Topic: Dielectric and Ohmic Heating

Dielectric and infrared (IR or radiant) energy are two forms of electromagnetic energy. The term '***dielectric***' is used to represent both radio frequency (RF) and microwave heating. Dielectric and ohmic heating are used to preserve foods, whereas infrared radiation is mainly used to alter the eating qualities of foods by changing the surface colour, flavour and aroma.

The advantages of dielectric and ohmic heating compared to conventional heating can be summarised as:

- ✓ Rapid heating throughout the food without localised overheating or hot surfaces, which results in minimum heat damage and no surface browning.
- ✓ Heat transfer is not limited by boundary films and energy conversion efficiencies are high.
- ✓ Equipment is small, compact and suited to automatic control.
- ✓ There is no contamination of foods by products of combustion.

Theory of Dielectric Heating:

Microwave and radio frequency energy are transmitted as electromagnetic waves and the depth to which these penetrate foods is determined by both their frequency and the characteristics of the food. Microwave energy has a range of frequencies from 300 MHz to 300 GHz whereas RF energy has lower frequencies, from 1 to 200 MHz.

Table1: Applications of dielectric, ohmic and infrared heating

Method of heating	**Applications**
Microwave	Cooking, thawing, melting, finish-drying, freeze drying, tempering, pasteurization, sterilisation, rendering, frying, blanching
Radio frequency Ohmic	Drying, baking, cooking processed meat UHT sterilisation, pasteurisation
Infrared	Drying, baking, frying, thawing, freeze drying, cooking, surface pasteurization

The relationship between wavelength, frequency and velocity of electromagnetic waves is shown in Eq. (1).

$$\lambda = v / f' \ldots\ldots (1)$$

Where,

λ (m) = wavelength,
v (m/s) = velocity and
f'(Hz) = frequency.

The lower frequency and longer wavelengths. The amount of energy absorbed by foods from electromagnetic waves depends on a characteristic known as the 'dielectric loss factor' (ε''), a dimensionless number, which relates to the ability of the food to dissipate electrical energy. The higher the loss factor, the more energy is absorbed by the food.

Working of Dielectric Heating:

Water has a negatively charged oxygen atom separated from two positively charged hydrogen atoms, which form an electric dipole. When alternating microwave or RF energy is applied to a food, dipoles in the water and other polar components reorient themselves to the direction (or polarity) of the elec- tric field in a similar way to a compass in a magnetic field. Since the polarity rap- idly alternates from positive to negative and back again several million times per second (e.g. at the microwave frequency of 2450 MHz, the polarity changes 2.45 x 10^9 cycles s^-), the dipoles rotate to align with the rapidly changing polarity. The microwaves give up their energy and the molecular movement creates frictional heat that increases the temperature of water molecules. They in turn heat the surrounding components of the food by conduction and/or convection.

The amount of heat absorbed by a food, the rate of heating and the location of 'cold spots' (points of slowest heating) depend on:

- ✓ The composition of the food
- ✓ Its shape and size
- ✓ The microwave frequency
- ✓ The applicator design.

As a result, for foods that have high salt or moisture contents, the interior part is heated less. At RF frequencies, the conductivity of foods and hence the amount of energy absorbed, increases at higher temperatures, but at microwave frequencies the loss factor decreases at higher temperatures and so reduces the amount of energy absorbed.

The other important electrical properties of the food, in addition to the loss factor, are:

1) the dielectric constant (ε'), a dimensionless number that relates to the rate at which energy penetrates a food.
2) the loss tangent (tan δ), which gives an indication of how easily the food can be penetrated by electromagnetic waves and the extent to which it converts the electrical energy to heat.

$$\varepsilon'' = \varepsilon' \tan\delta \quad \ldots\ldots (2)$$

The dielectric constant and the loss tangent are properties of the food and they influence the amount of energy that is absorbed by the food as shown in Eq. (3).

$$P = 55.61 \text{ x } 10^{-14} f\, E^2 \varepsilon'' \quad \ldots\ldots\ldots (3)$$

Where, P (W cm^{-3}) = power absorbed per unit volume,
f (Hz) = frequency and
E (V cm^{-1}) = electrical field strength.

The depth of penetration of electromagnetic waves (x) (m) is found from the loss factor and the frequency of the waves:

$$X = \frac{\lambda}{2\Pi\sqrt{\varepsilon' \tan\delta}} \quad \ldots\ldots (4)$$

The electrical properties of the food also determine how energy is distributed through the food, as represented by the attenuation factor (α') (m^{-1})

When RF and microwave energy heat water in foods, it increases the vapour pressure and causes movement of moisture from the interior to the surface and rapid evaporation from the surface, therefore making this technology particularly suitable for dehydration as well as heating.

Table 3: Summary of process factors in microwave heating

Factor	Examples
Food	Shape, size, composition (e.g. moisture, salt), multiple components (e.g. frozen meals), liquid/solid proportion
Package Process	Transparency to microwaves, presence of metals (e.g. aluminium foil) Power level, cycling, presence of hot water or air around the food, equilibration time
Equipment	Dimensions, shape and other electromagnetic characteristics of the oven, wave frequency, agitation of the food, movement of the food by conveyors and turntables, use of stirrers

Equipment used for Dielectric heating:

1. Microwave heaters

Microwave heaters are very efficient in energy use because moist foods absorb most of the microwave energy, and flat metal surfaces reflect microwaves so that neither the metal of the chamber nor the air are heated. Power outputs of continuous industrial equipment range from 500 W to 15 kW in the 2450 MHz band and 25 to 120 kW in the 915 MHz band.

The high rates of heating and absence of surface changes have led to studies of dielectric heating of a large number of foods. ***The most important industrial applications are dehydration, baking, tempering and thawing.*** Microwave and especially RF drying overcome the barrier to heat transfer caused by the low thermal conductivity, by selectively heating moist areas while leaving dry areas unaffected.

Dielectric heating reduces product shrinkage during the falling rate period, prevents damage to the food surface and eliminates case hardening. The use of microwave drying by itself has limitations: the inherent non uniformity of the microwave electromagnetic field and limited penetration of the microwaves into bulk products compared to RF energy, leads to uneven heating. microwaves and RF units have higher cost and smaller scales of operation.

Application of Dielectric Heating:

1. Dehydration:

The main disadvantages of hot-air drying are the low rates of heat transfer, caused by the low thermal conductivity of dry foods, and damage to sensory characteristics and nutritional properties caused by long drying times and overheating at the surface.

Microwave and especially RF drying overcome the barrier to heat transfer caused by the low thermal conductivity, by selectively heating moist areas while leaving dry areas unaffected. This improves moisture transfer during the later stages of drying by heating internal moisture and thus increasing the vapour pressure and the rate of drying.

Dielectric heating reduces product shrinkage during the falling rate period, prevents damage to the food surface and eliminates case hardening.

However, the use of microwave drying by itself has limitations: the inherent non-uniformity of the microwave electromagnetic field and limited penetration of the microwaves into bulk products compared to RF energy, leads to uneven heating; also microwaves and RF units have higher cost and smaller scales of operation compared with traditional drying methods.

For example, in pasta drying the fresh pasta is pre-dried in hot air to 18% moisture and then in a combined hot-air and microwave dryer to lower the moisture content to 13%. Drying times are reduced from 8 h to 90 min with a reduction in energy consumption of 20-25%, bacterial counts are 15 times lower, there is no case hardening, the drying tunnel is reduced from 36 - 48 m to 8 m, and clean-up time is reduced from 24 to 6 person-hours.

2. Baking

Conventional ovens operate effectively when products have relatively high moisture contents, but the thermal conductivity falls as baking proceeds and considerable time is needed to bake the centre of the product adequately without causing excessive changes to the surface colour.

RF or microwave heaters are located at the exit to tunnel ovens to reduce the moisture content and to complete baking without further changes in colour. This reduces baking times by 30-50% and hence increases the throughput of the ovens.

RF or microwave finishing (removing the final moisture) improves baking efficiency for thin products such as breakfast cereals, infant foods, biscuits, crackers.

Other advantages include:

- Savings in energy, space and labour costs and
- Close control of final moisture contents.
- Separate baking and drying stages allow control over the internal and external product colour and moisture content.
- Improved product texture and elimination of ‘centre bone’

3. Thawing, Melting and Tempering:

During conventional thawing of frozen foods, the lower thermal conductivity of water, compared with ice, reduces the rate of heat transfer and thawing slows as the outer layer of water increases in thickness. RF energy are used to rapidly thaw small portions of food and for melting fats (e.g.butter, chocolate).

A more common application is 'tempering' frozen foods, in which the temperature is raised from around -20 ^{0}C to -3 ^{0}C and the food remains firm but is no longer hard. After frozen food has been tempered, it is more easily sliced, diced or separated into pieces. Tempering is widely used for meat and fish products, which are more easily boned, sliced or ground at a temperature just below the freezing point.

The advantages over conventional tempering in cold rooms include:

- Faster processing (e.g. meat blocks are defrosted in 10 min instead of several days),
- The costs of operating a tempering room are eliminated and savings are made in storage space and labour,
- No drip losses or contamination, which improves product yields and reduces nutritional losses,
- better control over defrosting conditions and more hygienic defrosting because products are defrosted in the storage boxes, leading to improved product quality.

Topic: Ohmic Heating

Also termed '*resistance heating'*, '*electroconductive heating*' or 'J*oule heating*', this is a process in which an alternating electric current is passed through a food, and the electrical resistance of the food causes the generation of heat.

Compared to dielectric heating, ohmic heating has higher energy conversion efficiencies (90% of the energy is converted to heat in the food) and whereas dielectric heating has a finite depth of penetration into a food, ohmic heating has no such limitation.

However, whereas microwave heating requires no contact with the food, ohmic heating requires electrodes to have good contact. This means that the food should have sufficient fluidity to be able to pump it through the heater (i.e. foods that contain up to 60% solids).

The advantages of ohmic heating are as follows:

- The food is heated rapidly (>1 $^{0}C\ s^{-1}$) throughout the bulk of the food (i.e. volumetric heating), for example from ambient to 129 ^{0}C in 90s. The absence of temperature gradients results in even heating of solids and liquids if their resistances are the same, which cannot be achieved in conventional heating.
- There are no hot surfaces and heat transfer coefficients do not limit the rate of heating, as in conventional heating. As a result, there is no risk of food burning onto equipment surfaces or damage to heat-sensitive foods by localised overheating.
- Particles in liquids are not subject to shearing forces that are found when they are pumped through conventional heat exchangers and the method is also suitable for viscous liquids, such as apple sauce or carbonara sauce,

because heating does not have the problems associated with poor convection in these materials.

- It has a lower capital cost than microwave heating and it is suitable for continuous processing, with instant switch on and shutdown.

Ohmic heating is used commercially for aseptic processing of high-added-value ready meals, stored at ambient or chill temperatures, for pasteurisation of particulate foods.

Limitation of Ohmic Heating:

1. Differences in the electrical conductivities of the liquid and solid components of multi component foods and changes in conductivity with increasing temperature, which can cause irregular and complex heating patterns and difficulties in predicting the heating characteristics.
2. Lack of data on the critical factors that affect the rate of heating
3. Lack of accurate temperature-monitoring techniques to profile heat distribution and locate cold-spots during the process. This risk under processing and the consequent survival of pathogenic spores in low-acid foods.

Theory of Ohmic Heating:

Foods and other materials have a resistance (known as the 'specific electrical resistance') that generates heat when an electric current is passed through them. Electrical 'conductivity' is the inverse of electrical resistance and is measured in a food using a multimeter connected to a conductivity cell.

The relationship between electrical resistance and electrical conductivity is found using:

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

where,

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

Note: *Foods that contain water and ionic salts are more capable of conducting electricity because they have a lower resistance.*

Table : Electrical conductivity of selected foods

Food	**Electrical Conductivity (S m^{-1})**	**Temperature (^{0}C)**
Apple juice	0.239	20
Beef	0.42	19
Beer	0.143	22
Carrot	0.041	19
Carrot juice	1.147	22
Chicken meat	0.19	20

In a two component food consisting of a liquid and particles where the particles have a higher conductivity, they are heated at a higher rate. This is 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 therefore be used to heat sterilise particulate foods without causing heat damage to the liquid carrier or overcooking the outside of particles.

Electrical conductivity of the components, the rate of heating also depends on the *density, pH, thermal conductivity and specific heat capacities of each component*, the *way that food flows through the equipment* and *its residence time* in the heater. Each of these may change during processing and hence alter the heating characteristics of the product.

The calculation of heat transfer is therefore very complex, involving the simultaneous solution of equations for changes in electrical fields, thermal properties and fluid flow. A simplified theory of heating is given below.

The resistance in an ohmic heater depends on the specific resistance of the product, and the geometry of the heater:

$$R = \frac{(\mathrm{Rs\ L})}{\mathrm{A}}$$

Where,

R (ohms) = total resistance of the heater,
R_s (ohms m^{-1}) = specific resistance of the product,
L (m) = distance between the electrodes and
A (m^2) = area of the electrodes.

Every product has a critical current density and if this is exceeded there is likely to be arcing (or flashover) in the heater. The current density is found by:

$$\mathrm{Id} = \frac{I}{A}$$

Where, I_d (amps cm^{-2}) = current density.

The minimum area for the electrodes can therefore be calculated once the limiting current density and maximum available current are known. The rate of heating is found using:

$$Q = m\,Cp\,\Delta\theta$$

and the power by $P = V\,I$

and $P = R\,I^2$

Assuming that heat losses are negligible, the temperature rise in a heater is calculated using:

$$\Delta_\theta = \frac{\mathrm{V}^2\ \sigma\mathrm{a}\ \mathrm{A}}{\mathrm{L\ m\ cp}}$$

where

Δθ (^{0}C) = temperature rise,
σa (S m^{-1}) = average product conductivity throughout temperature rise,
A (m^2) = tube cross-sectional area,

L (m) = distance between electrodes,

m (kg s^{-1}) = mass flow rate and

cp (J kg^{-1} $^{0}C^{-1}$) = specific heat capacity of the product.

Equipment and Applications of Ohmic Heater:

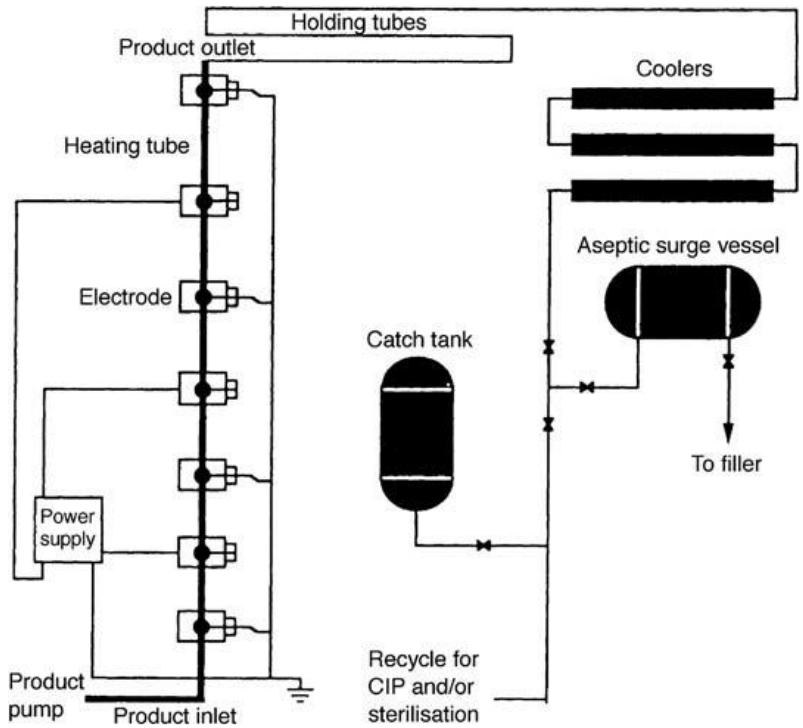

Figure: Layout of an ohmic heating system

Because the product itself is an electrical component, the design of ohmic heaters must take account of the electrical properties of the specific food to be heated. The factors that are taken into account include:

i. The type of product, its composition, electrical resistance and change in resistance over the expected temperature increase, shape, size, orientation, specific heat capacity, thermal conductivity and density.

ii. The temperature rise, which determines the power requirement, and rate of heating required.

iii. Flow rate and holding time required.

- Early ohmic heater designs used DC power, which caused electrolysis (corrosion of electrodes and product contamination) but the use of AC mains power at 50 Hz reduces this risk.
- The heater consists of a vertical tube containing a series of pure carbon cantilever electrodes (supported from one side) that are contained in a PTFE housing and fit across the tube.
- The tube sections are made from stainless steel, lined with an insulating plastic such as polyvinyidene fluoride (PVDF), polyether ether ketone (PEEK) or glass.
- Food is pumped up through the tube and an alternating current flows between the electrodes and through the food to heat it to the required process temperature.
- The system is designed to maintain the same impedance between the electrodes in each section.
- The tube sections therefore increase in length between inlet and outlet because the electrical conductivity of the food increases as it is heated.
- Food then passes from the heater to a holding tube where it is held for sufficient time to ensure sterility and is then cooled and aseptically packaged.

Typically, a heater tube of 2.5 cm diameter and 2 m length could heat several thousand litres per hour. Ohmic heating has been used to process various combinations of meats, vegetables, pasta and fruits when accompanied by a suitable carrier liquid.

In operation, a small amount of carrier liquid is used to suspend the particles as they pass through the heater. The bulk of the carrier liquid is sterilised by conventional plate or tubular heat exchangers and is then injected into the particle stream as it leaves the holding tube. This has the advantage of reducing the capital and operating costs for a given throughput. The combined product is then aseptically packaged.

Effects of Ohmic Heating on Foods and Microorganisms:

Ohmic heating is an HTST process and therefore has similar benefits to other methods of rapid heating that destroy microorganisms before there are adverse effects on nutrients or organoleptic qualities:

- It also causes similar changes to foods as does conventional heating, such as starch gelatinisation, melting of fats and coagulation of proteins.
- Ohmic heating increases diffusion of material from solid particles to the carrier liquid, which may be due to electroporation,
- membrane rupture caused by the voltage drop across the membrane, and cell lysis, disrupting internal components of the cell.
- Losses of material from cells only alter the nutritional value if the liquid is not consumed, for example in blanching.

TOPIC: PULSED ELECTRIC FIELD PROCESSING

Pulsed electric field (PEF) processing involves the application of short pulses of high-intensity electric fields (10 - 80 kV cm^{-1}) for a short time (microseconds to milliseconds), with the processing time being a multiple of the number of pulses and the pulse duration.

The product is located between a set of electrodes in a treatment chamber at, or close to, ambient temperature. The applied high voltage produces an electric field that causes microbial inactivation. After the treatment, the food is aseptically packaged and stored under refrigeration.

PEF has several ***advantages over conventional heat treatments***, including better retention of flavour, aroma, colour and nutritional value and improved protein functionality with increased shelf-life and reduced microbial contamination. The process has also been applied to sugar beet, oilseeds and fruits to disrupt cells and increase the yields of extracted sugar, oil or juice, respectively.

Theory of PEF:

High electric field intensities are achieved by storing energy from a DC power supply in a bank of capacitors, which is then discharged to form high-voltage pulses.

When a liquid food is placed between two electrodes and subjected to high electric field strengths in short pulses, there is a rapid and significant reduction in the number of vegetative microorganisms in the food.

Two mechanisms have been proposed by which microorganisms are destroyed by electric fields:

1) electrical breakdown of cells and
2) electroporation (the formation of pores in cell membranes).

1) **In the electrical breakdown mechanism:** A normal microbial membrane has a charge separation across the membrane, which leads to a potential difference of ≈10 mV. An increase in the membrane potential due to PEF causes a reduction in the cell membrane thickness and, if a critical breakdown voltage (≈ 1 V) is reached, it leads to localised decomposition of the membrane. Above the critical field strength and with longer exposure times, larger areas of the membrane break down to cause irreversible destruction.
2) **Electroporation:** is caused when high electric field pulses temporarily destabilize the lipid bilayer and proteins of cell membranes. The main effect is to increase membrane permeability due to compression and poration. Pores in the membrane cause the cell to swell and rupture, followed by leakage of cytoplasmic materials and cell death

The factors that affect microbial inactivation are:

- Processing conditions (electric field intensity, pulse waveform and frequency (Hz) and duration, treatment time and temperature). Inactivation of vegetative cells is greater at higher electric field intensities and/or with an increase in the number and duration of the pulses. Economically, it is preferable to use higher field strengths and shorter pulses
- Type, numbers and growth stage of microorganisms
- Properties of the food (pH, conductivity, ionic strength, presence of antimicrobial compounds). The electrical conductivity of most foods is 0.1 - 0.5 S m^{-1} but some products (e.g. those with added salt) have a higher ionic strength and hence a higher electrical conductivity. This reduces their resistance and hence microbial inactivation decreases with increasing conductivity at an equivalent input energy.

Electric field pulses may be ***monopolar or bipolar*** and the waveform may be ***sinusoidal, rectangular or exponentially decaying*** (Fig.1).

- Rectangular wave pulses are more energy-efficient and more effective at inactivation of microorganisms than other types.
- Bipolar pulses are more lethal than monopolar pulses because the rapid reversals in orientation of the electric field cause stress in cell membranes and enhance their breakdown.
- Bipolar pulses also produce less deposition of solids on electrodes and cause less electrolysis in foods, which may be organoleptically, nutritionally and toxicologically beneficial

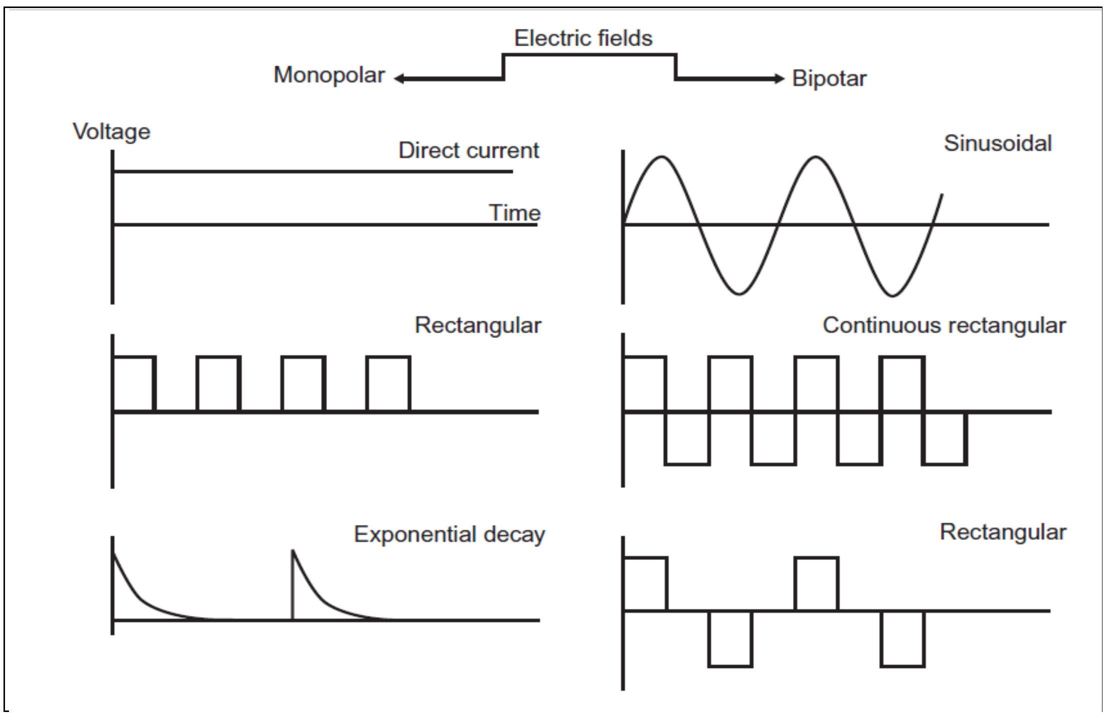

Figure 1: Different types of electric field waveforms

Equipment and Operation (PEF)

Batch PEF equipment is available but continuous operation is preferable for commercial applications. The main components are a high voltage repetitive pulse generator, capacitors to store the charge, inductors to modify the shape of the electric field pulse, discharge switches to release the charge to electrodes, a fluid handling system to control the product flow, and a treatment chamber in which the product is subjected to the electric field (**Fig. 2**).

Monitoring and control equipment includes a data acquisition and control microprocessor, fibre optic temperature sensors, and voltage and current monitors. After processing, treated food passes to an aseptic packaging line.

Two designs of treatment chamber used for continuous processing are coaxial and cofield arrangements. In coaxial chambers **Fig.3**, the product flows between inner and outer cylindrical electrodes, which are shaped to control the electrical field in the treatment zone. Cofield chambers have two hollow cylindrical electrodes, separated by an insulator, forming a tube that the product flows through.

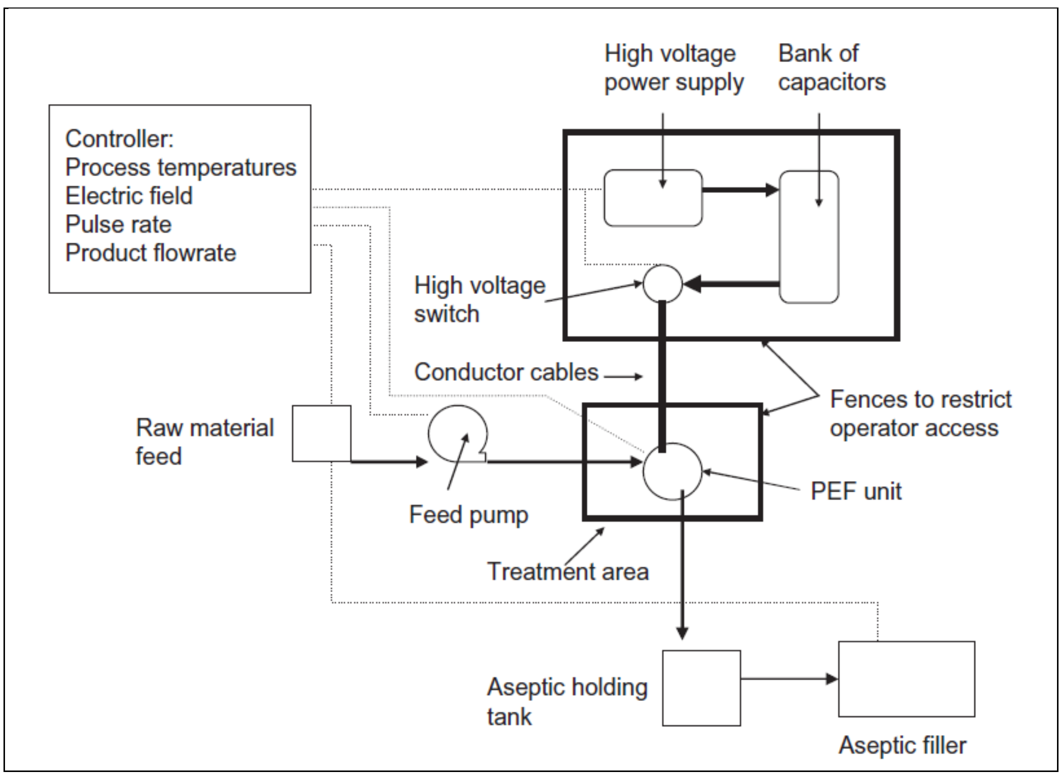

Figure 2: Schematic diagram of PEF equipment

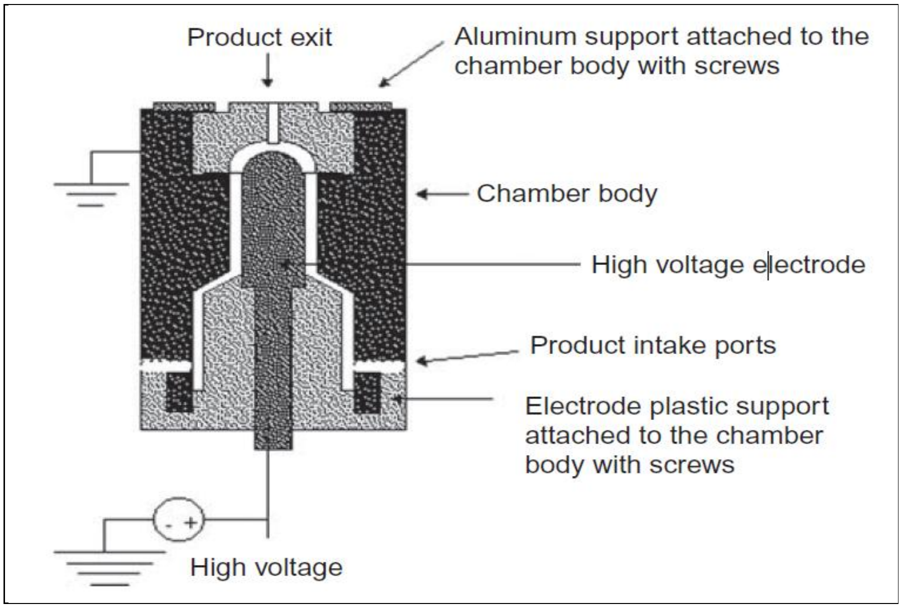

Figure 3: Cross-sectional view of a coaxial PEF treatment chamber

Although the process is intended to operate at ambient temperatures, PEF treatment causes a rise in the product temperature of up to ≈ 30 ^{0}C; the extent of which depends on the field strength, pulse frequency and number of pulses.

To control the product temperature, equipment is either fitted with refrigeration coils or the food is pumped through heat exchangers before and after treatment.

In a **single-chamber operation**, the food is recirculated for the required number of times, whereas **multichamber operations** have two or more chambers connected in series, with cooling systems between the chambers. The heat produced by PEF is lost in the refrigeration systems and cannot be regenerated.

To **protect operators from the high voltages**, the entire apparatus is contained within a restricted-access area with interlocked gates, and all connections to the chamber including product pipework and refrigeration units, are *isolated and earthed to prevent leakage of energy*.

The main limitations of PEF processing are as follows:

- *It is restricted to liquid foods* or those with small particles. Dielectric breakdown may occur at particle_liquid interfaces due to differences in their electrical conductivity.
- *Restricted to foods that can withstand high electric fields* (homogeneous liquids that have low electrical conductivity). If salt is to be added to foods, it should be done after PEF processing.
- *The presence of bubbles in a food causes non-uniform treatment and safety problems* (If the electric field exceeds the dielectric strength of the bubbles, it causes discharges inside the bubbles that increase their volume and volatise the liquid). [Sparking results if the bubbles become large enough to bridge the gap between the two electrodes. Air bubbles must therefore be removed by vacuum-degassing the product before processing].

Effects of PEF on Microorganisms, Enzymes and Food Components:

- *Vegetative microbial cells are more sensitive to PEF in the logarithmic phase of growth than in the stationary phase* (This is because cells are undergoing division, during which the cell membranes are more susceptible to the applied electric field. Inactivation increases at higher temperatures, lower ionic strength and lower pH).
- Bacterial spores and yeast are considerably more resistant than vegetative cells and spores are able to withstand very high voltage gradients (>30 kV cm^{-1}).
- Moderate heating of foods (e.g. to 40 ^{0}C) significantly increases the lethal effect of PEF.
- enzymes are more resistant then microorganisms to PEF processing but different enzymes exhibit a wide range of inactivation.

Summarise the factors that affect enzyme inactivation by PEF as:

- PEF parameters (electric field strength, number of pulses, pulse duration and width, total treatment time)
- Enzyme structure (active site, secondary and tertiary structure)
- Temperature
- Suspension medium for the enzyme.

There have been numerous studies of the **effect of PEF on the nutritional value** and **organoleptic qualities of foods** like;

- In general, vitamins are not inactivated to any appreciable extent.
- Reviewed studies of PEF-treated milk, which showed no physicochemical or sensory changes compared to untreated products.
- PEF extended the shelf-life of fresh apple juice to more than 56 days at 22 – 25^{0}C with no apparent change in its physicochemical and sensory properties.

Table: Advantages and limitations of some novel methods of minimal processing

Processes	**Advantages**	**Limitaion**	**Examples on commercial application and products**
Pulsed electric fields :	• Kills vegetative cells • Colours, flavours and nutrients are preserved • No evidence of toxicity • Relatively short treatment time	• No effect on enzymes and spores • Difficult to use with conductive materials • Only suitable for liquids or particles in liquids • Only effective in combination with heat • Products of electrolysis may adversely affect foods • Safety concerns in local processing environment • Energy efficiency not yet certain • Regulatory issues remain to be resolved • May be problems with scaling-up process	• For liquid foods • Pasteurisation of fruit juices, soups, liquid egg and milk • Accelerated thawing • Decontaminatio n of heat sensitive foods