Freeze-Drying Process Design

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Process Summary:

5 mm apple slices

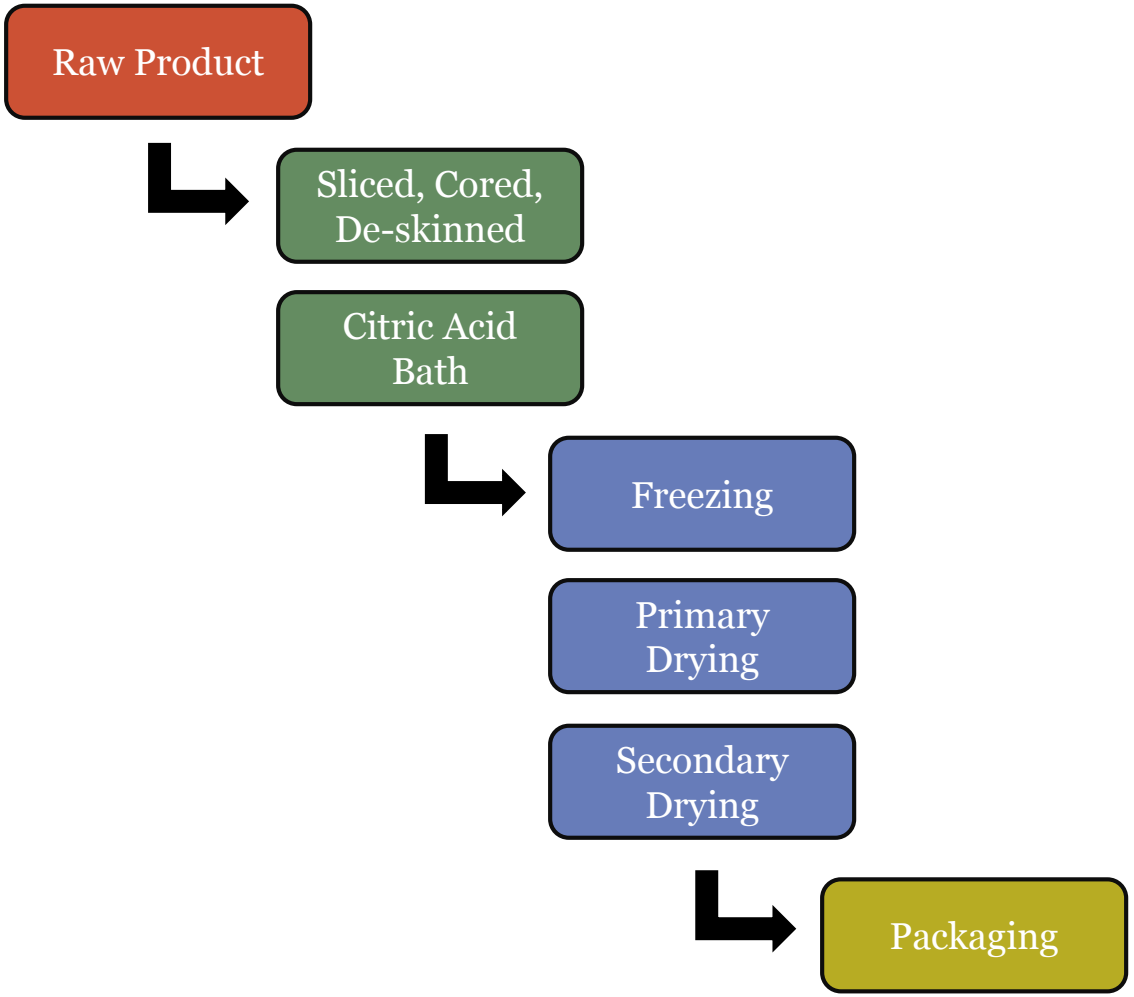
Four Stage Process:

- Pre-treatment
- Freezing
- Primary Drying
- Secondary Drying

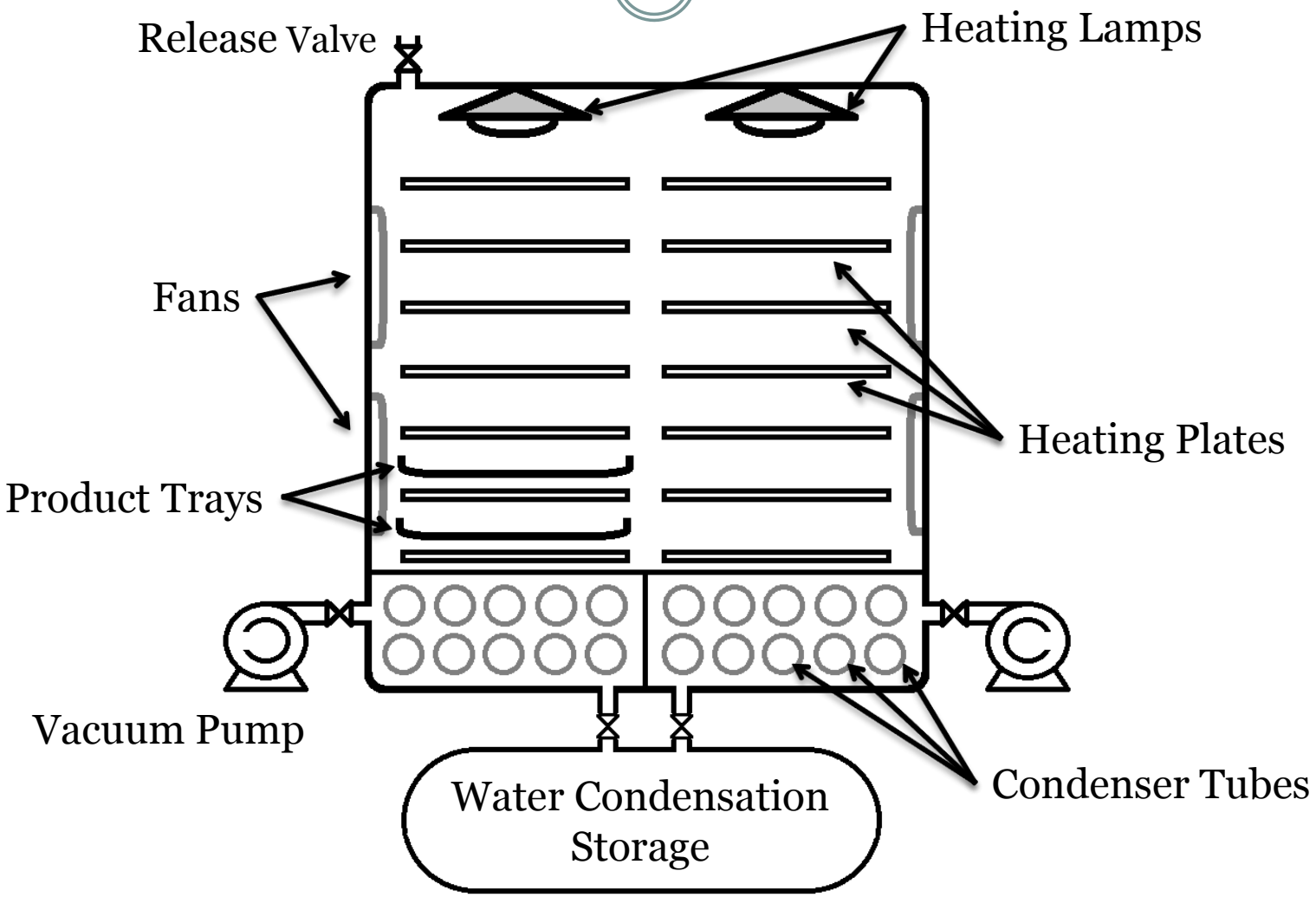
Assumptions:

- Average apple size (150 g, 8.25 cm diameter)
- 85.6% wet basis moisture content
- Quasi-Steady state heating

Process Flow Diagram



Cabinet Freeze Dryer



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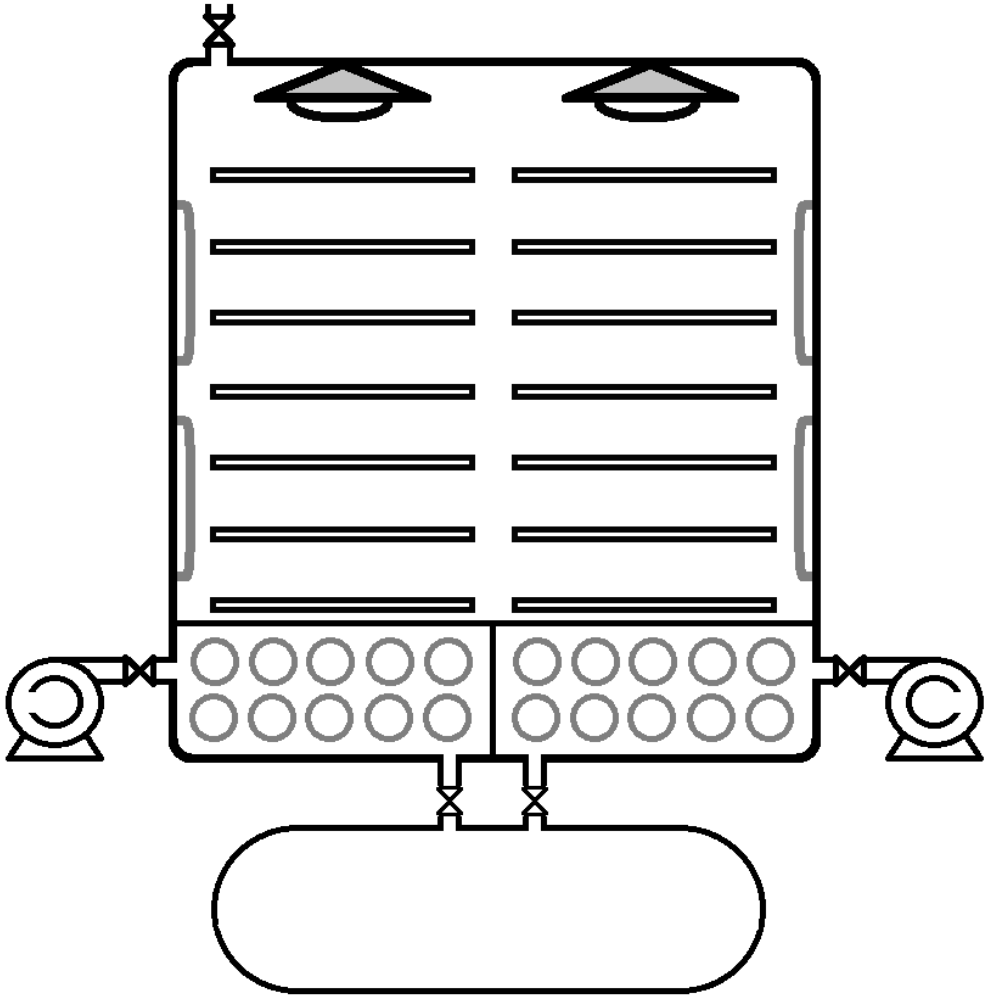

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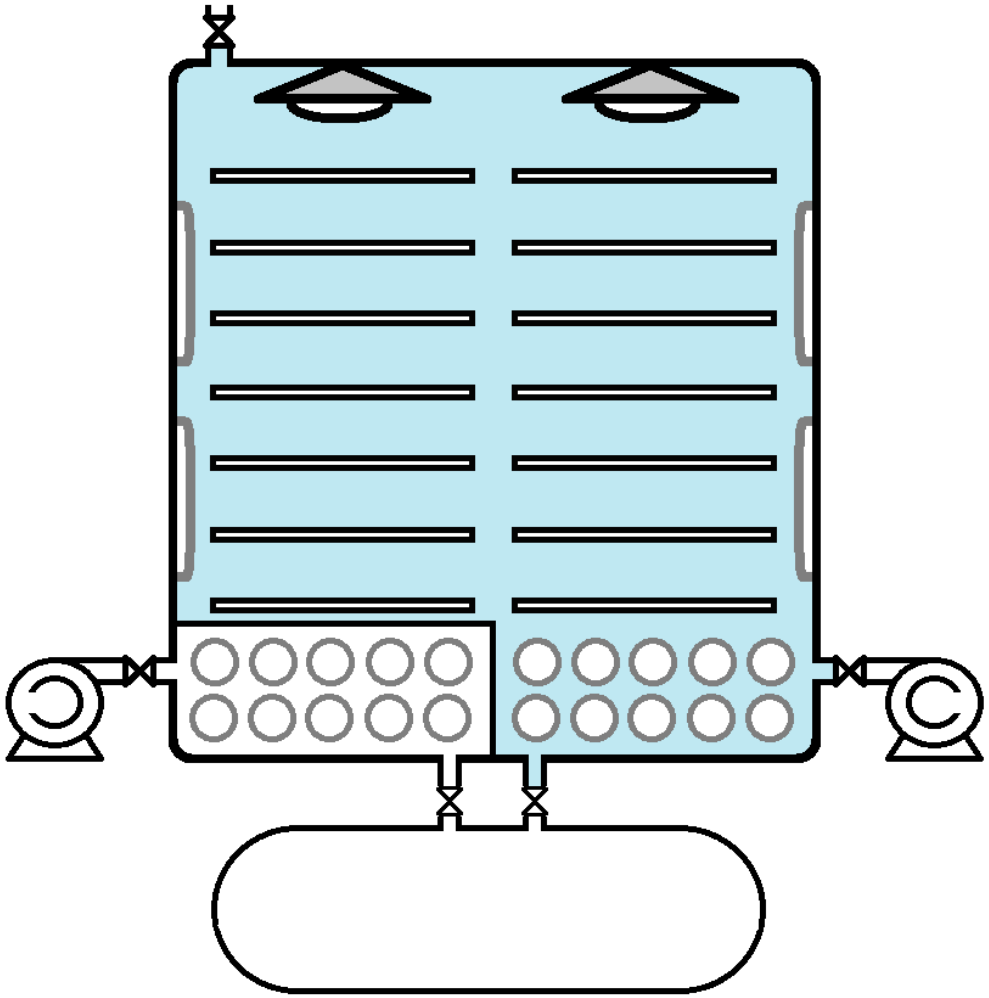
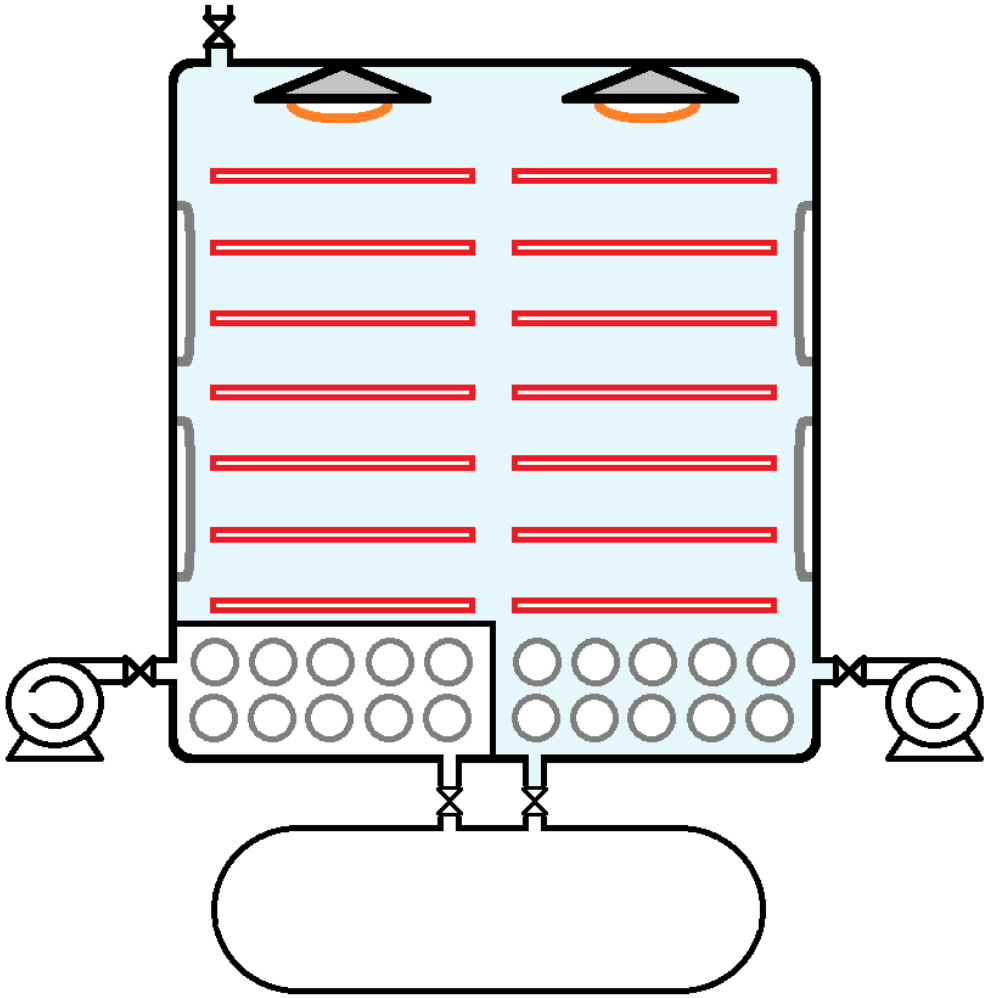


- Product Trays Loaded, Condenser Tubes Exposed
- Cabinet Temperature is Lowered, Vacuum Pulled

Cabinet Freeze Dryer



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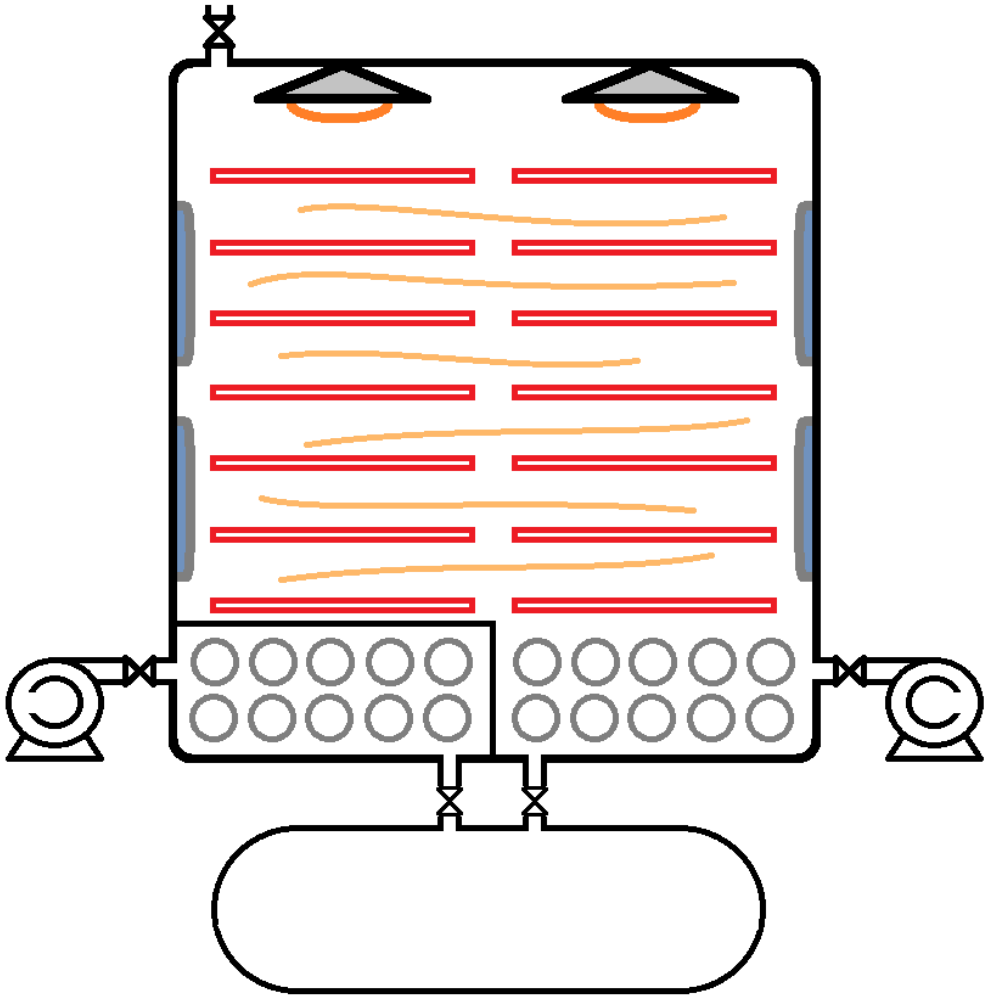
- Cabinet Temperature is Lowered, Vacuum Pulled
- Conductive Heat through Lamps, Radiative Heat through Stainless Plates

Cabinet Freeze Dryer



- Product Trays Loaded, Condenser Tubes Exposed
- Cabinet Temperature is Lowered, Vacuum Pulled
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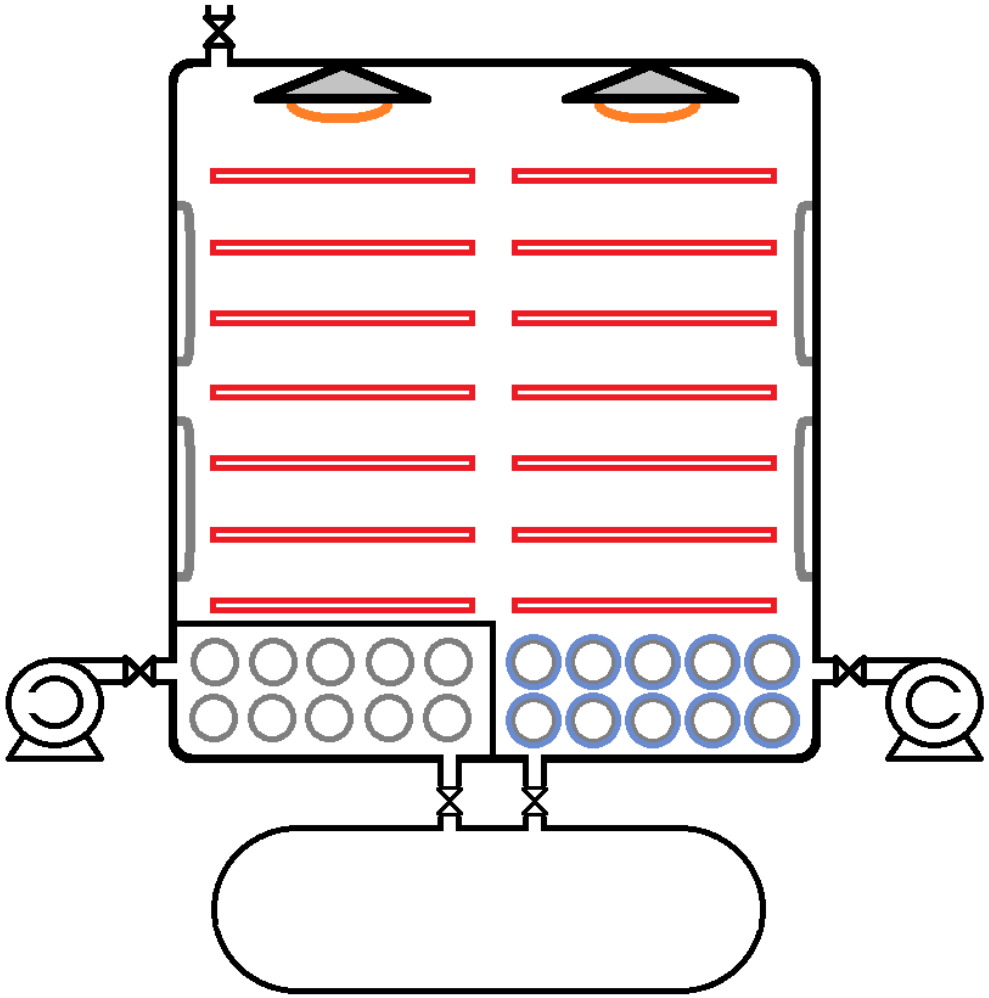
- Wall fans distribute heated air evenly throughout cabinet

Cabinet Freeze Dryer



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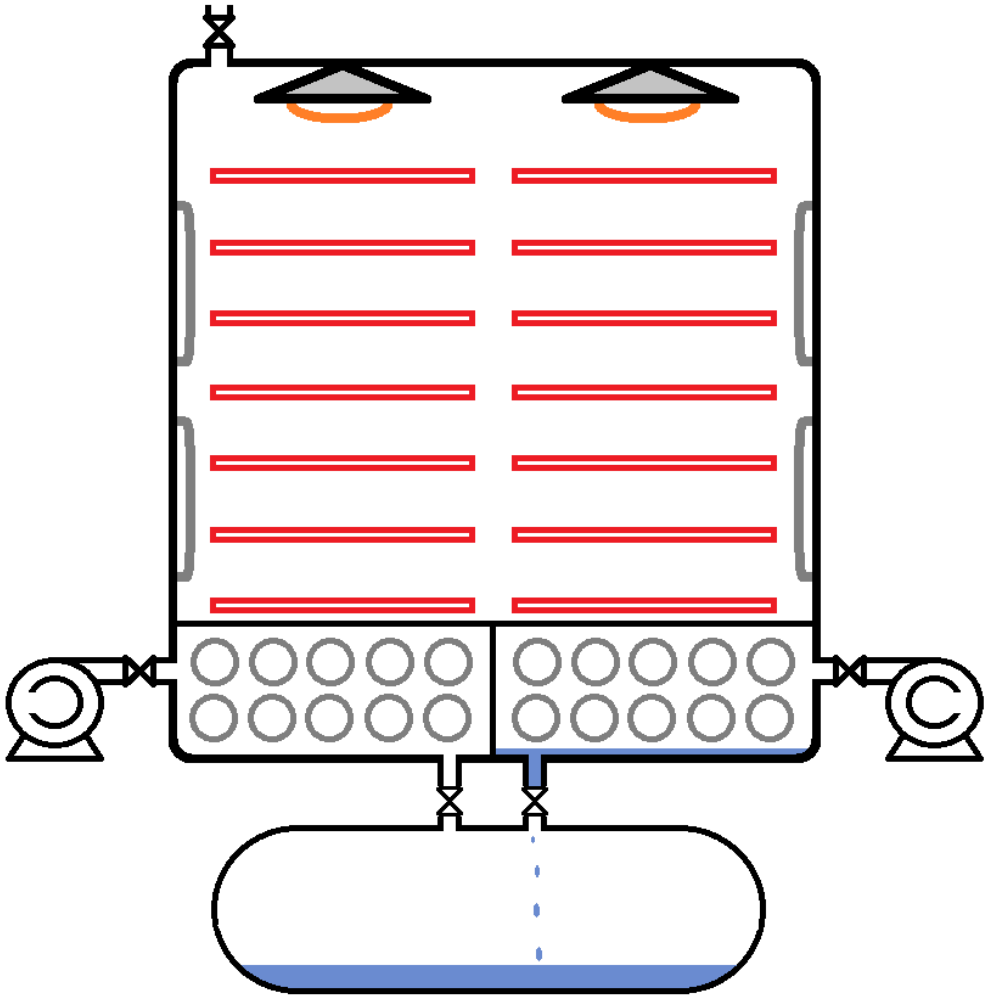
Cabinet Freeze Dryer



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- Condensation Collects on Tubing
- Condensate sealed off and drained between loading cycles

Process Pre-Treatment

Process Steps:

- Water wash
  - Removes dirt and debris
- Mechanically peeled, cored and cut into 5 mm slices
  - Half-ring shape
- Citric acid rinse
  - Inactivates microorganisms
  - Prevents enzymatic browning

Industrial Apple Washer[1]



Freezing Process

- Freezing point depression: -5°C

$$\Delta = \frac{-\beta}{\lambda} \ln\left(\frac{1-X_s}{1-X_s+EX_s}\right)$$

  - Clausius-Clayperon Equation
  - Δ is the freezing point depression, β is the molar freezing point constant of water, λ is the molecular weight and E is the ratio of the molecular weight of water to the molecular weight of solids
- Freezing temperature: -20°C
  - Ensures quick, uniform freezing of product
  - Prevents formation of large ice crystals

Freezing Process

- Freezing Time: 1.973 minutes

$$t_f = \frac{\rho H_L}{T_f - T_{inf}} \left(\frac{Pd}{h_c} + \frac{Rd^2}{k}\right)$$

  - Plank's Equation
  - P and R are shape dependent constants, k is the thermal conductivity of apples, h_c is the convective heat transfer coefficient, d is the diameter of the sample, T_f is the freezing temperature of the sample, H_L is the latent heat of fusion of the sample, and T_{inf} is the temperature of the freezing medium

Process Freezer

Freezer Conditions

- -20°C
- Atmospheric Pressure
- Air circulated via fans
- Trays of product on carts placed in freezer

Cabinet Freezer[2]



Drying Process: Primary Drying

- Dehydration through sublimation of ice
  - Latent heat of sublimation of water: 2.84 MJ/kg
- Drying mechanisms: Conduction and Radiation
- Conduction: Heated stainless steel shelves
  - Product sits on shelf in tray
- Radiation: 375 W heat lamp
  - Hangs above product on roof of drying chamber

Drying Process: Primary Drying

- Minimum energy requirement: 3033.37 kJ/kg apple
  - Heat required for sublimation and heating of plates
- Heat from 10°C shelf plates: 52.8 kJ/kg apple

$$Q = mC_p\Delta T$$

- Heat from radiative heat lamps: 2980.57 kJ/kg apple

$$q = e\sigma A(T^4 - T_c{}^4)$$

  - Stefan-Boltzmann law
  - σ is the Stefan-Boltzmann Constant and equal to 5.6703 W/m^2K^4 , T_c is the temperature of the surroundings, e is the emissivity and assumed to be equal to 0.5 , and A is the area of the emitting body
- Drying time: 2.207 hours

Drying Process: Secondary Drying

- Desorption phase
  - Removal of moisture that did not freeze (~5% moisture content remaining)
- Energy requirement: 280 kJ/kg apple
  - Latent heat of evaporation of product
- Heat from 10°C shelf plate (conduction)

$$Q = mC_p\Delta T$$

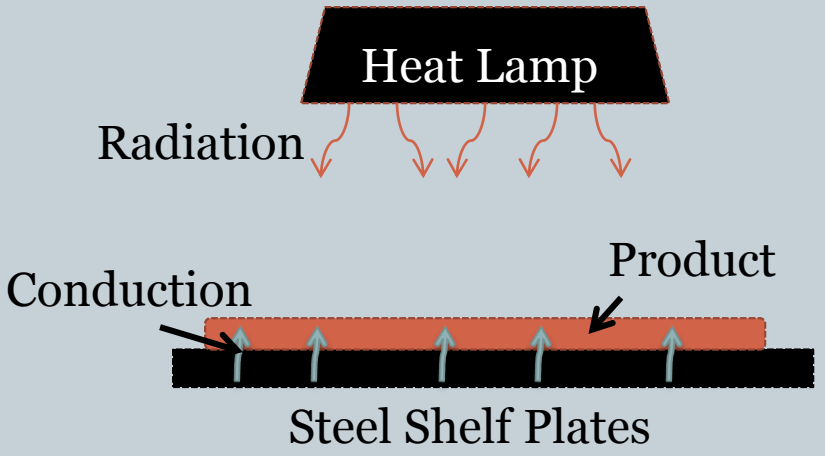
- Drying time: 3.889 hours

Drying Chamber

Chamber Conditions

- Vacuum conditions:
  - T=-20°C, P=0.04 psi
- Total drying time: 6.095 hours
- 512 ft^3 stainless steel
  - Polyurethane foam insulation
- 375 W Heat lamp above trays of product
  - Provides radiation
- Trays of product sit on stainless steel plates
  - Provides conduction

Drying Chamber



Critical Processing Parameters

- Freezing temperature and time
  - Determines size of ice crystals in product
  - Ensures sublimation, not evaporation, of moisture
- Primary drying energy input
  - Ensures sublimation occurs
    - Determines if any browning and burning of product occurs
- Secondary drying energy input
  - Determines final moisture content
    - Low water activities prevents microbial growth and enzymatic activity

Packaging

Packaging Criteria

- Vacuum-sealed foil pouches
  - Prevents resorption of moisture
    - Low water activity crucial for quality and safety
  - Prevents air contamination
    - Oxidation leads to fruit spoilage

Freeze-Dried Fruit Packaging[3]



Impact on Quality

- Minimal impact on food quality
  - Color and flavor retention
  - Texture and taste retention even after rehydration
- Higher quality than conventionally-dried fruits
  - Higher antioxidant levels after storage
- High quality due to minimal heat addition and minimal alteration

Microbial Safety and Validation

- Pre-treatment: citric acid wash
  - Prevents enzymatic browning, provides microbial reduction
- Equipment sterilization
  - Accomplished with high temperature steam to prevent contamination during processing
- Freezing: slows enzyme and microbial activity
- Drying: significantly lowers water activity
  - Inhibits microbial growth
- Validation: measure water activity post processing

$$a_w = \frac{P}{P_o};\ a_w < 0.6$$

- Packaging: Prevent moisture from reaching product during shelf-life
  - Vacuum-sealed, air tight foil pouches

Plant Automation

- Automation maximized in order to decrease production time and costs
- Pre-treatment:
  - Mechanically washed, peeled, cored, and sliced
  - Mechanically sprayed with citric acid and fed onto trays
- Packaging:
  - Finished product mechanically fed into film pouches
  - Pouches mechanically sealed
- Labor intensive process, despite automation

Sustainability

- Increase Heat Transfer Efficiency
  - Microwave Heating
    - High Start Up Cost & Complex Technology
  - Osmosis Dehydration Pretreatment
    - Submerge Into Salt or Sugar
- Re-use Waste
  - Send Waste, Cores & Skins, To Local Farms
  - Use Water Removed From Apples During Drying

References

1. "Automatic Fruit Washer/ Apple Washing and Waxing Line." *China (Mainland) Fruit & Vegetable Processing Machinery*. WEIKU, n.d.
2. "Cryoline CF." *Linde Industrial Gases*. The Linde Group, n.d.
3. "Freeze Dried Fruit." Mother Earth and Products, 2012