HVAC Systems for Controlled Environment Agriculture

Dr. Nadia Sabeh, P.E., LEED AP
Agricultural and Mechanical Engineer
Guttmann & Blaevoet Consulting Engineers
May 21, 2015
HVAC Systems for CEA

• Define HVAC and Climate Control
• Factors that impact climate control needs
• HVAC systems and strategies
What is “HVAC”?

Heating, Ventilation, & Air Conditioning (Cooling)

CLIMATE CONTROL: To create and maintain desirable climate conditions within an enclosed space.

• Temperature (T)
• Humidity (RH, VPD)
• Air Flow (AF)
• Carbon Dioxide (CO2)
Why Climate Control?

1. Grow crops in any climate
2. Provide optimal climate
3. Cultivate year round
4. Control pests (molds, insects, etc)
5. Maximize crop yields
6. Maximize crop quality
7. Maximize profits $$
Design Considerations & System Selection
HVAC Selection Criteria

1. What crop → growing conditions?
2. What system(s) do you need?
3. What equipment size (capacity)?
4. How will equipment be controlled/maintained?
5. What are associated costs?
6. System options/alternatives?
1. Crop

- Growing Conditions
  - Temp, RH, CO2, Air Speed, (Light)
  - Plant/Environment interactions
    - Transpiration: Moisture addition
    - Gas exchange: CO2 removal/O2 addition

- Crop Layout
  - Bench or ground
  - Flat or Vertical
    → airflow and distribution
2. Geographical Location

- Outdoor Conditions (Climate)
  - Air temperature
  - Humidity
  - Solar radiation
  - Wind
3. Grow Structure

- **Type**
  - Greenhouse (GH)
  - Indoor Grow (IG)
    - Vertical Farm (VF), Closed Plant Production System (CPPS)

- **Envelope/Cover**
  - Greenhouse: Glass, plastic → transparent
  - Indoor: Concrete, metal → opaque

- **Size**
  - Floor area and volume
4. Sources of Heat Gains/Losses

- Outdoor Conditions
  - Cover/Envelope
  - Ventilation
- Interior Equipment
  - Lighting
  - Pumps/motors
  - Dehumidifiers
5. Crop Management

• Crop Cycle
  • Growing season
  • Crop rotation

• Controllability
  • Mitigate extremes
  • Tight control (minimize deviations)

• Personnel (complexity)
6. Cost $$

Purchase Cost
Installation Cost
(Design Cost)

Operating Costs
Maintenance Costs

Budget

Payback

Growing Conditions

Yield
Quality

Revenue
Profit

$BOTTOM LINE$
HVAC Systems & Strategies
Climate Control Strategies

1. “Open” – all outside air
2. “Closed” – no outside air
3. “Semi-Closed” – strategic use of outside air
4. Pressurization
   1. Negative Pressure - Exhaust fans pull air into space
   2. Positive - Supply fans push air into space
   3. Neutral - Supply = Exhaust
HVAC Systems for CEA

1. Ventilation
2. Cooling
3. Heating
4. Humidification
5. Dehumidification
6. Air Circulation
7. CO2 Enrichment
8. Climate Management
9. Opportunities & Synergies
1. Ventilation

- Air exchange between inside and outside
- 1st Stage of Cooling
- Benefits
  - Replenish CO2
  - Remove moist air
- Air exchange rate depends on:
  - Outside climate
  - Heating/cooling equipment
- Methods
  1) Mechanical Ventilation (MV)
  2) Natural Ventilation (NV)
1. Ventilation

1) Mechanical Ventilation (MV)
   - *Actively* produced by FANS
   - Fans pull air through vents located at opposite end of greenhouse, along side walls, or in roof
   - Fans deliver/extract air from VF using diffusers at many locations
1. Ventilation

2) Natural Ventilation (NV)
   - *Passively* produced by VENTS in roof & walls
   - Air moves in and out of greenhouse/VF by
     1) buoyancy (“chimney effect”)
     2) wind

Photo courtesy of Dr. Sadanori Sase
1. MV: Design Tip (GH, VF)

Try a Variable Speed Fan (Direct Drive, VFD)

- Control RPM of Variable speed fans based on need
- Small additional cost

1. Use for Summer *and* Winter needs

2. Limit On/Off Cycling
   - Provides more stable conditions
   - Reduces wear and tear

3. Reduce Energy Usage (costs)
   - More efficient operation (not working against high static pressure as when vent opening reduced)
   - Less energy needed to operate fan at lower RPM
   - Reduce energy surges from On/Off cycling
1. NV: Design Tip (GH)

Location/Direction of vent openings is important

- Roof vent toward wind → max velocity of air into GH
- Roof vent away from wind → max uniformity in GH
- Side vent toward wind → more air into GH
- Side vent away from wind → air in prohibited (most out)
1. Ventilation

**Mechanical Ventilation**
- Easy to Control → Turn fans on and off
- Predictable → Know vent rate & flow direction
- Use with wet pad, mist, or fog evap cooling
- Fans at end of greenhouse → Airflow in one direction
- *Needs energy: Energy use by fans (1-1.5 hp/fan)*

**Natural Ventilation**
- Very little energy required to open/close vents
- Uniformity with many vent locations (roof, wall)
- Use with fog or mist evaporative cooling
- Most effective during cold outdoor conditions
- Least effective during hot outdoor conditions
- Dependent on outside conditions
- Difficult to control and predict vent rates
2. Cooling

• Reduce indoor air temperature
  • Remove heat energy within grow space

• Common methods
  a) Ventilation: Remove hot air
  b) Shading: Block heat from entering GH
  c) Evaporative cooling: Transfer heat to water
  d) Refrigerant-based cooling:
     Transfer heat to refrigerant
2. Shading

- Block solar radiation above conditioned space
  - Block 10-60% of solar radiation
  - Can reduce inside temp by 1-3\(^\circ\)C (2-6\(^\circ\)F)
- Shade cloth/screen
  - Permanent or moveable
  - Internal or external
- Shade compounds
  - Outside surface
2. Evaporative Cooling

• Simultaneous cooling and humidification
• Most effective in hot, dry climates
  • Least effective in hot, humid climates
• Common methods (GH)
  1) Pad-and-Fan (Wet wall)
  2) High-Pressure-Fog
  3) Low-Pressure-Mist
2. Pad-and-Fan (GH)

Maximum Effect of
↓ Air Temperature
↑ Water Vapor in Air

All water is vapor → no wet plants or surfaces

3 Non-uniformity
↑ $T_{\text{Air}}$ (1-3°C)
↑ RH (5-15%)

4 Air exits through Fans

Water in wet pad absorbs Sensible Heat from air

Water from holding tank pumped to top of pad
3. Mist & Fog

• Low-pressure-mist
  – Large nozzle orifices (holes)
  – Working pressure < 0.4 MPa (50 psi)
  – Large water droplets (> 100 μm = 0.1 mm)
    \(\rightarrow\) slow evaporation mostly on surfaces (plants, ground, etc)

• High-pressure-fog
  – Small nozzle orifices (holes)
  – Working Pressure = 7-14 MPa (1000-2000 psi)
  – Very small water droplets (5-20 μm)
    \(\rightarrow\) fast evaporation...in the air!
2. Mist & Fog

1. Series of Filters and water softeners removes debris and Ca++ salts

2. Pump delivers water to fog/mist lines

3. Fog line distributes water to nozzles and can be placed virtually anywhere in GH

4. Nozzles inject water directly into greenhouse

5. Natural or Mechanical Ventilation can be used

Nozzle-Plant Distance influences plant wetting
2. Evaporative Cooling (VFs)

- "Direct Evaporative Cooling" (DEC)
  - Evaporate water directly in air to be delivered to grow room
- "Indirect Evaporative Cooling" (IEC)
  - Spray HEX to enhance heat transfer and increase efficiency of equipment
- "Indirect-Direct Evaporative Cooling" (IDEC)
  - Do both
2. Cooling Pad: Design Tip

Higher air velocities aren’t necessarily better

\[
\text{Pad Area (ft}^2\text{)} = \frac{\text{Vent Rate (ft}^3\text{ min}^{-1}\text{)}}{\text{Velocity through pad (ft min}^{-1}\text{)}}
\]

• If you want more cooling, increase pad area, not velocity
  • ↑ Airspeed → smaller pad, but less cooling effect
  • ↓ Airspeed → larger pad, more cooling effect (5-10%)

• Max velocity depends on material type and thickness
  • Corrugated cellulose:
    – Pad thickness = 4” → velocity through pad = 250 ft min\(^{-1}\)
    – Pad thickness = 6” → velocity through pad = 400 ft min\(^{-1}\)
  • Aspen Fiber:
    – Pad thickness = 4” → velocity through pad = 200 ft min\(^{-1}\)

• For dry climates → use 250 ft min\(^{-1}\)
Maximize evaporation w/careful nozzle placement

• Direct fog into air stream (place close to vents)
• The higher the better → minimize water on plants (try 1 m distance from nozzle to plant)
• Mechanical ventilation
  → Stagger lines from vent to fans
• Natural ventilation
  → Roof vent: put fog injection in attic where max heat
## 2. Evaporative Cooling

### Pad-and-Fan Cooling

+ Simple system to operate and control  
+ Easy to predict performance & cooling efficiency  
+ All water is vaporized  
- All evaporation occurs at wet pads (nonuniformity)  
- Cannot use natural ventilation  

→ *Energy use by fans (1-1.5 hp/fan) and pad pump (< 1.0 hp)*

### High-Pressure-Fog Cooling

+ Use with natural or mechanical ventilation  
+ Ability to achieve very uniform greenhouse climate  
- Difficult to determine best operation/control procedures  
- Unevaporated water can increase risk for pathogens  

→ *Energy use by fog pump (> 3 hp) and fans (1-1.5 hp each)*
2. Refrigerant-Based Cooling

- Simultaneous cooling and dehumidification
- Most effective in
  - Hot, humid climates
  - Closed/semi-closed environments (vertical farms)
- Common Systems
  - Ducted
  - Split Systems

“DX” = Direct Expansion
Heat from air transfers to refrigerant, causing it to evaporate and “expand”
2. Refrigerant-Based Cooling

1. **Cooling**: Heat transferred from air to refrigerant in evaporator coil

2. **Dehumidification**: Water vapor condenses on evaporator coil

3. **Heat Rejection**: Heat absorbed by refrigerant is rejected outside grow space
2. Ducted Cooling Systems (GH)

1. Cooling coils outside
   - Air Temperature &
   - Water Vapor in Air

2. Add Outside Air for CO2 control

3. Distribution Ducts
   - Remove hot, moist air &
   - Deliver cold, dry air

Uniform Temperature and Moisture Control
2. Ducted Cooling Systems (VF)

1. Cooling coils outside
   - \( \downarrow \) Air Temperature &
   - \( \downarrow \) Water Vapor in Air

2. Add Outside Air for CO2 control

3. Distribution Ducts
   - Remove hot, moist air &
   - Deliver cold, dry air

Uniform Temperature and Moisture Control
2. Split Cooling Systems

1. Refrigerant absorbs heat, which is rejected to air, ground, or water.

2. Indoor Units circulate air across refrigerant-filled coils.

3. Maximum Effect of:
   - ↓ Air Temperature
   - ↓ Water Vapor in Air

Many indoor units = Uniform temperature and humidity.
2. Refrigerant-Based Cooling

**Ducted Systems**

+ Easy to Control
+ Uniform conditions
+ Best in VFs & CPPS
+ Can also use for heating

- Overhead ducts → Reduce light transmission in GHs
- Control based on 1 thermostat or averaging of Tstats in space
- Requires large volumes of air to be circulated
- Energy Intensive: Large energy use by compressors and fans

**Split Systems**

+ High energy efficiency
+ Can also be used for heating
+ Individual control of indoor units → operation based on local need
+ Ducted or non-ducted → flexible ventilation control

- Overhead/Wall units reduce light transmission
- Need many indoor units to achieve uniformity
- Requires special contractor to install refrigerant piping
3. Heating

• Increase indoor air temperature
  • Add heat energy to grow space
• Reduce RH, but not water vapor content
• Common methods
  a) Hot Air: Add heat to air directly
  b) Hot Water: Heated water to pipes, radiators, and heat exchangers
  c) Radiant: Emit heat to surfaces (leaves)
  d) Refrigerant: Heat pump
  e) Steam: Radiators
3. Heating: Hot Air

- **Types**
  - Unit heaters
  - Duct furnace
  - Electric strip
  - Steam/Hot water coil

- **Distribution**
  - Overhead direct to room air
  - Heat supply air in duct
  - Under bench/floor
3. Heating: Hot Water

• Types
  – Boiler/HW Heater
  – Heat exchanger
  – Renewables: Solar, geothermal

• Distribution
  – Bench/Ground heat
  – Pipe rail
  – Grow pipe
  – Snow pipe
3. Heating: Refrigerant-Based

- Heat Pumps
- Reverse Cycle of Cooling

Outdoor Condensing Units

Indoor Fan Coil Units

Photos courtesy of Dr. Tong Yuxin, and Dr. Toyoki Kozai
2. Heat Pump: Design Tip

“Right-size” the heat pump for best performance

- Max COP: Heat Load/Heat Capacity = 0.6-0.8
- Calculate max heat gains
  - Solar radiation, Wind, Lights
- Don’t overheat
  - Lower Air Temp → Lower Loads → Lower efficiency
- Don’t oversize
  - Higher capacity → Lower efficiency
- Install many HPs
  - Max uniformity, max efficiency
# 3. Heating

### Hot Air
+ Fossil fuels are cheap
+ Can combine w/heat recovery & HEX
+ Can use off-gas for CO2 enrichment
- Non-ducted: Poor circulation
- Non-ducted: Off-gas from indoor furnace contains ethylene and CO
- Ducted: Reduce light transmission in GHs
- Ducted: Fan energy required to distribute hot air

### Hot Water
+ Can use solar thermal, geothermal, heat recovery
+ Heat delivery closer to plants
+ More energy efficient to “move” water than air
- Hot pipes near work zone
- Perimeter heating is far from plants
- More complicated to design and install
3. Heating

**Refrigerant**
+ High energy efficiency
+ Can use same system for cooling
+ Good uniformity with many indoor units
+/− Uses electricity
− Overhead/Wall units reduce light transmission
− Need many indoor units to achieve uniformity
− Requires special contractor to install refrigerant piping

**Radiant**
+ Emits heat directly to plant surfaces
+ Does not require air movement for distribution
− Requires direct line of sight
− Inefficient use of electricity
− Overhead/Wall units reduce light transmission
− Need many radiators to achieve uniformity
4. Humidification

- Add moisture to grow space
  - Reduce plant stress
  - Facilitate nutrient delivery
  - Reduce irrigation
- Best applications
  - Dry climates
  - Refrigerant-based cooling
- Common methods
  a) Evap Cooling (Fog or Mist)
  b) Steam
## 4. Humidification

<table>
<thead>
<tr>
<th>Misting/Fogging/Ultrasonic</th>
<th><img src="Misting/Fogging/Ultrasonic.png" alt="Image" /></th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Can simultaneously cool</td>
<td><img src="Misting/Fogging/Ultrasonic.png" alt="Image" /></td>
</tr>
<tr>
<td>+ Best in dry, warm grow space</td>
<td><img src="Misting/Fogging/Ultrasonic.png" alt="Image" /></td>
</tr>
<tr>
<td>+ Uniform humidification</td>
<td><img src="Misting/Fogging/Ultrasonic.png" alt="Image" /></td>
</tr>
<tr>
<td>- Risk of moisture on plants</td>
<td><img src="Misting/Fogging/Ultrasonic.png" alt="Image" /></td>
</tr>
<tr>
<td>- Poor control</td>
<td><img src="Misting/Fogging/Ultrasonic.png" alt="Image" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Steam</th>
<th><img src="Steam.png" alt="Image" /></th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Can simultaneously heat</td>
<td><img src="Steam.png" alt="Image" /></td>
</tr>
<tr>
<td>+ Best in cold, dry climates</td>
<td><img src="Steam.png" alt="Image" /></td>
</tr>
<tr>
<td>+ Ducted or non-ducted</td>
<td><img src="Steam.png" alt="Image" /></td>
</tr>
<tr>
<td>- Maintenance intensive</td>
<td><img src="Steam.png" alt="Image" /></td>
</tr>
<tr>
<td>- Requires steam piping and delivery (sophisticated design)</td>
<td><img src="Steam.png" alt="Image" /></td>
</tr>
</tbody>
</table>
5. Dehumidification

• Remove moisture from grow space
• Best applications
  – Humid climates (hot or cold)
  – Humidity control is critical
  – Mold control
• Three primary methods
  a) DX Cooling
  b) Dessicant Wheels
  c) Salt-Brine
5. Dehumidification: Design Tip

Don’t forget heating and cooling

• Dehumidification $\rightarrow$ over-cooling/over-heating
• Balance Temp/RH outputs
  • Choose DX system w/multiple, variable speed compressors
  • Offset heat output w/DX cooling
• Don’t dehumidify all air
• Use Psychrometrics!
5. Dehumidification

<table>
<thead>
<tr>
<th>DX Cooling Coil</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Can simultaneously cool</td>
<td></td>
</tr>
<tr>
<td>+ Best in hot, humid climates &amp; VFs</td>
<td></td>
</tr>
<tr>
<td>+ Can collect and reuse condensate</td>
<td></td>
</tr>
<tr>
<td>- Cooling and dehumid. don’t always match</td>
<td></td>
</tr>
<tr>
<td>→ may need to reheat or rehumidify</td>
<td></td>
</tr>
<tr>
<td>- Requires large volumes of air to be circulated</td>
<td></td>
</tr>
<tr>
<td>- Energy Intensive: Large energy use by compressors and fans</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dessicant/Salt-Brine</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Can simultaneously heat</td>
<td></td>
</tr>
<tr>
<td>+ Best in cold, dry climates</td>
<td></td>
</tr>
<tr>
<td>+ Heat production generally cheaper than electricity</td>
<td></td>
</tr>
<tr>
<td>- Cannot collect and reuse condensate</td>
<td></td>
</tr>
<tr>
<td>- Heating and dehumid. don’t always match</td>
<td></td>
</tr>
<tr>
<td>→ may need to recool or rehumidify</td>
<td></td>
</tr>
</tbody>
</table>
6. Air Circulation

• Air movement
  • Enhances gas exchange
  • Prevents condensation on plants

• Methods
  – Horizontal Airflow Fans (HAF)
  – Air Diffusers (Ducted Systems)
7. CO2 Enrichment

• Increase plant growth rate when high light levels

• Ventilation
  – Replenish CO2 to ambient levels

• Combustion byproducts
  – CO2, but also ethylene and CO

• Manufactured: Cylinders, tanks, or bulk
  – Morning light, before ventilation
  – Closed or semi-closed structures w/no ventilation

• Decomposition of biomass

• Exhaust air from commercial/industrial buildings
8. Climate Management

• Control Methods
  – Manual
  – PLC (Programmable Logic Controller)
  – Building Management System

“Monitoring Point”: What is measured.
- T, RH, CO2, etc

“Control Points”: What is controlled
- Fan speed, boiler operation, etc
9. Opportunities & Synergies

• Reductions in
  • Energy use
  • Potable water use
  • Equipment size/capacity
  • Pollution (GHG, CO$_2$e)

{Utility & Operating Costs}
9. Solar Energy

Solar Photovoltaics
(Electricity)

Solar Thermal
(Hot Water)

 Courtesy of Murat Kacira,
University of Arizona
9. Geothermal

Heat Source
Power Production
9. Heat Recovery

Examples:

- Combustion air preheating
- Boiler feedwater preheating
- Power generation
- Space heating
- Water preheating
- Steam generation
9. Co-Gen
(Combined Heat & Power)

Simultaneous Generation of:
Electricity, Chilled Water, Hot Water, (and CO2?)
9. Thermal Storage

Peak electricity shifting
9. Symbiotic Relationships

Gas exchange
Water recirculation
9. System Integration
9. Energy Cost Savings: Design Tip

Choose energy saving materials and equipment

- Reduce heat gains/losses
- Select high-efficiency equipment
- Use renewables
- Use waste streams
- Shift peak energy use
You may ask: “What system is best for me?”

I will respond with my own questions:
1. “What plants do you grow or plan to grow?”
2. “Where is your facility located?”
3. “What type of facility do you have? GH or VF?”
4. “When will you be in production?”
5. “What is your budget? Your desired ROI?”
6. “How do you rank sustainability, and reducing your overall energy, water, and carbon footprint?”

In other words:
There are many factors to consider when designing the HVAC system for your grow facility.
System Design & Analysis

- Load calculations
- Psychrometric analysis
- Advanced energy modeling
- Life Cycle Cost Analysis (LCCA)
- Energy Auditing (existing facilities)

One Size Fits All!
HVAC Systems for CEA

Thank you!!

Dr. Nadia Sabeh, P.E., LEED AP
Agricultural & Mechanical Engineer
Team Leader: Indoor Plant Production Systems
nsabeh@gb-eng.com
www.doctorgreenhouse.com