Dielectric | Ohmic | Infrared Heating

PRO

Ch. 18 of Fellows

Esveld, E. 2004. Advanced Food Process & Production Engineering. Course material. WU

- Dielectric (microwave (MW) & radio frequency (RF)) energy & infrared (IR or radiant) energy: forms of electromagnetic energy
- transmitted as waves, penetrate food, be absorbed & converted to heat.
- Ohmic (or resistance) heating uses electrical resistance of foods to directly convert electricity to heat.
- Dielectric & ohmic heating are direct methods; heat is generated within product
- IR heating is an indirect method relies on heat generated externally; applied to the surface of food mostly by radiation, by convection & to a lesser extent, conduction.

Dielectric

- induces molecular friction in water molecules to produce heat
- is determined in part by the moisture content of food
- to preserve foods

Ohmic

- heating is due to the electrical resistance of a food
- heating depends on the electrical resistance of food
- to preserve foods

IR

- energy is simply absorbed & converted to heat
- the extent of heating by radiant energy depends on surface characteristics & colour of food
- used to alter the eating qualities by changing the surface colour, flavour & aroma

- Commercially, MWs & RF energy are produced at specified frequency bands to prevent interference with radio transmissions;

  radiant heat is less controlled & has a wider range of frequencies;

  Ohmic heating uses mains frequency electricity.

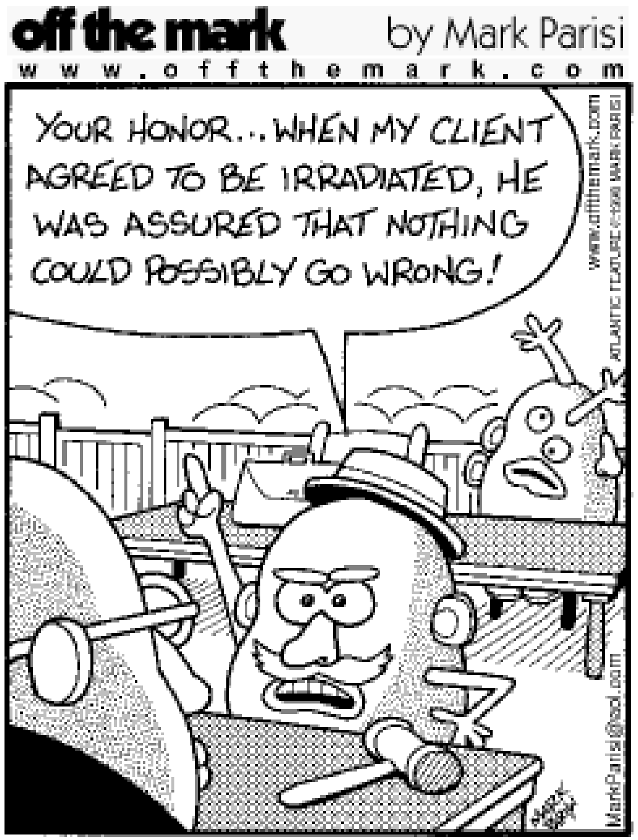
- Penetration depth into a food is directly related to frequency;

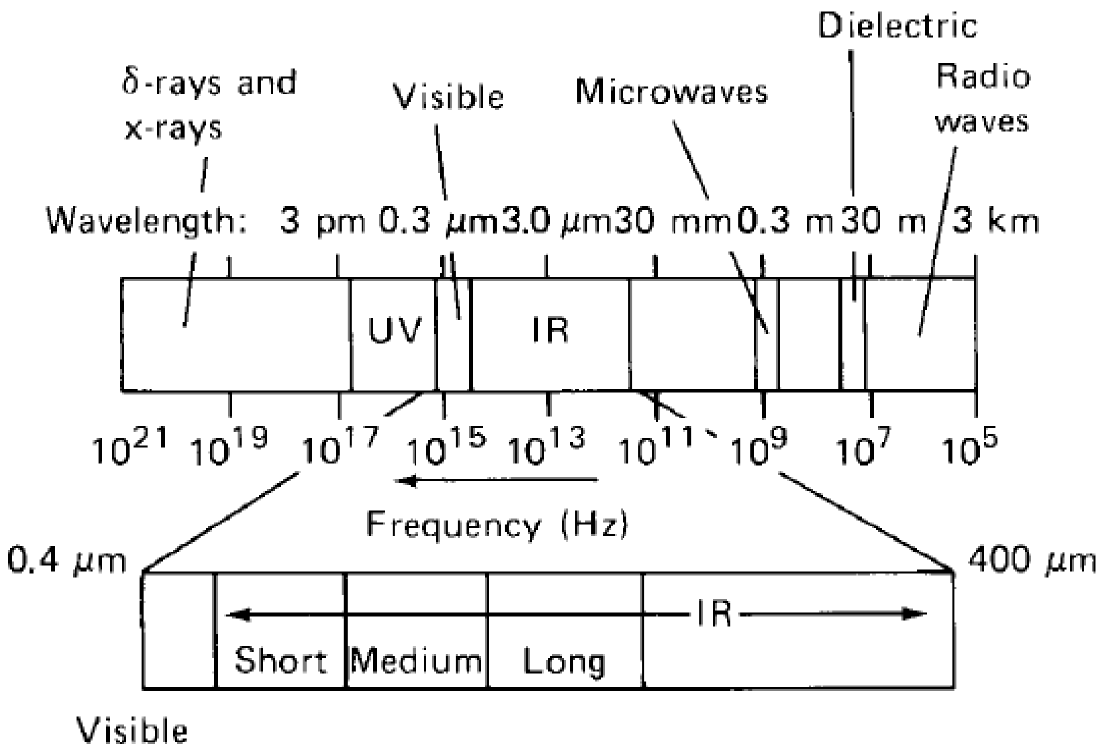
  the lower frequency dielectric energy penetrates more deeply than radiant energy;

  ohmic heating penetrates throughout food instantly.

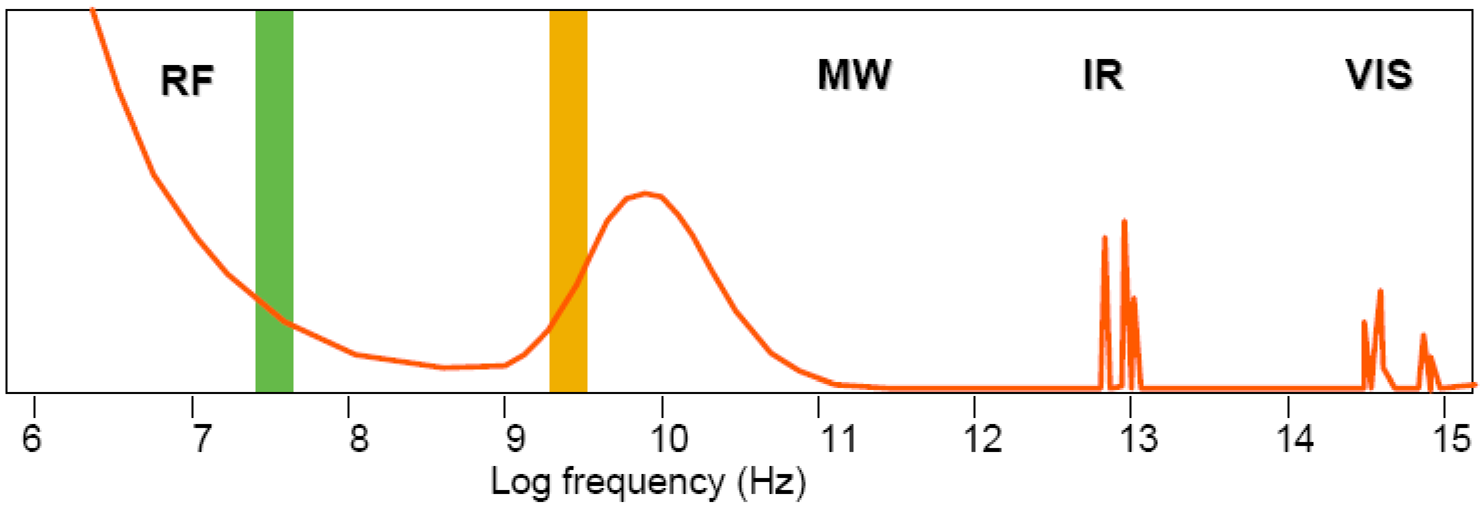
- Thermal conductivity of food is a limiting factor in IR heating;

  it is not so important in dielectric & ohmic heating.

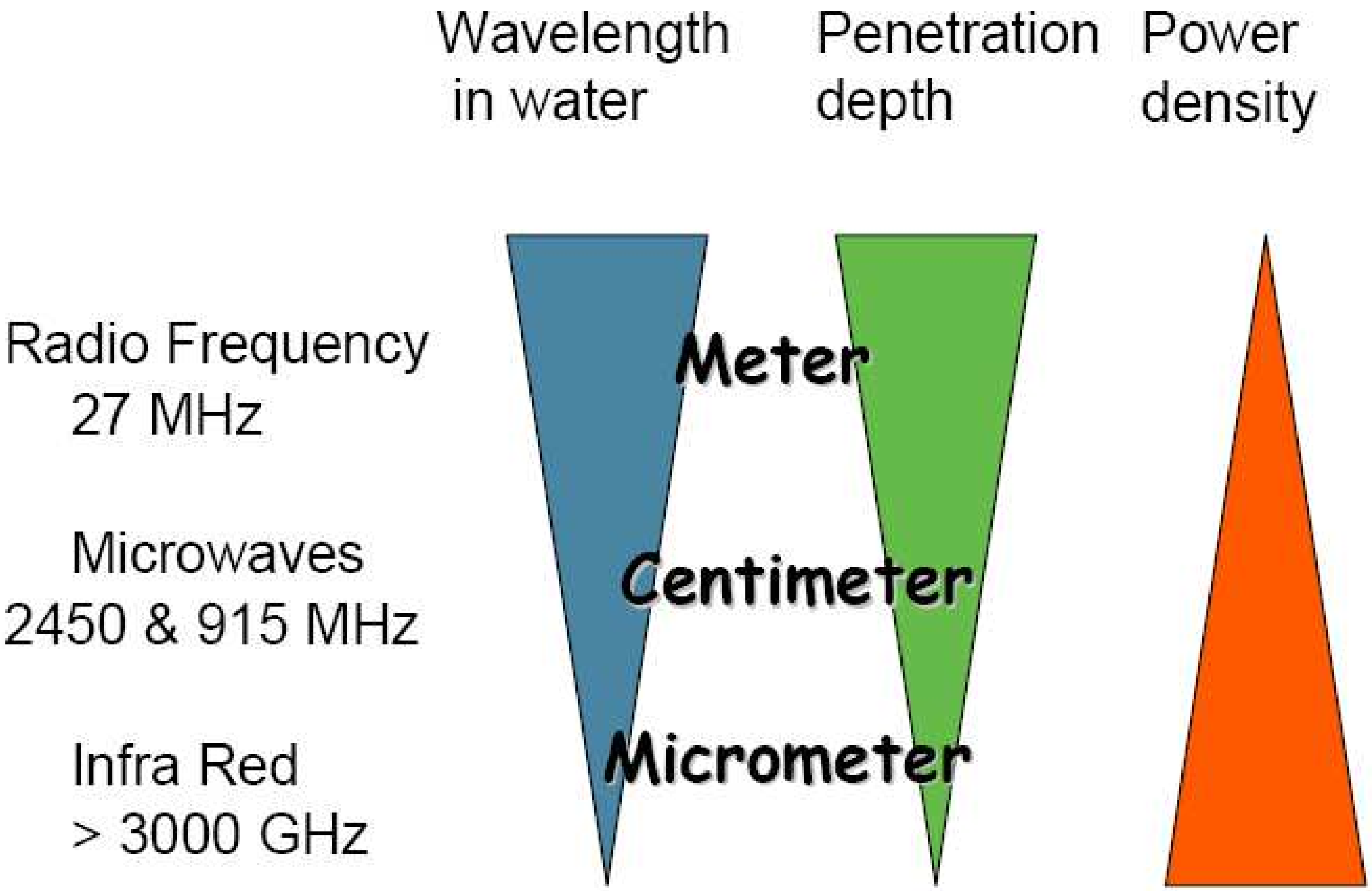




Electromagnetic spectrum.
(Courtesy of the Electricity Council.)



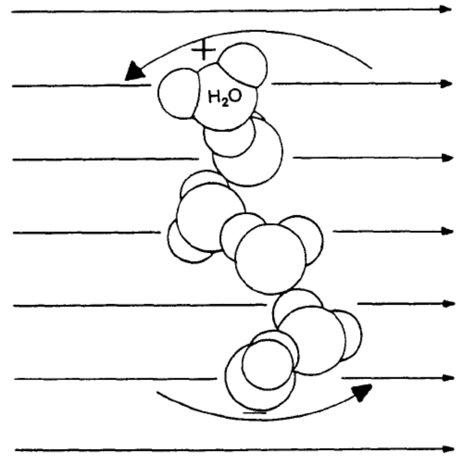
RF – MW – IR



Wavelength in water
Penetration depth
Power density
Radio Frequency 27 MHz
Microwaves 2450 & 915 MHz
Infra Red > 3000 GHz
Meter
Centimeter
Micrometer

Dielectric heating

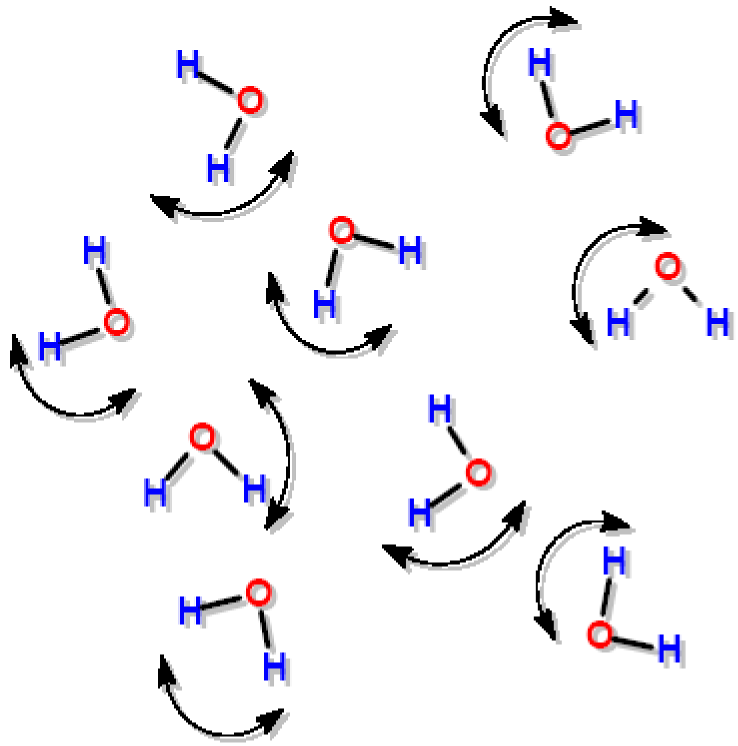
Theory



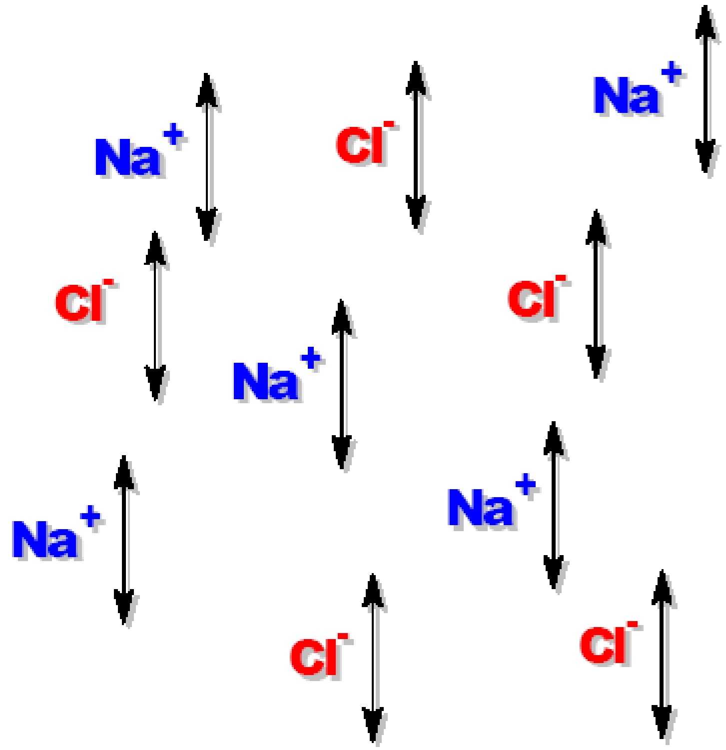
Water molecules in an electric field (Walker, 1987).

- Water → H^+ and O^- = electric dipole.
- MW or RF electric field is applied to a food,
  → dipoles in the water & in some ionic components (e.g. salt) → orient themselves to the field.
- Rapidly oscillating electric field changes from (+) to (-) & back again several million times per sec
  → the dipoles attempt to follow → frictional heat.
- Increase in temperature of water molecules heats surrounding components of food by conduction &/or convection.

MW – RF

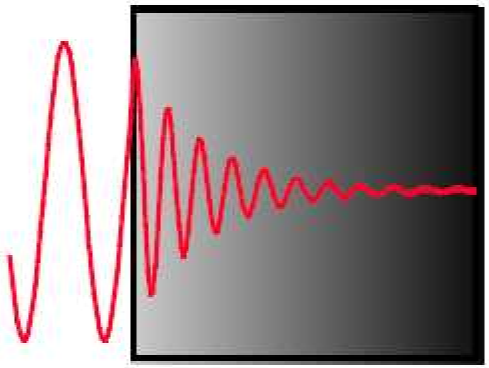


MW: Dipole Rotation

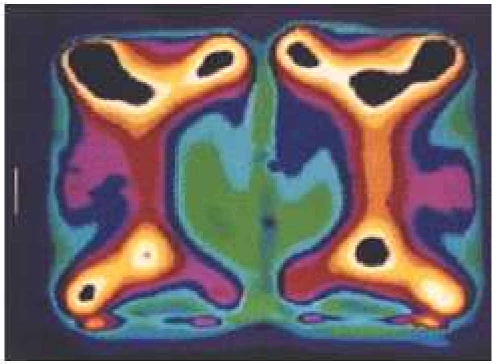


RF: Ionic Translation (polarisation)

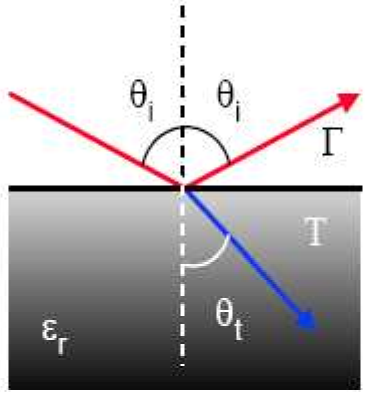
- Outer parts receive the same energy as inner parts; the surface loses its heat faster to the surroundings by evaporative cooling.
- Distribution of water & salt within a food mainly affects the amount of heating (although differences also occur in rate of heating as a result of the shape of food, at its edges etc.).
- Penetration depth of MWs & RF energy is determined by the dielectric constant & the loss factor of food.



Penetration depth



Standing waves



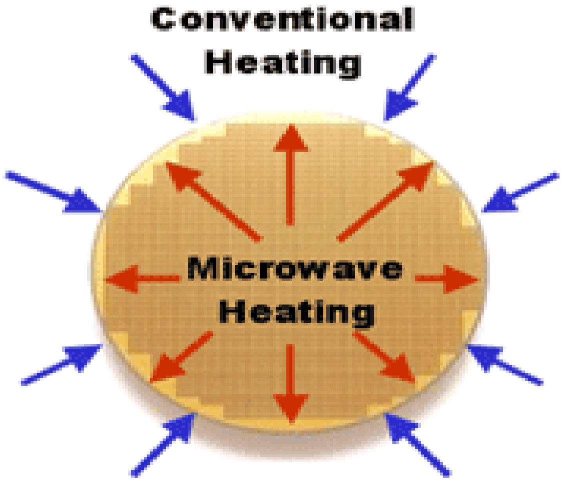
Reflection

- In general, the lower the loss factor (i.e. greater transparency to MWs) & the lower the frequency, the greater the penetration depth.

- Most foods have high moisture content & high loss factor → readily absorb MW & RF energy & flash-over is not a problem.

- When selecting equipment for drying low moisture foods → should prevent electric field strength from exceeding a level at which flash-over would take place.

- RF energy is mostly used to heat or evaporate moisture from a product; higher frequency MWs are used for defrosting & low pressure drying



Dielectric properties of materials at 20–25°C and 2450 MHz

Material	Dielectric constant ($F\,m^{-1}$)	Loss factor	Penetration depth (cm)
Banana (raw)	62	17	0.93
Beef (raw)	51	16	0.87
Bread	4	0.005	1170
Brine (5%)	67	71	0.25
Butter	3	0.1	30.5
Carrot (cooked)	71	18	0.93
Cooking oil	2.6	0.2	19.5
Distilled water	77	9.2	1.7
Fish (cooked)	46.5	12	1.1
Glass	6	0.1	40
Ham	85	67	0.3
Ice	3.2	0.003	1162
Paper	4	0.1	50
Polyester tray	4	0.02	195
Potato (raw)	62	16.7	0.93

Adapted from Mudget (1982), Buffler (1993) and Mohsenin (1984).

Microwaves (MWs)

Penetration depth of MWs

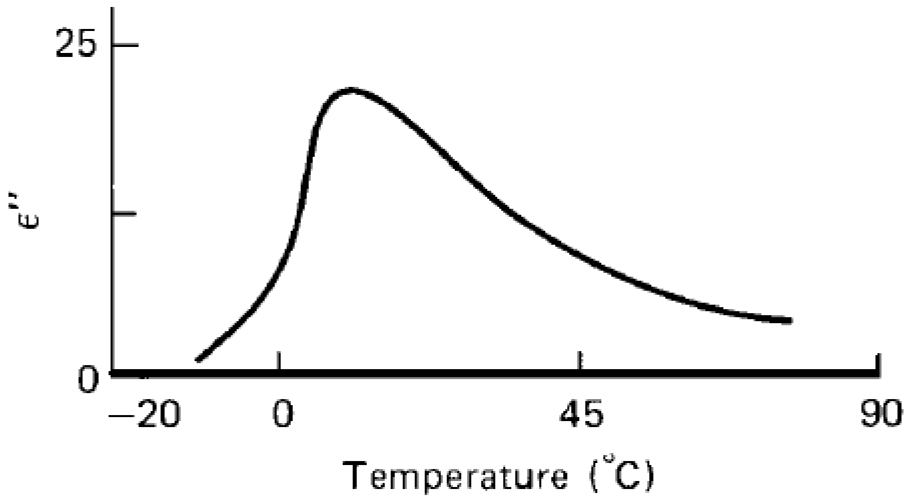
$$x = \frac{\lambda_0}{2\pi\sqrt{(\epsilon' \tan\delta)}}$$

- x (m): depth of penetration;
- λ_0 (m): the wavelength,
- ϵ' : dielectric constant
- tan δ: loss tangent (or loss factor or dissipation constant).

Power absorbed by the food:

$$P = 55.61 + 10^{-14} f E^2 \epsilon''$$

- P (Wm^{-3}): power per unit volume,
- f (Hz): frequency
- E (Vm^{-1}): electrical field strength.



Variation in dielectric loss factor of water and ice. (After Lewis (1990).)

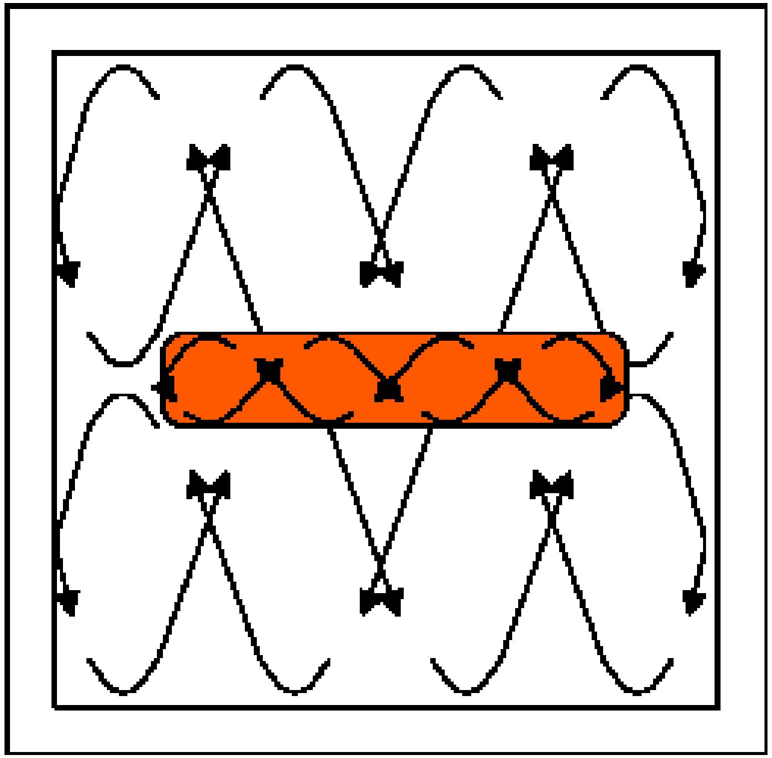
- MW penetration increases when water changes phase to ice,

  → possibly molecules are less free to move or absorb energy from alternating electric field.
- Loss factor of ice < water
- Glass, papers & some polymer films have a low loss factor & are not heated.
- Metals reflect MW & are not heated → making MW ovens very efficient in energy use.

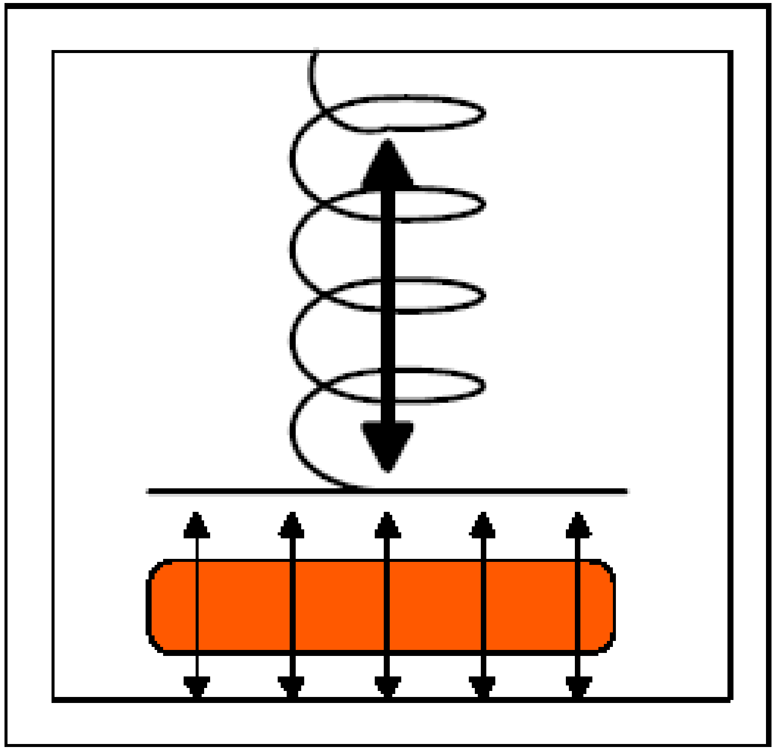
Radio frequency (RF) heating

- Operating principle = MW heating, but at lower frequencies
- Food is passed between electrodes & a RF voltage is applied across the electrodes.

  → changes the orientation of water dipoles in a similar way to MWs → very rapid heating.
- RF heating allows greater concentration of heat energy, selectivity in the location of heating & accuracy in control of heating duration.
- Thickness of food is restricted by the distance between the capacitor plates.



Microwaves
2.45 GHz



Radio-frequency 27 MHz

- Amount of RF energy needed for a particular process

$$E = \frac{m(\theta_1 - \theta_2)C_\mathrm{p}}{863}$$

- E = energy supplied (kW),
- m = mass flow rate of product (kg h^{-1}),
- θ_1 = final product temperature (ºC),
- θ_2 = initial product temperature (ºC),
- C_p = specific heat ($kJ^{-1}kg^{-1}K^{-1}$).

- Additions to the calculated amount of energy required:
  - 1 kW is added for each 1.4 kg of water to be evaporated per hour in a drying application.
  - Additional 10–20% of energy required is added to account for surface cooling, depending on the surface area to volume ratio of the product.
  - If it is assumed that the equipment is 65% efficient in the use of energy supplied, an additional correction is needed to calculate the actual power requirement.

- In drying applications for baked goods,
  - RF ovens heat to a point of rapid evaporation of water, then supply the latent heat of evaporation.
  - If targeted at around 4% moisture; usually ‘free’ moisture easily removed at 100ºC.
  - For lower final moisture, it is necessary to remove moisture that is ‘bound’ into the cellular structure of food & higher temperatures are needed.
  - Typically 102–105ºC achieve 3% moisture, 105–110ºC for 2% moisture & 116ºC for 1.5% moisture.
  - Products are likely to be changes to colour of baked goods = conventional ovens.

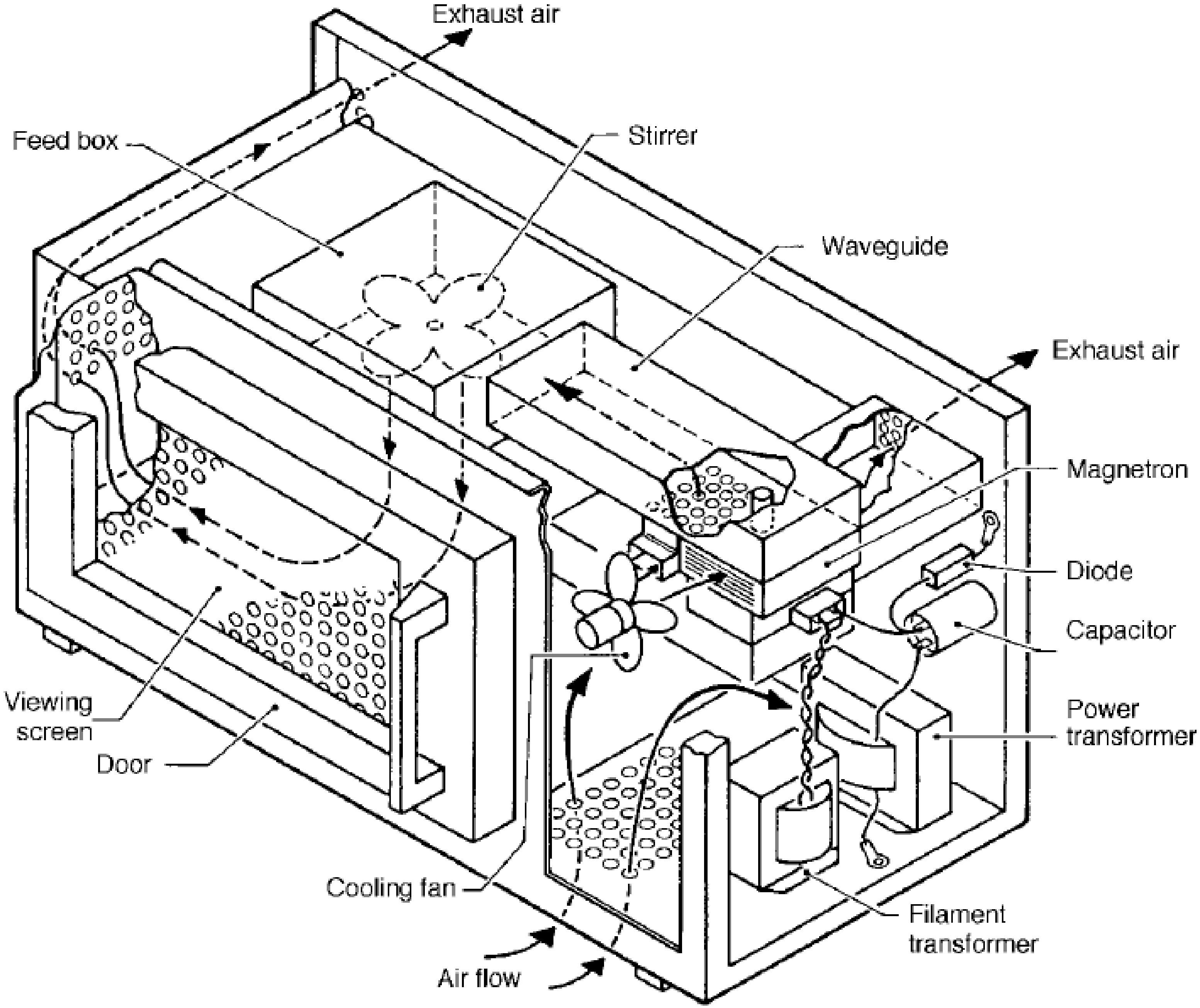
- Advantages of MW & RF heating:
  - heating is rapid
  - the surface of food does not overheat; produces minimum heat damage & no surface browning
  - equipment is small, compact, clean in operation & suited to automatic control
  - no contamination of foods by products of combustion.

Equipment

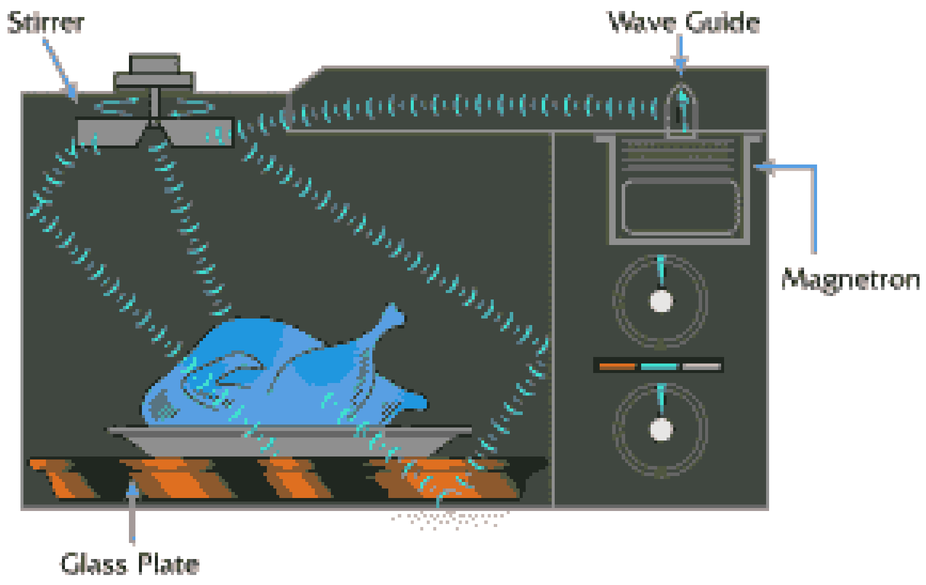
- MW equipment:
  - a MW generator (*magnetron*),
  - aluminium tubes (*wave guides*),
  - a metal chamber (batch) or a tunnel fitted with a conveyor belt (continuous).

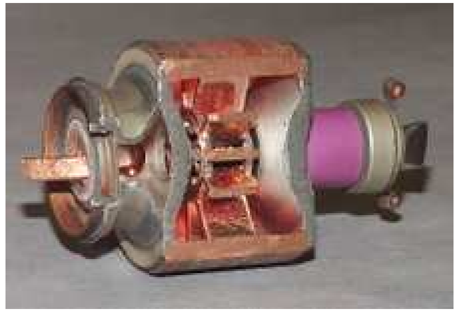
- A risk of leaking radiation causing injury to operators, particularly to eyes.

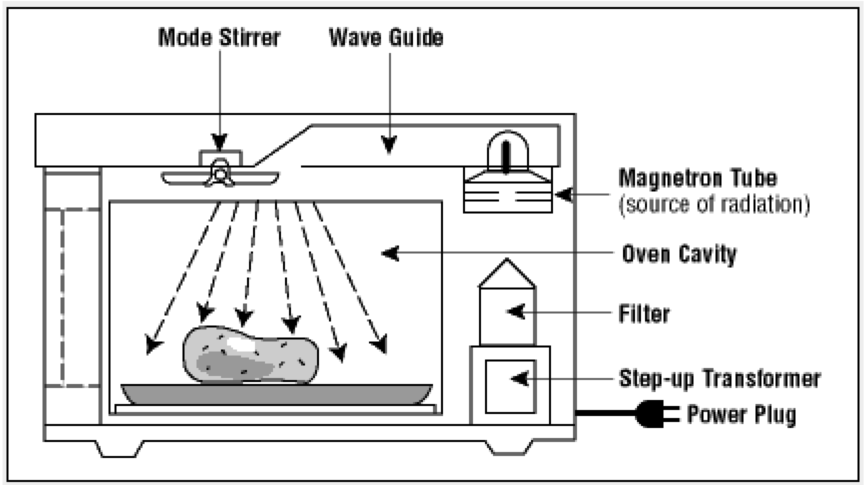
- Chambers & tunnels are sealed to prevent the escape of microwaves.



A microwave oven showing the magnetron.
(From Buffler (1993).)


Stirrer
Wave Guide
Magnetron
Glass Plate




Mode Stirrer
Wave Guide
Magnetron Tube
(source of radiation)
Oven Cavity
Filter
Step-up Transformer
Power Plug

- RF heaters consist of banks of capacitor plates, most often located at the end of bakery tunnel ovens or conveyor driers with the conveyor band passing between the plates.

- Electrical circuit is arranged so that food becomes an essential electrical component.

- Variations in the amount of food passing between the plates, its temperature & moisture content cause a variation in the power output of the generator.

  → Self controlling: e.g. the loss factor of a food falls as the moisture content is reduced & the power output falls; so reducing the possibility of burning food.

Applications

Thawing & Tempering

- Thermal conductivity of water < ice

  → reduces rate of heat transfer & thawing slows as the outer layer of water increases in thickness.

- MW & RF energy rapidly thaw small portions of food & for melting fats (e.g. butter, chocolate & fondant cream).

- Difficulties with larger (e.g. 25 kg) frozen blocks (e.g egg, meat, fish & fruit juice) used in industrial processes.

- Loss factor of water > ice → heats rapidly once ice melts.

- In large blocks, thawing not uniformly
- Some portions of food may cook while others remain frozen.

- Overcome to some extent by reducing the power & extending thawing period or by using pulsed MWs to allow time for temperature equilibration.

- ‘*Tempering*’ frozen foods: temperature is raised from around -20ºC to 3ºC; food remains firm but no longer hard.

  → more easily sliced, diced or separated into pieces.

- for meat & fish products (more easily boned or ground at a temperature just below the freezing point); & for butter & other edible fats.

- Energy to temper frozen beef, e.g. 62.8 J/g from 17.7 to 4.4ºC; 123.3 J/g to raise temperature a further 2.2ºC as more rapid melting begins to occur.

- Production rates from 14 t of meat per hour or 1.5–6 t of butter per hour in equipment which has power outputs of 25–150 kW.

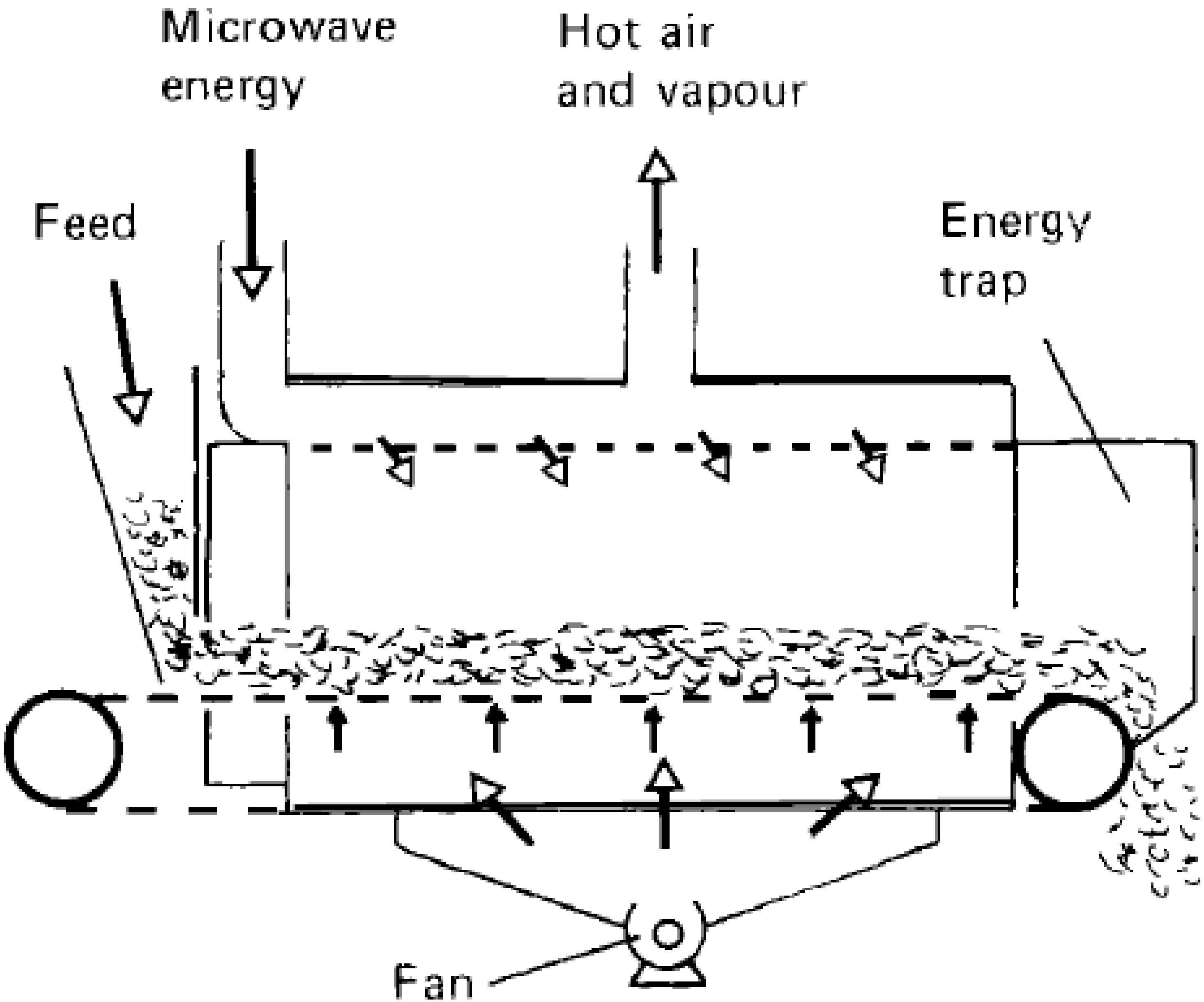
Advantages over conventional tempering in cold rooms:

- faster (e.g. meat blocks are defrosted in 10 min; several days in a cold room)
- minimal amount of food being processed at any one time & little loss or spoilage in the event of a process delay
- greater flexibility in operation
- cost is eliminated
- no drip loss or contamination
- improved plant productivity
- savings in storage space & labour
- more hygienic defrosting
- better control over defrosting conditions
- improved product quality.

Radio Frequency
Tunnel
70 kW

ADVANTAGES OF THE
50 Ω RADIO FREQUENCY SYSTEM:

✓ excellent temperature homogeneity
(± 1° C)



Continuous microwave finish drying equipment.
(After Decareau (1985).)

Dehydration

- MW & RF energy overcome the barrier to heat transfer caused by low thermal conductivity (in conventional hot air drying).

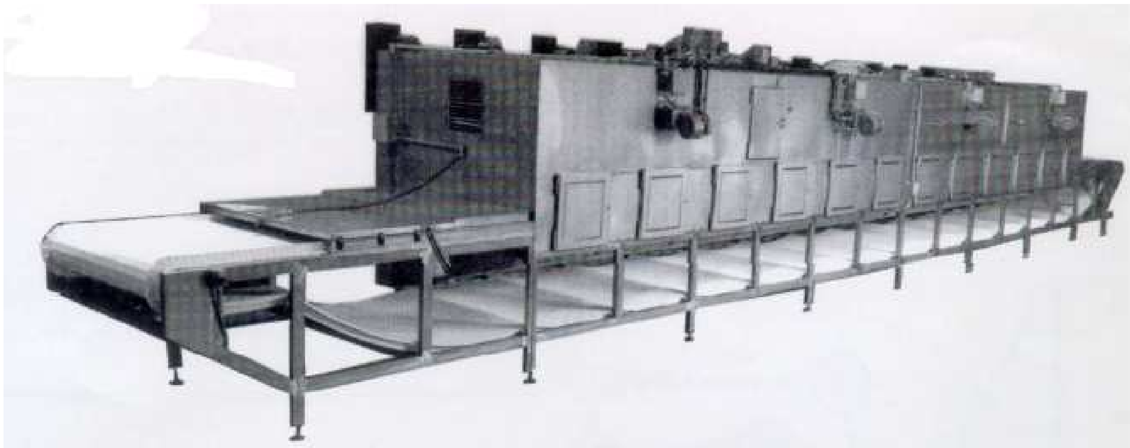
  → prevents damage to the surface, improves moisture transfer during the later stages of drying & eliminates case hardening.

- Radiation selectively heats moist areas; dry areas unaffected.
- Not necessary to heat large volumes of air; & oxidation by atmospheric oxygen is minimised.

- Higher cost & smaller scale of operation → MW drying for ‘finishing’ (removing the final moisture) of partly dried or low-moisture foods.

- E.g.: in pasta drying:
- Fresh pasta is pre-dried in hot air to 18% moisture; then in a combined hot air & MW drier to 13%.
- Drying times are reduced 8 h to 90 min; bacterial counts 15x lower; reduction in energy consumption 20–25%; drying tunnel is reduced 36–48m to 8 m; clean-up time is reduced 24 to 6 person-hours; no case hardening

- E.g.: in grain finish drying:
- MWs are cheaper; energy efficient; quieter; do not cause dust pollution; improves grain germination rates.



- In conventional freeze drying:
- Low rate of heat transfer to the sublimation front limits the rate of drying.

- In MW freeze drying:
- Heat is supplied directly to the ice front.

- Careful control over drying conditions to prevent localised melting of the ice.

- Any water produced in the drying food heats rapidly (higher loss factor); & causes a chain reaction, leading to widespread melting & an end to sublimation.

Baking

- Efficiency of baking is improved by RF or MW finishing for thin products, e.g. breakfast cereals, baby foods, biscuits, crackers, crisp bread & sponge cake.

- Conventional ovens operate effectively when products have relatively high moisture contents, but thermal conductivity falls as baking proceeds;

  considerable time is necessary to bake the centre of the product adequately without excessive changes to the surface colour.

- RF or MW heaters are located at the exit to tunnel ovens to reduce moisture content & to complete baking without further changes in colour.

Other advantages:

- reduces baking times by up to 30%; increases the ovens throughput.
- meat pies can be baked in about 1/3 of the time in a conventional oven by RF heating.
- increases in production by up to 50%
- savings in energy, space & labour costs
- close control of final moisture contents (typically ± 2%) & automatic levelling of moisture contents as only moist areas are heated
- separate control over baking & drying stages allows separate control over internal & external product colour & moisture content
- improved product texture & elimination of ‘centre bone’ (dense dough in the centre of cookies)
- improved taste as flavours are subjected to shorter periods at high temperatures.

Other applications

- MW *rendering* of fats improves the colour; reduces fines by 95% & costs by 30%; not cause unpleasant odours

- MW *frying* is not successful when deep baths of oil are used, but can be used with shallow trays in which food is heated rapidly.

  Less deterioration in oil quality.

  Doughnuts are cooked without oil using MWs; reduces times by 20% & increases product yield by 25%.

- *Blanching* by MWs; higher costs than steam blanching

- *Pasteurisation* of packed complete pasta meals, soft bakery goods & peeled potatoes by MWs.
- Involve packaging in flat packages using thermoform/vacuum/gas flush seal.
- Packages are heated in tunnel conveyors, up to 25m long, using a combination of MWs & hot air at 70–90ºC,
- then equilibrated; the slowest heating parts reach 80–85ºC within 10 min,
- then cooled to 1–2ºC & have a shelf life of appr. 40 days at 8ºC.

- *Sterilisation* by MWs in laminated pouches from PP/EVOH or PVDC/PP in the Multitherm process.

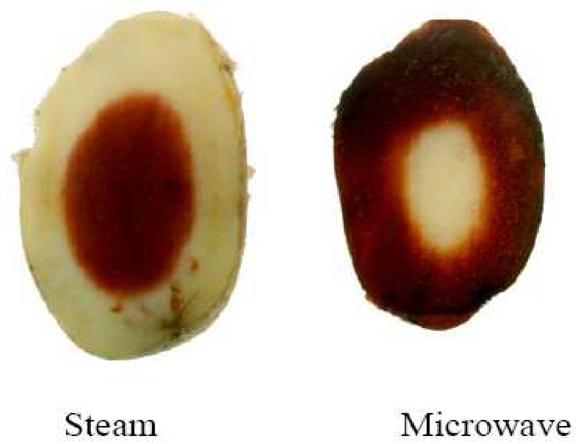
- Pouches (transparent to MWs) are formed & filled from a continuous reel of film but are not separated.

- Produces a chain of pouches passes through a continuous hydrostat system.

- Pouches are submerged in a medium has a higher dielectric constant than the product; & heating is by MWs instead of steam.

Effect on foods

- No direct effect on micro-organisms; all changes are caused by heat alone.
- In pasteurisation & blanching applications; reduced losses of heat-sensitive nutrients (e.g. no loss of carotene in MW-blanched carrots)
- Results for some foods are highly variable; MW heating offers no nutritional advantage over steaming.



Ohmic heating

- = ‘resistance heating’ or ‘electroheating’

  → alternating electric current is passed through a food

  → electrical resistance of the food causes the power to be translated directly into heat.

- Food is an electrical component of the heater; so its electrical properties (its resistance) must match to the capacity of the heater.

- Commercial use in Europe, the USA & Japan:
  - aseptic processing of high added-value ready meals, stored at ambient temperature
  - pasteurisation of particulate foods for hot filling
  - pre-heating products before canning
  - high added-value prepared meals, distributed at chill temperatures.

- Efficiency of Ohmic heating > MW heating because nearly all of the energy enters the food as heat.
- MW & RF heating have a finite depth of penetration into a food; Ohmic heating no
- MW heating requires no contact with the food; Ohmic heating requires electrodes to be in good contact.
- In practice the food should be liquid or have sufficient liquid with particulate foods

  → to allow good contact & to pump the product through the heater.

Advantages of ohmic heating:

- food is heated rapidly (1ºCs^{-1}) at the same rate throughout; & even heating of solids & liquids if their resistances are the same
- heat transfer coefficients do not limit the rate of heating
- temperatures sufficient for UHT processing can be achieved
- no hot surfaces for heat transfer; no risk of surface fouling or burning of the product
- heat sensitive foods or food components are not damaged by localised over-heating
- liquids containing particles can be processed & are not subject to shearing forces
- suitable for viscous liquids
- energy conversion efficiencies are very high (>90%)
- lower capital cost than MW heating
- suitable for continuous processing.

Theory

- Foods contain water & ionic salts; capable of conducting electricity, but also have a resistance which generates heat when an electric current is passed through.

- Electrical resistance of a food is the most important factor in determining how quickly it will heat.

- Conductivity measurements are made in product formulation, process control & quality assurance for all foods that are heated electrically.

- Measured resistance is converted to conductivity

$$\sigma = (1/R)(L/A)$$

- σ (Sm^{-1}): product conductivity,
- R (ohms): measured resistance,
- L (m): length of the cell
- A (m^2): area of the cell.

- In composite foods, the conductivity of the particle is measured by difference (i.e. product conductivity - carrier medium conductivity).

Electrical conductivity of selected foods at 19°C

Food	Electrical conductivity ($S\ m^{-1}$)
1 Potato	0.037
2 Carrot	0.041
3 Pea	0.17
4 Beef	0.42
5 Starch solution (5.5%)	
(a) with 0.2% salt	0.34
(b) with 0.55% salt	1.3
(c) with 2% salt	4.3

From Kim *et al.* (1996).

- Electrical conductivity expressed as the inverse: *specific electrical resistance.*

- Electrical resistance of a food falls by a factor of 2 to 3 over a temperature rise of 120ºC.

- can also vary in different directions (e.g. parallel to, or across, a cellular structure),

- can change if the structure changes (e.g. gelatinisation of starch, cell rupture or air removal after blanching).

- Implications for UHT processing of particles:

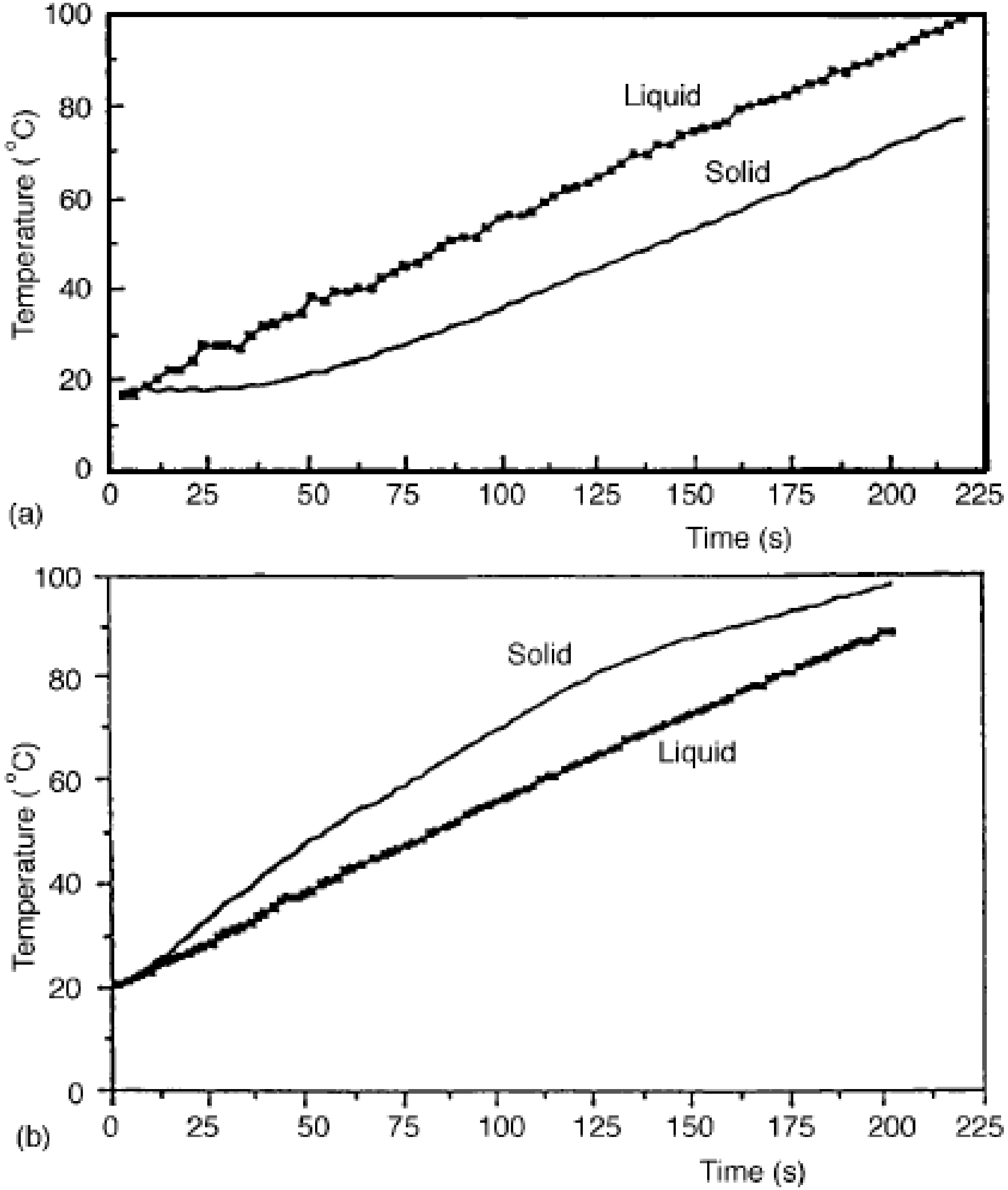
  if in a two-component food, a liquid and particles,

  the particles have a lower electrical resistance; are heated at a higher rate.

- not possible in conventional heating due to the lower thermal conductivity of solid foods, which slows heat penetration to the centre of the pieces

- Ohmic heating can heat sterilise particulate foods under UHT conditions without causing heat damage to the liquid carrier or over-cooking of the outside of particles.

- Lack of agitation in the heater maintains the integrity of particles and it is possible to process large particles (up to 2.5 cm) that would be damaged in conventional equipment.



Heat penetration into solid pieces of food by (a) conventional heating and (b) ohmic heating.
(Adapted from Fryer (1995).)

- Rate of heat generation depends on
  the specific heat capacities of each component,
  the way that food flows through the equipment
  its residence time in the heater.

- If the two components have similar resistances, the lower moisture (solid portion) heats faster than the carrier liquid.

- Calculation of heat transfer is extremely complex,
  A simplified theory of heating...

- The resistance in ohmic heater depends on specific resistance of product & geometry of the heater

$$R = (R_s x)/A$$

- *R* (ohms): total resistance of the heater,
- *R*s (ohms m^{-1}): specific resistance of the product,
- *x* (m): distance between the electrodes
- *A* (m^2): area of the electrodes.

- The resistance determines the current that is generated in the product

$$R = \frac{V}{I}$$

- *V* (volts): voltage applied
- *I* (amps): current.

- If the resistance is too high, the current will be too low at maximum voltage.
- If the resistance is too low, the maximum limiting current will be reached at a low voltage and the heating power will be too low.

- Every product has a critical current density
- if this is exceeded → arcing (flash-over) in the heater.
- The current density $I_{\mathrm{d}} = I/A$

- where *I*d (amps cm2) current density

- The design of the heater is tailored to products that have similar specific electrical resistances
- cannot be used for other products without modification.

- Rate of heating

$$Q = m.C_{\mathrm{p}}.\Delta\,\theta$$

- the power

$$P = V\,I \qquad\qquad P = R\,I^2$$

- Assume heat losses are negligible,
- Temperature rise in a heater

$$\Delta\theta = \frac{V^2 \sigma_a A}{x m c_p}$$

- θ (ºC): temperature rise,
- σ_a (Sm^{-1}): average product conductivity throughout temperature rise,
- A (m^2): tube cross-sectional area,
- x (m): distance between electrodes,
- m (kg s-1): mass flow rate
- c_p (J kg-1 ºC-1): specific heat capacity of product.

Equipment and applications

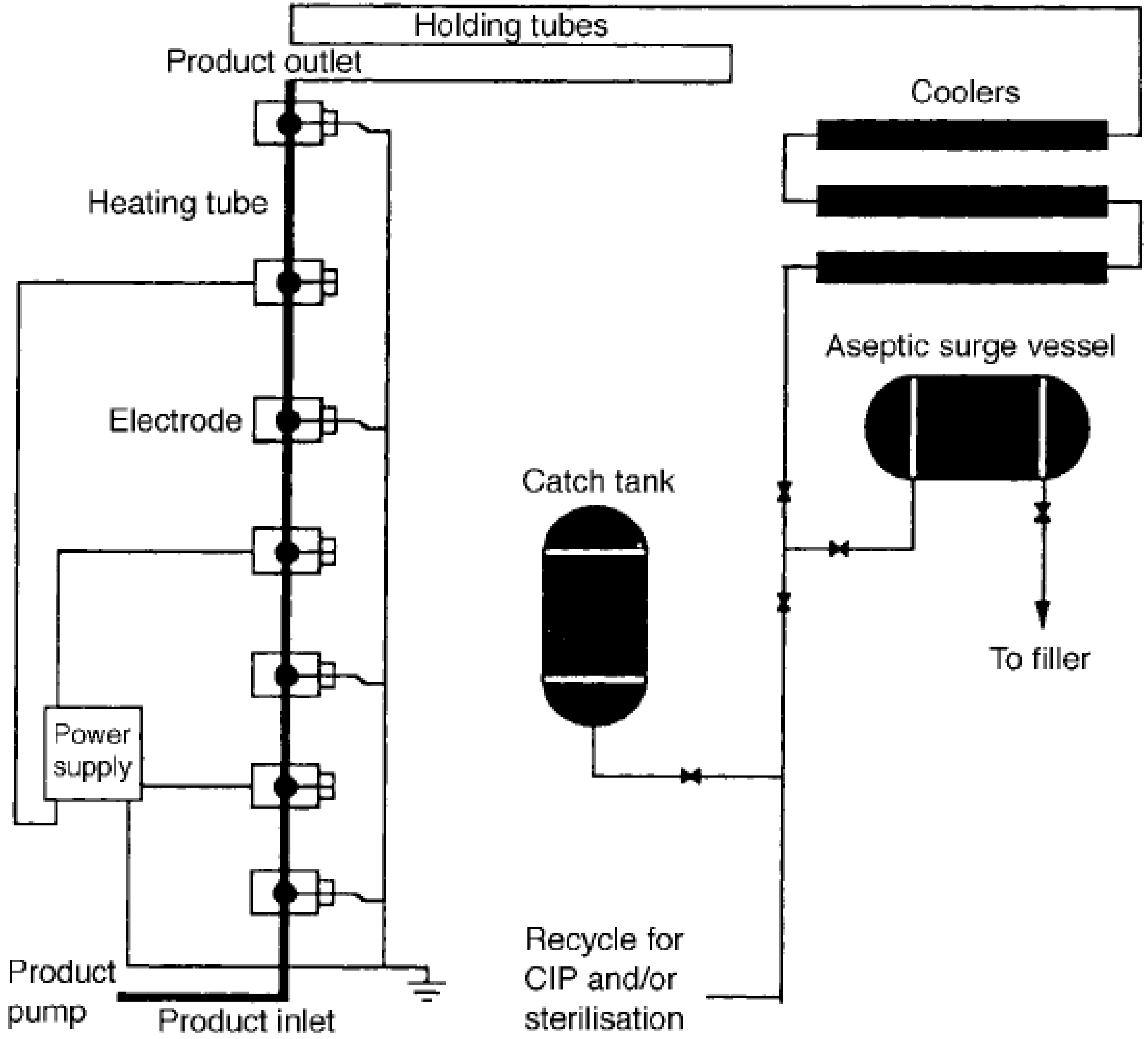
- Design of ohmic heaters must include electrical properties of the specific product to be heated,

- because the product itself is an electrical component.

  → also in RF heating

- Ohmic heaters should be tailored to a specific application

- taken into account:
  - the type of product
    - electrical resistance
    - change in resistance over the expected temperature rise
  - flowrate
  - temperature rise (determines the power requirement)
  - heating rate required
  - holding time required.



Flowsheet for ohmic heating system.
(After Parrott (1992).)

Pre-treatments of solid components:

- pre-heating in the carrier liquid to equilibrate resistances
- blanching pasta for moisture absorption
- heating the carrier liquid to pre-gelatinise starch
- heating to melt and expel fats
- stabilisation of sauces by homogenisation, especially dairy sauces or others that contain fats and heat sensitive proteins
- blanching vegetables to expel air and/or to denature enzymes
- enzymic marinades to soften texture and enhance flavour of meats
- soaking in acids or salts to alter the electrical resistance of particles
- sauteing to improve appearance of meat particles.

- Ohmic heating → process various combinations of meats, vegetables, pasta & fruits when accompanied by a suitable carrier liquid.

- In operation, bulk of carrier liquid is sterilised by conventional plate or tubular HEs & then injected into the particle stream as it leaves the holding tube.

- Advantage: reducing capital & operating costs & allows a small amount of carrier liquid to be used to suspend the particles to process efficiency.

- Ohmic heating costs comparable to those for freezing and retort processing of low acid products.

- Food is pumped up through a vertical tube containing a series of electrodes where it is heated to process temperature.

- The stainless steel cantilever electrodes in a PTFE housing fit across the tube.

- Current flows between the electrodes & through the food as it moves along the tube.

- The system maintain the same impedance in each section between the electrodes; the tubes increase in length between inlet & outlet because electrical conductivity of food increases as it is heated.

- Almost complete absence of fouling in ohmic heaters
  → after one product has been processed, the plant is flushed through with a base sauce and the next product is introduced.
- End of processing, the plant is flushed with a cleaning solution.

- Electric current flows through the product at the speed of light & no temperature gradients (temperature is uniform across the cross-section of flow)

- Flow rate of product is negligible compared to the velocity of the electric current, but
  if flow rate is not uniform across cross-sectional area, the very high rates of heating → slower moving food will become hotter.

- Uniform (‘plug’) flow conditions must be maintained in the heater.
- Type of pump should provide a continuous flow of material without pulses.
- High pressure in the heater (up to 4 bar for UHT processing at 140ºC) to prevent the product from boiling.
- Food passes from the heater to a holding tube where it is held for sufficient time to ensure sterility; then cooled & aseptically packaged

- Suitable for particulate foods contain up to 60% solids.
- High solids content is desirable:

  faster heating of low-conductivity particles than the carrier liquid &

  plug flow in the heater tubes.

- High solids concentrations can be processed if the particles are pliable & small or varied geometry to reduce the void spaces between particles.

- Lower concentrations require a higher viscosity carrier liquid to keep the particles in suspension.

- Particles density should match to carrier liquid:

  too dense particles or not sufficiently viscous liquid → particles will sink in system and be over-processed.

  too light particles → float → variable product composition & the risk of under-processing.

- Almost impossible to determine the residence time or heating profiles of particles that float or sink.
- The viscosity of the fluid (sauce or gravy) should be controlloed, e.g. pre-gelatinised starches be used to prevent viscosity changes during processing.

Sterile as UHT processing?

- not easy to measure heat penetration into particles,
- relatively easy to measure temperature of carrier liquid.
- Solid particles are heated to an equal or greater extent than the liquid when they enter the holding tube.
- By adjustment of the electrical properties of each component (e.g. by control of salt content & position in the formulation) it is possible to ensure that this takes place for homogenous particles
- Presence of fats & other poorly conductive materials → particles will heat mostly by conduction & a cold spot will be created within the particle.
- No accidental inclusion of highly conducting materials, or insulating materials, e.g pieces of bone, fat, nuts or ice in a food, because neither will be heated.
- If this happens, the surrounding food may also be under-processed.

Other factors:

- size & shape of particle pieces
- moisture content of solids
- aolids/liquid ratio
- viscosity of liquid component
- amount & type of electrolytes
- pH
- specific heat
- thermal conductivity.

- effect of processing on those factors?

  → change & alter the heating characteristics of the product?

Infrared (IR) heating

Theory

- IR energy is electromagnetic radiation emitted by hot objects.
- When it is absorbed, the radiation gives up its energy to heat materials.
- Rate of heat transfer depends:
  - surface temperatures of heating & receiving materials
  - surface properties of the two materials
  - shapes of the emitting & receiving bodies.

- Amount of heat emitted from a *perfect radiator* (*black body*) → the Stefan–Boltzmann eq:

$$Q = \sigma A T^4$$

- *Q* (J s^{-1}): rate of heat emission,
- s = 5.7×10^{-8} (J $s^{-1} m^{-2} K^{-4}$): the Stefan-Boltzmann constant,
- *A* (m^2): surface area
- *T* (K = ºC + 273): absolute temperature.

- also used for a *perfect absorber* of radiation (*black body*).

- Radiant heaters are not perfect radiators & foods are not perfect absorbers, although they do emit and absorb a constant fraction of the theoretical maximum.

  → concept of *grey bodies*:

$$Q = \varepsilon \sigma A T^4$$

- ε = emissivity of the grey body (a number from 0 to 1).
- Emissivity varies with the temperature of the grey body & the wavelength of the radiation emitted.

- Amount of absorbed energy & degree of heating varies from zero to complete absorption.

  → determined by the components of the food absorb radiation to different extents & the wavelength of radiated energy.

- Amount of radiation absorbed by a grey body = *absorptivity* (α) and is numerically = emissivity

- Radiation not absorbed is reflected = *reflectivity* (1-α).

- Types of reflection:

  takes place at the surface of the food

  takes place after radiation enters food structure & becomes diffuse due to scattering.

- Surface reflection produces the gloss observed on polished materials; body reflection produces colours & patterns of a material.

- Wavelength of IR radiation is determined by the temperature of the source.

- Higher temperatures produce shorter wavelengths have a greater depth of penetration.

- Net rate of heat transfer to a food = rate of absorption – rate of emission

$$Q = \varepsilon \sigma A (T_1^4 - T_2^4)$$

- T_1 (K): temperature of emitter
- T_2 (K): temperature of absorber.

Approximate emissivities of materials in food processing

Material	Emissivity
Burnt toast	1.00
Dough	0.85
Water	0.955
Ice	0.97
Lean beef	0.74
Beef fat	0.78
White paper	0.9
Painted metal or wood	0.9
Unpolished metal	0.7–0.25
Polished metal	< 0.05

From Earle (1983) and Lewis (1990).

Equipment

- Radiant heaters: flat or tubular metal heaters, ceramic heaters, quartz or halogen tubes fitted with electric filaments.
- Application: drying low-moisture foods (e.g. bread crumbs, cocoa, flours, grains, malt, pasta products & tea) & baking or roasting ovens.
- Products pass through a tunnel, beneath banks of radiant heaters, on a conveyor
- Not widely used as a single source of energy for drying larger pieces of food due to limited depth of penetration.
- used in vacuum band driers & cabinet driers, accelerated freeze driers, in some domestic MW ovens to brown the surface of foods; & to heat-shrink packaging film.

Infrared emitter characteristics

Type of emitter	Maximum running temperature (°C)	Maximum intensity ($kW\,m^{-2}$)	Maximum process temperature (°C)	Radiant heat (%)	Convection heat (%)	Heating–cooling time (s)	Expected life
Short wavelength							
Heat lamp	2200	10	300	75	25	1	5000 h
IR gun	2300	2	1600	98	2	1	–
Quartz tube	2200	80	600	80	20	1	5000 h
Medium wavelength							
Quartz tube	950	60	500	55	45	30	Years
Long wavelength							
Element	800	40	500	50	50	< 120	Years
Ceramic	700	40	400	50	50	< 120	Years

From Anon. (1981).

Effect on foods

- The rapid surface heating of foods seals in moisture & flavour or aroma compounds.
- Changes to surface components of foods are similar to those that occur during baking.

Thank you