DRYING | DEHYDRATION

PRO

Ch. 15 of Fellows

Greensmith, M. 1998. Practical dehydration 2nd ed. Woodhead. Cambridge.

- Application of heat under controlled conditions to remove majority of water normally present in a food by evaporation or by sublimation.

- excludes mechanical separations & membrane concentration, evaporation and baking

  → these normally remove much less water than dehydration.

- Main purpose: extend the shelf life (reduction of Aw)

  → inhibits microbial growth & enzyme activity

  → processing temperature is usually insufficient to cause their inactivation.

  → any increase in moisture content during storage will result in rapid spoilage.

- reduction in weight & bulk of food
- provides convenient product, easily handled ingredients.
- deterioration of eating quality & nutritional value.

  → selection of appropriate drying conditions for individual foods.
- Dried foods: coffee, milk, raisins, sultanas and other fruits, pasta, flours (including bakery mixes), beans, pulses, nuts, breakfast cereals, tea and spices.
- Dried ingredients: egg powder, flavourings & colourings, lactose, sucrose or fructose powder, enzymes & yeasts.

Theory

- Dehydration involves simultaneous application of heat & removal of moisture from foods (except for osmotic dehydration).

- Please re-read heat and mass transfer (Ch. 1 of Fellows).

- factors control rate at which foods dry:
  - those related to processing conditions
  - those related to nature of food
  - those related to drier design.

Drying using heated air

Psychrometrics

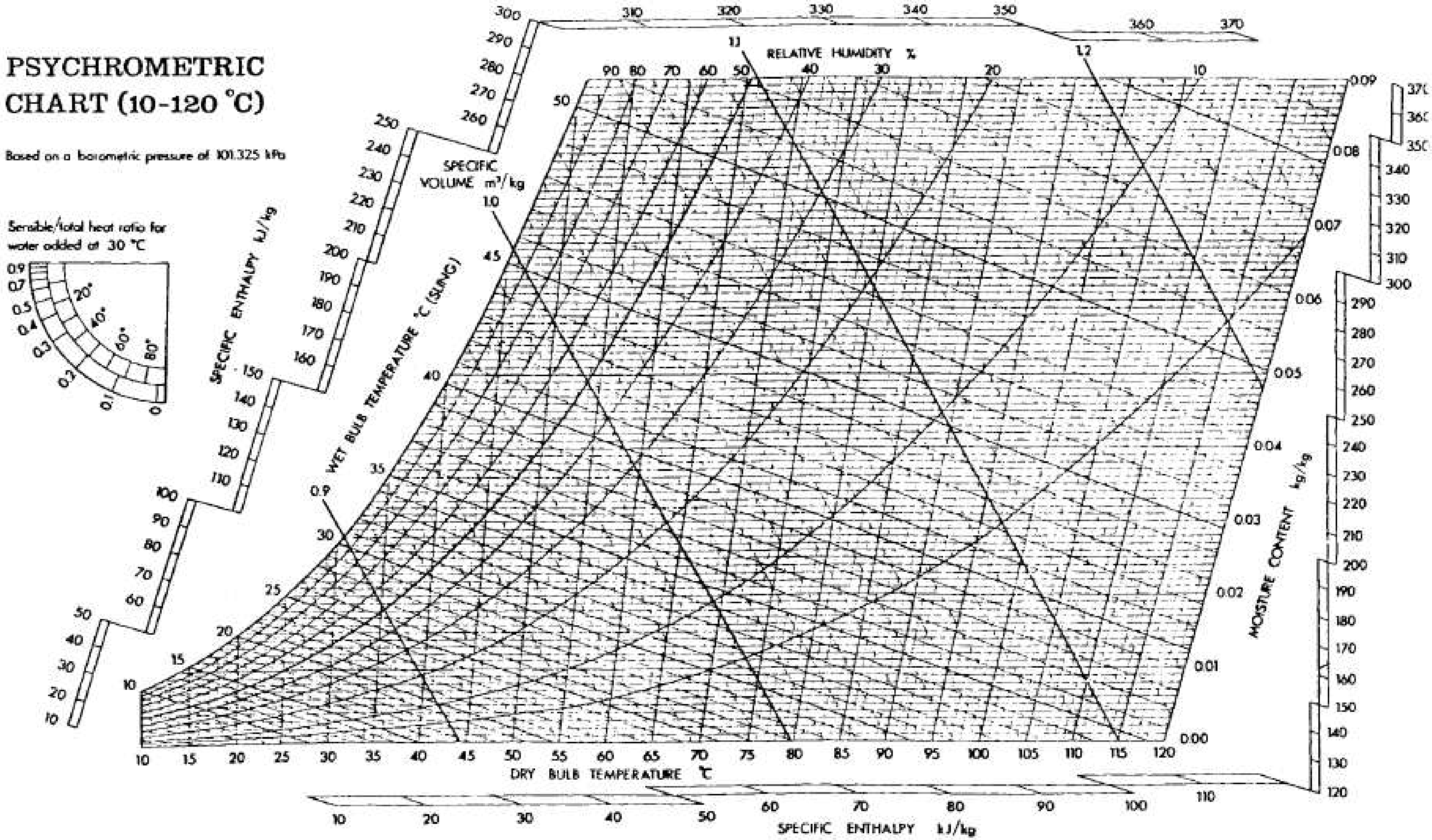
- Inter-related factors control the capacity of air to remove moisture from a food:

1. amount of water vapour already carried by the air
2. air temperature
3. amount of air that passes over the food.

- Amount of water vapour in air : *absolute humidity* (*moisture content*) or *relative humidity* (RH) (in %).

- Psychrometry: study of inter-related properties of air–water vapour systems.

  → *psychrometric chart*



Psychrometric chart (10–120°C) based on barometric pressure of 101.325 kPa. (Courtesy of Chartered Institution of Building Service Engineers.)

- Heat from drying air is absorbed by food & provides latent heat to evaporate water from surface.

- Temperature of air = the *dry-bulb* temperature (measured by a thermometer bulb).

- If thermometer bulb is surrounded by a wet cloth, heat is removed by evaporation of water from the cloth & temperature falls.

  → This lower temperature = the *wet-bulb temperature*.

- Difference between the two temperatures is used to find RH of air on psychrometric chart.

- An increase in air temperature, or reduction in RH, causes water to evaporate more rapidly from a wet surface → produces a greater fall in temperature.

- The *dew point :* the temperature at which air becomes saturated with moisture (100% RH)

- any further cooling from this point results in condensation of the water from the air.

- Adiabatic cooling lines : the parallel straight lines sloping across the chart → show how absolute humidity decreases as the air temperature increases.

Mechanism of drying

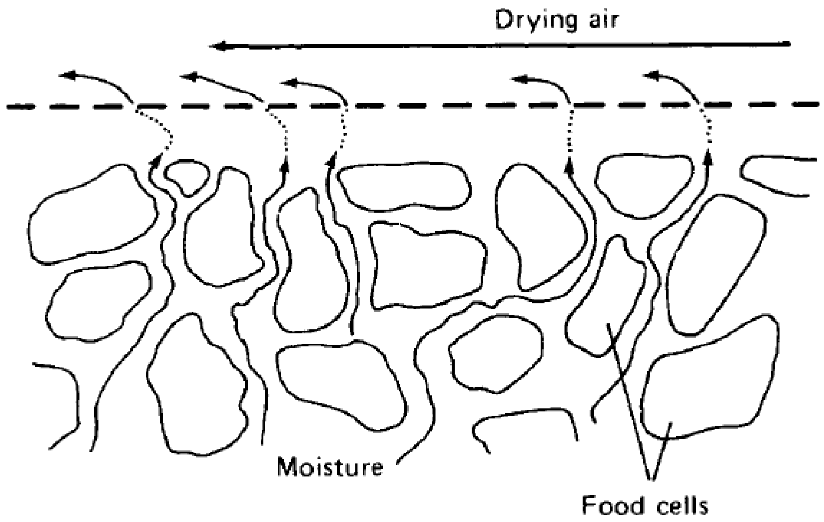
- Factors control rate of drying:

  air temperature; humidity; air velocity.

- When hot air is blown over a wet food, water vapour diffuses through a boundary film of air surrounding the food & is carried away by the moving air

- A water vapour pressure gradient is established from the moist interior of food to the dry air.

  → provides the 'driving force' for water removal from food.



Movement of moisture during drying.

- Boundary film is a barrier to heat transfer & water vapour removal during drying.
- Thickness of the film by air velocity

  → if the velocity is low, the boundary film is thicker

  → reduces heat transfer coefficient & rate of water vapour removal.
- Water vapour leaves the surface of food & increases humidity of the surrounding air

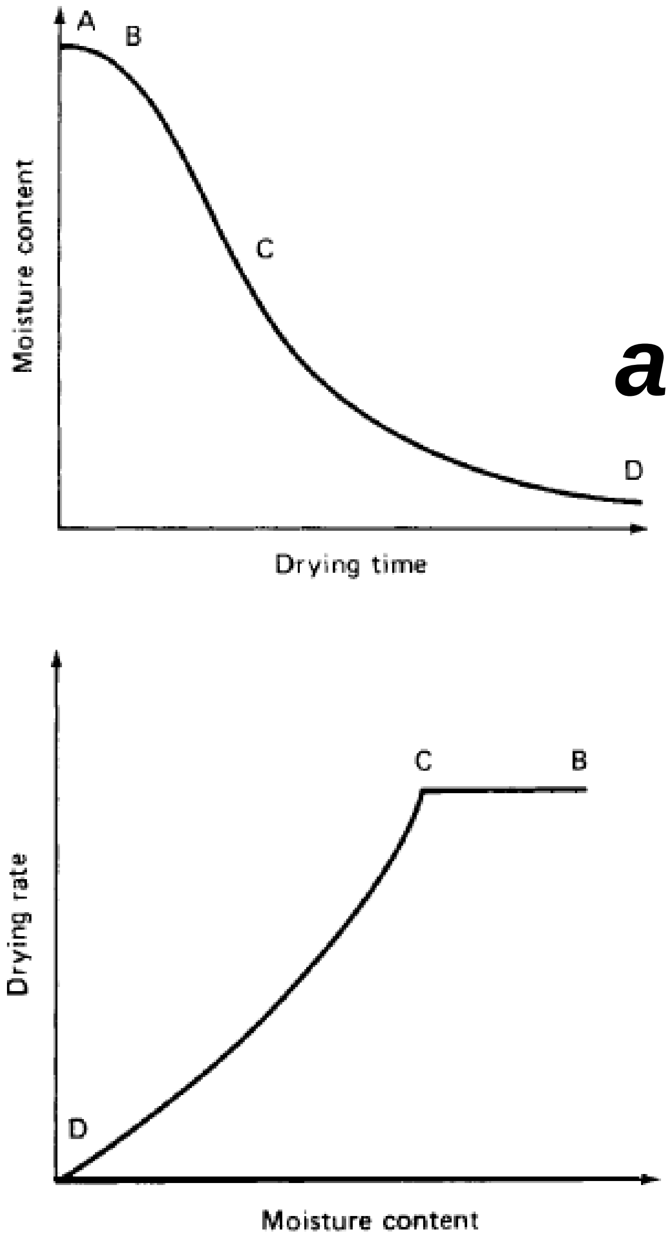
  → reduction in the water vapour pressure gradient & rate of drying.
- The faster the air, the thinner the boundary film & the faster the rate of drying.

- Characteristics of air necessary for successful drying when the food is moist:

1. a moderately high dry-bulb temperature
2. a low RH
3. a high air velocity.

Constant-rate period

and Falling-rate period



Drying curves. The temperature and humidity of the drying air are constant and all heat is supplied to the food surface by convection.

- During the falling-rate period(s)

  → rate of water movement from interior to surface falls below the rate at which water evaporates to surrounding air

  → surface dries out (assuming temperature, humidity & air velocity are unchanged).

- If the same amount of heat is supplied by air,

  → surface temperature rises

  → until it reaches dry-bulb temperature of the drying air.

- Most heat damage to food can occur in the falling-rate period

  → air temperature is controlled to balance rate of drying & extent of heat damage.

- Most heat transfer is by convection from drying air to the surface of food, but there may also be heat transfer by radiation.
-
- If food is dried in solid trays, there will also be conduction through the tray to food.
-
- Calculation of heat transfer is often very complex in drying systems.

- The falling-rate period is usually the longest part of a drying operation

  in some foods (e.g. grain drying) the initial moisture content is below the critical moisture content

  the falling-rate period is the only part of the drying curve to be observed.

- During the falling-rate period, factors control the rate of drying change.

- Initially the important factors = to those in the constant-rate period; gradually rate of water movement (mass transfer) becomes the controlling factor.

- Mechanisms of water moving from the interior of the food to surface:
  - liquid movement by capillary forces, particularly in porous foods
  - diffusion of liquids, caused by differences in the concentration of solutes at the surface & in the interior of food
  - diffusion of liquids which are adsorbed in layers at the surfaces of solid components of food
  - water vapour diffusion in air spaces within food caused by vapour pressure gradients.

- During drying, one or more mechanisms may be taking place; their relative importance can change as drying proceeds.
- E.g. in the 1^{st} part of the falling-rate period, liquid diffusion may be the main mechanism, whereas in later parts, vapour diffusion may be more important.
- Sometimes difficult to predict drying times in the falling-rate period.
- The mechanisms depend on the air temperature & the food pieces size.

  → unaffected by the RH of air (except in determining the equilibrium moisture content) & air velocity.

- Size of food pieces has important effect on drying rate in constant-rate & falling-rate periods.

- In the constant-rate period,

  smaller pieces have a larger surface area available for evaporation

- In the falling-rate period,

  smaller pieces have a shorter distance for moisture to travel through the food.

- Calculation of drying rates is further complicated if foods shrink during the falling-rate period.

- Other factors influence the rate of drying:
- ***Composition and structure*** of the food

  influence on the mechanism of moisture removal.

  → E.g. the orientation of fibres in vegetables (e.g. celery) & protein strands in meat allow more rapid moisture movement along their length than across the structure.

  → moisture is removed more easily from intercellular spaces than from within cells.

  → Rupturing cells by blanching or size reduction increases the rate of drying but may adversely affect texture of the rehydrated product.

→ High concentrations of solutes (e.g.= sugars, salts, gums, starches, etc.) increase viscosity & lower Aw & reduce the rate of moisture movement.

- ***Amount of food*** placed into a drier in relation to its capacity

  → in a given drier, faster drying is achieved with smaller quantities of food.

Calculation of drying rate

- Moisture content of a food → wet weight basis or a dry weight basis.

- Rate of heat transfer

$$Q = h_S A\left(\theta_a - \theta_s\right)$$

- Rate of mass transfer

$$-m_c = K_g A(H_s - H_a)$$

- During the constant-rate period,

  equilibrium between rate of heat transfer to food & rate of mass transfer in the form of moisture loss from food

$$-m_c = \frac{h_c A}{\lambda}(\theta_a - \theta_s)$$

- Q (J s^{-1}): rate of heat transfer,
- h_c ($Wm^{-2}K^{-1}$): surface heat transfer coefficient for convective heating,
- A (m^2): surface area available for drying,
- θ_a (ºC): average dry bulb temperature of drying air,
- θ_s (ºC): average wet bulb temperature of drying air,
- m_c (kg s^{-1}): change of mass with time (drying rate),
- K_g (kg m^{-2} s^{-1}): mass transfer coefficient,
- H_s (kg moisture per kg dry air): humidity at the surface of food (saturation humidity),
- H_a (kg moisture per kg dry air): humidity of air
- λ (J kg^{-1}): latent heat of vaporisation at the wet bulb temperature.

- Relation surface heat transfer coefficient (h_c) to mass flow rate of air

- for parallel air flow: $$h_c = 14.3G^{0.8}$$
- for perpendicular air flow: $$h_c = 24.2G^{0.37}$$

- G (kg m^{-2} s^{-1}): mass flow rate of air per unit area.

- For a tray of food, in which water evaporates only from the upper surface,

  the drying time:

$$-m_c = \frac{h_c}{\rho \lambda x}(\theta_a - \theta_s)$$

- ρ (kg m^{-3}): bulk density of food
- x (m): thickness of the bed of food.

- The drying time in the constant rate period:

$$t = \frac{\rho \lambda x (M_i - M_c)}{h_c(\theta_a - \theta_s)}$$

- t (s): the drying time,
- M_i (kg per kg of dry solids): initial moisture content, and
- M_c (kg per kg of dry solids): critical moisture content.

- For water evaporating from a spherical droplet in a spray drier, the drying time:

$$t = \frac{r^2 \rho_1 \lambda}{3h_c(\theta_A - \theta_S)} \frac{M_i - M_f}{1 + M_i}$$

- *ρ* (kgm^{-3}): density of the liquid,
- *r* (m): radius of the droplet,
- M_f (kg per kg of dry solids): final moisture content.

- The drying time from the start of the falling-rate period to the equilibrium moisture content
- assumptions concerning, e.g., the nature of moisture movement and the absence of shrinkage of the food:

$$t = \frac{\rho x (M_c - M_e)}{K_g (P_s - P_a)} \ln \left(\frac{M_c - M_e}{M - M_e} \right)$$

- M_e (kg per kg of dry solids): equilibrium moisture content,
- M (kg per kg of dry solids): moisture content at time t from the start of the falling-rate period,
- P_s (Torr): saturated vapour pressure at the wet bulb temperature
- P_a (Torr): partial water vapour pressure.

Drying using heated surfaces

- Slurries of food are deposited on heated steel drum.
- Heat is conducted from hot surface through food
- Moisture is evaporated from the exposed surface.
- Resistance to heat transfer:

  → thermal conductivity of food.

  → partly dried food lifts off the hot surface forming a barrier layer of air between the food & drum.

Equipment

Hot-air driers

- Cost of fuel for heating air → main economic factor
- Overcoming? examples :
  - – insulation of cabinets and ducting
  - – recirculation of exhaust air through the drying chamber

- recovering heat from the exhaust air to heat incoming air or fore-warming feed material
- use of direct flame heating by natural gas & low nitrogen oxide burners
- drying in two stages

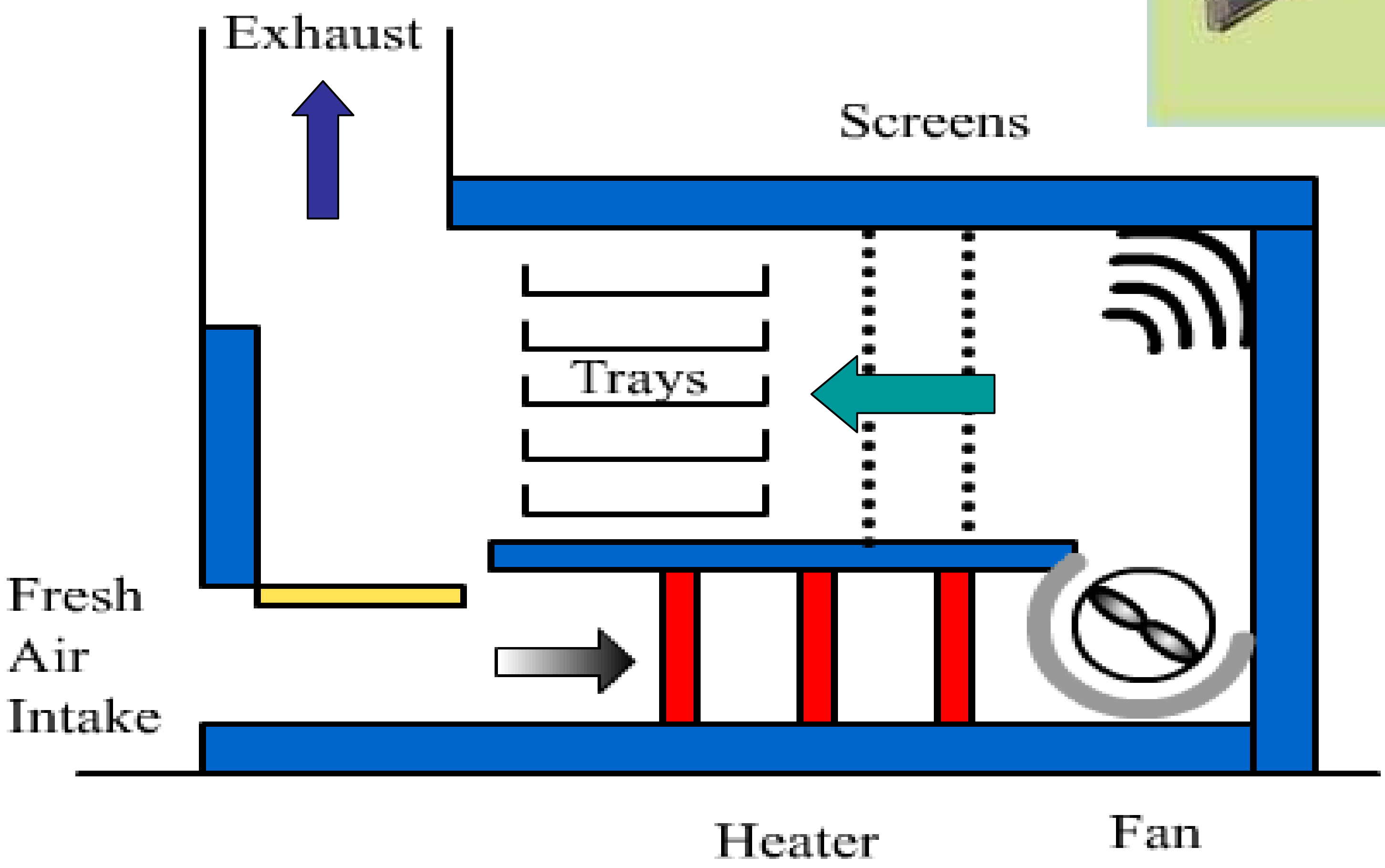
  (e.g fluidised beds followed by bin drying or spray drying followed by fluidised bed drying)
- pre-concentrating liquid foods to the highest solids content possible using multiple effect evaporation.

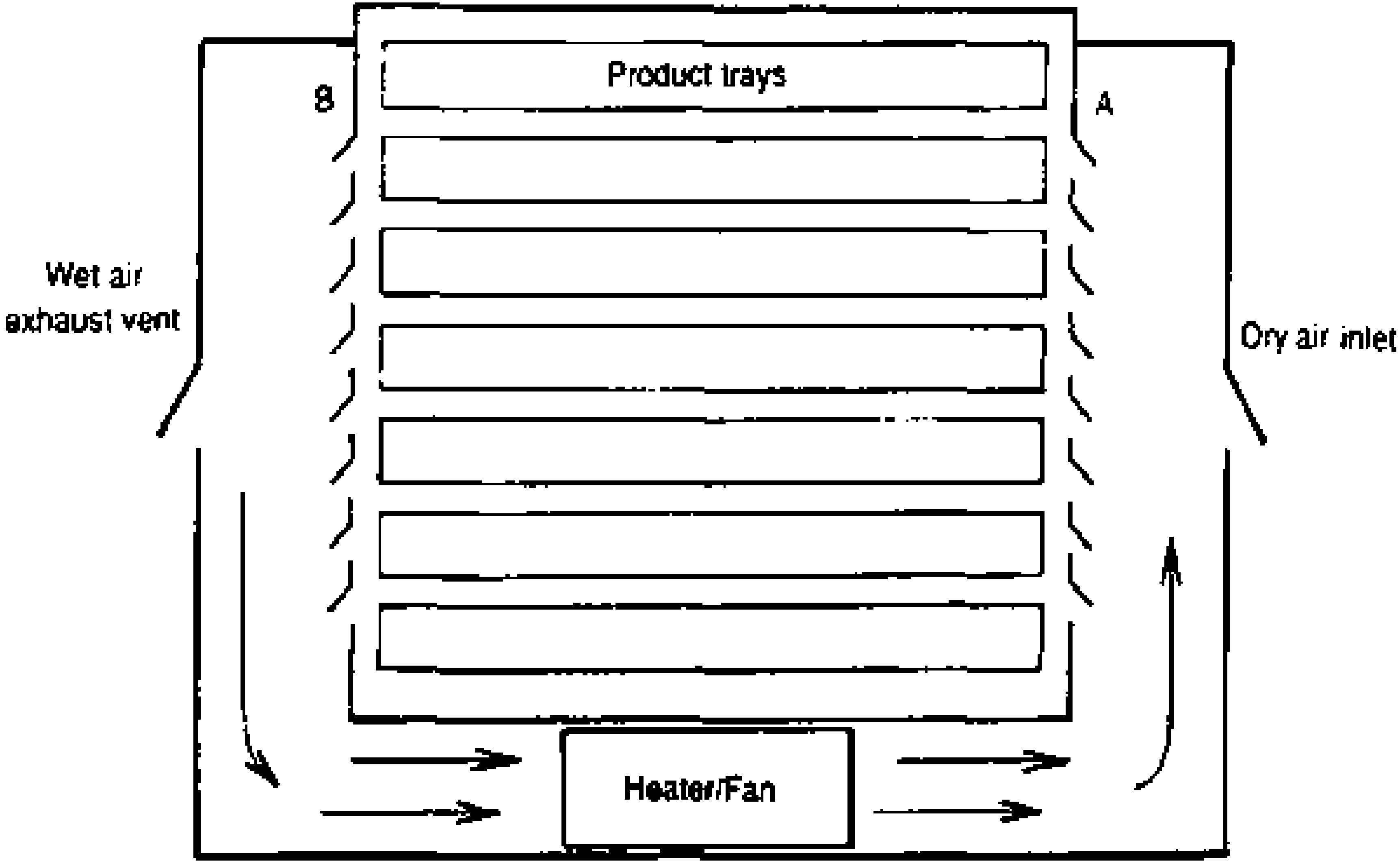
Bin driers

- large, cylindrical or rectangular containers fitted with a mesh base.
- Hot air passes up through a bed of food at relatively low velocities.
- high capacity; low capital & running costs; & are mainly used for ‘finishing’ after initial drying in other types of driers.
- improve the operating capacity of initial driers by removing the food when it is in the falling-rate period, when moisture removal is most time consuming.
- deep bed of food permits variations in moisture content to be equalised & acts as a store to smooth out fluctuations in the product flow.
- foods should be strong to compression & retain spaces between the pieces to permit the passage of hot air through the bed.

Cabinet driers (tray driers)

- insulated cabinet fitted with shallow mesh or perforated trays, each of which contains a thin (2–6 cm deep) layer of food.
- Hot air is blown through a system of ducts & baffles to promote uniform air distribution
- low capital & maintenance costs; flexible in operation for different foods.
- relatively poor control & produce more variable product quality as food dries more rapidly on trays nearest to the heat source.


Exhaust
Screens
Trays
Fresh
Air
Intake
Heater
Fan



A - Inlet Vents

B - Exhaust Vents

Opening/Closing controlled by humidistat

Characteristics of driers

Type of drier	Characteristics of the food						Drying conditions			Examples of products
	Batch or continuous	Solid/ liquid	Initial moisture content	Heat sensitive	Size of pieces	Should be mechanically strong	Drying rate	Final moisture content	Typical maximum evaporative capacity ($kg\,h^{-1}$)	
Bin	B	S	Low		Int	Yes	Slow	Low	–	Vegetables
Cabinet	B	S	Mod		Int		Mod	Mod	55–75	Fruits, vegetables
Conveyor/band	C	S	Mod		Int		Mod	Mod	1820	Breakfast cereals, fruit products, confectionery, vegetables, biscuits, nuts
Drum	C	S	Mod		Sm		Mod	Mod	410	Slurries, corn syrup, instant potato, gelatin
Foam mat	C	L	–	Yes	–		Fast	Fast	–	Fruit juices
Fluidised bed	B/C	S	Mod		Sm	Yes	Mod	Low	910	Peas, diced or sliced vegetables, grains, powders or extruded foods, fruits, desiccated coconut, herbs
Kiln	B	S	Mod		Int		Slow	Mod	–	Apple rings, slices, hops
Microwave/dielectric	B/C	S	Low		Sm		Fast	Low	–	Bakery products
Pneumatic/ring	C	S	Low	Yes	Sm	Yes	Fast	Low	15 900	Starches, gravy or soup powder, mashed potato
Radiant	C	S	Low		Sm		Fast		–	Bakery products
Rotary	B/C	S	Mod	Yes	Sm	Yes	Mod	Mod	1820–5450	Cocoa beans, nuts, pomace, cooked cereals
Spin flash	C	L	Mod	Yes	Int/Sm		Fast	Low	7800	Pastes, filter cakes, sludges, viscous liquids
Spray	C	S	–		–		Fast	Mod	15 900	Powders, instant coffee, powdered milk
Sun/solar	B	S	Mod		Int		Slow	Mod	–	Fruits, vegetables
Trough	C	S	Mod		Int		Mod	Mod	–	Peas, diced vegetables
Tunnel	C	S	Mod		Int		Mod	Mod	–	Vegetables, fruits
Vacuum band/shelf	C	L	–		–		Fast	Low	18 200	Juices, meat extracts, chocolate crumb

Key: S = Solid, L = Liquid, Mod = Moderate, Int = Intermediate to large (granules, pellets, pieces), Sm = Small (powders).
Data from Barr and Baker (1997).

Comparison of small and large scale drying technologies

Type of drier	Cost ($US)	Capacity (kg wet food/24 h)	Investment ($US per kg dry capacity)	Fuel efficiency	Labour requirement
'Brace' solar drier	50	10	50	n/a	v.low
Solar cabinet drier	70	30	23	n/a	v.low
'McDowell' drier	170	40	43	v.poor	low
Wood burning cabinet drier	340	80	43	v.poor	low
ITDG batch drier	3 400	240	140	poor	high
ITDG semi-continuous drier	6 800	360	190	medium	v.high
Cabinet drier (small)	85 000	500	1 700	good	high
Cabinet drier (large)	170 000	2 500	680	good	medium
Tunnel drier (12 carriage)	145 000	6 000	240	good	low
Band drier	800 000	48 000	170	v.good	v.low

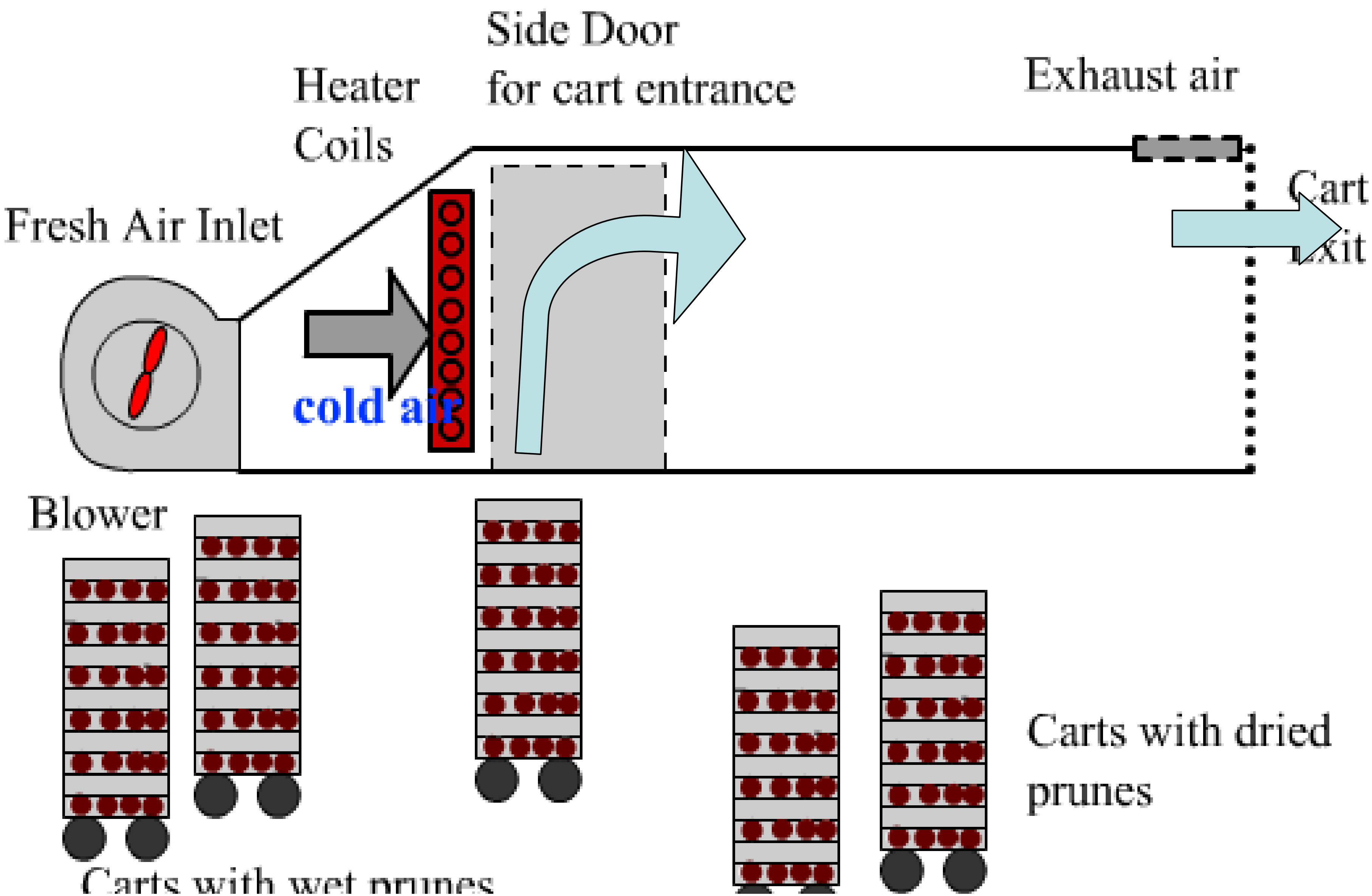
From Axtell and Bush (1991).

Tunnel driers

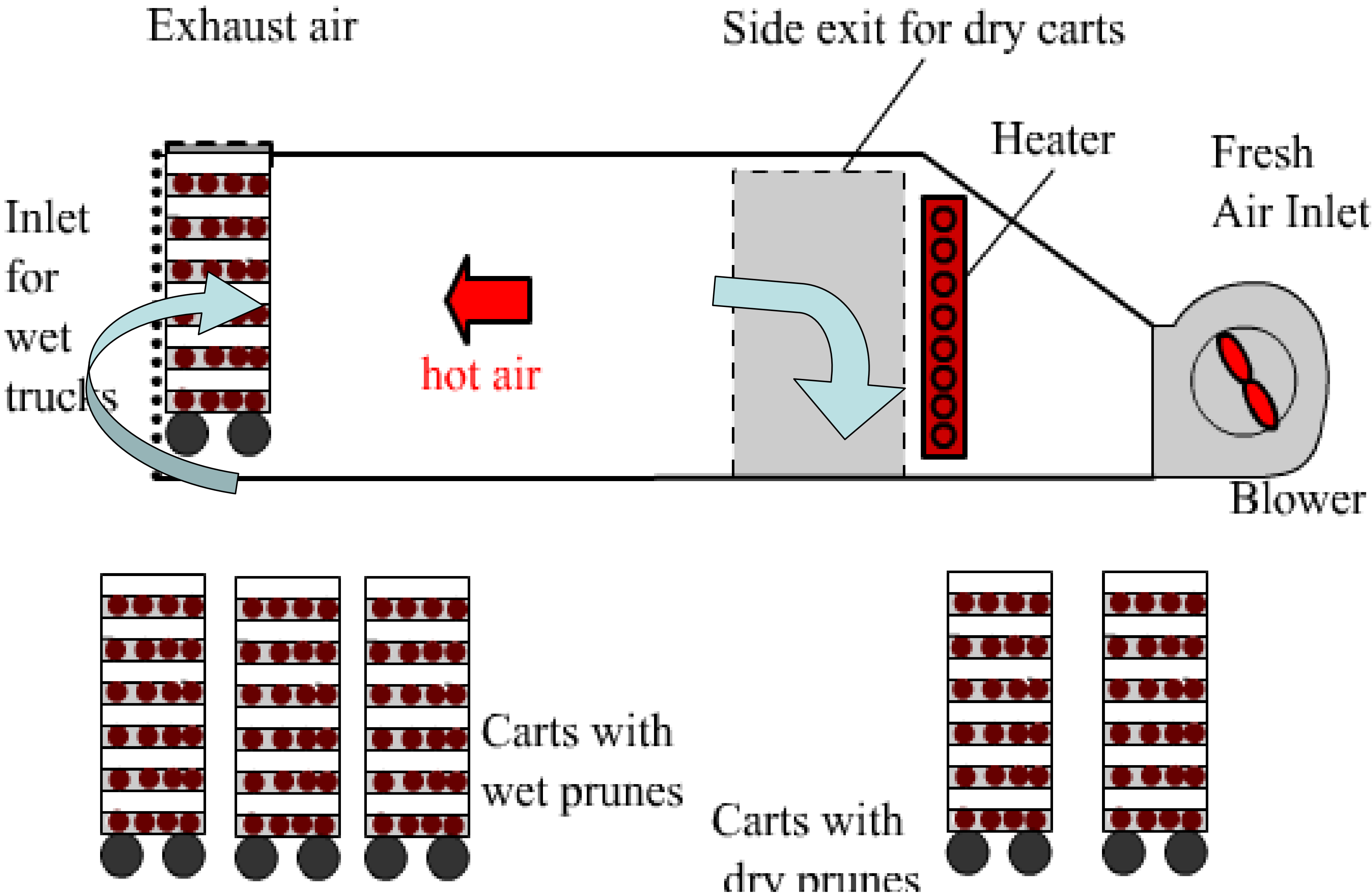
- Layers of food are dried on trays; stacked on trucks move semi continuously through an insulated tunnel, having one or more types of air flow
- Food is finished in bin driers.
- Dry large quantities of food in a relatively short time
- Superseded by conveyor drying & fluidised bed drying

  Higher energy efficiency, reduced labour costs & better product quality.

Parallel / Co-current Type



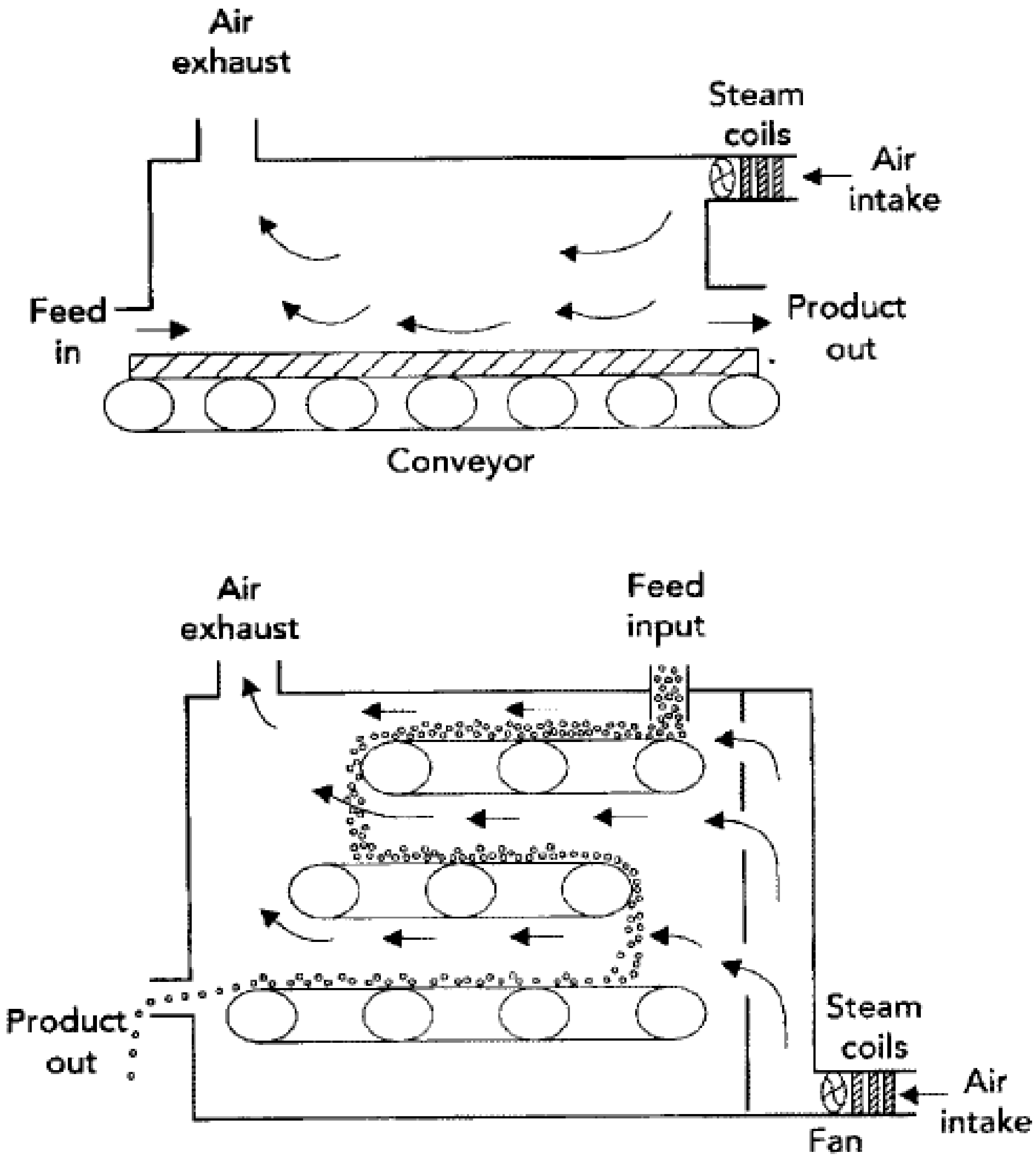
Counterflow / Counter-current



Conveyor driers (belt driers)

- Food is dried on a mesh belt in beds 5–15 cm deep.
- The air flow is initially directed upwards through the bed of food & then downwards in later stages to prevent dried food from blowing out of the bed.
- 2 or 3-stage driers mix & re-pile the partly dried food into deeper beds

  → improves uniformity of drying & saves floor space.
- Foods are dried to 10–15% moisture content then finished in bin driers.



(a) Conveyor drier and (b) three-stage conveyor drier.
(From Heldman and Hartel (1997).)

- 2^{nd} application of conveyor driers: ***foam mat drying***
- liquid foods are formed into a stable foam by the addition of a stabiliser & aeration with nitrogen or air.
- foam is spread on a perforated belt to a depth of 2–3mm & dried rapidly in two stages by parallel & then counter-current air flows.
- Foam mat drying 3x faster than drying a similar thickness of liquid.
- Thin porous mat of dried food is ground to a free-flowing powder.
- Rapid drying & low product temperatures result in a high-quality product
- Large surface area is required for high production rates.

Advantages and limitations of parallel flow, counter-current flow, centre-exhaust and cross-flow drying

Type of air flow	Advantages	Limitations
Parallel or co-current type: food → air flow →	Rapid initial drying. Little shrinkage of food. Low bulk density. Less damage to food. No risk of spoliage	Low moisture content difficult to achieve as cool moist air passes over dry food
Counter-current type: food → air flow ←	More economical use of energy. Low final moisture content as hot air passes over dry food	Food shrinkage and possible heat damage. Risk of spoilage from warm moist air meeting wet food
Centre-exhaust type: food → air flow →↑←	Combined benefits of parallel and counter-current driers but less than cross-flow driers	More complex and expensive than single-direction air flow
Cross-flow type: food → air flow ↑↓	Flexible control of drying conditions by separately controlled heating zones, giving uniform drying and high drying rates	More complex and expensive to buy, operate and maintain

Fluidised-bed driers

Main features:

- a distributor; to evenly distribute air at a uniform velocity around the bed of material;

- a plenum chamber; below the distributor to produce an homogenous region of air & prevent localised high velocities

- a disengagement or ‘freeboard’; region above the bed to allow dis-entrainment of particles thrown up by air.

- Air from the fluidised bed is usually fed into cyclones to separate out fine particles

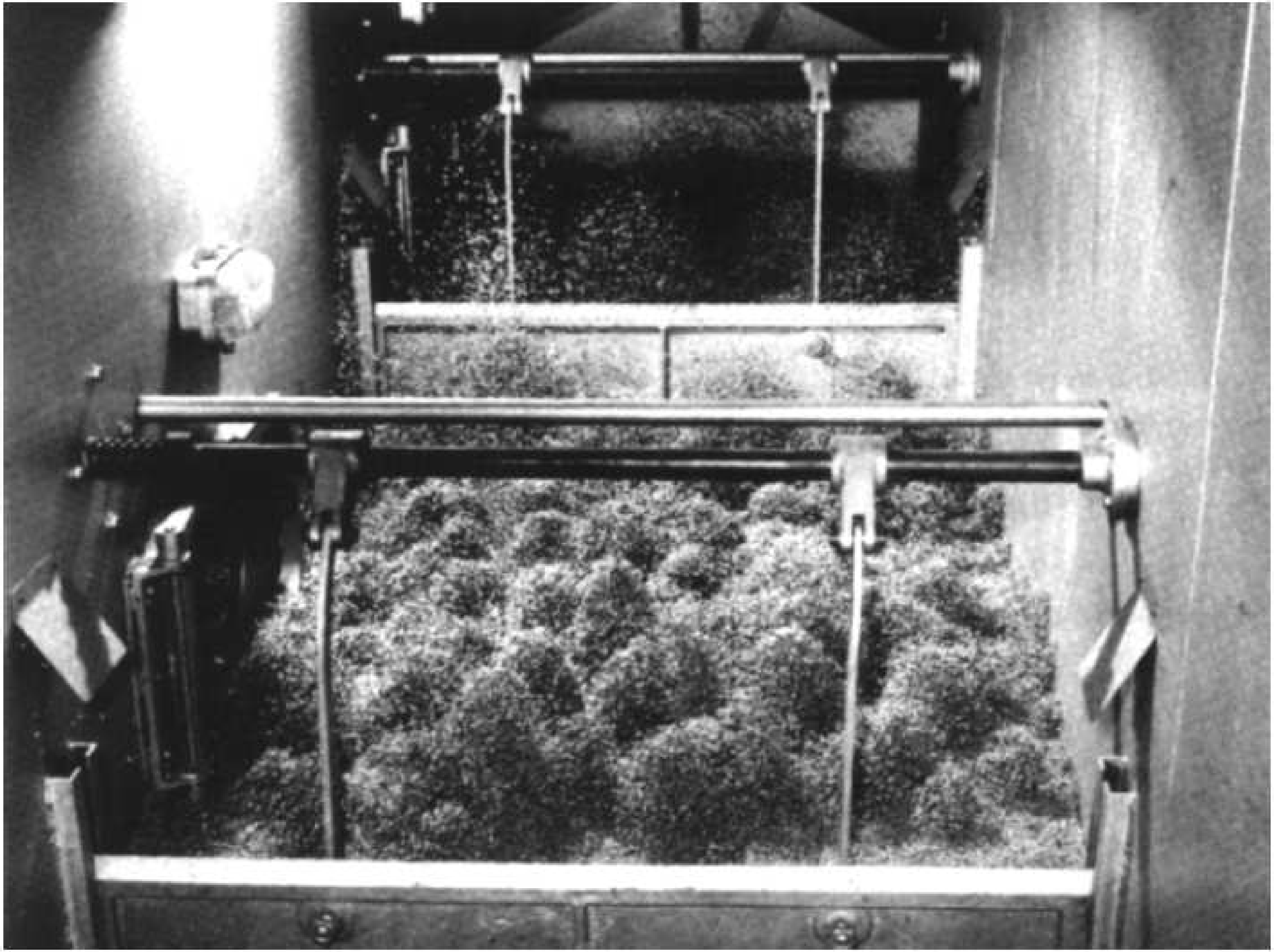
  → then added back to the product or agglomerated

- Above the distributor, mesh trays contain a bed of particulate foods up to 15 cm deep.

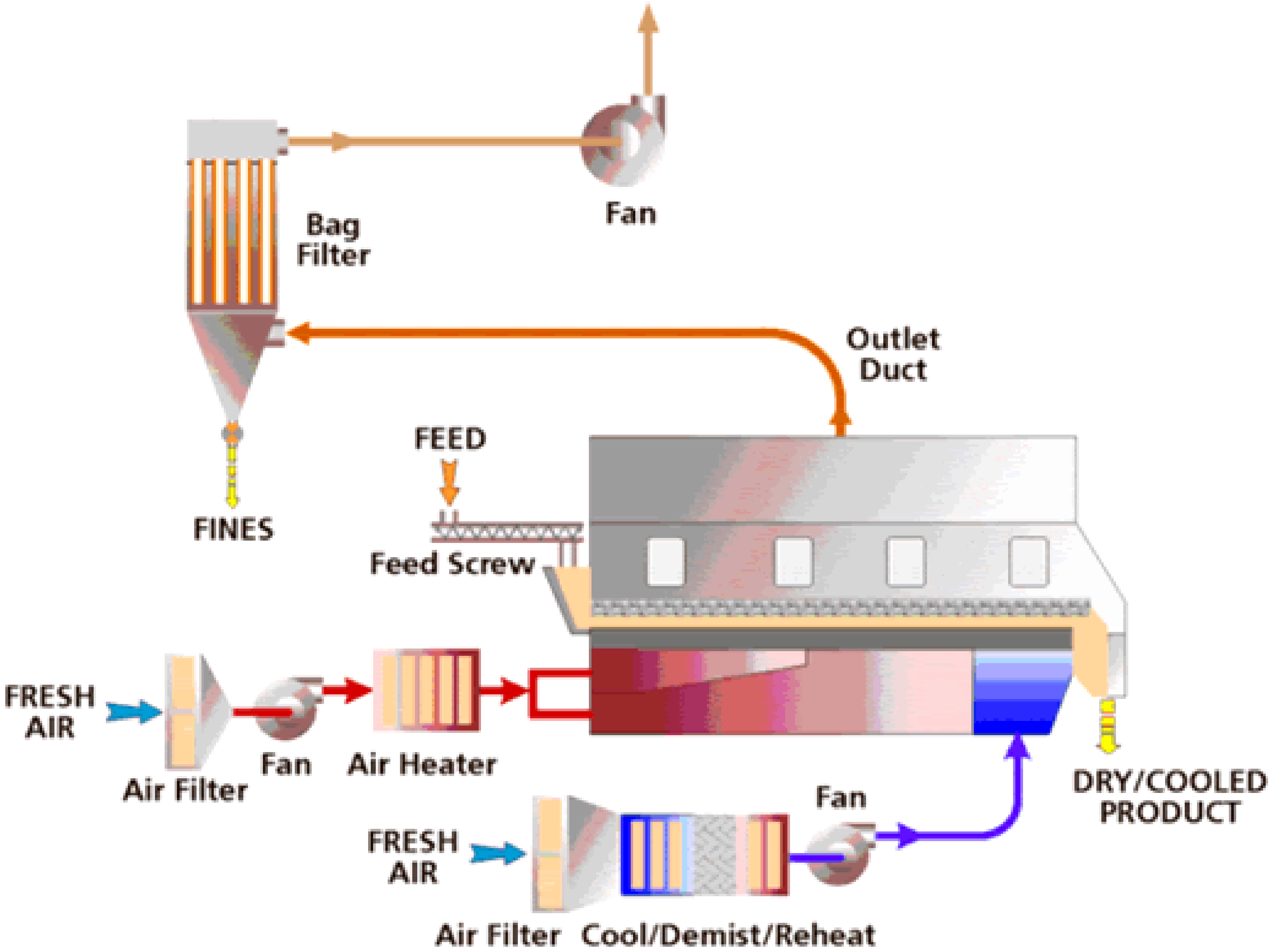
- Hot air is blown through the bed

  → food to become suspended & vigorously agitated (fluidised), exposing the maximum surface area of food for drying.

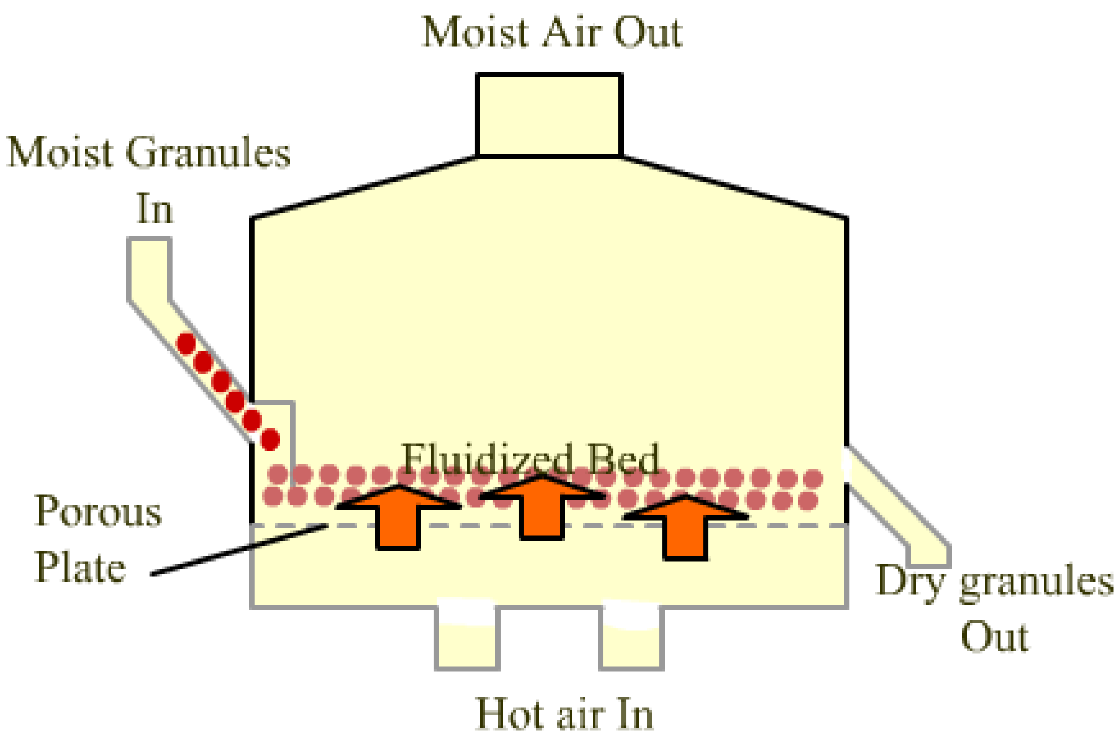
- These driers are compact and have good control over drying conditions and high drying rates.

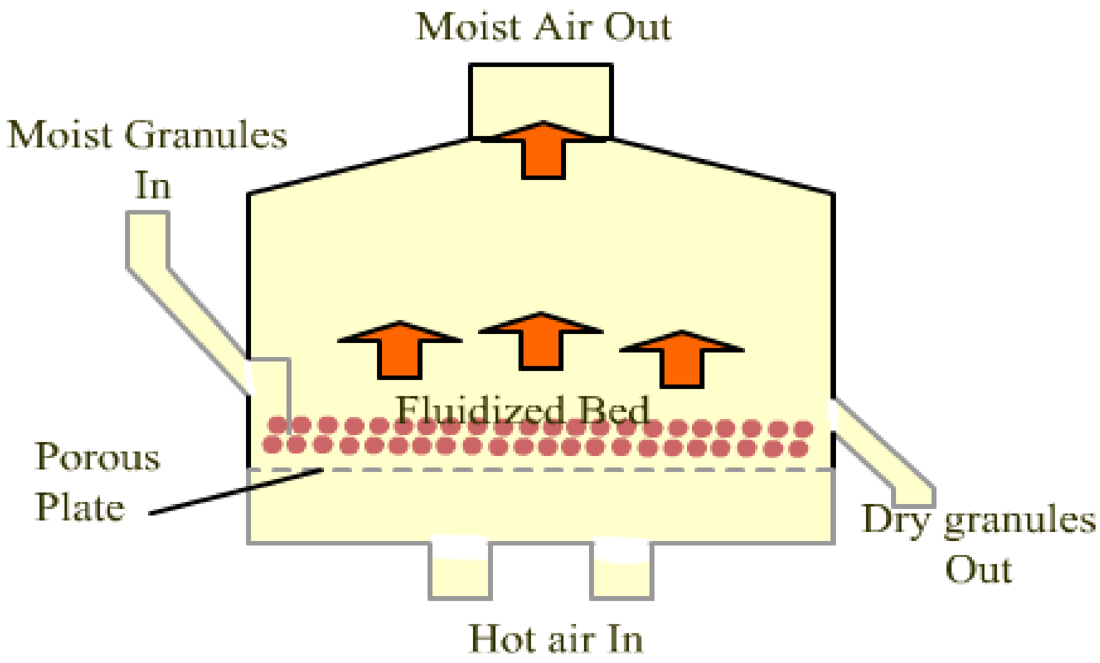


Fluidised-bed drying.
(Courtesy of Petrie and McNaught Ltd.)



Fan
Bag
Filter
Outlet
Duct
FEED
FINES
Feed Screw
FRESH
AIR
Air Filter
Fan
Air Heater
DRY/COOLED
PRODUCT
Fan
FRESH
AIR
Air Filter
Cool/Demist/Reheat


Moist Air Out
Moist Granules
In
Fluidized Bed
Porous
Plate
Dry granules
Out
Hot air In


Moist Air Out
Moist Granules
In
Fluidized Bed
Porous
Plate
Dry granules
Out
Hot air In

- batch operation, the product is thoroughly mixed by fluidisation → uniform moisture content.

- continuous operation, trays vibrate to move food under gravity from one tray to the next.

- Greater range of moisture contents in the dried product & bin driers are used for finishing.

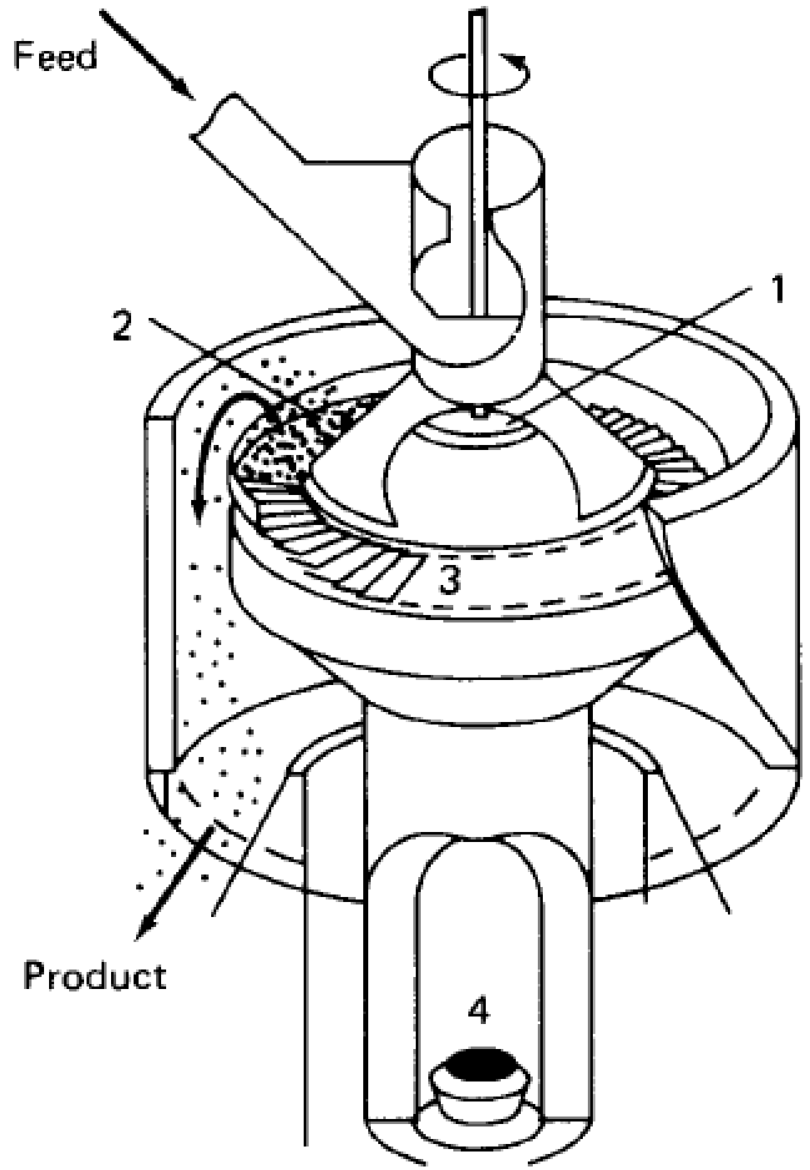
- Main applications: for small, particulate foods that are capable of being fluidised without excessive mechanical damage, incl. yeast, desiccated coconut, grain, herbs, instant coffee, sugar & tea.

- Examples development of fluidised-bed drier:
- ‘Torbed’ drier

  a fluidised bed of particles is made to rotate around a torus-shaped chamber by hot air blown directly from a burner.
- *Spin-flash drier*

  hot air enters tangentially and together with the action of the rotor, causes a turbulent rotating flow of air up through the chamber
- *Centrifugal fluidised-bed drier*

  particulate food is filled into a drying chamber which rotates at high speed; hot air is forced through the bed of food to overcome the centrifugal force and fluidise the particles.



Torbed drier: (1) rotating disc distributor to deliver raw material evenly into processing chamber; (2) rotating bed of particles; (3) fixed blades with hot gas passing through at high velocity; (4) burner assembly.
(Courtesy of Torftech Ltd.)

Kiln driers

- Two-storey buildings; a drying room with a slatted floor is located above a furnace.
- Hot air & the products of combustion from the furnace pass through a bed of food.
- Limited control over drying conditions; drying times are relatively long.
- High labour costs; to turn the product regularly, manually loading and unloading.
- Large capacity, easily constructed & maintained at low cost.

Pneumatic driers

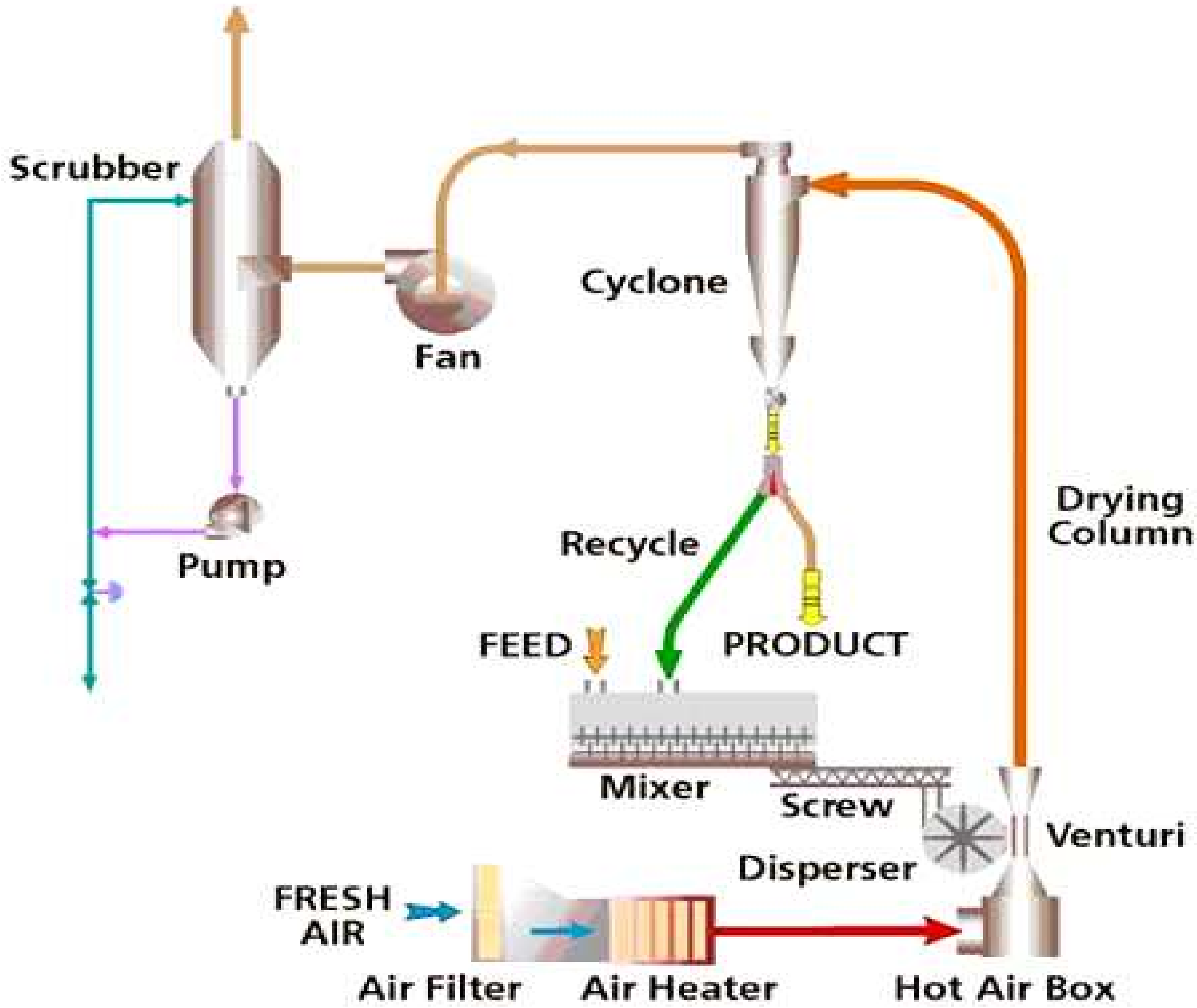
- Moist powders or particulate foods, usually < 40% moisture & particle size 10–500 µm, are metered into metal ducting & suspended in hot air.

- In **vertical driers** the air-flow is adjusted

  → lighter & smaller particles are carried to a cyclone separator more rapidly than are heavier & wetter ones

- For products require longer residence times the ducting is formed into a continuous loop (***pneumatic ring driers***) and the product is re-circulated until it is adequately dried.

- High temperature short-time ring driers (***flash driers***) to expand the starch in potatoes or carrots to give a rigid, porous structure.


Scrubber
Fan
Cyclone
Pump
Recycle
Drying
Column
FEED
PRODUCT
Mixer
Screw
Venturi
Disperser
FRESH
AIR
Air Filter
Air Heater
Hot Air Box

- low capital & maintenance costs,
- high drying rates
- close control over drying conditions; suitable for heat sensitive foods.
- often used after spray drying

  → produce foods have a lower moisture content than normal (e.g. special milk or egg powders and potato granules).

Rotary driers

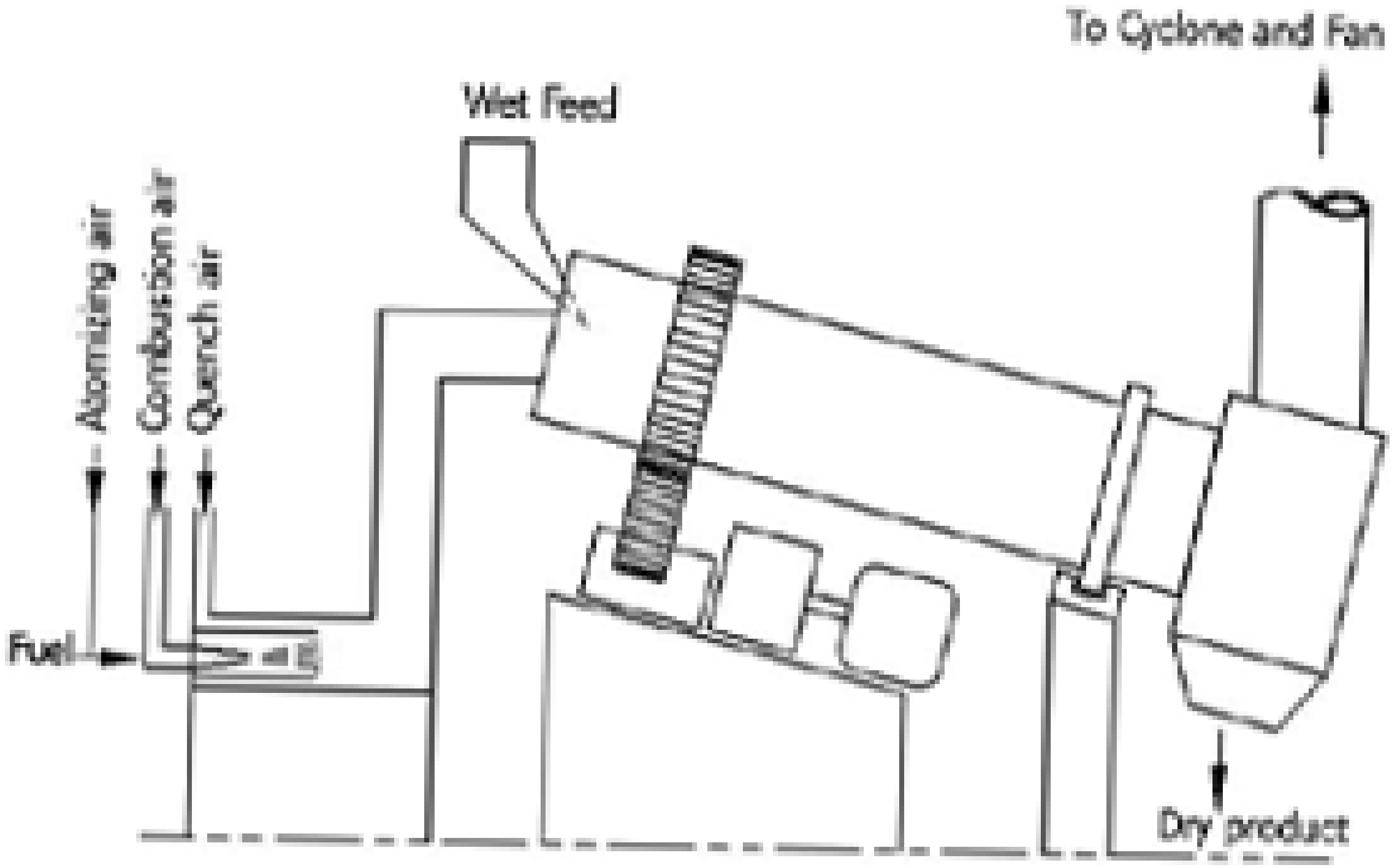
- A slightly inclined (up to 5º) rotating metal cylinder is fitted internally with flights to cause food to cascade through a stream of parallel or counter-current hot air as it moves through the drier.

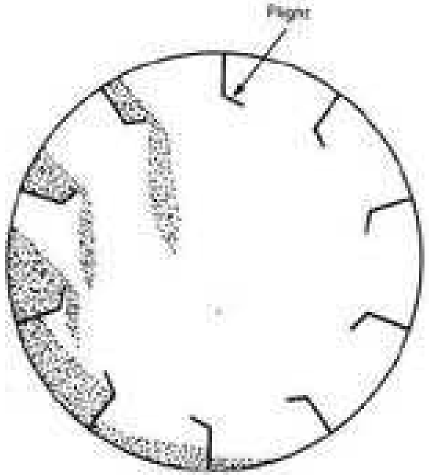
- Large surface area of food exposed to the air produces high drying rates & a uniformly dried product.

- Suitable for foods tend to mat or stick together in belt or tray driers.

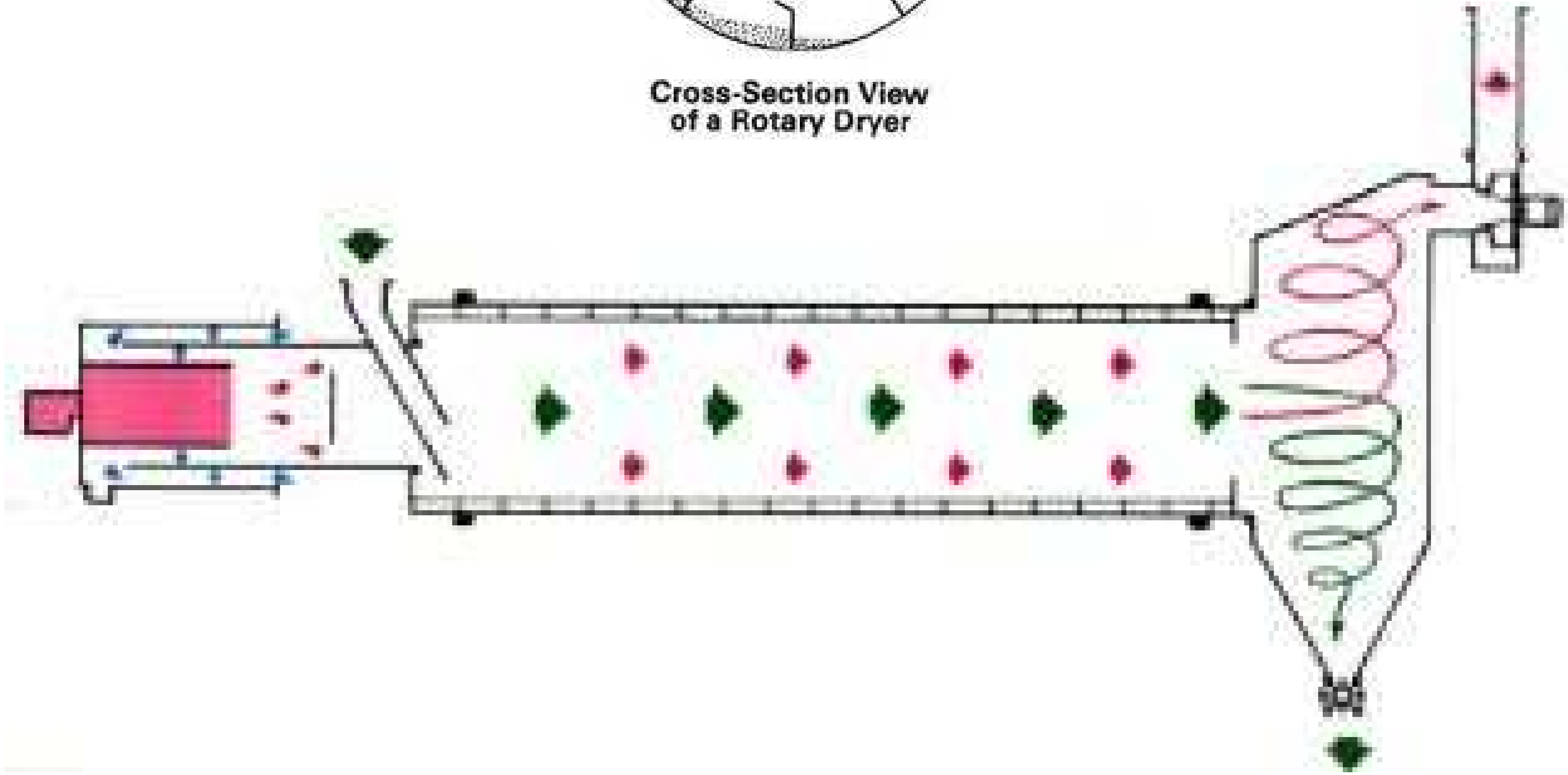
- Damage caused by impact & abrasion in the drier restricts this method to relatively few foods (e.g. nuts & cocoa beans).

A slightly inclined, slowly rotating metal cylinder





Cross-Section View of a Rotary Dryer



Spray driers

- A fine dispersion of pre-concentrated food (40–60% moisture) is 1st ‘atomised’ to form fine droplets then sprayed into a co- or counter-current flow of heated air at 150–300ºC in a large drying chamber.

Types of atomiser:

- *Centrifugal atomiser*.

  Liquid is fed to the centre of a rotating disc or bowl; Droplets, 50–60 μm ø, are flung from the edge to form a uniform spray.

- *Pressure nozzle atomiser*.

  Liquid is forced at a high pressure through a small aperture to form droplet sizes of 180–250 μm.

  Grooves inside the nozzle → the spray form into a cone shape & to use the full volume of the drying chamber.

- *Two-fluid nozzle atomiser*.

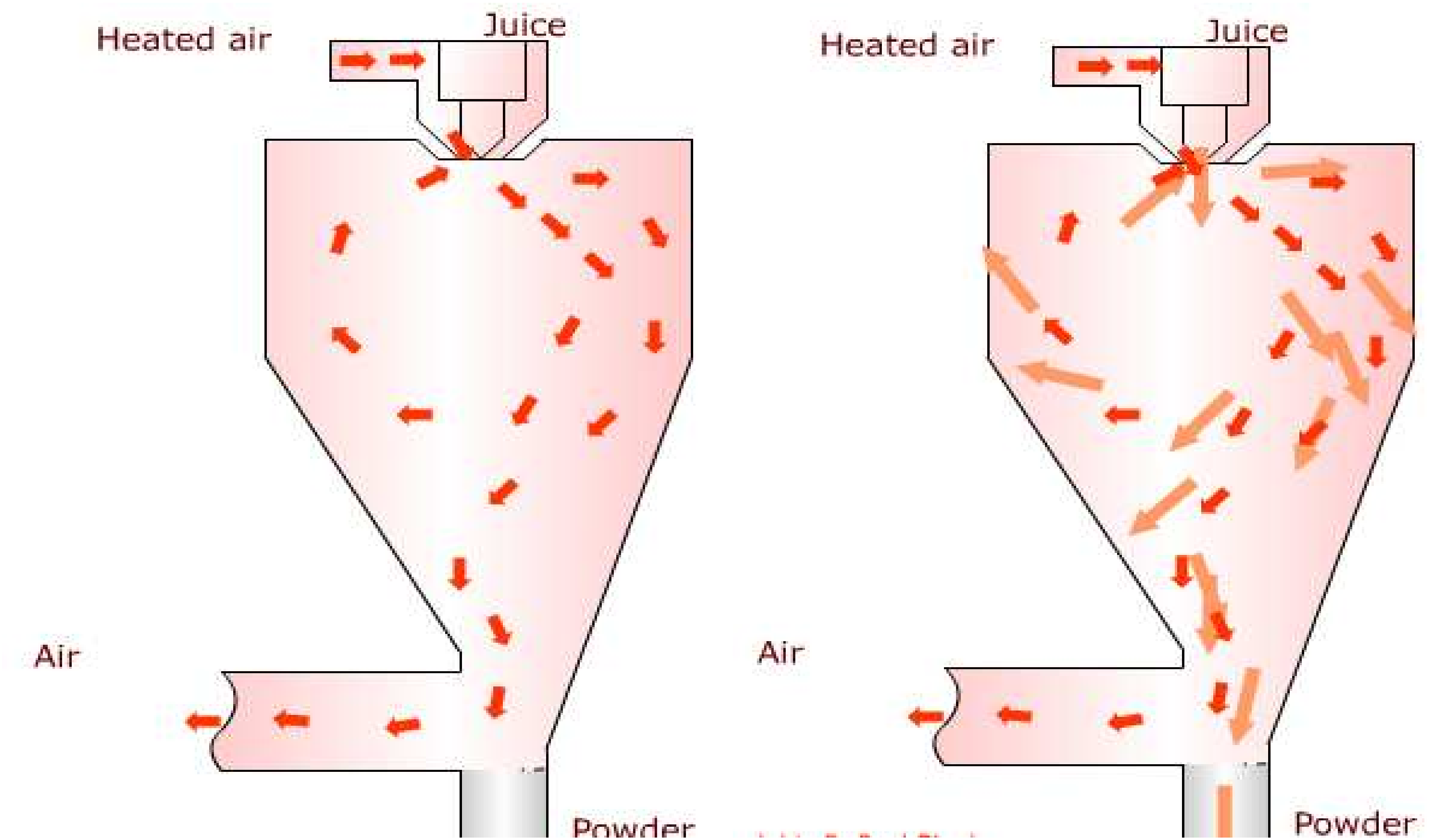
  Compressed air creates turbulence which atomises the liquid.

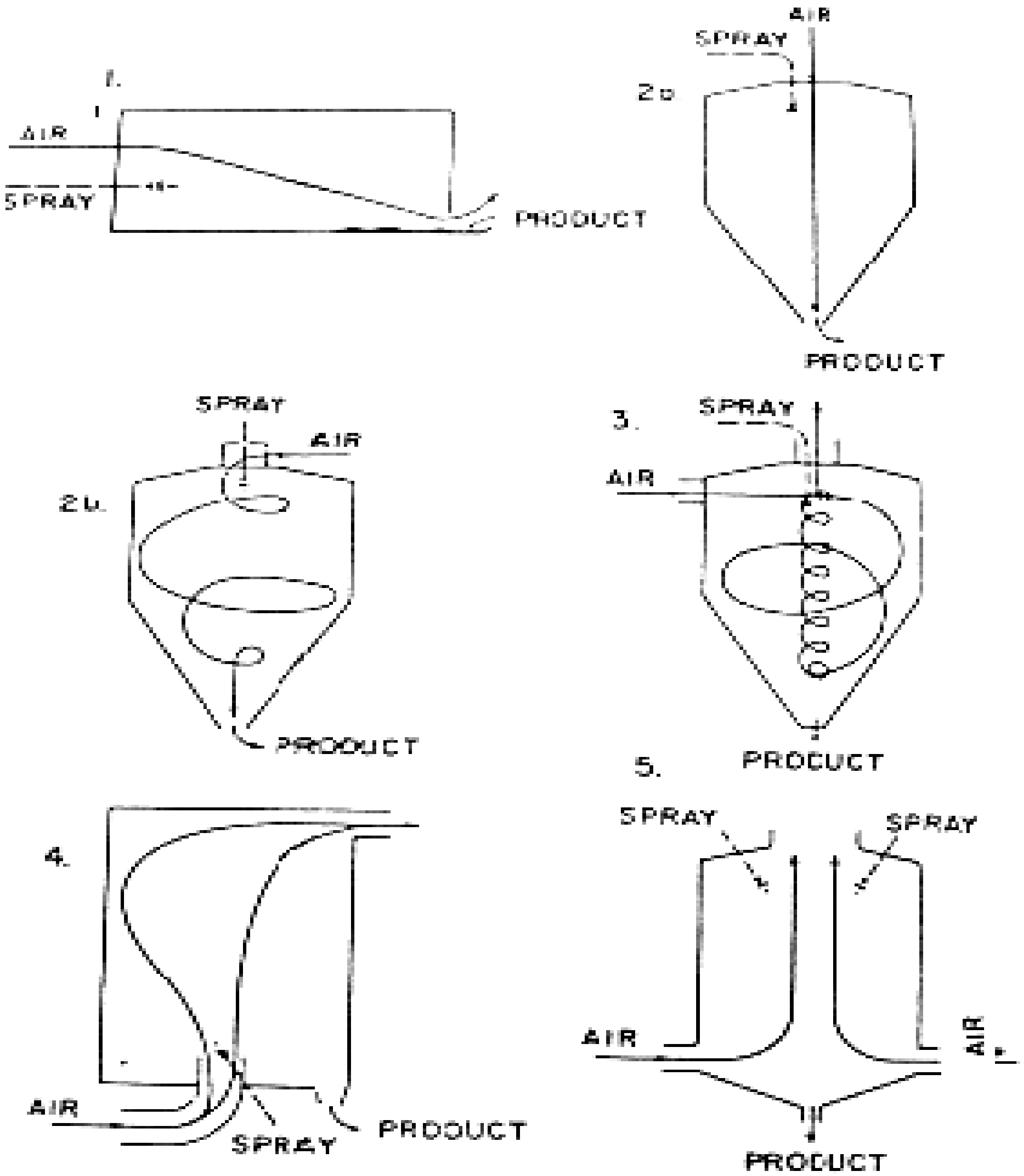
- *Ultrasonic nozzle atomiser*.

  A two-stage atomiser; liquid is 1^{st} atomised by a nozzle atomiser, 2^{nd} using ultrasonic energy to induce further cavitation.

  Nozzle atomisers are susceptible to blockage by particulate foods; abrasive foods gradually widen the apertures & increase the average droplet size.

Limited to foods that can be atomized, such as liquids & low viscosity pastes or purees





1.
AIR
SPRAY
PRODUCT
AIR
SPRAY
2a
PRODUCT
SPRAY
AIR
2b.
PRODUCT
3.
SPRAY
AIR
PRODUCT
4.
AIR
SPRAY
PRODUCT
5.
SPRAY
SPRAY
AIR
AIR
PRODUCT

- Rapid drying (1–10 s) → very large surface area of droplets.
- Feed rate is controlled to produce an outlet air temperature of 90–100ºC,

  → corresponds to a wet-bulb temperature (and product temperature) of 40–50ºC to produce little heat damage to the food.
- The dry powder is collected at the base of drier & removed by a screw conveyor or a pneumatic system with a cyclone separator.
- Large number of designs of atomiser, drying chamber, air heating & powder collecting systems.
- Spray driers may be fitted with fluidised bed facilities to finish powders taken from the drying chamber.

- Advantages: rapid drying, large-scale continuous production, low labour costs, & relatively simple operation & maintenance.
- Limitations: high capital costs, requirement for a relatively high-feed moisture content to ensure that food can be pumped to the atomiser (higher energy costs & higher volatile losses)
- Development → *ultrasonic drying*

→ Small droplets are produced in a liquid by ultrasound

→ Heated to remove the water.

→ Rapid drying & the dried residue is collected.

→ Works well with low-fat solutions, less well with oily or fatty foods, which do not dry easily.

Sun and solar drying

- the most widely practised
- foods are simply laid out in fields or on roofs or other flat surfaces and turned regularly until dry.
- More sophisticated methods (solar drying) collect solar energy and heat air, which in turn is used for drying.
- Solar driers:
  - direct natural-circulation driers (a combined collector and drying chamber)
  - direct driers with a separate collector
  - indirect forced-convection driers (separate collector and drying chamber).

Open-Air Sun Drying

Advantages	Disadvantages
Almost without cost	Open to dust contamination & animals attack
Ideal for products where little or no value is added	Totally dependent on good weather
	Very slow drying rates with danger of mold growth
Food usually dried to close to the home	May not possible to dry to a sufficiently low level of moisture to prevent mold growth

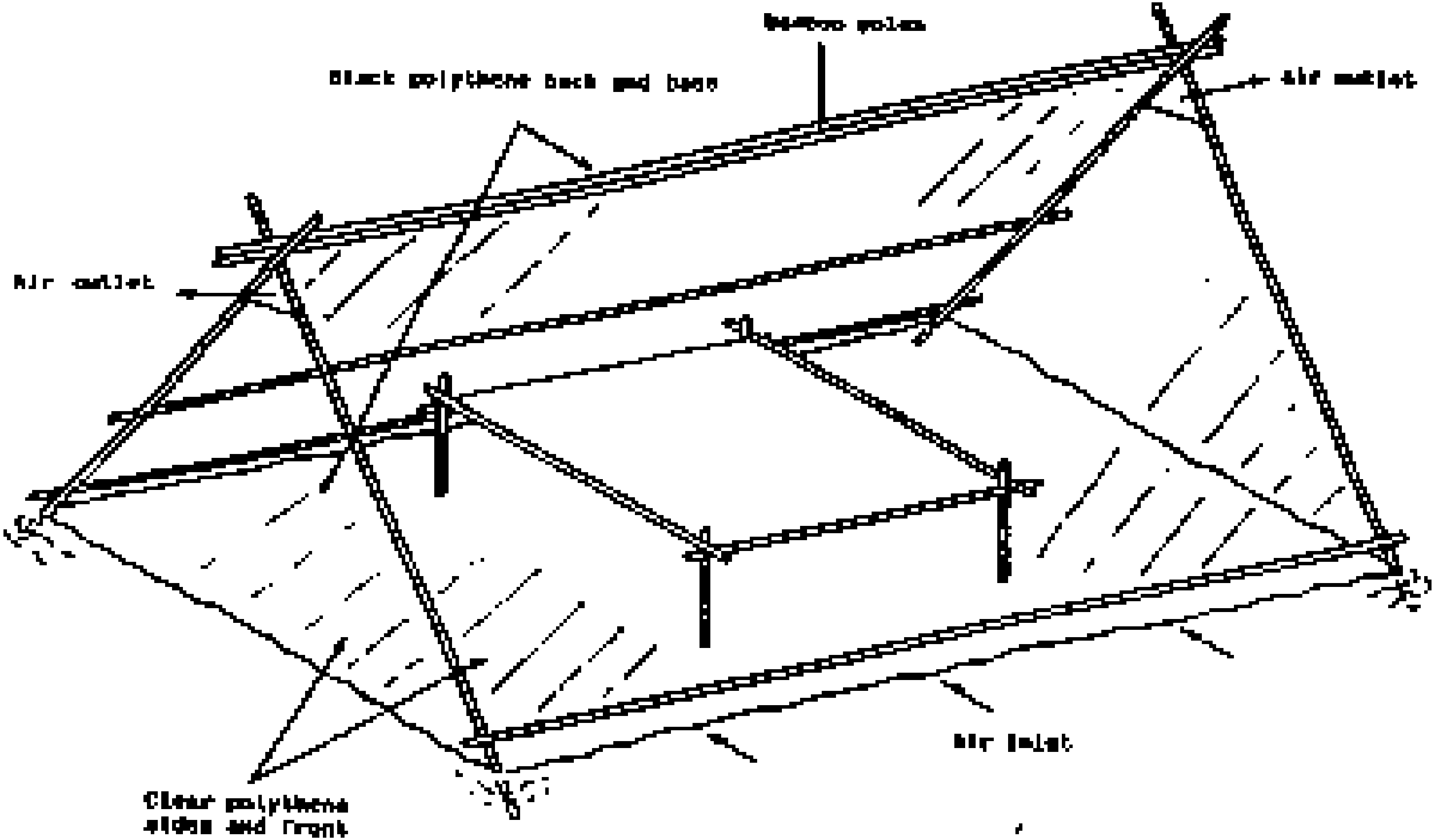
- simple inexpensive technologies.
- poor control over drying conditions;
- lower drying rates than in artificial driers;
- lower quality & greater variability;
- dependent on weather & time of day;
- requires a larger labour force.

Solar Dryers

- Solar dryers use a simple construction to more efficiently make use of the sun heat
- Under the correct climatic conditions, they can provide many advantages over sun drying :
  - Higher drying temperatures which results in shorter drying times & the ability to dry to a lower final moisture content
  - Protection from dust contamination & from rain
  - Low cost & simple to construct in local workshops

Tent Solar Dryer

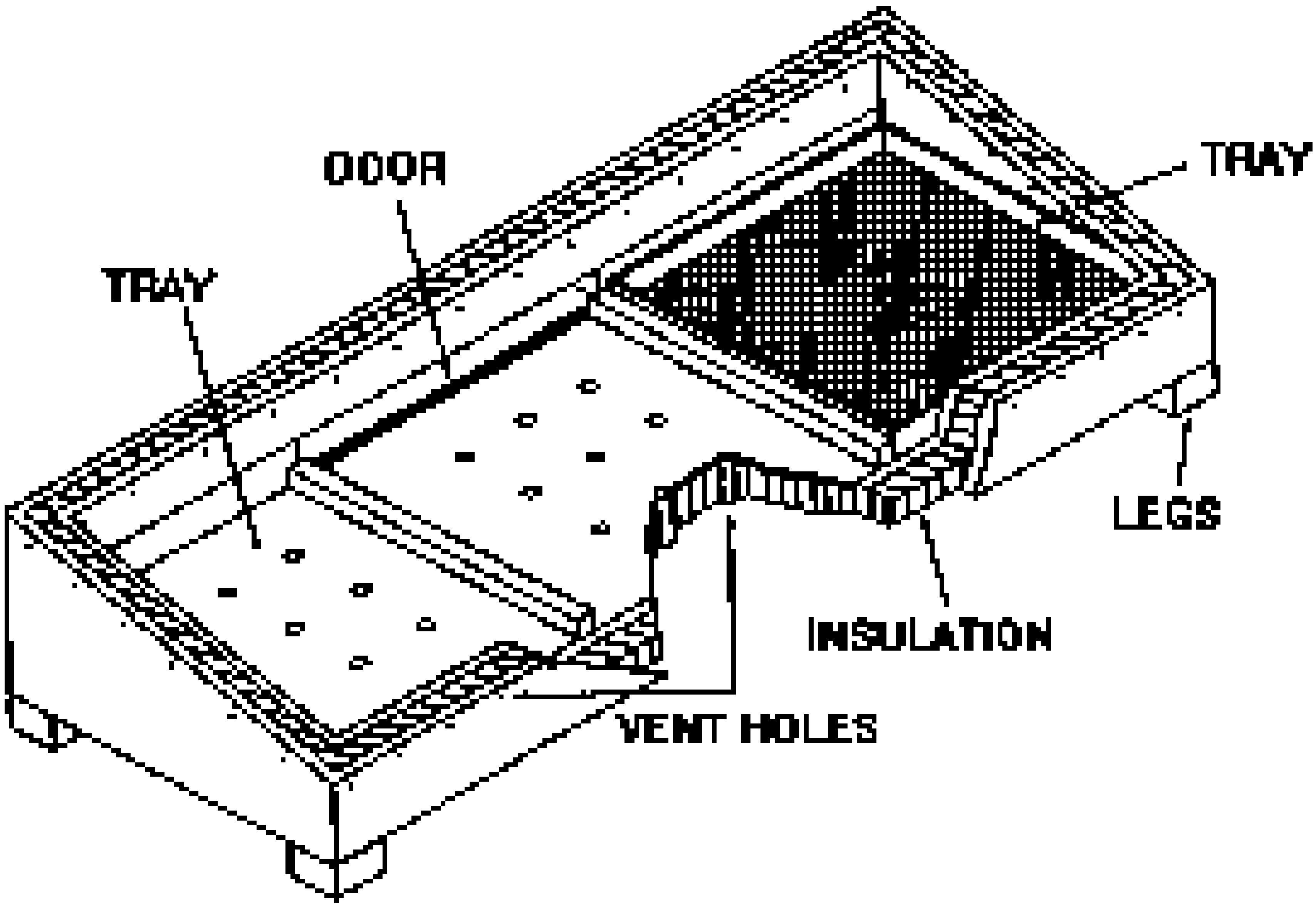
- Cheap & simple to build
- Consist of a frame of wood poles covered with plastic sheet. Black plastic should be used on the wall facing away from the sun. The food to be dried is placed on a rack above the ground
- Provide protection against rain, insects and dust and, in the case of fish for example, can reduce drying times by 25%
- Can be taken down and stored when not in use, have the disadvantage of being easily damaged by strong winds



Bamboo poles
Black polythene back and base
Air outlet
Air outlet
Clear polythene
sides and front
Air inlet

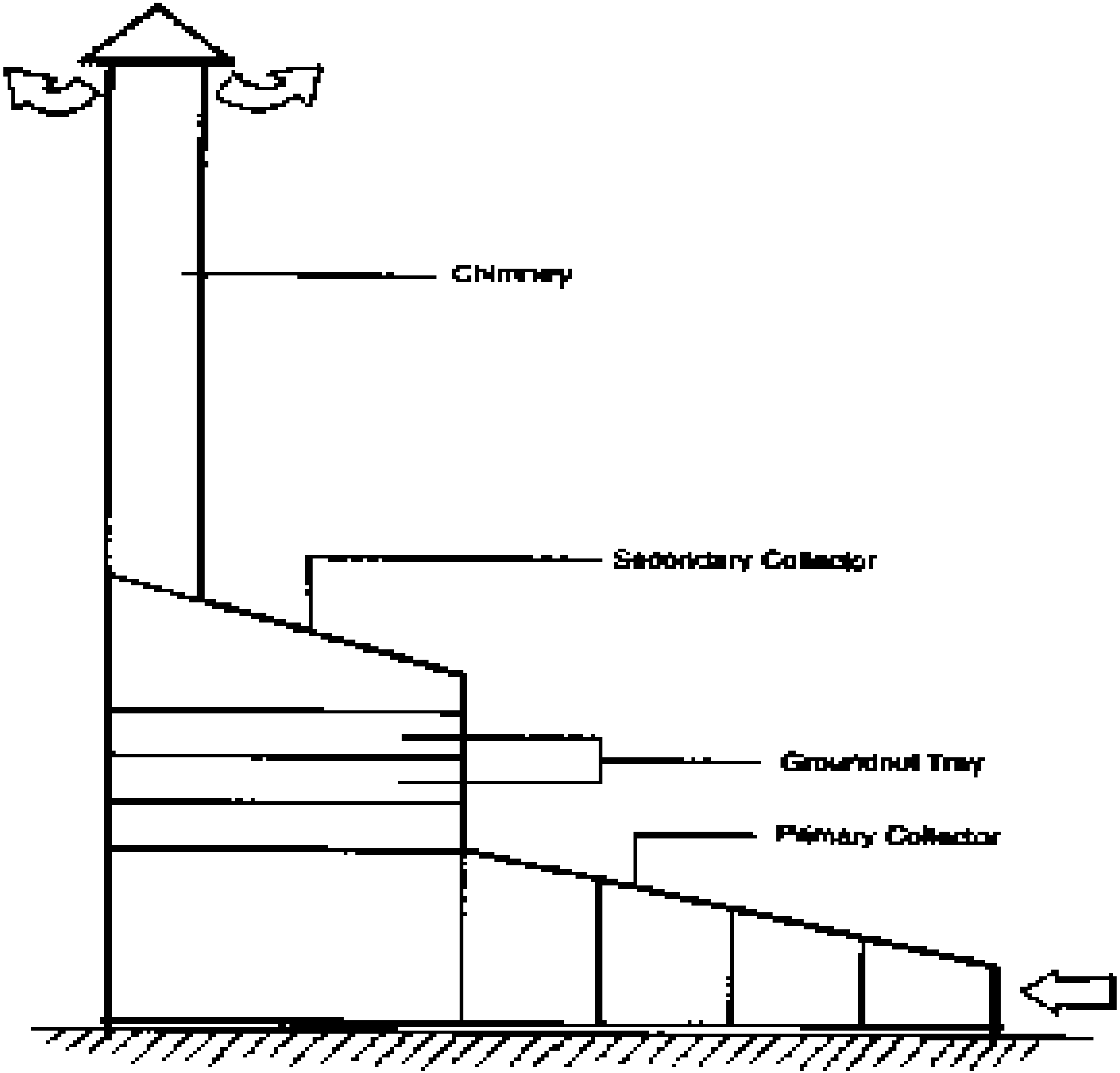
Brace Solar Dryer

- Consists of a wooden box with a hinged transparent lid
- The inside is painted black and the food supported on a mesh tray above the dryer floor
- Air flows into the chamber through holes in the front and exits from vents at the top of the back wall
- Achieve higher temperatures, and thus shorter drying times, than tent dryers


DOOR
TRAY
TRAY
LEGS
INSULATION
VENT HOLES

Indirect Solar Dryer

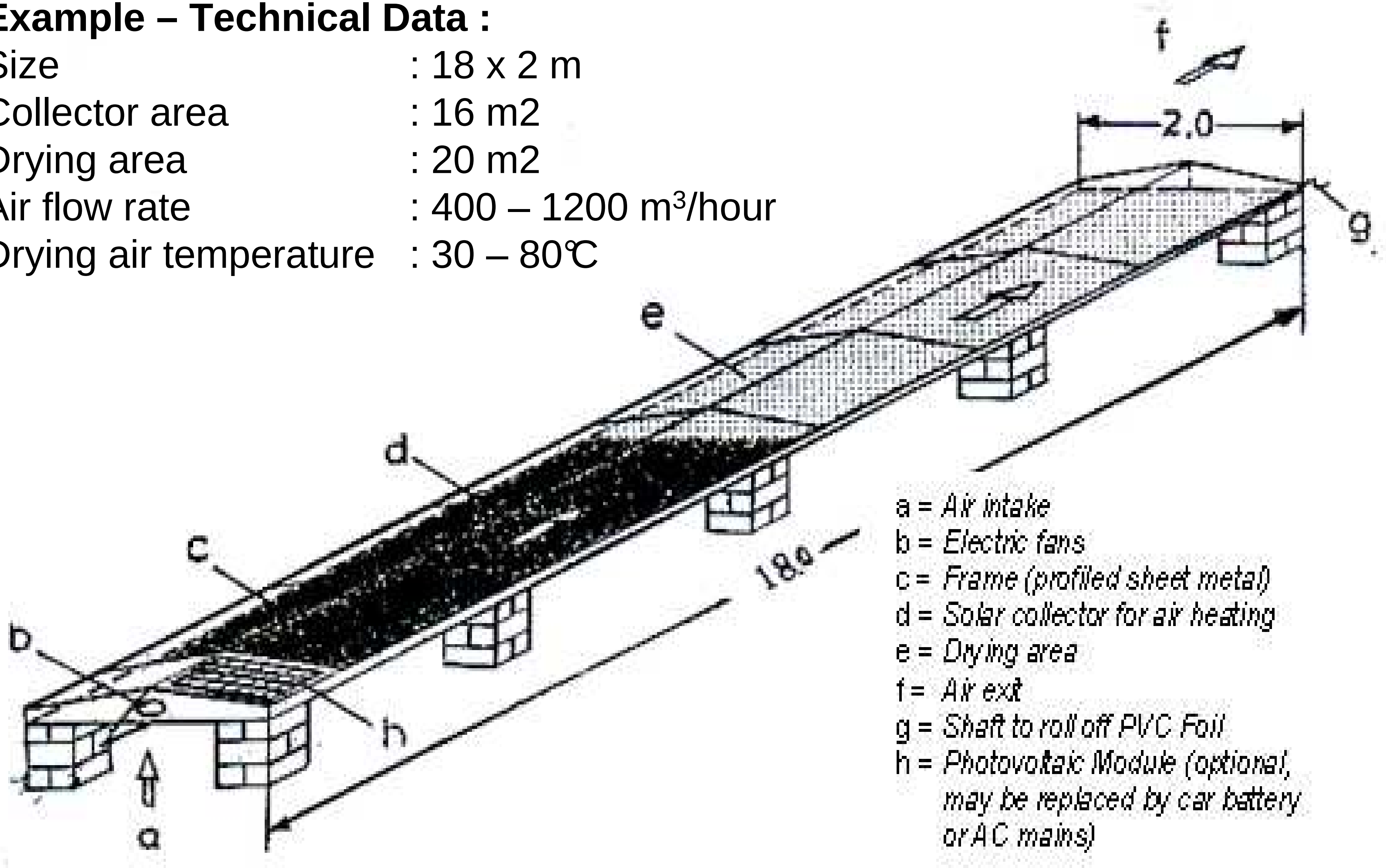
- Solar collector which supplies heated air is separated from chamber containing trays of food
- Several advantages over direct dryers:
  * the food is not exposed to the direct rays of the sun which reduces the loss of color and vitamins.
  * the collector can be large and thus heat greater quantities of air


Chimney
Secondary Collector
Groundnut Tray
Primary Collector

Solar Tunnel Dryer

Example – Technical Data :

Size	: 18 x 2 m
Collector area	: 16 m2
Drying area	: 20 m2
Air flow rate	: 400 – 1200 m^3/hour
Drying air temperature	: 30 – 80°C



Heated-surface (/contact) driers

- Heat is supplied to the food by conduction

- Advantages over hot-air drying:

1. not necessary to heat large volumes of air before drying begins; the thermal efficiency is therefore high.

2. may be carried out in the absence of oxygen to protect components of foods that are easily oxidised.

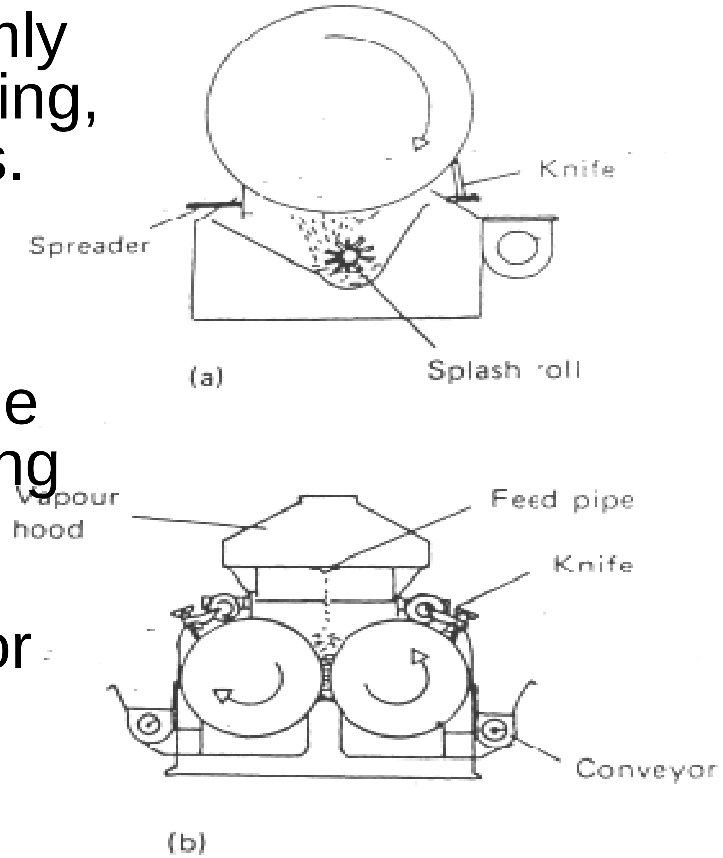
- Typical heat consumption: 2000–3000 kJ kg^{-1} of water evaporated vs. 4000–10,000 kJ kg^{-1} of water evaporated for hot-air driers.

- Foods have a low thermal conductivity, becomes lower as the food dries

  → thin layer of food is needed to conduct heat rapidly, without causing heat damage.

Drum driers (roller driers)

- Slowly rotating hollow steel drums are heated internally by pressurised steam to 120–170ºC.
- A thin layer of food is spread uniformly over outer surface by dipping, spraying, spreading or by auxiliary feed rollers.
- Before the drum has completed one revolution (within 20 *s*–3 min), dried food is scraped off by a 'doctor' blade contacts drum surface uniformly along its length.
- Driers: single drum, double drums, or twin drums.



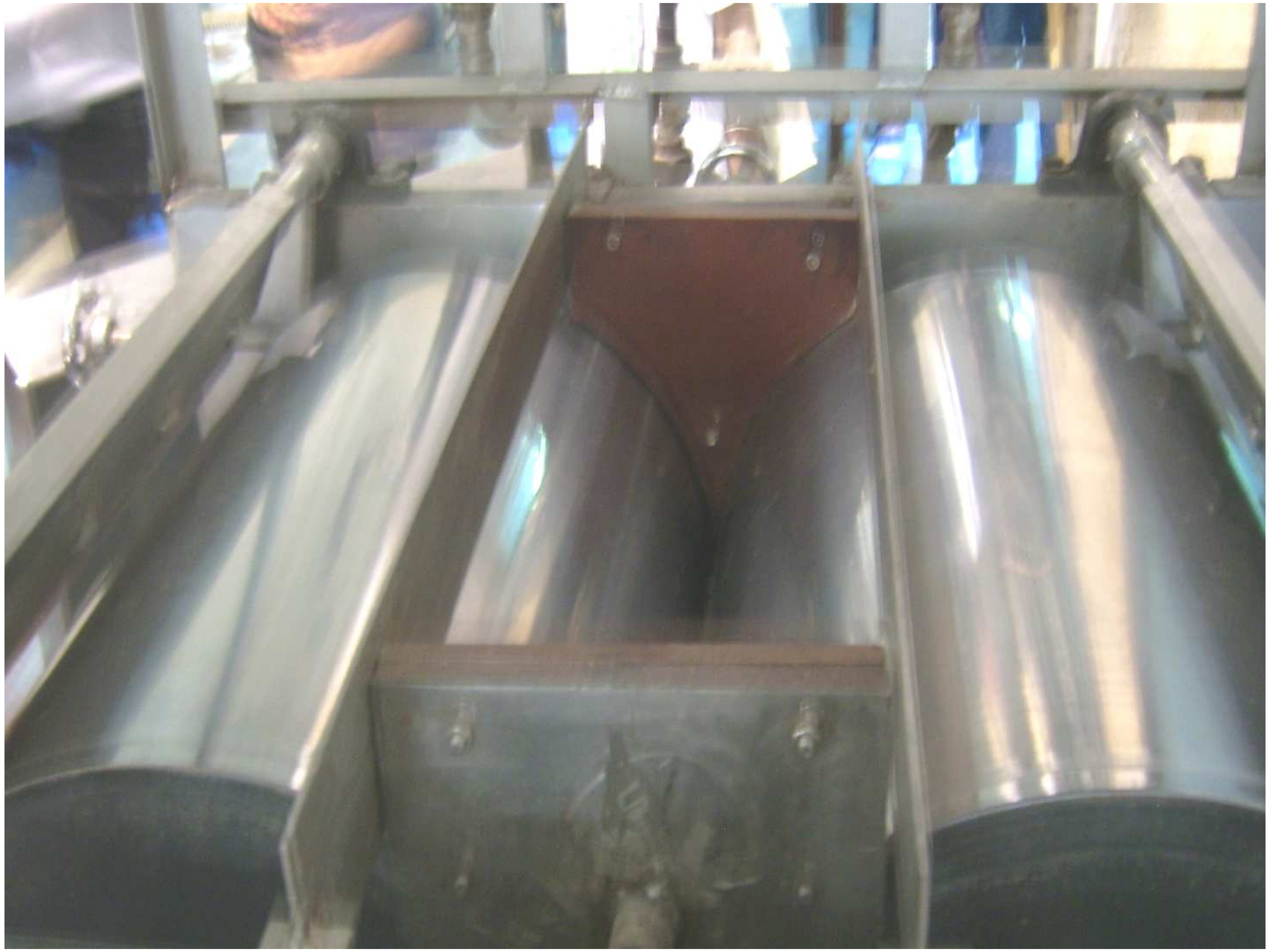
- Single drum → greater flexibility, a larger proportion of the drum area, easier access for maintenance, no risk of damage caused by metal objects falling between the drums.

- High drying rates, high energy efficiencies, suitable for slurries.

- To produce potato flakes, pre-cooked cereals, molasses, some dried soups & fruit purees, & whey or distillers' solubles for animal feed formulations.

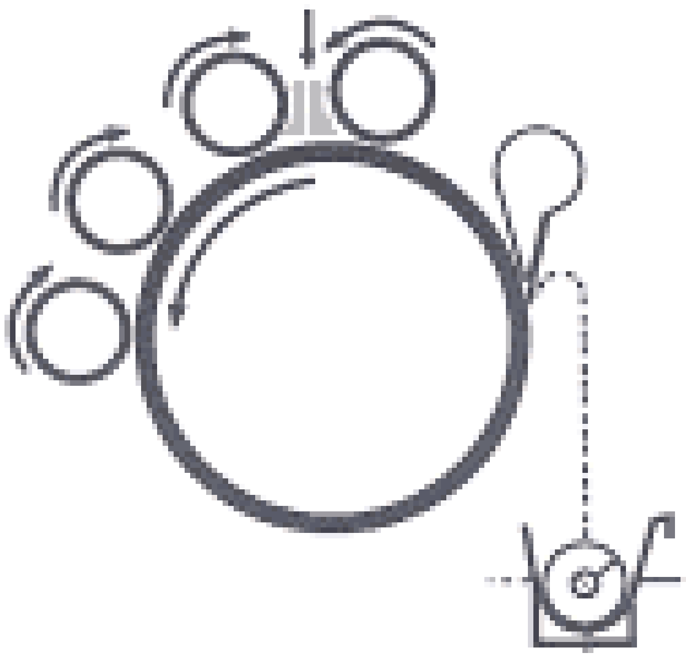
- High capital cost & heat damage to sensitive foods caused by high drum temperatures

Drum Dryer : Double Drum



Single Drum Dryer with Multiple Applicator Rolls
wet product is applied to the drum by means of applicator rolls

Double Drum Dryer with Feed Rolls



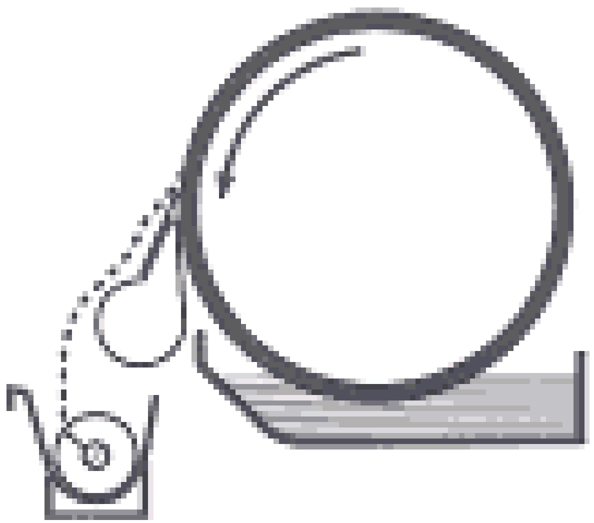
Twin Cylinder Dryer with Nip Feed

The thickness of the product film may be varied by adjustment of the gap between the drying drums or cylinders

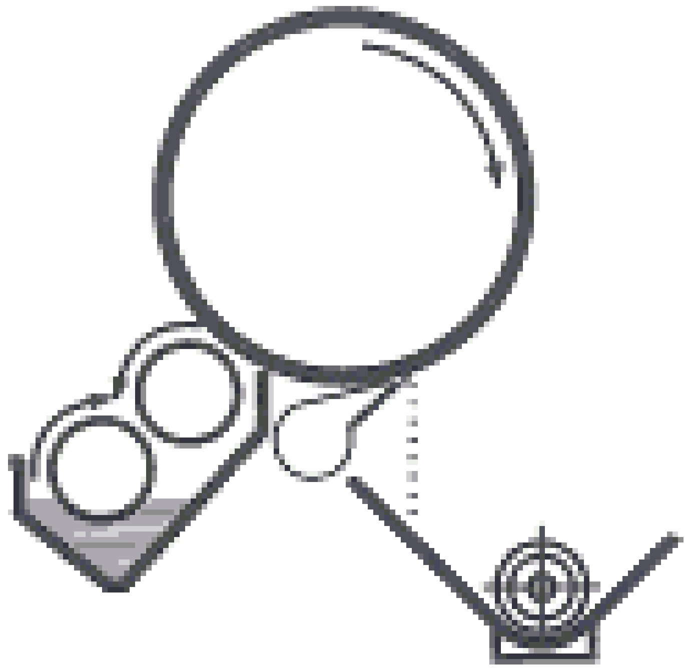
Single Drum Dryer with Applicator Roll

The applicator roll is located underneath the drum dryer and dips into the product. A liquid film is then transferred to the drying drum

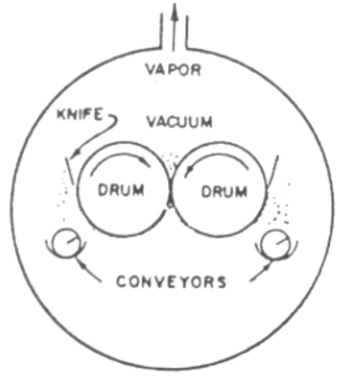
Dip Feed Drum Dryer
A film of the product to be dried is picked up on the surface of the dryer drum as it rotates through a feed tray mounted below



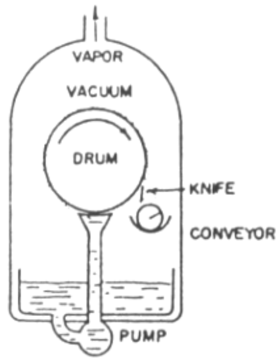
Single Drum Dryer with Double Applicator Roll
The tray containing the feed to the dryer drum and product film is applied by an intermediate applicator roll



- Developments:
  the use of auxiliary rolls
  to remove & re-apply
  food during drying; the use
  of high-velocity air to increase
  the drying rate;
  the use of chilled air to cool the product.



C. VACUUM DOUBLE DRUM (TOP FED)



D. VACUUM SINGLE DRUM (PAN FED)

- Drums may be enclosed in a vacuum chamber to dry food at lower temperatures but high capital cost

- In ***ball-drying****,*
  drying chamber is fitted with a slowly rotating screw & contains ceramic balls heated by hot air, blown into the chamber.
  Particulate foods are dried mainly by conduction

Vacuum band & vacuum shelf driers

- Food slurry is spread or sprayed onto a steel belt (or ‘band’) which passes over two hollow drums, within a vacuum chamber at 1–70 Torr.
-
- The food is dried by steam-heated drum, then by steam-heated coils or radiant heaters located over the band.

- The dried food is cooled by water-cooled drum & removed by a blade.

- Vacuum shelf driers consist of hollow shelves in a vacuum chamber.
- Food is placed in thin layers on flat metal trays.
- A partial vacuum of 1–70 Torr is drawn in the chamber & steam or hot water is passed through the shelves to dry the food.
- Rapid drying & limited heat damage to food → suitable for heat-sensitive foods.
- Care to prevent dried food from burning onto trays in vacuum shelf driers, and shrinkage reduces the contact between food & heated surfaces of both types of equipment.
- High capital & operating costs; low production rates & are used mainly to produce puff-dried foods.

Types of contact drier

Type of drier	Batch (B) or continuous (C)	Vacuum (V) or atmospheric (A)	Feed	Production rate	Typical applications
Vacuum tray	B	V	Any	Low	Fruit pieces, meat or vegetable extracts
Vacuum band	C	V	Pastes, solids	Low-medium	Chocolate crumb, meat or vegetable extracts, fruit juices
Plate	C	V or A	Free-flowing solids	Low-medium	Tea, coffee
Thin-film	C	V or A	Liquids	Low-medium	Tomato concentrate, gelatin
Drum	C	V or A	Liquids	Low-medium	Instant potato, corn syrup, baby foods
Rotating batch	B	V	Free-flowing solids	Low-medium	Gravy mix, pectin
Horizontally agitated	B or C	V or A	Liquids, pastes, powders	Low-high	Chocolate crumb, corn meal, confectionery
Indirect rotary	C	A	Free-flowing solids	Medium-very high	Brewer's grain, starch
Vertical agitated	B	V or A	Liquids, pastes, powders	Low-medium	Plant extracts, food colours, glucose, starch

From Oakley (1997).

Summary of some novel drying techniques

Technique	Applications	Advantages	Limitations
Microwave and dielectric drying (Chapter 18)	High value products	Low temperature, batch or continuous operation, good quality products	Slow, expensive
Microwave augmented freeze drying (Chapter 22)	High value products	Low temperature, rapid, good quality products	Expensive
Centrifugal fluidised-bed drying	Small particles, vegetable pieces, powders	Rapid, easy to control	Loss of product integrity, noisy
Ball drying	Small particles, vegetable pieces	Low temperature, rapid, continuous operation, good quality products	Loss of product integrity, difficult to control
Ultrasonic drying	Liquids	Rapid	Requires low fat liquids
Explosive puff drying	Produces honeycomb structure in small particles	Rapid, good rehydration of products	Loss of product integrity, high levels of heat

Adapted from Cohen and Yang (1995).

Explosion puff drying

- involves partially drying food to a moderate moisture content, then sealing it into a pressure chamber.

- The pressure & temperature in the chamber are increased, then instantly released.

- The rapid loss of pressure causes the food to expand & develop a fine porous structure.

  → faster final drying & rapid rehydration.

- Sensory & nutritional qualities are well retained.

Effect on foods

- Main changes to texture & loss of flavour or aroma; changes in colour & nutritional value are significant in some foods.

Texture

- Nature & extent of pre-treatments (e.g. $CaCl_2$ added to blancher water), type & extent of size reduction & peeling;

  → affect texture of rehydrated fruits and vegetables.

Approximate ratios for drying, shrinkage and rehydration of selected vegetables

Vegetable	Drying ratio	Overall shrinkage ratio	Rehydration ratio
Cabbage	11.5	21.0	10.5
Carrots, sliced	7.5	12.0	7.0
Onions, sliced	7.0	8.0	5.5
Peppers, green	17.0	22.0	8.0
Spinach	13.0	13.5	5.0
Tomato flakes	14.0	20.0	5.0

- Loss of texture due to
  - gelatinisation of starch,
  - crystallisation of cellulose,
  - localised variations in moisture content during drying.
- permanently distort the relatively rigid cells → a shrunken shrivelled appearance.
- On rehydration the product absorbs water more slowly & does not regain the firm texture of the fresh material.

- Drying pieces of meat

  → aggregation & denaturation of proteins

  → loss of water-holding capacity, which leads to toughening of muscle tissue.

- Rapid drying & high temperatures cause greater changes to the texture of foods

- As water is removed during drying, solutes move from the interior of food to the surface.

- The mechanism & rate of movement
  - are specific for each solute
  - depend on type of food & drying conditions used.

- High air temperatures (particularly with fruits, fish & meats), cause complex chemical and physical changes to solutes at the surface & the formation of a hard impermeable skin.

  → *case hardening*; reduces the rate of drying.

- minimised by controlling drying conditions

- Textural characteristics of powders,

  → related to bulk density & the ease of rehydration.

- Bulk density of powders depends on dried particles size & on whether they are hollow or solid.

  → determined by nature & composition of food & drying conditions (e.g. uniformity of droplet size, temperature, solids content & degree of aeration of the feed liquid).

- Low fat foods (e.g. fruit juices, potato and coffee) are more easily formed into free flowing powders than are whole milk or meat extracts.

- Powders are ‘instantised’ by treating individual particles so that they stick together to form free-flowing agglomerates or aggregates; relatively few points of contact.

- The surface of each particle is easily wetted when the powder is rehydrated & the agglomerates break up to allow particles to sink below the surface & disperse rapidly through the liquid.

  : *wettability*, *sinkability*, *dispersibility* & *solubility*.

- A powder, to be considered ‘instant’, should complete these four stages within a few seconds.

Bulk density and moisture content of selected powdered foods

Food	Bulk density ($kg\,m^{-3}$)	Moisture content (%)
Cocoa	480	3–5
Coffee (ground)	330	7
Coffee (instant)	330	2.5
Coffee creamer	470	3
Corn starch	560	12
Egg, whole	340	2–4
Milk, powdered, skimmed	640	2–4
Milk, instant, skimmed	550	2–4
Salt, granulated	960	0.2
Sugar, granulated	800	0.5
Wheat flour	450	12

Adapted from Watt and Merrill (1975) and Peleg (1983).

Flavour and aroma

- Heat not only vaporises water during drying but also causes loss of volatile components from food

- Most dried foods have less flavour than the original.

- Extent of loss depends on
  - temperature & moisture content of food
  - vapour pressure of the volatiles & their solubility in water vapour.

- Open porous structure of dried food allows access of oxygen

  → aroma loss due to oxidation of volatile components & lipids during storage.

- Rate of deterioration → storage temperature & Aw.

- In dried milk the oxidation of lipids produces rancid flavours → formation of secondary products incl. δ-lactones.

- Most fruits & vegetables contain only small quantities of lipid, but oxidation of unsaturated fatty acids to produce hydroperoxides, which react further by polymerisation, dehydration or oxidation to produce aldehydes, ketones and acids, causes rancid & objectionable odours.

- Some foods (e.g. carrot) may develop an odour of ‘violets’ produced by the oxidation of carotenes to β-ionone.

- These changes are reduced by:
  - vacuum or gas packing
  - low storage temperatures
  - exclusion of ultraviolet or visible light
  - maintenance of low moisture contents
  - addition of synthetic antioxidants
  - preservation of natural anti-oxidants.

- Enzyme glucose oxidase is used to protect dried foods from oxidation.
- Milk powders are also stored under an atmosphere of nitrogen with 10% carbon dioxide.
- Flavour changes prevention (due to oxidative or hydrolytic enzymes)

  - in fruits by the use of sulphur dioxide, ascorbic acid or citric acid,

  - by pasteurisation of milk or fruit juices

  - by blanching of vegetables.

- Other methods to retain flavours in dried foods:
  - recovery of volatiles & their return to the product during drying
  - mixing recovered volatiles with flavour fixing compounds, which are then granulated & added back to the dried product (e.g. dried meat powders)
  - addition of enzymes, or activation of naturally occurring enzymes, to produce flavours from flavour precursors in the food (e.g. onion and garlic are dried under conditions that protect the enzymes that release characteristic flavours).

Colour

- Drying changes surface characteristics of a food; alters its reflectivity & colour.
- In fruits and vegetables,

  chemical changes to carotenoid & chlorophyll due to heat & oxidation during drying

  residual PPO activity causes browning during storage.
- Prevented by blanching or treatment of fruits with ascorbic acid or sulphur dioxide.
- Sulphur dioxide bleaches anthocyanins
- Residual sulphur dioxide is also linked to health concerns.

- The rate of Maillard browning in stored milk & fruit products depends on

  - water activity of the food

  - temperature of storage.

- The rate of darkening increases at high drying temperatures, when the moisture content of the product exceeds 4–5% & at storage temperatures above 38ºC.

Nutritional value

- In fruits and vegetables,

  losses during preparation usually exceed those caused by the drying operation.

  E.g. losses of vitamin C during preparation of apple flakes: 8% during slicing, 62% from blanching, 10% from pureeing, & 5% from drum drying.

- Vit. have different solubilities in water & as drying proceeds

- Some vit. (e.g. riboflavin) become supersaturated & precipitate from solution, so losses are small.

- Others (e.g. ascorbic acid) are soluble until the moisture content of the food falls to very low levels

  → react with solutes at higher rates as drying proceeds.

- Vitamin C is sensitive to heat & oxidation

- Thiamin is heat sensitive, but other water-soluble vitamins are more stable to heat & oxidation.

- Oil-soluble nutrients (e.g. essential fatty acids & vitamins A, D, E and K) are mostly contained within the dry matter of food & not concentrated during drying.
- Water is a solvent for heavy metal catalysts promote oxidation of unsaturated nutrients.
- As water is removed, the catalysts become more reactive, & rate of oxidation accelerates.
- Fat-soluble vitamins are lost by interaction with peroxides produced by fat oxidation.
- Losses during storage are reduced by lowering oxygen concentration & storage temperature and by exclusion of light.

- The biological value & digestibility of proteins in most foods does not change substantially as a result of drying.
- Milk proteins are partially denatured during drum drying, → reduction in solubility of the milk powder & loss of clotting ability.
- Spray drying does not affect the biological value of milk proteins.
- At high storage temperatures & at moisture contents > appr. 5%, the biological value of milk protein is decreased by Maillard reactions between lysine & lactose.
- Lysine is heat sensitive & losses in whole milk range from 3–10% in spray drying and 5–40% in drum drying.

Vitamin losses in selected dried foods

Food	Loss (%)						
	Vitamin A	Thiamin	Vitamin B_2	Niacin	Vitamin C	Folic acid	Biotin
Fruits[a]	6	55	0	10	56		
Fig (sun-dried)	–	48	42	37	–	–	–
Whole milk (spray dried)	–	–	–	–	15	10	10
Whole milk (drum-dried)	–	–	–	–	30	10	10
Pork		50–70					
Vegetables[b]	5	< 10	< 10				

[a] Fruits mean loss from fresh apple, apricot, peach and prune.
[b] Vegetables mean loss from peas, corn, cabbage and beans (drying stage only).
Adapted from Rolls (1982) and Calloway (1962).

Rehydration

- Water that is removed from a food during dehydration cannot be replaced in the same way when the food is rehydrated

  → rehydration is not the reverse of drying

- loss of cellular osmotic pressure,
- changes in cell membrane permeability,
- solute migration,
- crystallisation of polysaccharides
- coagulation of cellular proteins

➔ all contribute to texture changes & volatile losses and are each irreversible.

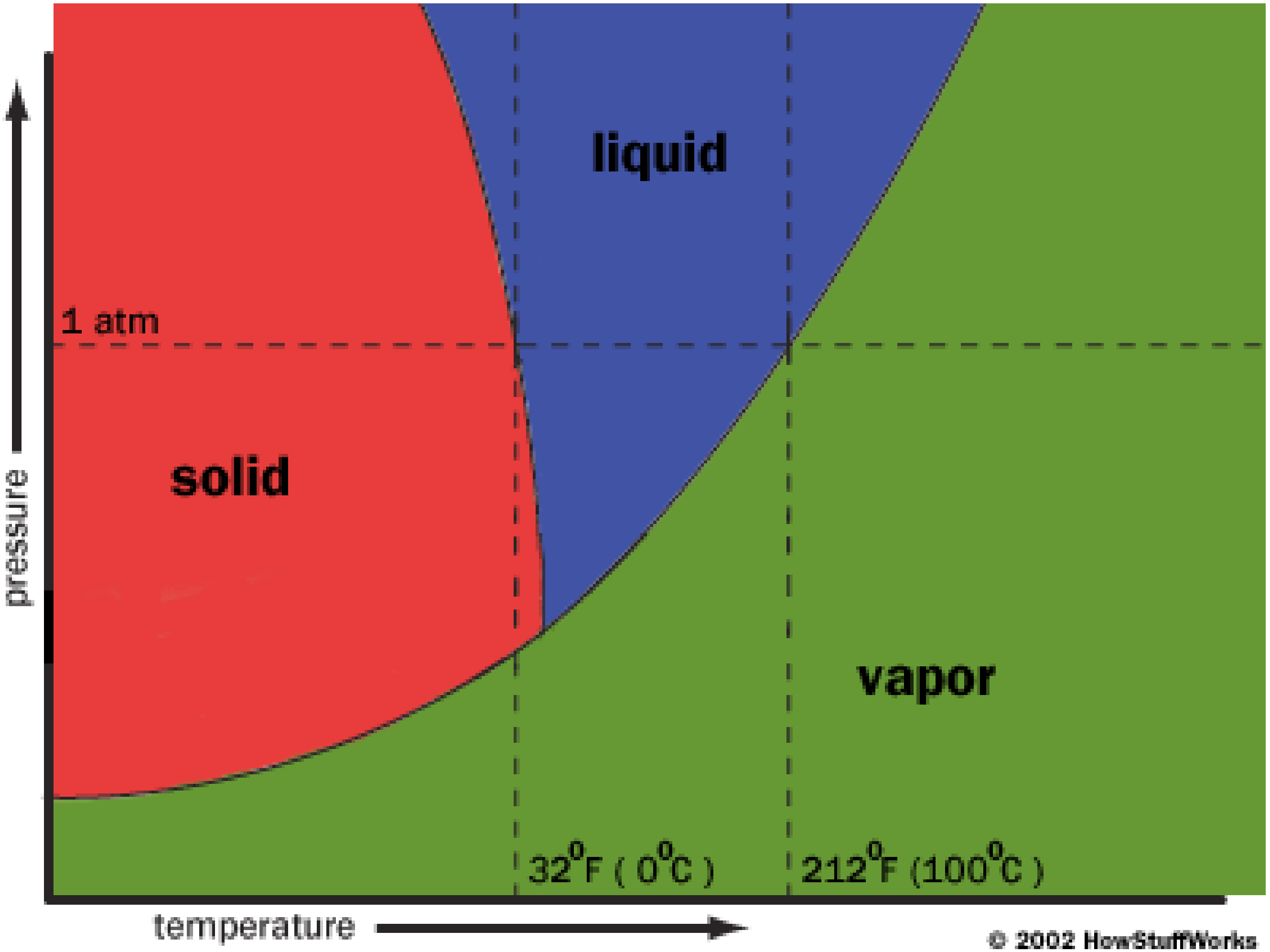
- Heat reduces the degree of hydration of starch & the elasticity of cell walls, and coagulates proteins to reduce their water-holding capacity.

- The rate and extent of rehydration may be used as an indicator of food quality;

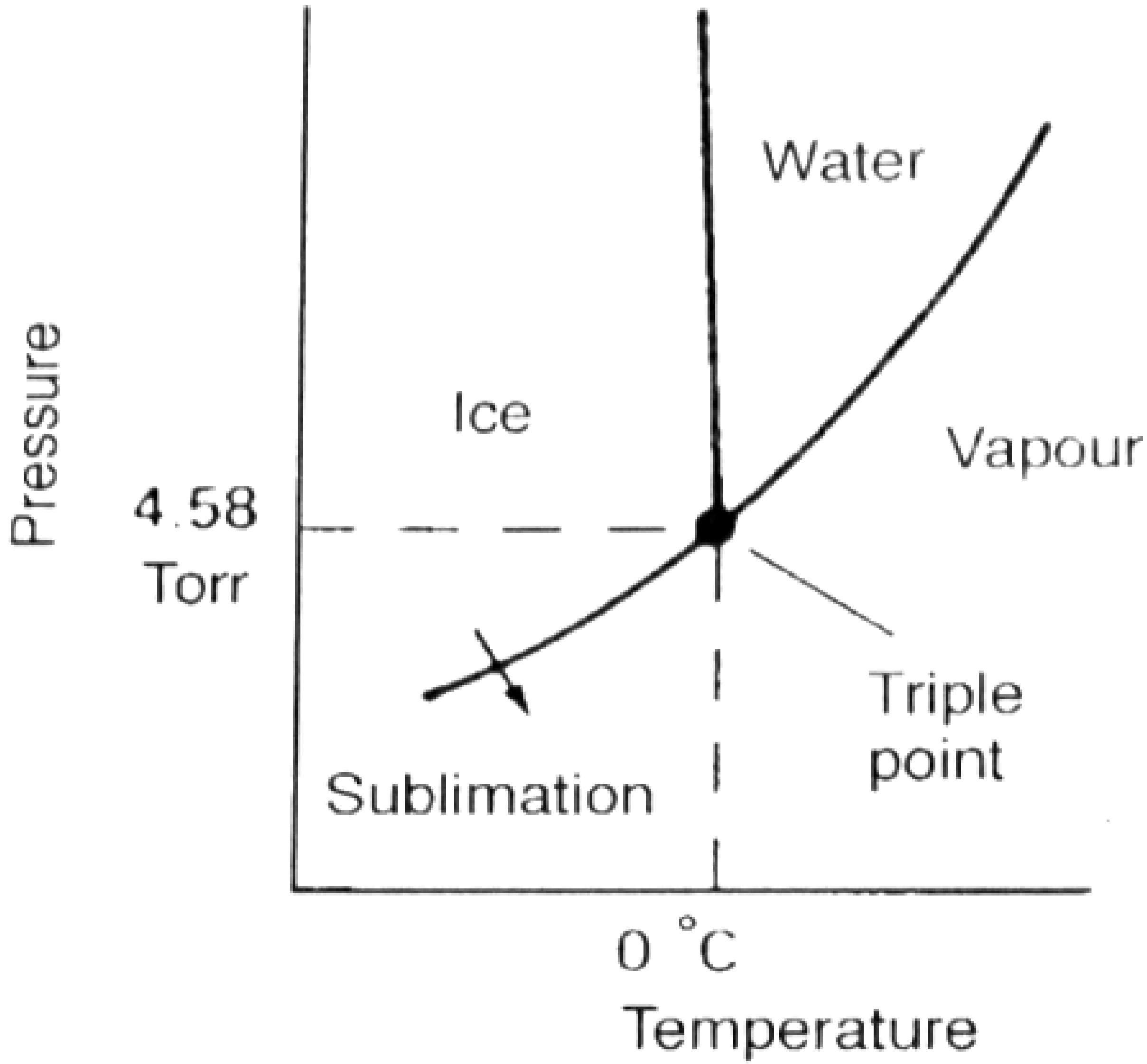
  those foods that are dried under optimum conditions suffer less damage & rehydrate more rapidly & completely than poorly dried foods.

Freeze Drying (Lyophilization)

- Freeze drying → the water content is first converted to ice & then changed into vapor without passing back through the water phase
- If the water vapor pressure of food is held below 4.58 Torr (610.5 Pa) & the water is frozen, when food is heated the solid ice sublimes directly to vapor without melting → vapor removal with a vacuum pump & condensation on refrigeration coils



Phase diagram of water

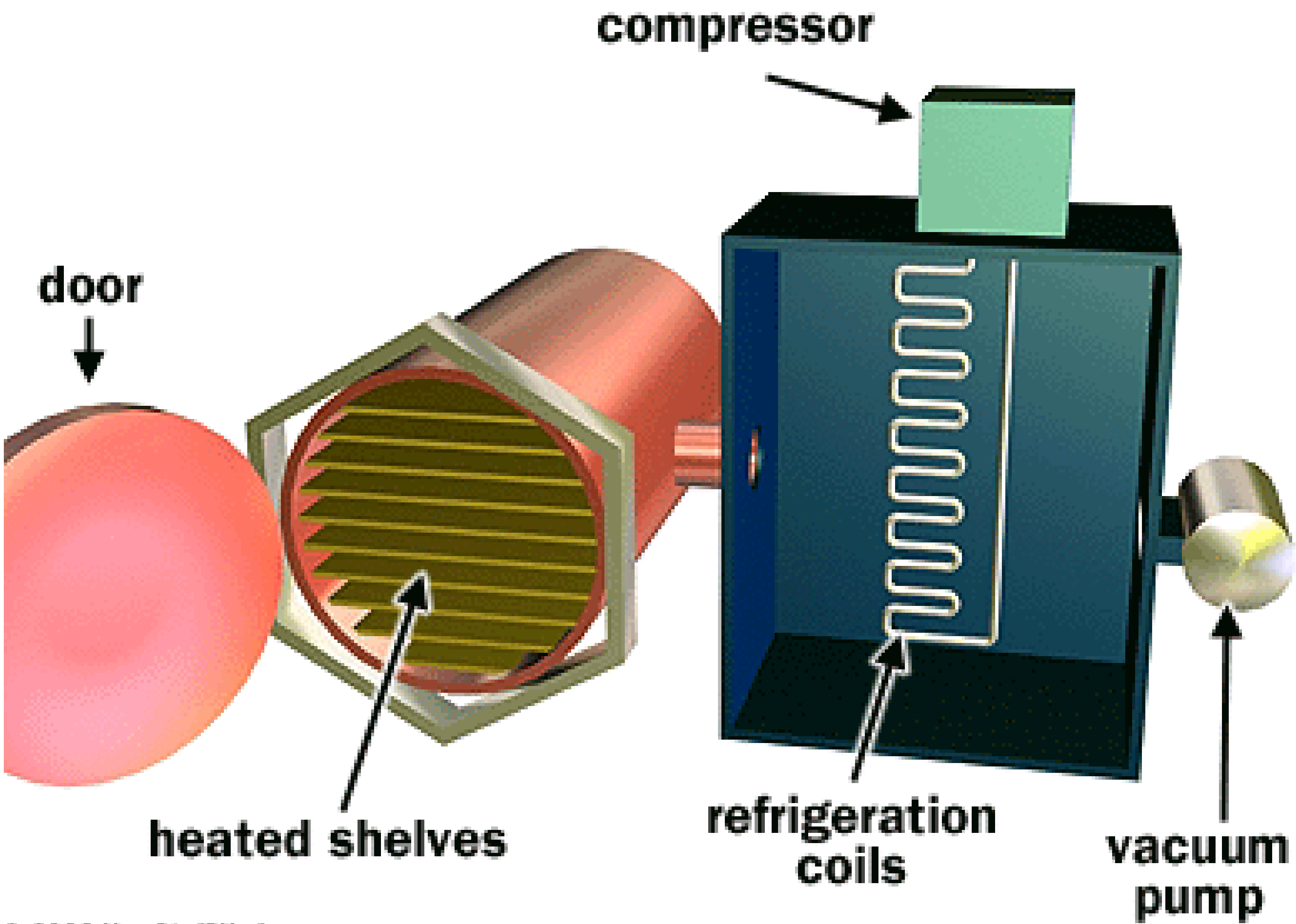


Phase diagram of water

- Frozen food remains rigid during sublimation → resulting in a porous sponge-like dried structure

- Ice has a greater volume than water → stretching of the capillary system in the product

- Especially suited to dry solid foods with high value → delicate flavors & colors; have textural & appearance attributes which can’t be well preserved by any drying method except freeze-drying



compressor
door
heated shelves
refrigeration coils
vacuum pump

Differences between conventional drying & freeze drying

- Type of foods
- Temperature
- Pressure
- Water removal
- Food structure
- Solute movement
- Dried food density
- Rehydration
- Flavor
- Color
- Nutritional value
- Cost

Freeze Drying & Rehydration

Freeze-Dried Product

A freeze-dried meal of spaghetti and meatballs, designed for campers: Left, the dried version; Right, the rehydrated version.

Thank you