# An Analysis of the Effects of Employing Split-Cycle Dehumidifiers and Water-Cooled Lights on HVAC System Requirements for Indoor Cultivation Facilities

**Robert W. McCullough, PhD.**

**BioPhotonic Systems, LLC**
**Sausalito, CA**

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## 1.0 Introduction

With the dramatic growth of the cannabis industry many new indoor cultivation facilities are being built. In many cases the facility designs are very intricate with many interlocking systems such as heat, air conditioning, dehumidification, lighting, irrigation, nutrient supply, pest control, etc. There is a wide range of planning and engineering going into the new facilities.

Unfortunately many systems are assembled on an "ad-hoc" basis as follows:

1. Locate a licensable facility.
2. Install electricity to support lights.
3. Install lights.
4. Install an air conditioner to remove the heat load from the lights.
5. Install an irrigation system.
6. Install plants.
7. When the plants start to grow note insufficient humidity control and add a dehumidifier inside the facility.
8. When the air conditioner cannot handle the added load from the dehumidifier output, add additional air conditioner capacity.

While the resulting facility will operate acceptably, understanding some of the processes involved and how they interact could produce substantial energy savings.

This paper will look at the impact of two technologies on the overall energy cost for operating a cultivation facility: 1. Split-cycle dehumidifiers and 2. Water-cooled LED lighting systems. We will analyze a cultivation facility with a 10,000-watt lighting source and compute the energy costs for each option.

We will use SI units throughout:

- Energy is measured in kilojoules (1 kJ = 1000 J = .95 BTU).
- Power is measured in kilowatts (1kW = 1000 Watts = 3414 BTU/hr.)
- Temperatures will be in °C. (23 °C = 77 °F)
- Enthalpy is measured in kJ/kg (1 kJ/kg = .43 BTU/lbm)

## 2.0 Differences between cultivation facilities and other types of facilities.

HVAC engineering is a mature discipline with many large engineering firms and equipment manufacturers to handle a wide variety of applications including housing, offices, grocery stores, florists, etc. There are two significant aspects of horticultural cultivation facilities that make designing an HVAC system for them slightly different: the nature of the load on the system from the lights and the high humidity and water vapor extraction rates. Let's look at each individually.

First we consider the lighting. In order to grow crops successfully indoors a substantial fraction of the photon flux from the sun must be provided. Currently, there are mainly two technologies in use today: high-pressure sodium (HPS) discharge lights and light emitting diode (LED) lights. These light systems share some common features and also some distinctive differences.

The common factor for both lighting systems is the operating efficiency in terms of photons delivered per unit of energy input to the lights. In both instances the lights generate a maximum of about 40% photon energy out of the electrical input energy. The balance is waste heat that occurs at the moment the light is turned on. This means that a 1000-watt light fixture produces about 600 watts of heat that must be removed from the facility in order to maintain the temperature level. This is true for lights used for illumination in houses and offices as well, but the density of lights necessary for illumination is much lower than that required for powering plant growth. Of the 400 watts of photon flux produced by the lights, only a fraction of that power will fall on plant canopy. A substantial portion will fall on the floors, growth medium, walls and equipment where the photons are instantly converted into heat. A reasonably well-designed cultivation facility may see half of the photons landing on the plant canopy. So the net result is that of the 1000 watts of electricity input only 200 watts are converted to photons that the plants use. The 800-watt balance goes into heat.

## 3.0 Lighting Systems and Heat Loads

There are significant differences between electric discharge lights such as HPS and LED lights. One difference is in the way in which the waste heat is generated and dissipated within the light. For an HPS light the radiation originates in a hot (10,000 K) plasma column sustained by an electric discharge. This column produces a complicated spectrum that contains radiation from the ultraviolet to the far infrared. This output includes substantial energy within the Photosynthetically Active Region (PAR) between 400 nm and 700 nm (blue to red) of the spectrum. The discharge is contained inside a glass or quartz envelope, which operates at a high temperature and radiates substantial energy, much like a heat lamp. So the waste heat from an HPS fixture is dissipated by convective heat transfer from the envelope surface to the surrounding air as well as by radiation from the envelope to the environment.

LED lights, by contrast, generate the light output in a semiconductor junction, which is a small piece of exotic semiconductor 1-2 mm in size. The spectral output from an LED is confined to a narrow spectral region 10-20 nm wide centered about a selectable center wavelength. Thus most LED grow lights have a blend of wavelengths covering the PAR region. The heat dissipated occurs across the semiconductor junction and is conducted away to a ceramic or metallic base. This base is mounted to a conductive plate that conducts the heat away to the environment. Most LED fixtures dump this heat into the surrounding air, but a few fixtures are water-cooled and dump the heat into a coolant circulated through internal passages in the fixture.

The key difference between the heat dissipation mechanisms of HPS and LED fixtures then is the manner in which the waste heat is dissipated. LED lights, particularly water-cooled lights, provide an opportunity to collect the heat for use in other aspects of the operation. A part of the radiated energy from HPS lights falls on the canopy where it is absorbed by the leaves, heating them up. While this additional heat provides additional driving force for transpiration, it can also overwhelm the leaf's cooling capacity. Since the heat flux and the photon flux are coupled in HPS fixtures, this means that it is impractical to increase the PAR flux above a certain level without damaging the plants. LED fixtures suffer no such limitation and the PAR levels can be increased to high levels without overheating the leaves as long as the waste heat is removed from the cultivation environment.

## 4.0 Humidity Effects

Next we consider what happens to the 200 watts of power that goes into producing a photon flux that is absorbed by the plants. Most people assume that the majority of photons absorbed by the plants are used in photosynthesis to produce organic material that becomes plant tissue. However, this is not correct. The plants only use 5-10% of the absorbed photons for photosynthesis. The balance is absorbed by the plants and converted into heat within the leaf. In order for the plant not to overheat and die, it must dissipate this heat, which it does by evaporative cooling through pores called stomata in the lower surface of the leaf and convective cooling to the surrounding air. The evaporative cooling process is called transpiration and is like perspiration in humans. Fortunately, it takes a lot of energy to evaporate water, so the plants are able to remain cool by transpiring relatively small amounts of water.

In essence the leaf is converting liquid water to water vapor. Essentially the balance of the energy in the form of photons is used to generate water vapor, or “boil” water. The side benefit of this cooling process is that, in drawing water up through the root and stem to stay cool, the plant imports nutrients through minerals that are dissolved in the water. As a result, the photon flux is mostly used to pump nutrients into the plant and, in fact, much more of the photon flux is used for this function than is used for photosynthesis.

As far as the cultivation facility is concerned, this flow of water vapor into the ambient air will quickly increase the humidity to unhealthy levels unless is removed, hence the need for dehumidifiers. We will discuss how dehumidifiers work in detail later, but for now but a point worth noting is that each plant in a cultivation facility will convert ½ to 1 liter of liquid water to water vapor per day. Each liter of water vapor has about 2257 kJ of energy in it, which is the energy level that a dehumidifier must extract. In simple term, if the cultivation facility is sealed, then every drop of water absorbed by the plant root system each day ends up in the form of water vapor in the ambient air.

Most facilities have split cycle air conditioning systems in which the heat removed from the air is dumped to the exterior of the cultivation facility through an external condenser coil outside the facility. This setup eliminates the need to duct large quantities of facility air to an integral unit, perhaps mounted on a rooftop. The evaporator is located inside the facility and refrigerant is pumped to the external condenser unit, which usually contains the compressor as well.

It is natural to ask whether such a configuration could also dehumidify. (Or conversely if a dehumidifier could also work to cool the facility air):

***"Can a split-cycle air conditioner also work as a dehumidifier?"***

The answer is that a few are capable of doing this but, most are not. The reason is that when air enters the chilling fan coil, it must be cooled below the dew point to remove moisture. Most units have such a large airflow that the temperature-drop never gets that low. Most air conditioners have fairly large air flow rates across the coil in order to maximize heat removal rate. The large airflow rate is beneficial for heat transfer and if all you want to do is cool air, that is fine. But if you want to condense water, the air must be chilled below the dew point. To do this requires lowering the flow rate of the air that so it can be chilled below the dew point to allow water to condense. In addition, provisions must be made to collect the condensate. In dehumidifier units designed to do this, the air is usually pulled into the heat exchanger. If the air is pushed through the heat exchanger units, as in most air conditioners, the condensate is entrained into the exiting airflow in the form of water drops blown out the exit that are difficult to collect.

***"Can a split-cycle dehumidifier also cool the facility?"***

This is the opposite question to the one above, and "yes" is the short answer. In order to condense water from the air, it must be chilled to below the dew point by removing heat energy from the air stream. In a conventional dehumidifier where the compressor, evaporator and condenser are located in the same enclosure, this removed heat is added back into the air stream. The heat that results from the work of the compressor is also added to the airstream.

However, in a split-cycle dehumidifier, this heat is dumped outside the facility, leaving a stream of cool air that is injected back into the environment. This removal of sensible heat from the facility air effectively cools the facility. Split cycle dehumidifiers often claim a "cooling credit", which represents the heat difference between the exit air stream and the desired temperature set point. For most systems, this set point is given for residential ambient comfort conditions of about 18.3 °C (65 °F) and 40% RH. This credit is actually higher when the ambient conditions are those of a cultivation facility: 23.9- 26.7 °C (75-80 °F) and 50% RH.

In the next section we delve into the operation of dehumidifiers from a thermodynamic frame of reference to understand in detail how these considerations affect the operation and efficiency of cultivation facilities. Appendix A also presents some further analysis based on two commercially available dehumidifier systems.

**The process of dehumidification**

We now consider how dehumidifiers work and how their functioning impacts the cultivation facility environment.  To do this we need to talk about air/water vapor mixtures.  Ambient air contains water vapor in varying amounts from none (totally dry) to condensing levels (rain and fog).  The saturation pressure of water vapor at the ambient temperature determines the maximum amount of water vapor in the air.  A dehumidifier functions by cooling ambient air below the saturation point (also known as the dew point) and removing condensed water.  The air at this point is chilled and is often heated back up to ambient temperature.

The thermodynamic properties of air/water vapor mixtures are summarized on a chart in which the water content of the air (kg water/kg dry air) is plotted on the vertical axis and the temperature of the mixture is plotted on the horizontal axis. These charts are known as psychrometric charts and are useful for understanding how dehumidifier systems operate.  Such a chart is shown in figure 1.

In addition to temperature and humidity, the chart also indicates relative humidity or RH (the fraction of water vapor in the air divided by the saturation amount) and enthalpy (a form of internal energy in the mixture).   We now analyze this process for an ambient condition typical of a flowering room of a cultivation facility.

Indicated on figure 1 is a simple dehumidification cycle where humid warm air at 23.9°C (75 °F) and 50% RH (point 1) is converted to cooler drier air at 23.9°C (75 °F) and 39% RH (point 4).   This process happens by first cooling the air to the dew point (point 2) which is 13.1 °C (56 ° F) and 100% RH, at which point moisture starts to condense.  Further cooling going from point 2 to point 3 reduced the absolute humidity ratio from .0096 to .00055 kg H2O/kg DA *( kg. of water per kg. of dry air*) by removing water from the air.  At point 3 the air is still saturated (100% RH) and cool 5.0°C (41 °F).  A reheater then raises the air temperature back up to 23.9 °C where the RH is 29% (point 4 on the chart).  The properties at each point in the cycle are summarized in table 1 below.

Note that the energy removed from the air going from point 1 to point 3 is about 30kJ/kg dry air and the energy required to reheat it from point 3 to point 4 is about 20 kJ/kg dry air.  So 10 kJ/kg of latent heat was removed and 20 kJ/kg of sensible heat were removed going from point 1 to point 3.

There are many ways to dehumidify air but the most commonly employed devices use vapor compression cycles similar to air conditioners or heat pumps.  These devices use evaporator coils to boil refrigerant, removing heat from the air; compressors to compress the refrigerant; and condenser coils to condense the refrigerant vapor and release the heat into the environment. These systems can be self-contained with all the components in a single package or split with the evaporator and condensers located at different positions.

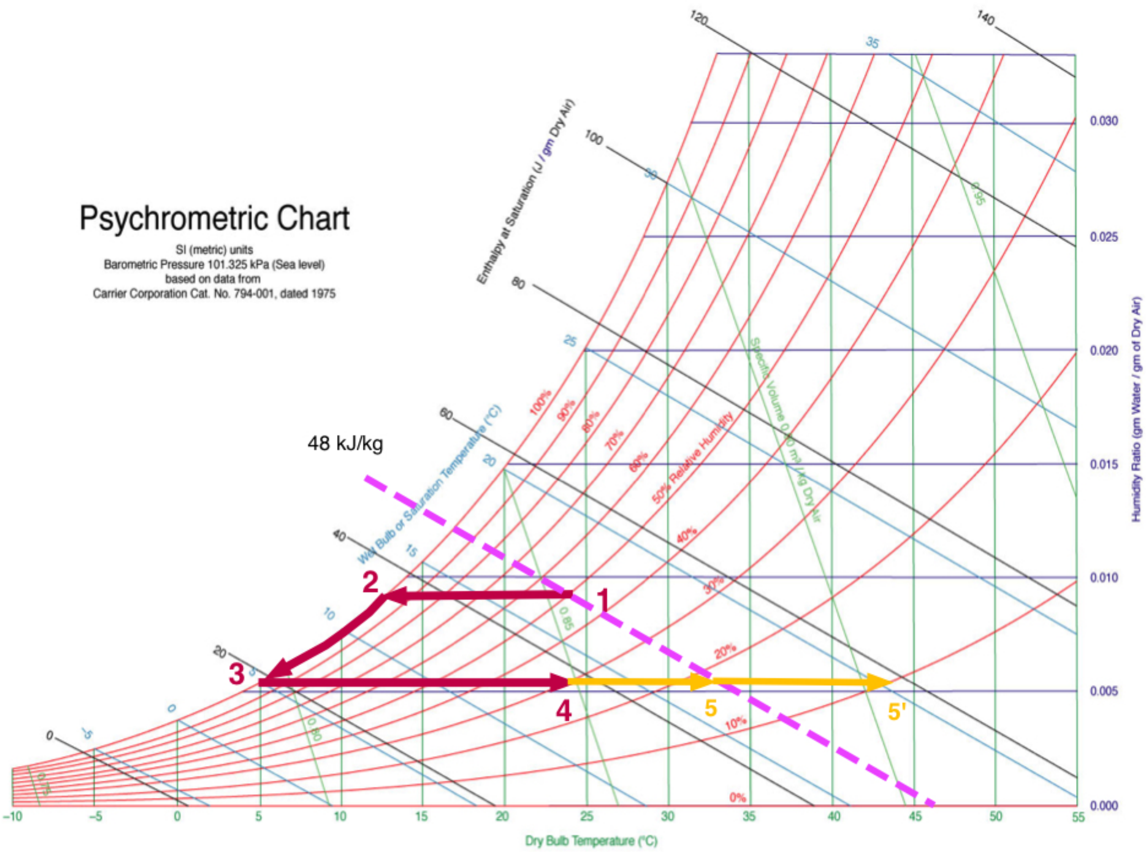


Figure 1. Psychrometric chart in SI units with a dehumidifier cycle.

| Point | T (°C) | RH (%) | Abs. Hum | Enthalpy (kJ/kg) |
|---|---|---|---|---|
| 1 | 23.9 | 50 | 0.00955 | 48.2 |
| 2 | 13.1 | 100 | 0.00955 | 37.2 |
| 3 | 5.0 | 100 | 0.00550 | 18.8 |
| 4 | 23.9 | 29 | 0.00550 | 37.9 |
| 5 | 34.1 | 16 | 0.00550 | 48.2 |
| 5' | 43.8 | 6 | 0.00550 | 58.0 |

Table 1. Data for points on the dehumidification cycle.

If the unit is self-contained, energy balance dictates that all of the energy in the process must reside in the exhaust stream.   Since the heat of vaporization of the water has been recovered, the exit air stream must contain that at well.  This energy will show up in the exhaust air stream.  Figure 1 shows the complete cycle for the case of an integrated dehumidifier where the total energy is added to the airstream. Since the total enthalpy is conserved, the resulting point chart will intercept the initial enthalpy (shown as point 5) on the chart..   This results in a temperature around 34.1 °C (93 °F) for the process we are considering.

Also note that the electrical energy to run the compressor and fans will end up in that air stream as well.  The Coefficient of Performance (COP) for a refrigeration device is the ratio of the energy moved divided by the energy input to run the process.  Most air-conditioners, refrigerators, etc. have a value of COP around 3. That is, it costs about one third of the energy transferred to run the process. (Readers may be familiar with the term Energy Efficiency Rating or EER. This is the COP expressed in ratio of heat to electricity or BTUs/Watt hour.  This is simply the COP multiplied by 3414 BTU/kWh.  So a COP of 3 is equivalent to an EER of 10.24). Commercial dehumidifiers claim a COP of 4, so the electrical energy required to run the process shown in figure 1 is one third of the energy difference between points 1 and 3 or about 10 kJ/kg.  If we add in the electrical energy to run the vapor compression cycle, the total enthalpy in the exhaust stream is about 44 kJ/kg, which corresponds to an exhaust temperature will be even higher.  This is indicated in figure 2 by point 5' or about 43.8°C (110 °F).

Some manufacturers mix in a flow of ambient air to the exhaust stream to reduce this temperature excess, but the net result is that the energy removed by condensing the water (2257 J/l) plus the electrical energy (500 J/l) is dumped into the confined environment of the cultivation facility.  Of course, this must be removed by the air conditioning system, which is already working hard to remove the waste heat from the lights.

In the case of the split-cycle dehumidifier, the condenser is located outside the confines of the cultivation facility so the heat is dumped to an external environment. The air exiting the evaporator is at state 3 or 5°C (41°F) and 100% RH.  This air mixes rapidly with ambient air to create a mixture with reduced humidity. However, in addition to not dumping the heat inside the facility, the split-cycle gets a credit for cooling as well, since its exit air has a temperature well below the ambient facility air.  In this case the credit is equal to the difference in enthalpy between points 3 and 4 or about 20 kJ/kg dry air.  This "cooling credit" goes to offset the air conditioner load.  So, in addition to not burdening the air conditioner more, *the split-cycle actually helps reduce the amount of air conditioning necessary.*

We can now apply these simple considerations to look at the impact of both water -cooling the lights and using a split-cycle dehumidifier on the overall cost to condition the cultivation facility environment.

## I. Analysis of a "Standard" cultivation facility.

Consider first a "Standard" cultivation facility shown schematically in figure 2. The lights, either LED or HPS, are air-cooled and the HVAC system is a conventional split cycle with the evaporator inside and the condenser outside the facility. An additional system provides water and nutrients to the plants and a standard dehumidifier extracts water vapor in the air and removes it from the facility.

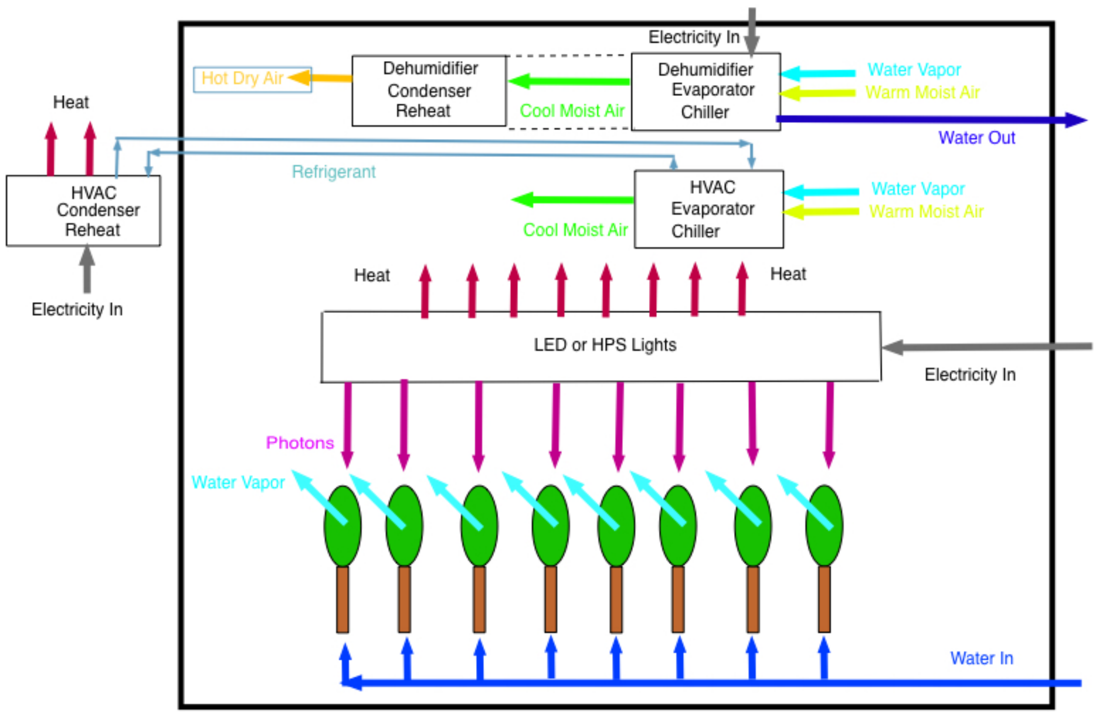


Figure 2. A "Standard" Cultivation Facility

Starting with a conventional cultivation facility installation as shown in Figure 2, lets do some basic energy accounting. We will use as a basis a system with a total of 10 kW lighting installation.

The immediate waste heat from the lights is 6 kW of heat or about 20,500 BTU/hr. We assume that half of the 4 kW balance of energy that goes into photons ends up in the plant canopy. The walls, soil, etc. absorb the other half, converting those photons to heat yielding 2 kW of additional heat. So the starting heat load on the air conditioner is 8 kW.

The dehumidifier has to remove the water vapor that the leaves introduce into the facility by transpiration. Neglecting the few percent of photon energy that is used for photosynthesis, this means that 2 kW of energy in the form of water vapor must be removed (this is roughly equivalent to 7 pints of water per hour or 168 PPD). The electrical power to do this is 1.26 kW for the dehumidifier (taken from an actual system (see Appendix A). This electrical energy is dissipated as heat inside the dehumidifier and also ends up as heat in the facility. The result is that the air conditioner must extract

**8 kW (lights) + 2 kW (water vapor) +1.26 kW (dehum. power) =11.26 kW**

of **heat** energy from the facility.

Now consider electrical energy used. Recalling that the COP of the air conditioner is about 3, this means that 3.75 kW of electricity must be consumed to run the air conditioner. So we must supply

**10 kW (lights) + 3.75 kW (AC) +1.26 kw (Dehumidifier) = 15.01 kW**

of electrical energy to the facility.

## II. Analysis of a "Standard" cultivation facility with a split-cycle dehumidifier.

Now consider what would happen if we simply replaced the integrated dehumidifier with a split-cycle system. The starting heat load on the air conditioner from the immediate waste heat from the lights and the heat from the converted photons is still 8 kW. The split-cycle dehumidifier now dumps the 2 kW of energy from the condensed water and the electrical energy required to run the process outside the cultivation facility, so the net load on the air conditioner is just the load from the lights or 8 kW. However, the exhaust flow from the dehumidifier is now at a lower temperature than that of the ambient air.

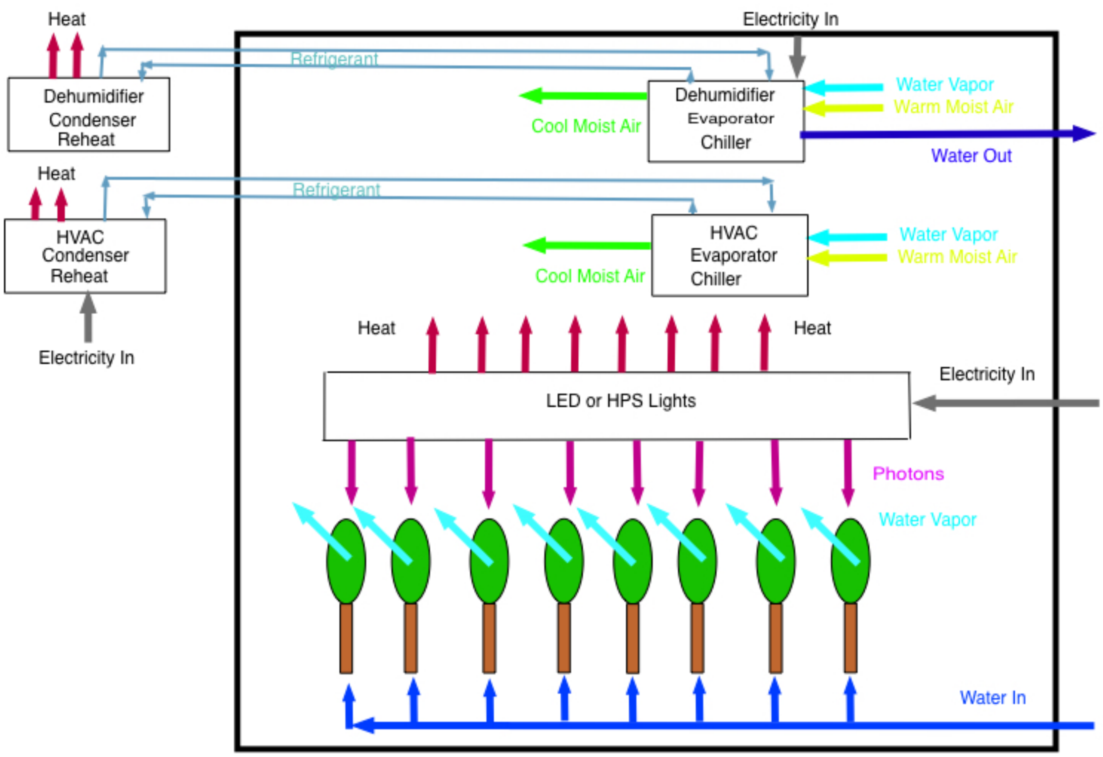


Figure 3. "Standard" Facility with a Split -Cycle dehumidifier,

As a result, the dehumidifier is actually removing sensible heat from the facility as well as condensed water vapor. *So there is a credit to the air conditioning load equal to the difference between the exit air enthalpy and the enthalpy of the ambient air.* This credit depends on the set point of the dehumidifier, but for our example case, this credit is 2.00 kW. This value is taken from an actual commercially offered split cycle dehumidifier. Details are provided in appendix A.

This means that the net air conditioner load is now reduced to 6.0 kW. The electricity required to run this air conditioner load is then about 2.0 kW. The savings are not just in reduced operating costs. The air conditioner unit size can be reduced to half the size and cost of the original facility. This savings is due merely to not making the air conditioner extract the heat dumped by the dehumidifier!

To summarize again, the total heat that must be removed from the facility is

**8.0 kW (lights) – 2.00 kW (Dehum. *Credit*) = 6.00 kW**

Total electricity used:

**10 kW (lights) + 2.00 kW (AC) + 1.14 kW (Dehum.) = 13.14 kW**

That is a 17% reduction in the overall electrical bill.

The value for the power required for the dehumidifier is again extracted from data from a commercially offered unit. The details are presented in appendix A. Note that the split cycle dehumidifier actually operates at a higher efficiency than the integrated unit, resulting in a reduced power requirement.

## III. Analysis of a cultivation facility equipped with water-cooled LED lights.

Now we consider the implications of switching the lights to a water-cooled system. This system is indicated schematically in Figure 4. We see that the waste heat from the lights is removed from the facility directly. It can be dumped into the surrounding air, a body of water or used for heating needs in other parts of the building.

Let's look at the impact on the HVAC system. The first benefit is that the 6 kW of waste heat from the lights is removed immediately from the facility by the light's cooling system. While it is true that pumps and fans are required to operate this system, their energy usage is an order of magnitude less than that required to operate a compressor in a vapor compression system.

So assuming again that half of the photons are converted to heat, the net immediate heat load on the air conditioner is 2 kW.

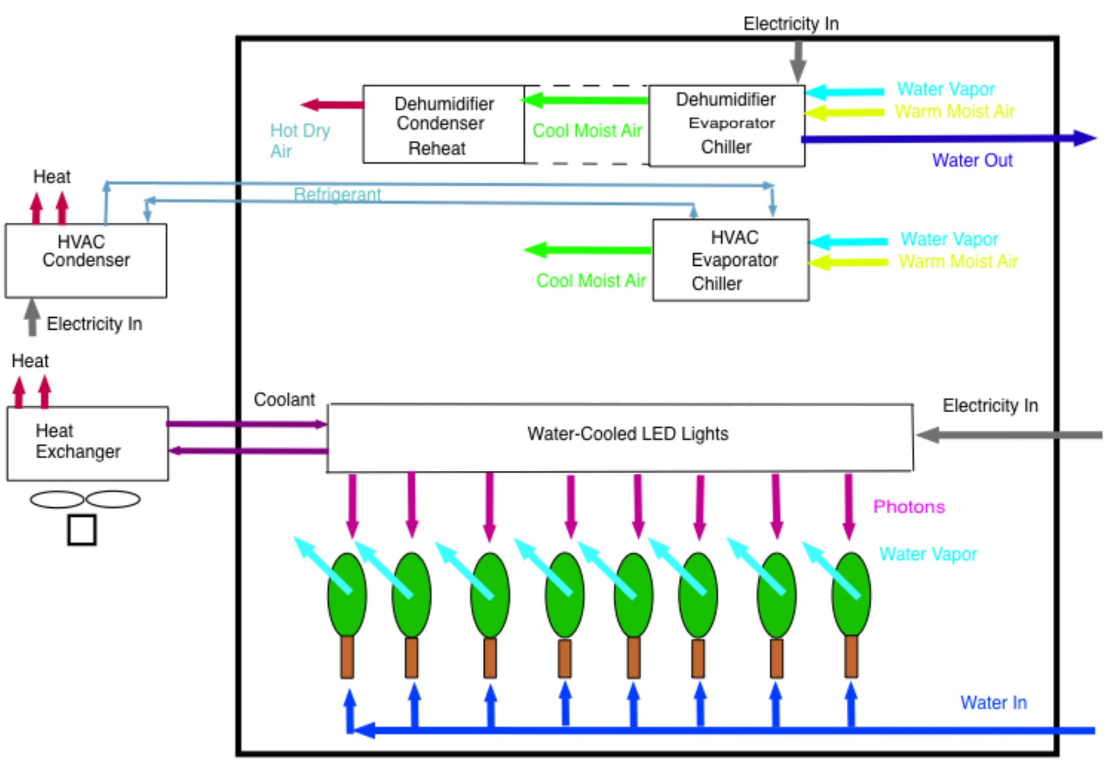


Figure 4. Cultivation facility with water-cooled light.

The operation of the integrated dehumidifier system is identical to the first case. It removes 2 kW worth of condensed water, dumping that heat into the facility along with the 1.26kW from the electricity required to run the dehumidifier.

As a result, the net air conditioning load on the facility is 5.26 kW. The electricity required to run this size air conditioner is 1.75 kW. Total heat removed from the facility:

**5.26 kW (AC) + 6.0 kW (water-cooled lights) = 11.26 kW**

Total electricity used:

**10 kW (lights) +1.75 kW (AC) + 1.26 kW (Dehum.) = 13.01 kW**

Again, the total electrical energy savings is 17%, but the reduction in non-lighting electrical costs has been reduced by 60%! This is substantial.

It is worth noting that although there are some HPS fixtures that are water-cooled, the combination of the high voltages necessary to run the discharges in combination with the heat transfer mechanism makes water cooling for HPS lights problematical.

LED lighting therefore is the only real candidate for water-cooling. Although this adds an additional level of complexity to the cultivation facility, the benefits are substantial. In addition to the energy savings, the heat captured by the cooling system can be used for a variety of purposes. It is possible to operate the LEDs at a reduced temperature compared to an air-cooled system, which yields twin benefits of higher efficiency and longer life for the LEDs themselves.

## IV. Analysis of a cultivation facility equipped with water-cooled LED lights and a split-cycle dehumidifier.

Finally, consider what happens when we combine both the split-cycle dehumidifier and a water-cooled lighting system into the cultivation facility. Such a facility is shown schematically in figure 5 below.

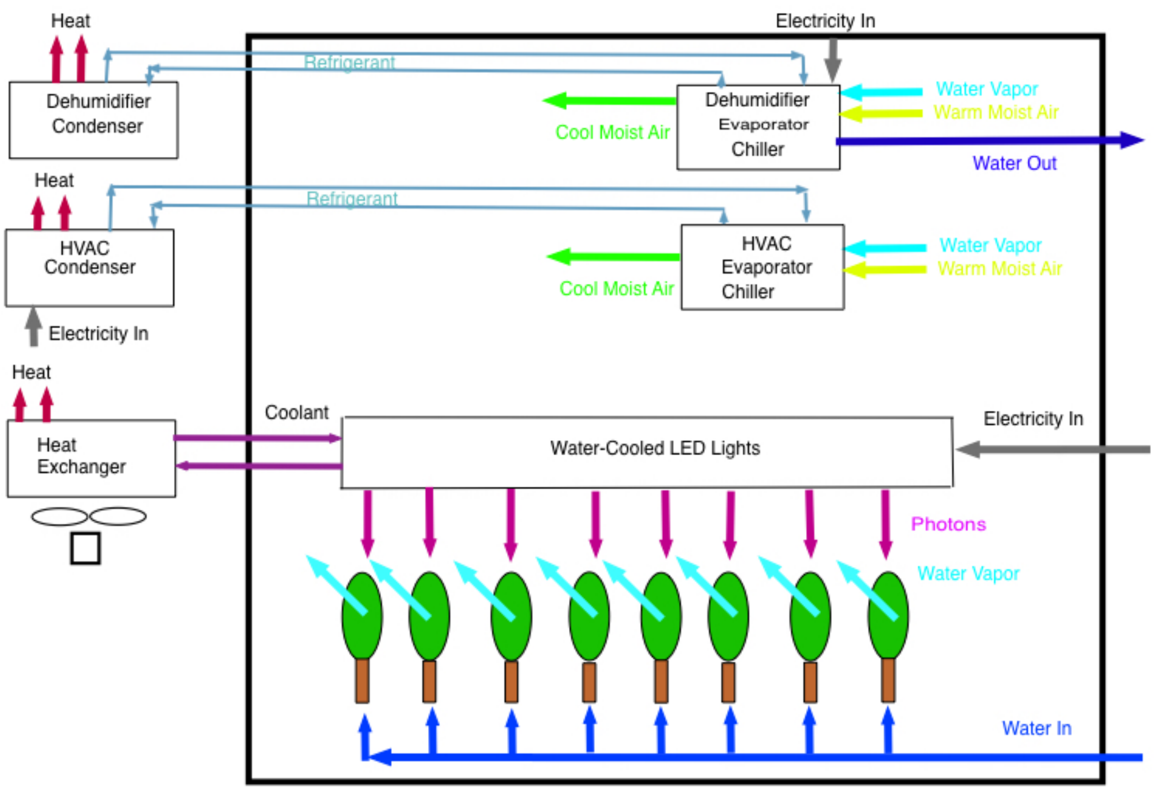


Figure 5. Cultivation Facility with both split-cycle dehumidification and water-cooled lights.

In this case the immediate heat load on the air conditioner is the same as the previous case: 2.0 kW from the photons absorbed by the walls, floors, etc. and converted to heat.

The operation of the split-cycle dehumidifier is the same as in case 2, above. The dehumidifier energy load both from the heat of vaporization and electrical energy is dumped outside the facility. In addition, the dehumidifier provides an additional 2.0 kW of heat removal, reducing the air conditioner load to zero. We note that if the end point of the dehumidifier had been set for slightly higher or lower terminal RH, the humidifier credit would have been slightly larger or smaller but would essentially cover the 2 kW of heat load from the water vapor. If the fraction of photons going to the plant canopy were higher than 50%, the water removal head load would be higher, but the dehumidifier easily handles this additional load by just setting a lower endpoint. This point is discussed in detail in appendix B.

Total heat removed from the facility:

**6.0 kW (water cooled lights) + 2.00 kW (dehumidifier) = 8.00 kW**

Total electricity used:

**10 kW (lights) +1.14 kW (Dehum.) = 11.14 kW**

Here the benefit is reduced operating costs and the elimination of the need for an air conditioner altogether! So the additional complexity of the water-cooling and split cycle dehumidifier is more than offset by obviating the need for the air conditioner completely.

This result is due to the fact that in order for a dehumidifier to operate, it must reduce the temperature of the air below the dew point. This requires a lot of refrigeration as the dew point is typically many degrees below ambient. To actually remove water, the air must be further cooled so that condensate forms on the coils. This further chills the air, removing sensible heat. As discussed before, most standard systems simply waste this cooling and further add insult to injury by dumping the waste heat from the dehumidification process into the facility where it must be removed by the air conditioner.

An additional benefit of this configuration is that the heat is removed from the facility by liquids (coolant and refrigerant), not air. So the massive amount of air ducting, fans and filters present in most cultivation facilities is gone! This reduces capital costs substantially, and also reduces the volume of space needed for the physical plant.

## Summary

These results are summarized in Table 1. Below. We also indicate cost savings for three power rates covering the range encountered in the United States.

| HVAC Comparison | Std System | Std Split Cycle Dehum | Light Rep. Only | Light Rep. Split Dehum. |
|---|---|---|---|---|
| Lights Cooling | Air | Air | Water | Water |
| Dehum System | Standard | Split cycle | Standard | Split Cycle |
| Input Power (kW) | 10.00 | 10.00 | 10.00 | 10.00 |
| Heat (kW) | 6.00 | 6.00 | 6.00 | 6.00 |
| Light (kW) | 4.00 | 4.00 | 4.00 | 4.00 |
| Photons to Water (kW) | 2.00 | 2.00 | 2.00 | 2.00 |
| Photons to Heat (kW) | 2.00 | 2.00 | 2.00 | 2.00 |
| Heat to Facility Direct (kW) | 8.00 | 8.00 | 2.00 | 2.00 |
| Dehum Heat to Facility (kW) | 3.26 | 0.00 | 3.26 | 0.00 |
| Total HVAC Heat Load (kW) | 11.26 | 8.00 | 5.26 | 2.00 |
| Cooling Credit (kW) | 0.00 | 2.00 | 0.00 | 2.00 |
| Net HVAC load (kW) | 11.26 | 6.00 | 5.26 | 0.00 |
| | | | | |
| HVAC Electrical Power (kW) | 3.75 | 2.00 | 1.75 | 0.00 |
| Dehum Elec. Power (kW) | 1.26 | 1.14 | 1.26 | 1.14 |
| Total Power (kW) | 15.01 | 12.99 | 13.01 | 11.14 |
| Power Minus Lights (kW) | 5.01 | 2.99 | 3.01 | 1.14 |
| | | | | |
| Monthly Costs @ $.04/kWh | $216 | $187 | $187 | $160 |
| Monthly Costs @ $.20/kWh | $1,081 | $935 | $937 | $802 |
| Monthly Costs @ $.40/kWh | $2,162 | $1,871 | $1,874 | $1,604 |

Table 1. Summary of the analysis comparing various systems in a cultivation facility (pink highlights = heat energy, blue highlights = electrical energy).

In conclusion, we have analyzed the effects of several strategies to optimize the operation of a cultivation facility by employing measures to remove heat from the facility environment. The majority of the heat load in the facility comes from the lights. Water-cooling them has the immediate benefit of reducing the HVAC load by over half. The energy cost savings can be substantial. In addition the capital cost for a facility can be reduced dramatically. A properly designed facility can dispense with entirely or at least reduce substantially the size of HVAC equipment by using a properly designed dehumidifier in conjunction with water-cooled lights.

**Caveats**

This analysis was run for a specific set of points on the psychrometric chart defining the operating cycle.  Other cycles will yield different results but the conclusions will be the same.   By selecting other dehumidification set of cycle parameters to make the AC load zero for all conditions of relative photon absorption by the crop.  For the water-cooled light case the humidifier AC credit exceeds or equals the total AC load and the system can be run with just a dehumidifier and water-cooled lights, with a portion of the waste heat from the lights providing make-up heat for the facility.

We have not accounted for heating/cooling loads on the facility due to the environmental conditions outside the facility.  These loads are seasonal and can be substantial.  Any detailed HVAC design study must include these effects.

Some facilities make extensive use of ventilation and air exchange with outside ambient air to remove humidity from the facility.  This method largely removes the need for a dehumidifier but introduces potential problems in conditioning the exterior air that is introduced and controlling the entry of pathogens in the facility. Also if CO2 augmentation is used, the excess CO2 is discarded with each cycle of the ventilator.

## Appendix A. QUEST Dehumidifier Operating Conditions.

Figures A-1 and A-2 are data sheets from two dehumidifiers from QUEST, a reputable manufacturer. Performance data is quoted for standard conditions of 80 °F (26.7 °C) and 60% RH. In table A-1 below we summarize the relevant data extracted from the data sheets for two of the QUEST models: the 185 Cool, a split-cycle unit, and the 205 Dual, an integral unit. The split cycle unit gets a cooling credit equal to the sensible cooling of 1.26 kW (4,300 BTU/hr.)

| Design | Split | Integral |
|---|---|---|
| Model | 185 Cool | 205 Dual |
| PPD | 184 | 205 |
| CFM | 406 | 526 |
| Power (kW) | 1.24 | 1.53 |
| Cooling credit (kW) | 1.26 | 0 |
| Efficiency (l/kWh) | 3.1 | 2.7 |
| T1 (°C) | 26.7 | 26.7 |

Table A-1. Quest Dehumidifier Summary

We now convert these parameters to the relevant conditions in the cultivation facility under consideration. We need to make adjustments for the reduced water removal rate of 168 PPD and adjust the cooling credit to reflect the difference between conditions in a cultivation facility as opposed to a living space.

For the reduced water removal rate, we merely scale the power by the ratio of the PPD outputs. This is probably a liberal estimate since many units do not have lower power requirements when operating off design point.

We need the outlet conditions for the split cycle unit in order to compute the cooling credit scaled to our conditions. We can do this by noting that for the ambient conditions assumed, the absolute humidity is .0136 kg H2O/kg dry air. Knowing that 406 CFM is equivalent to .19 kg/sec dry air flow and the 184 PPD is equivalent to .001 kg H2O/sec removal rate yields an outlet airflow With an absolute humidity of .0085 kg H2O/kg DA. The dew point for this condition is 11.4 °C with an enthalpy of 33 kJ/kg DA.

The cooling credit cited in the data sheet corresponds to returning the air to an ambient state of 17.8 °C (65 F) and RH = 66%, a comfortable setting for residential environments for which the unit was originally designed. The four cycle points are summarized in Table A-2 below.

| Point | T (°C) | RH (%) | Abs. Hum | Enthalpy (kJ/kg) |
|---|---|---|---|---|
| 1 | 26.7 | 60 | 0.01359 | 61.3 |
| 2 | 18.5 | 100 | 0.01359 | 52.9 |
| 3 | 11.4 | 100 | 0.00853 | 32.9 |
| 4 | 17.8 | 66 | 0.00853 | 39.4 |

Table A-2. Dehumidifier Cycle Points for the QUEST 185 Cool at Nominal Conditions.

For our application, the enthalpy of the mix at the starting temperature of 23.9°C (75 °F) and .0085 kg H2O/kg DA is about 45.6 kJ/kg. The cooling credit for this higher ambient temperature increases to 2.4 kW for an air flowrate of .19 kg/sec. For the reduced flow rate of our application this is reduced to 2.0 kW. The scaled values used in our calculation in the main part of the text are shown in table A-3.

| Design | Split | Integral |
|---|---|---|
| Model | 185 Cool | 205 Dual |
| PPD | 184 | 205 |
| CFM | 406 | 526 |
| Power (kW) | 1.24 | 1.53 |
| Cooling credit (kW) | 1.26 | 0 |
| ***Scaled to 169 PPD*** | | |
| PPD | 169 | 169 |
| CFM | 373 | 434 |
| Power (kW) | 1.14 | 1.26 |
| Cooling credit (kW) | 2.0 | 0 |

Table A-3. Scaled operating parameters for the split cycle and integral dehumidifiers used in the example calculation.

QUEST
DEHUMIDIFIERS

# Quest 185 Cool

*High-Efficiency Dehumidifiers*

1.877.420.1330
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| Dehumidifier Specifications | |
|---|---|
| **Part Number:** | 4037391 |
| **Blower:** | 406 CFM @ 0.0" WG<br>374 CFM @ 0.2" WG<br>348 CFM @ 0.4" WG |
| **Power:** | 160 Watts @ 80°F and 60% RH |
| **Supply Voltage:** | 115 volt - 1 Phase - 60 Hz |
| **Amps:** | 1.4 |
| **Energy Factor:** | 3.1 L/kWh |
| **Operating Range:** | 56°F Min - 95°F Max<br>(Inlet Air Temperature) |
| **Minimum Performance @ 80°F and 60% RH:** | |
| Water Removal: | 184 Pints/Day |
| Sensible Cooling: | 4,300 BTUs/Hour |
| Efficiency: | 6.6 Pints/kWh |
| **Air Filter:** | MERV-11 Standard Pleat |
| Efficiency: | 65% ASHRAE Dust Spot |
| Size: | 16" x 20" 2" |
| **Optional Air Filter:** | MERV-14, Embossed Pleat<br>(will need filter housing) |
| Efficiency: | 95% ASHRAE Dust Spot |
| Size: | 20" x 24" x 4" |
| **Power Cord:** | 10' - 115 Volt Grounded Plug |
| **Drain Connection:** | 3/4" Threaded NPT |
| Refrigerant Type: | R410A |

| Condensing Unit Specifications | |
|---|---|
| **Part Number:** | 4037392 |
| **Power:** | 1080 Watts @ 80°F and 60% RH |
| **Supply Voltage:** | 115 volt - 1 Phase - 60 Hz |
| **Amps:** | 9.7 |
| **Minimum Circuit Ampacity:**<br>**Maximum Fuse/Breaker Size:** | 20 Amps<br>20 Amps |
| **Operating Range:** | 40°F Min - 110°F Max |
| **Power Cord:** | Hard-Wired |
| Refrigerant Type:<br>Refrigerant Ammount: | R410A<br>42oz |

| Dehumidifier and Condensing Unit Specifications | |
|---|---|
| **Part Number:** | 4033180 |

| Dimensions | Dehumidifier | Condenser | Shipping |
|---|---|---|---|
| Width: | 20.25" | 10" | 35" |
| Height: | 21.75" | 25.5" | 44" |
| Length: | 37.25" | 33" | 44" |
| Weight: | 109 lbs. | 75 lbs. | 225 lbs. |

QUEST
DEHUMIDIFIERS

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Figure A-1. Quest 185 Cool Dehumidifier Data Sheet

# Quest 105, 155, and 205 Dual

*High-Efficiency Dual Air Distribution Dehumidifier*


| Unit: | 4032270 105 Dual | 4031490 155 Dual | 4033060 205 Dual |
|---|---|---|---|
| **Blower:** (Tested with duct collars on) | 257 CFM @ 0.0" WG<br>206 CFM @ 0.2" WG<br>146 CFM @ 0.4" WG | 391 CFM @ 0.0" WG<br>363 CFM @ 0.2" WG<br>337 CFM @ 0.4" WG | 526 CFM @ 0.0" WG<br>495 CFM @ 0.2" WG<br>458 CFM @ 0.4" WG |
| **Power:** | 530 Watts @ 80°F and 60% RH | 920 Watts @ 80°F and 60% RH | 1525 Watts @ 80°F and 60% RH |
| **Supply voltage:** | 115 volt - 1 Phase - 60 Hz. | 110-120 VAC - 1 Phase - 60 Hz. | 110-120 VAC - 1 Phase - 60 Hz. |
| **Current Draw:** | 4.9 Amps | 8.0 Amps | 13.2 Amps |
| **Energy Factor:** | 4.2 L/kWh | 3.5 | 2.7 |
| **Operating Temp:** | 56°F Min - 95°F Max | 56°F Min - 95°F Max | 56°F Min - 95°F Max |
| **Minimum Performance @ 80°F and 60% RH:** | | | |
| **Water Removal:**<br>**Efficiency:** | 105 Pints/Day<br>8.8 Pints/kWh | 155 Pints/Day<br>7.3 Pints/kWh | 205 Pints/Day<br>5.7 Pints/kWh |
| **Air Filter:** | MERV-11 Size: 16" x 20" x 2" | MERV-11 Size: 16" x 20" x 2" | MERV-11 Size: 16" x 20" x 2" |
| **Power Cord:** | 10', 110-120 VAC, Ground | 10', 110-120 VAC, Ground | 10', 110-120 VAC, Ground<br>*This unit requires a dedicated 20A circuit |
| Drain Connection: | 3/4" Threaded NPT | 3/4" Threaded NPT | 3/4" Threaded NPT |
| Dimensions:<br>Width:<br>Height:<br>Length:<br>Weight: | Unit / Shipping<br>20.25" / 24"<br>21.75" / 28.25"<br>38" / 42"<br>140 lbs / 160 lbs | Unit / Shipping<br>20.25" / 24"<br>21.75" / 28.25"<br>38" / 42"<br>140 lbs / 160 lbs | Unit / Shipping<br>20.25" / 24"<br>21.75" / 28.25"<br>38 " / 42"<br>150 lbs / 170 lbs |

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Therma-Stor LLC
4201 Lien Rd
Madison, WI 53704
1-866-933-7486
www.QuestProtect.com
sales@QuestProtect.com

**Figure A-2. – Quest 105, 155 and 205 Dehumidifier Data Sheet**

# Appendix B. Dehumidifier Operation Under Varying Conditions

In the main body of text we showed that it was possible under certain conditions for a split cycle dehumidifier to handle all of the cooling requirements for the cultivation facility in addition to removing the water vapor from the air. We now take a look at the range of conditions over which this is feasible for both the air-cooled light and water-cooled light cases

In order to look at this we consider first a simple example where we wish to remove a *fixed amount of water* from the air per unit time and examine the effect of changing the airflow rate. Again we use a 10,000-watt cultivation facility. As before we assume that the amount of input energy that ends up as water vapor is 20% or 2000 watts worth of boiled water. This equates to 6828 BTU/hr. or 6.8 pints of water per hour (163 pints per day).

We can remove this amount of water in several ways with different T3 settings on our dehumidifier. Figure B-1 below shows what happens when we lower the cycle temperature T3 from 14°C to 7 °C . The amount of water removed per mass of air is just the difference between points 1 and 4. So the lower temperature results in more water removed per mass of air and therefore we can set the air flowrate lower to get the same amount of water removed.

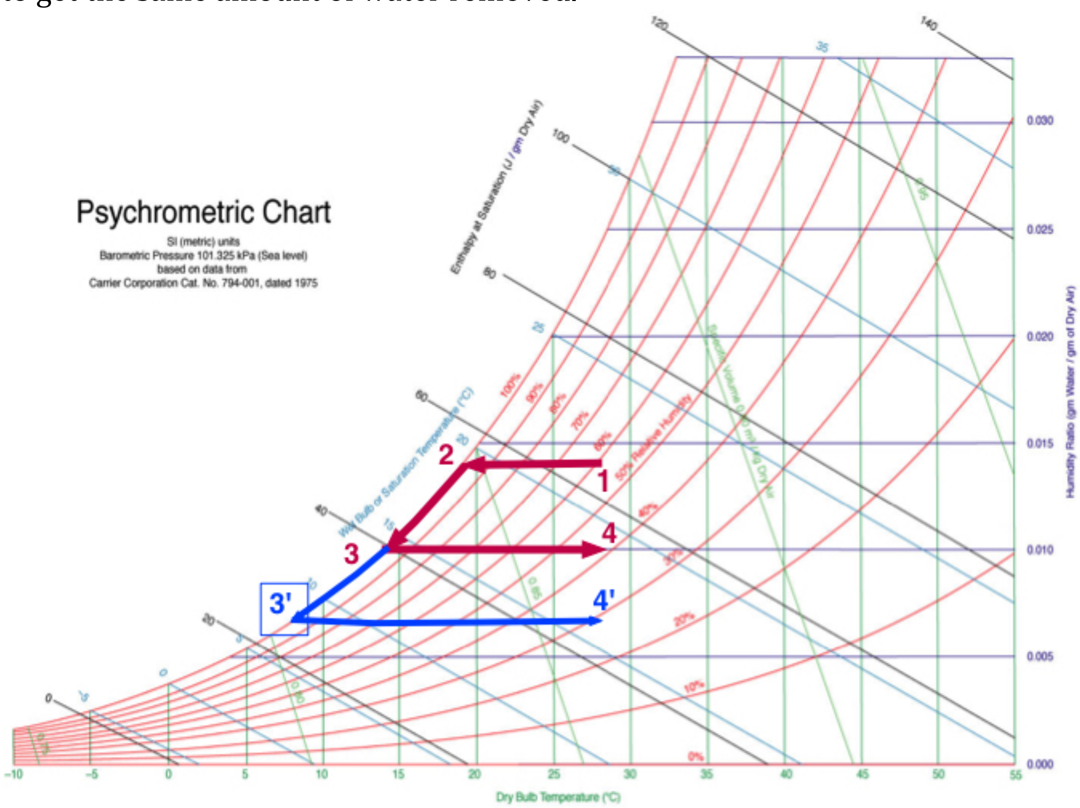


Figure B-1. Effect of lowering the lowest temperature in the dehumidification cycle on heat removal rate.

Table B-1 below shows the result for T3 values from 1.7 °C to 12.8 °C for the case of half the photons converted to water vapor. Now if we compare how much heat is added to the facility by air-cooled and water-cooled lights to the cooling credit from the dehumidifier, we can see that the heating by the lights and cooling by the dehumidifier system offset each other. In fact, for the water-cooled case, if we set T3 to about 3.5 °C, they balance exactly! Note that for the water-cooled lights, make-up heat is easy to supply to be supply for any condition. This is easily accomplished by the addition of an additional fan coil in the cultivation facility to recover some of the extracted heat.

50% Photon Conversion

| | | | | | |
|---|---|---|---|---|---|
| Air T3 (° C) | 10.0 | 7.2 | 4.4 | 1.7 | -1.1 |
| Coolant Inlet T (° C) | 4.4 | 1.7 | -1.1 | -3.9 | -6.7 |
| Coolant Outlet T (° C) | 4.7 | 1.9 | -0.6 | -3.1 | -5.6 |
| Air Flow (kg/sec) | 0.50 | 0.28 | 0.21 | 0.17 | 0.15 |
| Water removal heat rate (kW) | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| Air Sensible heat removal rate (kW) | -5.15 | -2.93 | -2.15 | -1.76 | -1.52 |
| Heat added to room air cooled lights | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 |
| Make up heat required (air cooled lights) | -2.85 | -5.07 | -5.85 | -6.24 | -6.48 |
| Heat added to room water cooled lights | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| Make up heat required (water cooled lights) | 3.15 | 0.93 | 0.15 | -0.24 | -0.48 |

Table A-4. Effects of lowering T3 on cooling requirements 50% Conversion (Heat units are kW)

So far we have shown that for the conditions in the example (20% input energy converted to photons absorbed by the plants and converted to water vapor) and the use of a split-cycle dehumidifier with water-cooled lights, we can select a dehumidifier setting that balances out the heat load in the facility obviating the need for an air conditioner. The question is then what happens if more or less energy is converted to water vapor.

First we note that the range of possible values lies between 40% of the input energy (all the photons absorbed by the canopy to 0% (none of the photons absorbed by the canopy). In practical situations the minimum absorbed would probably be closer to the 20% we used in the example. However, it is possible that in a large facility with the plants close packed that a higher fraction of the photons would be absorbed by the canopy. It would be hard to imagine a facility in which more than 90% of the photons were absorbed by the plant canopy, which would yield a 36% energy flow into water vapor.

Table B-2 shows the results if we use a 90% photon conversion rate. In this case the water-cooled lights, which are now only releasing 0.4 kW of heat into the room can never balance out the cooling credit. Make up heat is always required but as mentioned previously can easily by supplied by recovering a fraction of the latent heat removed by the dehumidifier.

90% Photon Conversion

| | | | | | |
|---|---|---|---|---|---|
| Air T3 (° C) | 10.0 | 7.2 | 4.4 | 1.7 | -1.1 |
| Coolant Inlet T (°C) | 4.4 | 1.7 | -1.1 | -3.9 | -6.7 |
| Coolant Outlet T (° C) | 4.9 | 2.1 | -0.3 | -2.5 | -4.8 |
| Air Flow (kg/sec) | 0.90 | 0.51 | 0.38 | 0.31 | 0.27 |
| Water removal heat rate (kW) | 3.60 | 3.60 | 3.60 | 3.60 | 3.60 |
| Air Sensible heat removal rate (kW) | -9.28 | -5.28 | -3.87 | -3.16 | -2.74 |
| Heat added to room air cooled lights | 6.40 | 6.40 | 6.40 | 6.40 | 6.40 |
| Make up heat required (air cooled lights) | 2.88 | -1.12 | -2.53 | -3.24 | -3.66 |
| Heat added to room water cooled lights | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| Make up heat required (water cooled lights) | 8.88 | 4.88 | 3.47 | 2.76 | 2.34 |

Table A-5. - Effects of lowering T3 on cooling requirements 90% Photon Conversion (Heat units are kW)

It is interesting to note that for the air cooled case (in which an additional 6 kW of heat are released directly into the room) that the dehumidifier system can balance the load if the value of T3 is around 8 °C . However, in order to do this the airflow is increased substantially. The effect of temperature set point on airflow rate is shown for both photon conversion values in figures B-2. Since this rate is driven solely by the water removal rate requirement, it is independent of the type of light used.

The size of the heat exchanger scales roughly as the airflow meaning that the water-cooled case can get by with a heat exchanger that is 1/3 the size of the air-cooled case. This added expense is offset however by the elimination of the requirement for an air conditioner at all in the former case. The airflow requirements are summarized in Figure B-2, which shows the CFM of air required to remove our water vapor load as a function of T3. Note that at 1.7 °C only 600 CFM of airflow is required while at 10°C it takes 1800 CFM of air to get the same amount of water out. Of course the sensible heat removed for the higher airflow is much greater (5.15 kW vs 1.76 kW)

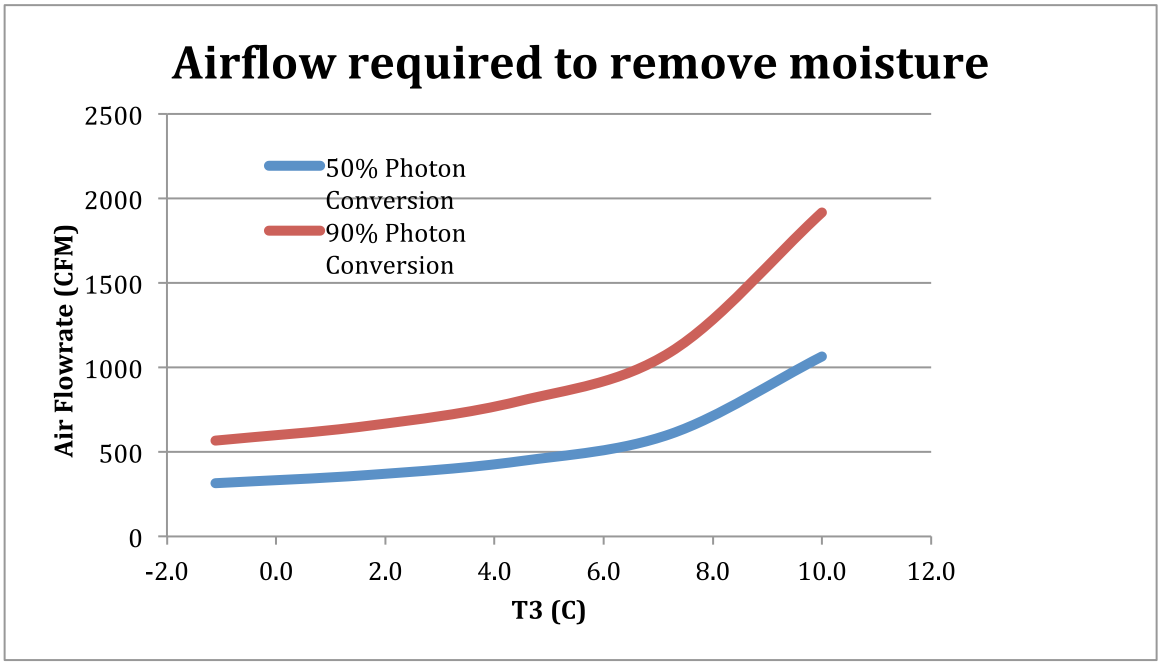


Figure B- 2. Effect of lowering T3 on required airflow rate.

In a dehumidifier system we have the option of controlling the evaporator temperature and the airflow rate. So the question then becomes – "How do we know that we can always adjust the dehumidifier controls to remove the water and balance the heat?" A simple way to look at this question is to realize that when we traverse the psychrometric chart in the vertical direction we are effectively looking at removing water and therefore the latent heat of vaporization. When we traverse the psychrometric chart in the horizontal direction we are effectively looking at removing sensible heat. If instead of plotting the chart as the temperature of the air mix versus the water vapor mass ratio, we could think of it as plotting sensible heat versus latent heat. So if we look at a situation where the ratio of removed water vapor heat to removed sensible heat is 1 to 1 (e.g. 2 kW water heat to 2 kW of sensible heat as in the example then we need only move across the chart along a line with a slope of 1. If the ratio is changed to 3 to 1 (e.g. kW latent heat to 1kW of sensible heat) then the slope steepens to 3:1.

## Appendix C. What happens when the lights go off?

When the lights are off, the input energy to the grow facility is reduced dramatically. The plants, which have been using the photons for photosynthesis and to pump nutrients into the leaves through transpiration, switch off. They do however continue to emit water vapor through their stomata to the environment through a process known as respiration. In this process they are "burning" some of the sugar that they produced using photosynthesis to promote tissue growth.

The chemical reaction for photosynthesis can be described as:

$$6\ CO_2 + 6\ H_2O + 6\ h\nu \rightarrow C_6H_{12}O_6 + 6\ O_2$$

In other words carbon dioxide and water with photons make a sugar and release oxygen. Respiration is the opposite reaction described as:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{heat}$$

In other words, sugar is oxidized using oxygen to produce carbon dioxide, water and heat. The plants release water vapor and some heat into the room when the lights are off.

This water vapor must be removed through dehumidification and if a split cycle dehumidifier is used the net effect is to cool the room. Electrical heaters or other heat sources can supply make-up heat. If an integral dehumidifier is used of course the room is heated by the latent heat removed and the compressor power as discussed above. If water-cooled lights are used and the heat from the lights is stored externally, this heat can be used to offset the dehumidification cooling effects from a split cycle dehumidifier.

The obvious solution is to figure out a way to parse the heat from the dehumidifier to use part of it to reheat the outlet air and to dump the unwanted excess out of the facility. Commercial systems are available that do just this and are used in the application of food storage cooling.

## Appendix D. Optimal System

In this section we discuss what an optimized system would look like that uses the results from the analysis in the main body of the text.

We require a system with the minimum amount of components that effectively removes the heat from the grow facility. The system in figure D-1 does this.

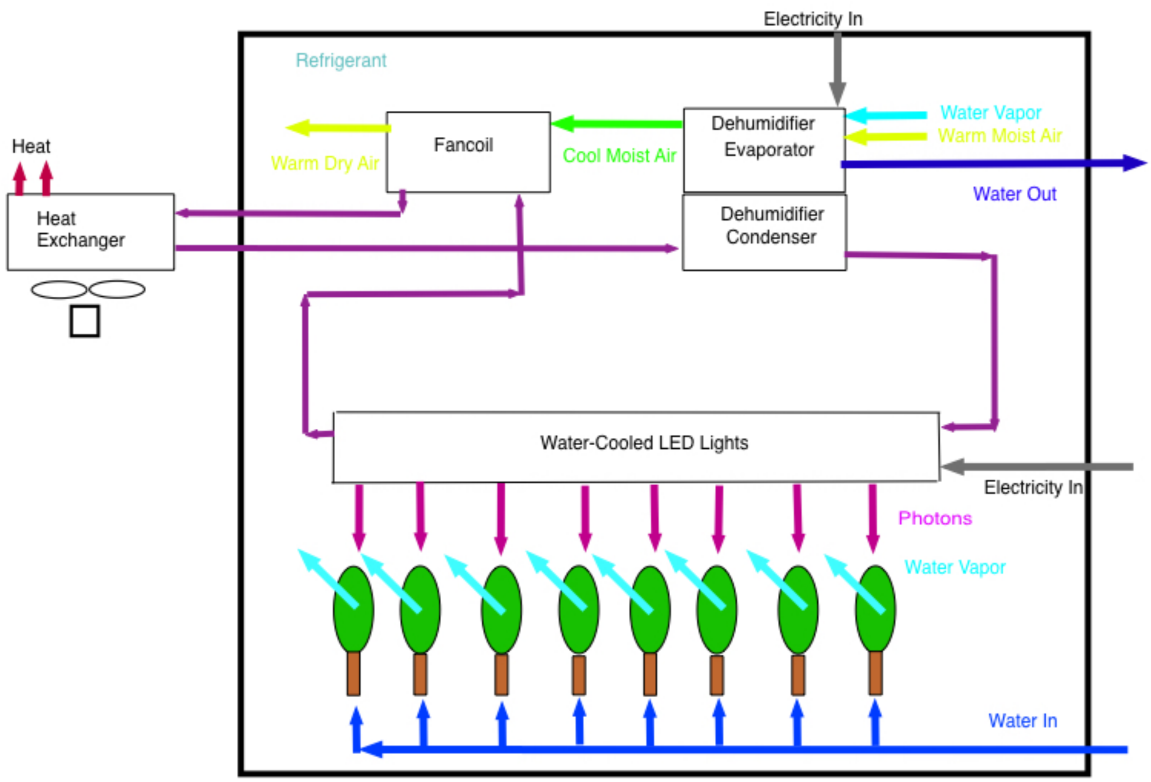


Figure D-1. Optimized integrated system.

Note that we have not used a split-cycle dehumidifier but have achieved the same result by using a water-cooled dehumidifier. The latent heat recovered from the water removal along with the compressor work is transferred to the cooling loop at the lowest point in its path – just after the external heat exchanger. The output flow of coolant from the dehumidifier is then sent through the water-cooled lights where it is heated. Next the coolant goes to a fancoil inside the dehumidifier. This fancoil serves as a reheat exchanger within the dehumidifier and can also add heat to the facility if necessary. Using the compressor heat lets the system operate with the lights off without cooling the room.

There would have to be a damper in the dehumidifier that allowed ambient air to mix with the output of the evaporator to modulate the energy flows but such systems are standard in many dehumidifiers. The coolant leaving the dehumidifier fancoil then exits the cultivation facility for the external heat exchanger where the heat is dumped to ambient.

Note that all the long plumbing lines now only run coolant, not refrigerant. In addition the external heat exchanger can use a water misting system to effectively reduce the outlet temperature to something between the ambient dry bulb and wet bulb temperatures.