

**24AG301- APPLIED THERMODYNAMICS AND THERMAL
SYSTEMS IN AGRICULTURAL ENGINEERING**

**UNIT 4 PSYCHROMETRICS AND CONTROLLED
ATMOSPHERE APPLICATIONS**

HANDLED BY

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Methods / technologies for control

Drying Chambers

Drying chambers have different goals: you want to remove moisture from the product (e.g., grains, spices, medicinal plants) under controlled conditions, without damage to product (e.g. color loss, case hardening, nutrient losses). Humidity control is thus central, along with temperature and airflow.

Key considerations

- **Humidity must be low enough** to remove moisture from the product, but not so low (or temperature so high) that it damages or overdries or causes case hardening (surface dries too fast, trapping moisture inside).
- **Airflow** is important, to carry away moist air, replace with drier air; avoid stagnation.
- **Temperature control:** since drying rate depends both on temperature and RH. Too high temperature may degrade product quality.
- **Moisture content of product** at different stages; drying curves often have “constant rate period” then “falling rate period” etc. Humidity control helps manage the falling-rate period effectively.
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Effective control of **humidity in drying chambers** is critical for product quality, energy efficiency, and process speed. The methods and technologies employed largely depend on the required humidity level, temperature, chamber size, and application (e.g., food, pharmaceuticals, industrial materials).

Methods / technologies for controlling humidity in drying chambers

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Effective control of **humidity in drying chambers** is critical for product quality, energy efficiency, and process speed. The methods and technologies employed largely depend on the required humidity level, temperature, chamber size, and application (e.g., food, pharmaceuticals, industrial materials).

The primary technologies for controlling humidity are:

1. Desiccant Dehumidification Systems

These systems use a **hygroscopic material** (a desiccant) to remove moisture directly from the air through adsorption or absorption. They are particularly effective for achieving **very low humidity** levels (down to 1% RH or lower) and can operate well at low temperatures where refrigeration methods become impractical (below freezing dew points).

- **Rotary (Wheel) Desiccant Systems:**
 - A rotating wheel, impregnated with a solid desiccant like **silica gel** or **zeolites**, passes through two separate airstreams.
 - **Process Air:** The moist air from the drying chamber passes through a section of the wheel, and the desiccant **adsorbs** the moisture, returning dry air to the chamber.
 - **Regeneration Air:** A separate, heated airstream passes through the saturated section of the wheel, driving off the collected moisture and venting it outside. This reactivates the desiccant.
- **Liquid Desiccant Systems:**
 - These use a liquid sorbent, often a salt solution like **lithium chloride**, to absorb moisture.

- The liquid flows between a **conditioning chamber** (where it absorbs moisture from the process air) and a **regeneration chamber** (where it is heated to release the moisture and be reconcentrated).

2. Refrigeration and Reheat Systems (Two-Temperature Method)

This is a common method, particularly in commercial and laboratory chambers, for achieving a wide range of controlled humidity.

- **Cooling Coil Dehumidification:** The air is cooled below its **dew point** by passing it over a refrigeration coil. This causes the excess moisture to condense into liquid water, which is then drained out of the chamber, effectively dehumidifying the air.
- **Reheat:** After dehumidification, the air is typically **reheated** to the desired dry bulb temperature before being returned to the chamber.
- **Precise Control (Two-Temperature Method):** In high-precision systems, air may be saturated at a precisely controlled **saturator** (water spray/bubble column) temperature (which dictates the dew point), and then reheated to the desired final temperature. The relative humidity is precisely determined by these two controlled temperatures (dew point and dry bulb).

3. Air Circulation and Purge Methods

These methods focus on introducing dry air and removing saturated air.

- **Controlled Ventilation/Air Exchange:** Moist air is continuously exhausted from the chamber, and fresh, dry air (or conditioned air) is introduced. Controlling the flow rate and the temperature/humidity of the input air allows for humidity regulation.
- **Dry-Air/Nitrogen Purge:** For very low humidity requirements or small chambers, an external source of very dry, compressed air (often dried using a desiccant dryer) or an inert gas like **nitrogen** is slowly bled into the chamber to purge moisture-laden air.

4. Auxiliary Methods and Control

These components are essential for the operation of the primary systems:

- **Sensors and Control:** Accurate **humidity sensors** (Relative Humidity or Dew Point sensors) and **temperature sensors** are vital. A programmable logic controller (**PID controller**) uses feedback from these sensors to automatically adjust the dehumidification, humidification (if needed), heating, and cooling components to maintain the set point.
- **Airflow Management:** Fans and dampers ensure uniform air circulation and distribution, preventing localized humidity or temperature variations within the chamber

Humidity control in cold storage and drying chambers is achieved through dehumidification (for reducing moisture) using desiccant dehumidifiers and humidification (for adding moisture) via humidifiers, with careful management of air flow, insulation, and antechambers to prevent frost, spoilage, and energy loss. The ideal relative humidity (RH) varies by product and function, requiring a balance between moisture prevention and product needs.

Cooling load estimation for crop storage systems

Cooling Load calculation

- heat that leaks into the refrigerated space from the outside by conduction through the insulated walls;
- heat that enters the space by direct radiation through glass or other transparent materials;
- heat that is brought into the space by warm outside air entering the space through open doors or through cracks around windows and doors;
- heat given off by a warm product as its temperature is lowered to the desired level;
- heat given off by people occupying the refrigerated space;
- heat given off by any heat-producing equipment located inside the space, such as electric motors, lights, electronic equipment, steam, and materials handling equipment.

Cooling load estimation for crop storage systems is a critical process to determine the required capacity of the refrigeration equipment. The total cooling load is the sum of all heat gains that must be continuously removed from the cold room.

The total cooling load is typically broken down into several main components:

1. Transmission Load (Heat Leak)

This is the heat transferred through the insulated walls, ceiling, and floor from the warmer surroundings to the cold storage interior.

The calculation uses the formula:

$$Q_{transmission} = U \times A \times (\text{Temp}_{out} - \text{Temp}_{in}) \times \frac{24}{1000}$$

Where:

- Q is the heat load (kWh/day).
- U is the **overall heat transmission coefficient** or U-value of the insulation (W/m²·K).
- A is the **surface area** of the walls, roof, and floor (m²).
- Temp_{out} is the ambient external air or ground temperature (°C).
- Temp_{in} is the desired air temperature inside the room (°C).
- The factor 24/1000 converts W·h to kWh/day.

2. Product Load

This includes two major sources of heat associated with the crops:

a. Product Pulldown Load (Field Heat Removal)

This is the heat that must be removed to cool the newly added produce from its initial temperature (field temperature) down to the storage temperature.

The calculation uses the formula:

$$Q_{pulldown} = m \times C_p \times (\text{Temp}_{enter} - \text{Temp}_{store}) \times \frac{1}{\text{Conversion Factor}}$$

Where:

- Q is the heat load (e.g., kWh/day or BTU/hr).
- m is the **mass of new products** loaded per day (kg).
- Cp is the **specific heat capacity** of the product (kJ/kg·°C).

- Temp_{enter} is the entering temperature of the product (°C).
- Temp_{store} is the final storage temperature (°C).
- A conversion factor (e.g., 3600 for kJ to kWh conversion) is used depending on the units. The required cooling time is critical here to convert the total heat to be removed into a **rate** (load).

b. Respiration Load (Heat of Respiration)

Fresh fruits and vegetables are living organisms and generate heat as a natural by-product of their **respiration** process. This heat must be continuously removed.

The calculation uses the formula:

$$Q_{\text{respiration}} = m_{\text{total}} \times \text{Resp} \times \frac{1}{3600}$$

Where

- Q is the heat load (kWh/day).
- m_{total} is the **total mass of product** in storage (kg).
- Resp is the **respiration heat** of the product at the storage temperature (kJ/kg·h). This value varies significantly by crop type and temperature.
- The factor 1/3600 converts kJ/h to kWh

- Query successful

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- The factor 100024 converts W·h to kWh/day.

2. Product Load

This includes two major sources of heat associated with the crops:

a. Product Pulldown Load (Field Heat Removal)

This is the heat that must be removed to cool the newly added produce from its initial temperature (field temperature) down to the storage temperature.

The calculation uses the formula:

$$Q_{\text{pull down}} = m \times C_p \times (\text{Temp}_{\text{enter}} - \text{Temp}_{\text{store}}) \times \text{Conversion Factor}$$

Where:

- Q is the heat load (e.g., kWh/day or BTU/hr).
- m is the **mass of new products** loaded per day (kg).
- C_p is the **specific heat capacity** of the product (kJ/kg·°C).
- Temp_{enter} is the entering temperature of the product (°C).
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Where:

- Q is the heat load (kWh/day).
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- Resp is the **respiration heat** of the product at the storage temperature (kJ/kg·h). This value varies significantly by crop type and temperature.
- The factor 3600 converts kJ/h to kWh.

3. Infiltration Load (Air Change Load)

This is the heat gain from warm, humid air entering the cold room, typically when doors are opened or through leaks (infiltration). This load depends on the volume of the cold store, the difference in enthalpy (heat content) between the inside and outside air, and the estimated number of **air changes per day (ACH)**.

4. Internal Heat Loads (Service Loads)

These are heat gains generated inside the cold room from operational equipment and personnel:

- **Lighting:** Heat from lamps, calculated based on wattage and daily usage time.
- **Personnel:** Heat generated by people working inside, based on the number of workers, time spent, and heat output per person (which varies with temperature).
- **Equipment:** Heat from running motors for evaporator fans and other machinery like forklifts, or heat from electric defrost cycles
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a. Product Pulldown Load (Field Heat Removal)

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The calculation uses the formula:

$$Q_{\text{pulldown}} = m \times C_p \times (\text{Temp}_{\text{enter}} - \text{Temp}_{\text{store}}) \times \text{Conversion Factor}_1$$

Where:

- Q is the heat load (e.g., kWh/day or BTU/hr).
- m is the **mass of new products** loaded per day (kg).
- C_p is the **specific heat capacity** of the product ($\text{kJ}/\text{kg} \cdot ^{\circ}\text{C}$).
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- **Equipment:** Heat from running motors for evaporator fans and other machinery like forklifts, or heat from electric defrost cycles.

Total Cooling Load and System Sizing

The **Total Cooling Load** is the sum of all calculated loads, often with a **safety factor** (typically 10-30%) added to account for unforeseen variations and errors

$$\text{Total Cooling Load} = \left(\sum Q_{\text{all sources}} \right) \times \text{Safety Factor}$$

Finally, the required **Refrigeration Capacity** (kW or TR) is calculated by dividing the total daily heat load (kWh/day) by the anticipated run time of the refrigeration unit (e.g., 14 to 18 hours per day) to allow for defrosting and off-cycles.

Problem

- Room internal dimensions (net usable inside): 8 m (length) × 5 m (width) × 4 m (height) → volume = 160 m³
- Insulation: sandwich panels (walls, roof) of 80 mm polyurethane, with $U = 0.28 \text{ W/m}^2\cdot\text{K}$
- Floor: insulated slab / or semi-insulated, $U = 0.42 \text{ W/m}^2\cdot\text{K}$
- Outside (design) ambient temperature = 35 °C
- Inside (storage) temperature = 1 °C
- Ground / floor underside ambient = 10 °C
- Mass of produce to be cooled daily (new incoming) = 6,000 kg
- Incoming produce temperature = 25 °C
- Storage (inside) produce temperature = 1 °C
- Specific heat of produce (average) = 3.65 kJ / kg·K
- Respiration heat (average) = 1.9 kJ / kg per day
- Internal loads: 2 workers, each 271 W, working 4 hours per day
- Lighting: 3 lamps of 120 W, used 4 hours per day

- Fan motors: 3 fans, 300 W each, running 16 hours per day
- Defrost heater: 1.5 kW heater, runs 20 minutes $\times$ 3 cycles, with 30% of that heat going into room
- Air infiltration / door / ventilation: assume 5 air changes per day

Steps

1. Transmission / Conduction Load (Walls + Roof + Floor)

Walls:

- Two walls $8 \times 4 = 32 \text{ m}^2$ each $\rightarrow$ total = 64 m^2
- Two walls $5 \times 4 = 20 \text{ m}^2$ each $\rightarrow$ total = 40 m^2
- Roof = $8 \times 5 = 40 \text{ m}^2$
- Floor = $8 \times 5 = 40 \text{ m}^2$

So:

- Walls + Roof area = $64 + 40 + 40 = 144 \text{ m}^2$
- Floor area = 40 m^2

We treat roof + walls with $U = 0.28 \text{ W/m}^2\cdot\text{K}$; floor with $U = 0.42 \text{ W/m}^2\cdot\text{K}$ (because underside difference is smaller or insulation less effective).

Walls + Roof conduction

Use formula:

$$Q_{wr} = U \times A \times (T_{outside} - T_{inside})$$

Plug in:

- $U = 0.28$
- $A = 144 \text{ m}^2$
- $\Delta T = (35^\circ\text{C} - 1^\circ\text{C}) = 34 \text{ K}$

So:

$$Q_{wr} = 0.28 \times 144 \times 34 = 0.28 \times 4896 = 1,370.88 \text{ W} = 1.371 \text{ kW}$$

Over 24 hours, energy = $1.371 \text{ kW} \times 24 = 32.9 \text{ kWh/day}$.

Floor conduction

$$Q_{floor} = U \times A \times (T_{floor_ambient} - T_{inside})$$

- $U = 0.42$
- $A = 40 \text{ m}^2$
- $\Delta T = (10^\circ\text{C} - 1^\circ\text{C}) = 9 \text{ K}$

So:

$$Q_{floor} = 0.42 \times 40 \times 9 = 0.42 \times 360 = 151.2 \text{ W} = 0.1512 \text{ kW}$$

Over 24h: $= 0.1512 \times 24 = 3.63 \text{ kWh/day}$.

Transmission total

- Power (continuous): $1.371 + 0.1512 = 1.5222 \text{ kW}$
- Energy (daily): $32.9 + 3.63 = 36.53 \text{ kWh/day}$

2. Product Pull-Down Load (Cooling the new produce)

We need to cool 6,000 kg of produce from 25°C to 1°C .

Formula:

$$Q_{pd} = m \times c \times \Delta T$$

- $m = 6,000 \text{ kg}$
- $c = 3.65 \text{ kJ/(kg}\cdot\text{K)}$
- $\Delta T = (25 - 1) = 24 \text{ K}$

Compute energy:

$$E_{pd} = 6000 \times 3.65 \times 24 = 6000 \times 87.6 = 525,600 \text{ kJ}$$

Convert to kWh:

$$1 \text{ kWh} = 3,600 \text{ kJ} \implies E_{pd_kWh} = \frac{525,600}{3,600} = 146 \text{ kWh}$$

So the daily energy required to cool the incoming produce is ~146 kWh.

If the system is to run over, say, 16 hours of "active cooling" period per day, average power $= 146 / 16 = 9.125 \text{ kW}$ during that period (just for pull-down).

3. Respiration / Internal Heat from Stored Produce

Stored produce (say the existing stock) respire and generate heat.

Mass of stored produce (let's assume 30,000 kg)

Respiration rate $= 1.9 \text{ kJ/kg}\cdot\text{day}$

$$E_{resp} = m \times r = 30,000 \times 1.9 = 57,000 \text{ kJ/day}$$

Convert to kWh:

$$\frac{57,000}{3,600} = 15.83 \text{ kWh/day}$$

Average power $= 15.83 / 24 = 0.66 \text{ kW}$ (approx).

4. Internal Loads (People, Lighting, Fans, Defrost)

People

2 persons $\times$ 271 W each $\times$ 4 hours:

$$\text{Energy} = (2 \times 271 \text{ W}) \times 4 \text{ h} / 1,000 = 2 \times 271 \times 4 / 1,000 = 2.168 \text{ kWh/day}$$

$$\text{Average power} = 2.168 / 24 = 0.09 \text{ kW}$$

Lighting

3 lamps $\times$ 120 W $\times$ 4 hours:

$$\text{Energy} = (3 \times 120) \times 4 / 1,000 = 1.44 \text{ kWh/day}$$

$$\text{Avg power} = 1.44 / 24 = 0.06 \text{ kW}$$

Fan motors (evaporator fans)

3 fans $\times$ 300 W each $\times$ 16 h:

$$\text{Energy} = (3 \times 300) \times 16 / 1,000 = 14.4 \text{ kWh/day}$$

$$\text{Avg power} = 14.4 / 24 = 0.60 \text{ kW}$$

Defrost heater

1.5 kW heater, 20 min per cycle $\times$ 3 cycles = total 1 hour per day; 30% goes to room:

$$\text{Energy consumed} = 1.5 \text{ kW} \times 1 \text{ h} = 1.5 \text{ kWh}$$

$$\text{Energy entering room} = 0.30 \times 1.5 = 0.45 \text{ kWh/day}$$

$$\text{Avg power} = 0.45 / 24 = 0.0188 \text{ kW}$$

Sum internal loads (power average):

- People: 0.09
- Lighting: 0.06
- Fans: 0.60
- Defrost heat: 0.0188

Total $\approx$ 0.7688 kW

$$\text{Daily energy sum} = 2.168 + 1.44 + 14.4 + 0.45 = 18.458 \text{ kWh/day}$$

5. Infiltration / Ventilation / Air Change Load

Assume 5 air changes per day for the 160 m³ room $\rightarrow$ volume exchanged = 5 $\times$ 160 = 800 m³ per day.

We approximate the heat gain per cubic meter:

- Density of air $\approx$ 1.2 kg/m³
- Specific heat of air $\approx$ 1.0 kJ/(kg·K)
- ΔT (outside to inside) = 35 °C – 1 °C = 34 K

So for each m³,

$$q = 1.2 \times 1.0 \times 34 = 40.8 \text{ kJ per m}^3$$

Total per day:

$$E_{inf} = 800 \times 40.8 = 32,640 \text{ kJ/day}$$

Convert to kWh:

$$32,640 / 3,600 = 9.07 \text{ kWh/day}$$

$$\text{Average power} = 9.07 / 24 = 0.378 \text{ kW}$$

Load component	Average Power (kW)	Daily Energy (kWh/day)
Transmission (walls + roof + floor)	1.5222 kW	36.53 kWh
Respiration heat	0.66	15.83
Internal loads (people + lighting + fans + defrost)	0.7688	18.458
Infiltration / ventilation	0.378	9.07
Base "holding" total	3.329 kW	79.888 kWh

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