	2.51	2.55	2.60	2.65	2.70	2.75	2.79	2.84	2.89	2.94	2.99	3.04	3.08	3.13	3.18	3.23	3.28	3.32	3.37	4.82	90
89	1.87	1.91	1.96	2.01	2.05	2.10	2.15	2.19	2.24	2.29	2.33	2.38	2.43	2.47	2.52	2.57	2.61	2.66	2.71	2.76	2.80	2.85	2.90	2.94	2.99	3.04	3.08	3.13	3.18	3.22	3.27	4.67	89
88	1.81	1.86	1.90	1.95	1.99	2.04	2.08	2.13	2.17	2.22	2.26	2.31	2.35	2.40	2.44	2.49	2.53	2.58	2.62	2.67	2.71	2.76	2.81	2.85	2.90	2.94	2.99	3.03	3.08	3.12	3.17	4.52	88
87	1.75	1.80	1.84	1.88	1.93	1.97	2.02	2.06	2.10	2.15	2.19	2.24	2.28	2.32	2.37	2.41	2.45	2.50	2.54	2.59	2.63	2.67	2.72	2.76	2.81	2.85	2.89	2.94	2.98	3.02	3.07	4.38	87
86	1.70	1.74	1.78	1.83	1.87	1.91	1.95	2.00	2.04	2.08	2.12	2.17	2.21	2.25	2.29	2.34	2.38	2.42	2.46	2.51	2.55	2.59	2.63	2.67	2.72	2.76	2.80	2.84	2.89	2.93	2.97	4.25	86
85	1.64	1.69	1.73	1.77	1.81	1.85	1.89	1.93	1.97	2.02	2.06	2.10	2.14	2.18	2.22	2.26	2.30	2.34	2.39	2.43	2.47	2.51	2.55	2.59	2.63	2.67	2.71	2.76	2.80	2.84	2.88	4.11	85
84	1.59	1.63	1.67	1.71	1.75	1.79	1.83	1.87	1.91	1.95	1.99	2.03	2.07	2.11	2.15	2.19	2.23	2.27	2.31	2.35	2.39	2.43	2.47	2.51	2.55	2.59	2.63	2.67	2.71	2.75	2.79	3.98	84
83	1.54	1.58	1.62	1.66	1.70	1.74	1.77	1.81	1.85	1.89	1.93	1.97	2.01	2.04	2.08	2.12	2.16	2.20	2.24	2.28	2.31	2.35	2.39	2.43	2.47	2.51	2.55	2.58	2.62	2.66	2.70	3.86	83
82	1.49	1.53	1.57	1.61	1.64	1.68	1.72	1.75	1.79	1.83	1.87	1.90	1.94	1.98	2.02	2.05	2.09	2.13	2.17	2.20	2.24	2.28	2.31	2.35	2.39	2.43	2.46	2.50	2.54	2.58	2.61	3.73	82
81	1.45	1.48	1.52	1.55	1.59	1.63	1.66	1.70	1.73	1.77	1.81	1.84	1.88	1.92	1.95	1.99	2.02	2.06	2.10	2.13	2.17	2.20	2.24	2.28	2.31	2.35	2.39	2.42	2.46	2.49	2.53	3.61	81
80	1.40	1.43	1.47	1.50	1.54	1.57	1.61	1.64	1.68	1.71	1.75	1.78	1.82	1.85	1.89	1.92	1.96	1.99	2.03	2.06	2.10	2.13	2.17	2.20	2.24	2.27	2.31	2.34	2.38	2.41	2.45	3.50	80
79	1.35	1.39	1.42	1.46	1.49	1.52	1.56	1.59	1.62	1.66	1.69	1.73	1.76	1.79	1.83	1.86	1.90	1.93	1.96	2.00	2.03	2.07	2.10	2.13	2.17	2.20	2.23	2.27	2.30	2.34	2.37	3.39	79
78	1.31	1.34	1.38	1.41	1.44	1.47	1.51	1.54	1.57	1.61	1.64	1.67	1.70	1.74	1.77	1.80	1.83	1.87	1.90	1.93	1.97	2.00	2.03	2.06	2.10	2.13	2.16	2.19	2.23	2.26	2.29	3.28	78
77	1.27	1.30	1.33	1.36	1.39	1.43	1.46	1.49	1.52	1.55	1.58	1.62	1.65	1.68	1.71	1.74	1.77	1.81	1.84	1.87	1.90	1.93	1.96	2.00	2.03	2.06	2.09	2.12	2.16	2.19	2.22	3.17	77
76	1.23	1.26	1.29	1.32	1.35	1.38	1.41	1.44	1.47	1.50	1.53	1.56	1.59	1.62	1.66	1.69	1.72	1.75	1.78	1.81	1.84	1.87	1.90	1.93	1.96	1.99	2.02	2.05	2.08	2.12	2.15	3.07	76
75	1.19	1.22	1.25	1.28	1.30	1.33	1.36	1.39	1.42	1.45	1.48	1.51	1.54	1.57	1.60	1.63	1.66	1.69	1.72	1.75	1.78	1.81	1.84	1.87	1.90	1.93	1.96	1.99	2.02	2.05	2.08	2.97	75
74	1.15	1.18	1.20	1.23	1.26	1.29	1.32	1.35	1.38	1.41	1.43	1.46	1.49	1.52	1.55	1.58	1.61	1.63	1.66	1.69	1.72	1.75	1.78	1.81	1.84	1.86	1.89	1.92	1.95	1.98	2.01	2.87	74
73	1.11	1.14	1.16	1.19	1.22	1.25	1.28	1.30	1.33	1.36	1.39	1.41	1.44	1.47	1.50	1.53	1.55	1.58	1.61	1.64	1.66	1.69	1.72	1.75	1.77	1.80	1.83	1.86	1.89	1.91	1.94	2.77	73
72	1.07	1.10	1.13	1.15	1.18	1.21	1.23	1.26	1.29	1.31	1.34	1.37	1.39	1.42	1.45	1.47	1.50	1.53	1.55	1.58	1.61	1.64	1.66	1.69	1.72	1.74	1.77	1.80	1.82	1.85	1.88	2.68	72
71	1.04	1.06	1.09	1.11	1.14	1.17	1.19	1.22	1.24	1.27	1.30	1.32	1.35	1.37	1.40	1.43	1.45	1.48	1.50	1.53	1.55	1.58	1.61	1.63	1.66	1.68	1.71	1.74	1.76	1.79	1.81	2.59	71
70	1.00	1.03	1.05	1.08	1.10	1.13	1.15	1.18	1.20	1.23	1.25	1.28	1.30	1.33	1.35	1.38	1.40	1.43	1.45	1.48	1.50	1.53	1.55	1.58	1.60	1.63	1.65	1.68	1.70	1.73	1.75	2.50	70
69	0.97	0.99	1.02	1.04	1.07	1.09	1.11	1.14	1.16	1.19	1.21	1.23	1.26	1.28	1.31	1.33	1.36	1.38	1.40	1.43	1.45	1.48	1.50	1.52	1.55	1.57	1.60	1.62	1.65	1.67	1.69	2.42	69
68	0.94	0.96	0.98	1.01	1.03	1.05	1.08	1.10	1.12	1.15	1.17	1.19	1.22	1.24	1.26	1.29	1.31	1.33	1.36	1.38	1.40	1.43	1.45	1.47	1.50	1.52	1.54	1.57	1.59	1.61	1.64	2.34	68
67	0.90	0.93	0.95	0.97	0.99	1.02	1.04	1.06	1.08	1.11	1.13	1.15	1.17	1.20	1.22	1.24	1.27	1.29	1.31	1.33	1.36	1.38	1.40	1.42	1.45	1.47	1.49	1.51	1.54	1.56	1.58	2.26	67
66	0.87	0.89	0.92	0.94	0.96	0.98	1.00	1.03	1.05	1.07	1.09	1.11	1.13	1.16	1.18	1.20	1.22	1.24	1.27	1.29	1.31	1.33	1.35	1.38	1.40	1.42	1.44	1.46	1.48	1.51	1.53	2.18	66
65	0.84	0.86	0.89	0.91	0.93	0.95	0.97	0.99	1.01	1.03	1.05	1.08	1.10	1.12	1.14	1.16	1.18	1.20	1.22	1.24	1.26	1.29	1.31	1.33	1.35	1.37	1.39	1.41	1.43	1.45	1.48	2.11	65

1. **Using the grower's specified conditions, select the cell where the canopy temperature and humidity converge (for example, 80°F/60% converge at 2.10 kPa, canopy vapor-pressure).**
2. **Select the leaf vapor-pressure in the 100% RH column, using the measured or anticipated LST. For example, for an LST of 82°F, the leaf VP is 3.73 kPa.**
3. **Subtract the canopy VP from the leaf VP to obtain the actual VPD (3.73 – 2.10 = 1.63 kPa).**

