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Infrared heating and its application in food processing

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Abstract

Processing of food products is a necessary requirement for extending their shelflife. However, such processing generally involves heat treatment that can enhance the safety of the food, but reduce organoleptic quality. Fruit processing and preservation technologies must keep fresh-like characteristics while providing an acceptable and convenient shelf life as well as assuring safety and nutritional value. Processing technologies include a wide range of methodologies to inactivate microorganisms, improve quality and stability, and preserve and minimize changes of fruit fresh-like characteristics. Over the years, researchers have looked for many technologies to optimize time and temperature profiles in order to minimize the exposure of food to heat. The newer food-processing technologies may have potential to supplement or even eliminate the use of heat treatment. A number of potential opportunities exist for exploiting the benefits of electromagnetic radiations in food processing, which include technologies like ohmic, infrared (IR), and microwave heating. IR radiation is electromagnetic energy with wavelengths longer than those of visible light, gamma, and ultraviolet radiation, but shorter than those of microwave and radio frequency. IR radiation falls between the region of visible light (0.38-0.78 µm) and microwaves (11000 mm). IR mainly utilized for food processing because of the several advantages such as higher heat-transfer capacity, instant heating because of direct heat penetration, high energy efficiency, faster heat treatment, fast regulation response, better process control, no heating of surrounding air, equipment compactness, uniform heating, preservation of vitamins, and less chance of flavor losses from burning of foods. Heat transfer of IR processing occurs as radiation in the absence of an intervening medium between two surfaces at different temperatures. In food, apart from surface heating of foods and dehydration of agricultural products, IR radiation could conveniently be used for decontamination and disinfection of food and food-contact surfaces. The energy throughput is increased using a combination of microwave heating and IR heating. This combination heats food quickly and eliminates the problem of poor quality.

Keywords: Infrared heating, radiation, wavelength, emitters, inactivation, disinfestation, food quality

Introduction

Processing is one of the basic requirement of food products to increase the conventional shelf life of products. Food processing and preservation technologies must keep fresh like characterstics of product while providing better shelf life as well as safety and nutrition. Processing technologies involve various methods to inactivate microorganisms, improve quality and stability. Energy conservation is very important concern from the point of profitability and success of any unit operation. Heat transfer is done in three methods, conduction, convection and radiation. Infrared radiation or simply Infrared is one of the oldest technique to heat treat food but its potential is long been underestimated. Infrared heating offers many advantages over conventional heating which include reduced heating time, higher heat transfer coefficients, reduced quality losses, uniform heating, versatile, simple and compact equipment and saves energy under similar conditions. By exposing an object to infrared (IR) radiation, the heat energy generated can be absorbed by food materials (Krishnamurthy *et al*., 2008) [17]. Air is transparent to IR radiation, so the process can be performed at ambient air temperature. Equipment can be compact and automated with a high degree of control over process parameters. Similar to other electromagnetic waves such as microwaves and radio frequencies, IR rays attain their unique Radiative characteristics.

Infrared is electromagnetic radiation (EMR) with longer wavelengths than those of visible light, and is therefore invisible, although it is sometimes loosely called infrared light. It extends from the nominal red edge of the visible spectrum at 700 nanometers (frequency 430 THz), to 1 millimeter (300 GHz) (although specially pulsed lasers can allow humans to detect IR radiation up to 1050 nm).

Most of the thermal radiation emitted by objects near room temperature is infrared. Like all EMR, IR carries radiant energy, and behaves both like a wave and like its quantum particle, the photon (Gani *et al*., 2018) [13]. Two key radiative aspects of interest for designing the IR heater are its spectral distribution and energy intensity. The spectral region of IR radiation can be controlled by the use of appropriate optical filters and the surface temperature of its heating elements. The differential energy absorption of protein among several key components in the food complex can be found when the IR ray emits light in the narrow spectral region between 6 and 11 µm. Also, the radiation properties of food materials vary with decreasing water content; consequently, its reflectivity increases and the absorptivity decreases. So, it is very important to fully understand the above optic-thermal phenomena associated with IR and food products (Pan *et al.*, 2010) [36]. IR has been widely used in food industry for dehydration, pasteurization, frying, roasting, drying, freeze-drying, thawing, blanching, baking, cooking and enzyme inactivation.

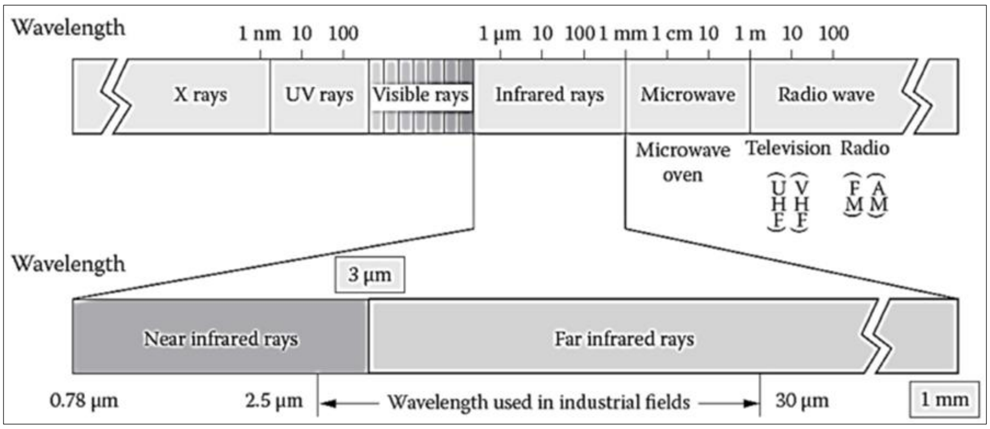


Fig 1: Electromagnetic wave Spectrum and Infrared wavelength range

Infrared radiation is divided into three types (Rosenthal, 1992) [40]:

1. Near-IR (NIR) with wavelength ranging from 0.75 to 1.4 µm.
2. Mid-IR (MIR) with a wavelength between 1.4 and 3 µm.
3. Far-IR radiation (FIR) with wavelength between 3 and 1000 µm.

Therefore, infrared radiation is defined as part of an electromagnetic spectrum whose wavelength ranges from 0.78 to 1000 µm. Infrared heating depends on the spectrum because the energy emitted from the emitter consists of different wavelengths and part of the radiation depends on the source temperature and the lamp emission. The phenomenon of radiation becomes more complex because the amount of radiation that falls on any surface depends not only on the spectrum, also on the direction. Electromagnetic radiation is weakened as a result of absorption by the medium as well as scattering. The process of converting radiation to other forms of energy is a phenomenon of absorption, while in the case of scattering, the radiated energy is directed to another destination from the original direction of propagation as a result of the combined effect of reflection, refraction, and deviation, and all these factors cause weak electromagnetic radiation (Modest, 1993; Sandu, 1986) [27, 42].

The radiation falling on a particular object is converted to heat and the energy can be absorbed and reflected, in addition, the radiation can be absorbed and transmitted as shown in figure 2. This figure shows that there are three basic radiation properties, they are reflectivity (ρ), which is the ratio of the reflected part of the radiation coming to radiation next macro. Absorptivity (α), which is the ratio of the absorbed portion of incoming radiation to total incoming radiation. Emissivity transmissivity (τ), which is the ratio of the emitted part of the incoming radiation to the total incoming radiation, and the energy balance is shown in the following equation:

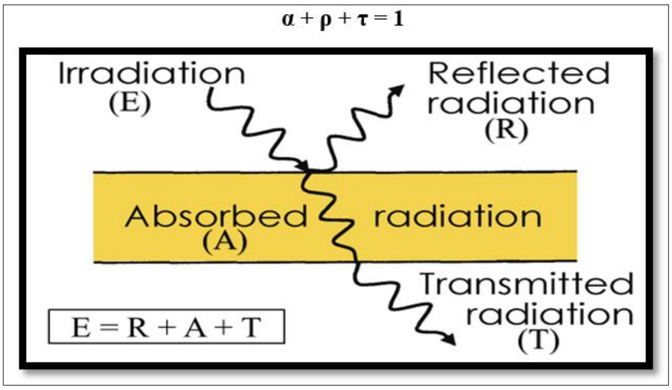


Fig 2: Extinction of Radiation and total energy

When infrared waves hit a material they are reflected, transmitted or absorbed (Figure 2). The amount of radiation absorbed by a grey body is termed the absorptivity and is numerically equal to the emissivity. Radiation, which is not absorbed, is reflected and this is expressed as the reflectivity. The amount of absorbed energy, and hence the degree of heating, varies from zero to complete absorption. This is determined by the components of food, which absorb radiation to different extents, and the temperature of the source determines the wavelength of infrared radiation. Higher temperatures produce shorter wavelengths and greater depth of penetration. The net rate of heat transfer to a food therefore equals the rate of absorption minus the rate of emission:

$Q = \varepsilon\sigma A (T_1^4 – T_2^4)$….. Stefan-Boltzmann's Law

Where T_1 (K) is the temperature of emitter and T_2 (K) the temperature of absorber and ε, σ and A are the emissivity (varies from 0 to 1), Stefan-Boltzmann constant (5.670 x 10^{-8} Wm^{-2} K^{-4}) and surface area (m^2), respectively.

The absorbed waves are transformed to heat and the temperature of the material increases. When the waves penetrate the material the vibrations and rotation of the molecules are changed. The two fundamental vibrations that occur are stretching and bending. Stretching means a decrease or an increase of the distance between atoms and bending means a movement of the atoms. When the infrared light hits a molecule, energy is absorbed and the vibration changes. When the state of the molecule returns to the absorbed, energy will be transformed to heat (Skjoldebrand 2001) [45].

Mechanism of Infrared treatment in food

Energy conservation is one of the factors that determine the usefulness and success of the operation of any food industry unit. Heat is transmitted by conduction, convection, and radiation. The goal of heating food is to increase the shelf life and improve the taste of foods (Lee *et al.*, 2006) [18]. Temperature is a measure of thermal motion at the molecular level. When the temperature of the material increases, the molecular motion gains more energy, and when it increases more, it causes physical and chemical changes in the heated material. In conventional heating, which comes from the combustion of fuel or electric heaters, heat is transferred to the material from the outside by convection by hot air or by thermal conduction.

The process of transferring energy from source to food depends on the type of cooking. Energy will be very close to the surface of the food and then heat food gradually from the hot surface towards the inside. Heat is transferred to the food through conduction only and this requires continuous processing of heat. The high temperature and time required for food depend on the thermal and engineering properties of the food (Rosenthal, 1992) [40]. When heating is done by radiation, the heat is transferred by convection and conduction. The broiling process takes place due to thermal radiation.

Electromagnetic radiation causes thermal movements of the molecules, but conversion efficiency is highly dependent on the frequency (energy) of the radiation. Radiation-transmitted energy at shorter wavelengths than infrared causes electron-chemical changes in radiation-absorbing molecules, such as chemical bonding, electronic excitation, and dissipation of absorbed energy in the form of less heat. The efficiency of converting absorbed energy into heat is great at high wavelengths in infrared radiation, so the electromagnetic radiation produced by infrared radiation deepens the food by a few millimeters. Infrared radiation is absorbed by organic matter at separate frequencies that correspond to the transport of internal molecules between energy levels. This transition within the range of infrared energy is expressed regarding the rotational movement and the vibrational (stretching) movement of internal atomic bonds. The rotational frequencies range from 1011 to 1013 Hz with a wavelength of 30 μm^{-1}mm. The energy transfer during the separation of liquids is very small, and therefore, infrared absorption is continuous. Infrared absorption bands associated with food heating are shown in Table 1.

Table 1: Infrared absorption band characteristics of chemical groups relevant to heating of food

Chemical group	Absorption wavelength (µm)	Relevant food components
Hydroxyl group (O-H)	2.7-3.3	Water, carbohydrates
Aliphatic carbon–hydrogen	3.25-3.7	Fats, carbohydrates, protein
Carbonyl group (C=O) (ester)	5.71-5.76	Fats
Carbonyl group (C=O) (amyl)	5.92	Proteins
Nitrogen–hydrogen group (-NH-)	2.83-3.33	Proteins
Carbon–carbon double bond (C=C)	4.44-4.76	Unsaturated fats

Table 1 shows that there is a strong absorption due to longitudinal vibrations. The absorption of the material to the radiation does not make it saturated with infrared radiation because the molecules excited by the vibratory movement continuously lose energy in random directions as a result of collisions between the molecules, which transfer energy to the surrounding environment in the form of heat. Therefore, there is no need for another method to transfer energy, for example, the use of hot air.

Interaction of IR with various food components

The heat from infrared heating is produced on the surface of the infrared treated material, so the inside of the material is heated by the connection between the food molecules, thus the temperature is graded from the surface to the center. The air in contact with the surface of the food is heated indirectly, but it is not as hot as it occurs in heating by convection and conduction. The infrared absorption ranges by food components are shown in Figure 4, which shows that the food components interfere with each other in the absorption of different infrared spectra. Water mainly affects the absorption of incident radiation at all wavelengths, while the absorption of proteins by infrared radiation is at wavelengths 3–4 and 6–9 µm. Fat absorption is at wavelengths 3–4, 6 and 9–10 µm, and sugars are 3 and 7–10 µm. The water absorption beams are 3, 4.7, 6, and 15.3 µm (Sandu, 1986) [42]. In addition, when the thickness of the food increases, the absorption increases.

Infrared radiation is heat radiated by an object. When an object gets heated, it gains energy as a result of which the atoms and molecules move or vibrate and radiate infrared which is heat. Objects that are not hot enough to radiate visible light will radiate infrared. When infrared waves touch a surface or fall on any substance/object, heat energy is released. This heat energy is not dependent on the temperature of the surroundings. Examples of infrared radiation are heat from the Sun, heat from fire and heat from radiator, etc.

Food materials can be considered complex matrices consisting of different biochemical macromolecules, biological polymers, inorganic salts, and water. During IR heating, the food object can absorb radiation at certain wavelengths, and reflectand transmit radiation at other wavelengths. The absorbed radiation energy creates the heat within the object. Amino acids, polypeptides, and proteins have two strong absorption bands localized at 3–4 and 6 –9 mm. Lipids show three strong absorption bands situated at 3–4, 6, and 9–10 mm, and carbohydrates have two strong absorption bands centred at 3 and 7–10 mm (Sandu, 1986; Rosenthal, 1992) [42, 40].

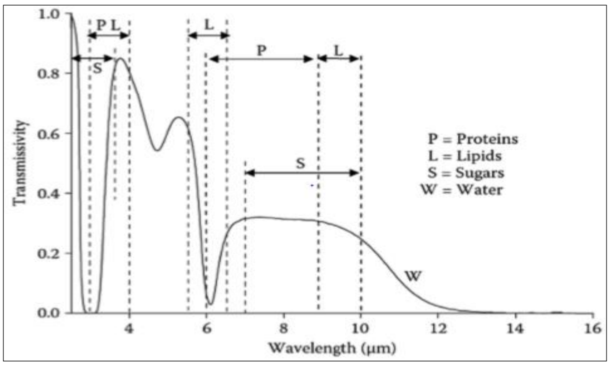


Fig 3: Principle absorption bands of the main food components compared with water (Krishnamurthy *et al*., 2008) [17]

Infrared emitters

Any substance above absolute zero temperature emits Infrared radiations. From sun to a small fire, no matter how small, emits Infrared radiations. Based on wavelengths, Infrared emitters (figure 6) can be classified into three categories: Short wave, long wave and medium wave emitters depending upon the voltage applied to it. Short wave emitters operate at a very high emissive power and temperature, so they have limited applications as it may cause overheating problems during prolonged processing of food materials. Medium wave emitters radiate in the range from 1.4 - 3.0 µm which can be used for drying and curing of food products. Long wave emitters are suitable for low temperature processing treatments requiring a combination of convection and IR heating (Pan *et al*., 2005). The heat transfer rate, thermal efficiency and effect of radiation on heated materials are closely related to the range of wavelengths emitted from the heating source (Pan *et al.*, 2016) [37]. Classification of IR emitters (Figure 4) is also done on the basis of electrical or gaseous type emitter. The emitters produce infrared radiation in a range of 343–1100 ^{0} C for gas and 1100–2200 ^{0} C for electric heaters. In order to prevent products from burning, the typical infrared temperature produced is between 650 and 1200 ^{0} C (Aboud *et al.*, 2019) [1]. The cost of gas heaters is very high but their operating cost is relatively low compared to the systems producing electrically infrared radiation (electric heaters). Infrared electric heaters are more widespread than gaseous because of their ease of control, fast heating rate, and clean energy. Infrared emitters are more flexible in producing the required wavelength for a particular application.

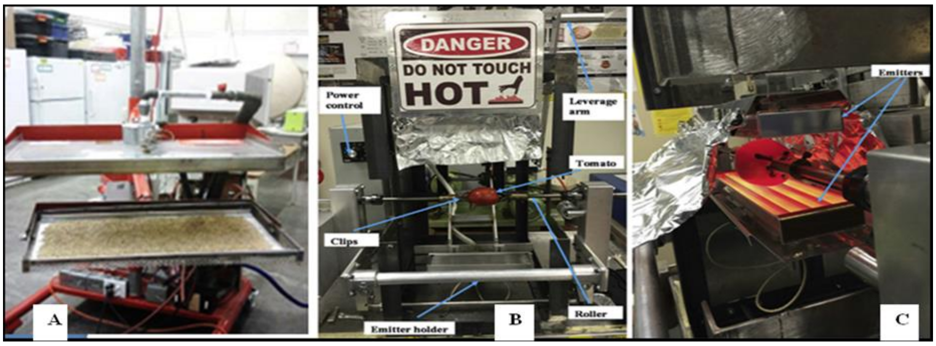
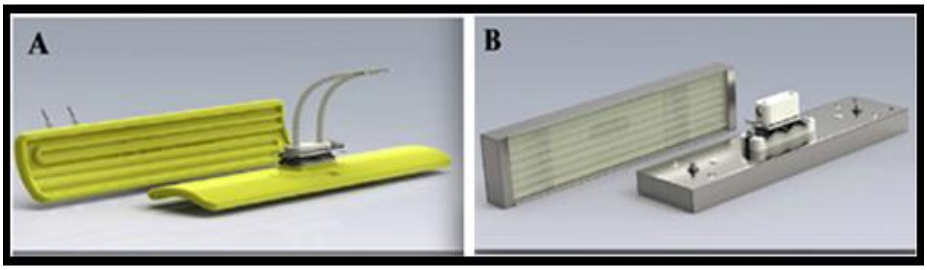


Fig 4: (A) Custom-designed catalytic infrared heating unit for rice drying and (B and C) electric IR heating system

Electrical infrared emitters consist of a metal filament placed inside a sealed container and filled with inert gas or empty. Infrared radiation is produced by heating the filament to a particular temperature using an electric heater by passing an electric current through a high-resistance wire such as nichrome wire, iron-chromium wire and tungsten filament. When the metal wire is heated and reaches the glow temperature and its temperature rises to 2200 K, this will lead to the emission of infrared radiation type NIR wavelength ranging between 0.7 and 1.4 µm. The types of electric IR emitters (Figure 5) include reflector type emitters, incandescent lamps, quartz tubes and resistance elements such as metallic tubes, ceramic tubes, and non-metallic rods (Vidyarthi *et al*., 2019) [47].



Ceramic full trough element Pillared quartz element (PQE)

Fig 5: Emitters

Infrared radiation emitted by Incandescent lamps are classified as short-wave emitters, while quartz tubes and resistance elements are classified as medium- wave and long-wave emitters, respectively. The electrical emitters made of ceramic or quartz can be manufactured with standardized energy values, such as 60, 100, 150, 200, and 500 W. A number of such emitters can be mounted on a panel to make a module, with the spacing between each emitter being selected to give the desired radiant intensity. In general, electric heaters are expensive and are convenient to manipulate the power distribution of a given system according to the design requirement. Electrical IR emitters normally have a conversion efficiency from 78% to 85%, whereas gaseous IR emitters have the conversion efficiency of 40–46% (Ramaswamy and Marcohe, 2005) [38]. Electrical emitters can reach a radiant intensity of up to 400 kW m^{-2}, while gas-fired emitters generally do not exceed the radiant intensity of 22 kW m^{-2} (Nindo and Mwithiga, 2010) [31].

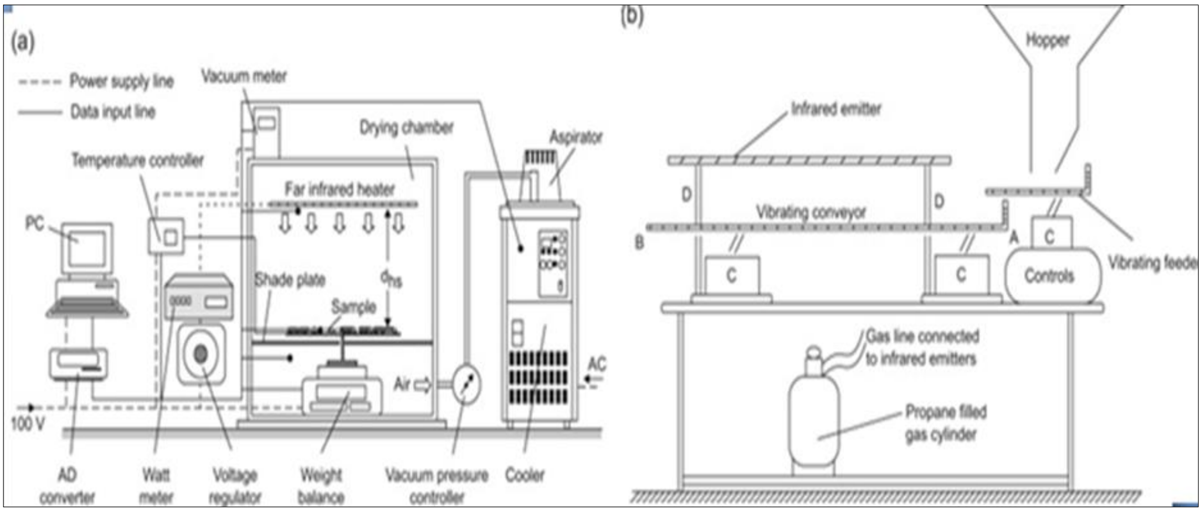


Fig 6: Infrared equipment Design

Gaseous IR emitters powered by propane or natural gas are commonly used in industrial applications, which demonstrate lower operating cost and higher reliability and durability compared to electrical IR emitters. There are two types of gaseous IR emitters: direct or open flame IR emitters and catalytic flameless IR emitters. The open flame IR emitters release IR radiation via normal flame combustion. During the combustion process, a portion of the fire flame may emit energy in the form of visible light, causing the wastage of energy and fuel (MacConnell, 1972) [23]. Incomplete combustion may result in smoke and soot built-up on emitters or release very small particles of carbon into the environment, which should be minimized. Hence, direct flame IR emitters have restricted usage in food processes because of the safety and environmental concerns. IR emitters have different penetration depths (table 2) depending upon product and spectral peaks.

Table 2: Penetration depth of near- IR into food products

Product	Spectral Peak (µm)	Depth of penetration (mm)
Dough, whaet	1.00	4 – 6
Bread, wheat	1.00	11 – 12
Biscuit	1.00	4
Biscuit	0.88	12
Grain, wheat	1.00	2
Carrot	1.00	1.5
Tomato paste	1.00	1
Potatoes	1.00	6
Potatoes	0.88	15 – 18
Apples, raw	1.16	4.1
Apples, raw	1.65	5.9
Apples, raw	2.36	7.4

The catalytic IR emitter emits radiation heat over a wide range of wavelengths without any visible flame. Typically, these emitters have radiant intensity varying from 6 to 28 kW m^{-2}, emitting MIR and FIR radiation with the heating-up period varying between 180 and 300 s and the radiation efficiency ranging from 30% to 75% (Das and Das, 2010) [7]. The gaseous IR emitters are available in several sizes for industrial application. For example, a catalytic IR emitter with an effective heating area of 30 cm by 30 cm can generate IR heat with an isothermal surface temperature of the emitter at ~500 C, which corresponds to a peak wavelength of 3.7 mm by assuming the emitter as a blackbody (Li *et al*., 2014) [21]. The efficiency of gaseous IR emitters depends on the size of the heater and the separation distance between the heater and the object being heated (Nindo and Mwithiga, 2010) [31].

Advantages of Infrared heating

Infrared technology is highly energy-effcient, less water-consuming and environmentally friendly and is also characterized by the homogeneity of heating, high heat transfer rate, low heating time, low energy consumption and improved product quality. Infrared radiation improves the quality of the treated product and improves the safety of treated food. It reduces the consumption of chemicals and water and also increases manufacturing efficiency (Pan and Atungulu, 2010) [31]. Infrared (IR) heating is a contactless and chemical-free method that has been used for disinfection. Other features include low energy costs, air is transparent to infrared, and the size of infrared equipment is small as well as controlling factors in it with high accuracy.

It also has unique radiative properties and high thermal effciency, and is considered an alternative source of energy and heating (Lee *et al*., 2006) [18]. Less costly to operate and provide more effective heating than traditional heaters. The energy is directly concentrated on the material to be heated and does not produce volatile organic compounds, carbon monoxide or nitrogen oxides. It does not need heat recycling and does not need an isolated system (Nindo and Tang, 2007). In addition, this processing preserves vitamins and has very little flavor loss, and the temperature of the surrounding air is not affected (Skjöldebrand, 2001) [45].

The Food and Drug Administration (FDA) has indicated that infrared radiation can be used in food processing, which is non-ionizing. Baking time can be shortened, energy consumption can be reduced, nutrition and appearance can be better preserved. Rapid heating method (normally faster than convective or conduction heating). IR heating helps reduce beta-carotene and chlorophyll degradation in the heating process. IR irradiation is more effective for pasteurization than NIR, killing bacteria and spores. It has many benefits such as efficient heat transfer, reduced time and energy, cool ambient surrounding air and high controllability.

Disadvantage

Inspite of many advantages Infrared has some disadvantages too. Some people have to be cautious when using infrared radiation because it produces high heat and exposure to cause burns, the depth of penetration of food is small and long-term exposure to infrared radiation causes tissue rupture and is not sensitive to the reflection properties of coatings. IR has limiting penetration power so size of food products should be considered accurately. It is not sensitive to reflective properties of coatings.

Various applications of Infrared Radiations are given below

Drying and Dehydration

Infrared heating form an important place in drying technology and extensive research work has been conducted in this area (figure 7). Most dried vegetable products are prepared conventionally using a hot-air dryer. This method is inappropriate when dried vegetables are used as ingredients of instant foods because of low rehydration rate of the vegetables. Freeze-drying technique is a competitive alternative, however, it is comparatively expensive. Application of FIR drying in the food industry is expected to represent a new process for the production of high quality dried foods at low cost (Sakai and Hanzawa 1994) [41].

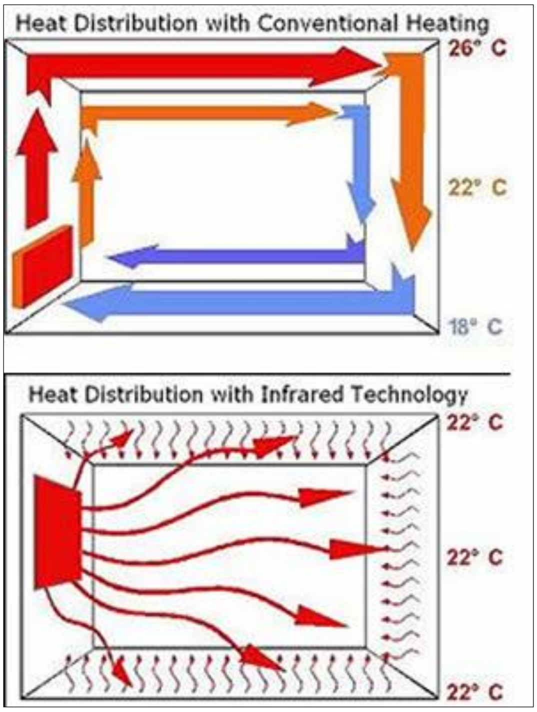


Fig 7: Heat distribution with Convective heating and Infrared heating

The use of IR radiation technology for dehydrating foods has numerous advantages including reduction in increased energy efficiency, drying time, alternate energy source, uniform temperature in the product while drying, better-quality finished products, a reduced necessity for air flow across the product, high degree of process control parameters, and space saving along with clean working environment (Mongpreneet *et al.*, 2002) [28]. Therefore, FIR drying operations have been successfully applied in recent years for drying of fruit and vegetable products such as potatoes (Afzal and Abe 1998), sweetpotatoes (Sawai *et al.*, 2004), onions (Mongpreneet *et al.*, 2002) [28] and kiwifruit (Fenton and Kennedy 1998). Drying of vegetables, seaweed, fish flakes, and pasta is also done in tunnel infrared dryers. Infrared drying has found its application in food analysis to measure water content in food products (Anonymous, 1995) [3]. Generally, solid materials absorb infrared radiation in a thin surface layer. However, moist porous materials are penetrated by radiation to some depth and their transmissivity depends on the moisture content. Energy and mass balance developed by Ratti and Mujumdar (1995) accounts for the shrinkage of the heated particle and absorption of infrared energy. Theoretical calculations showed that intermittent infrared drying with energy input of 10 W/m^2 becomes equivalent to convective drying in which the heat transfer coefficient would be as high as 200 W/m^2 K.

Peeling

Peeling is very important process before using any fruit or vegetable. The conventional peeling process applies hot lye or steam for peel removal and is an energy and water- intensive operation. Particularly, the hot lye peeling using sodium hydroxide or potassium hydroxide solution results in a significant amount of peeling effluent discharges containing high salinity and organic solids. Disposal of the wastewater and threat to long-term water supply associated with lye peeling have become serious concerns to the tomato processors. To minimize the chemical contamination and negative environmental impacts, steam peeling has been adopted by food processors as an alternative peeling technique. However, steam peeling produces inferior products with deteriorated peeling appearance, high loss in firmness, and reduced peeling yields compared to conventional hot lye peeling. Therefore, there is an urgent need to develop sustainable and cost-effective peeling alternatives which can reduce water usage and wastewater generation while producing high quality peeled products without using lye and steam (Li *et al*., 2014) [21].

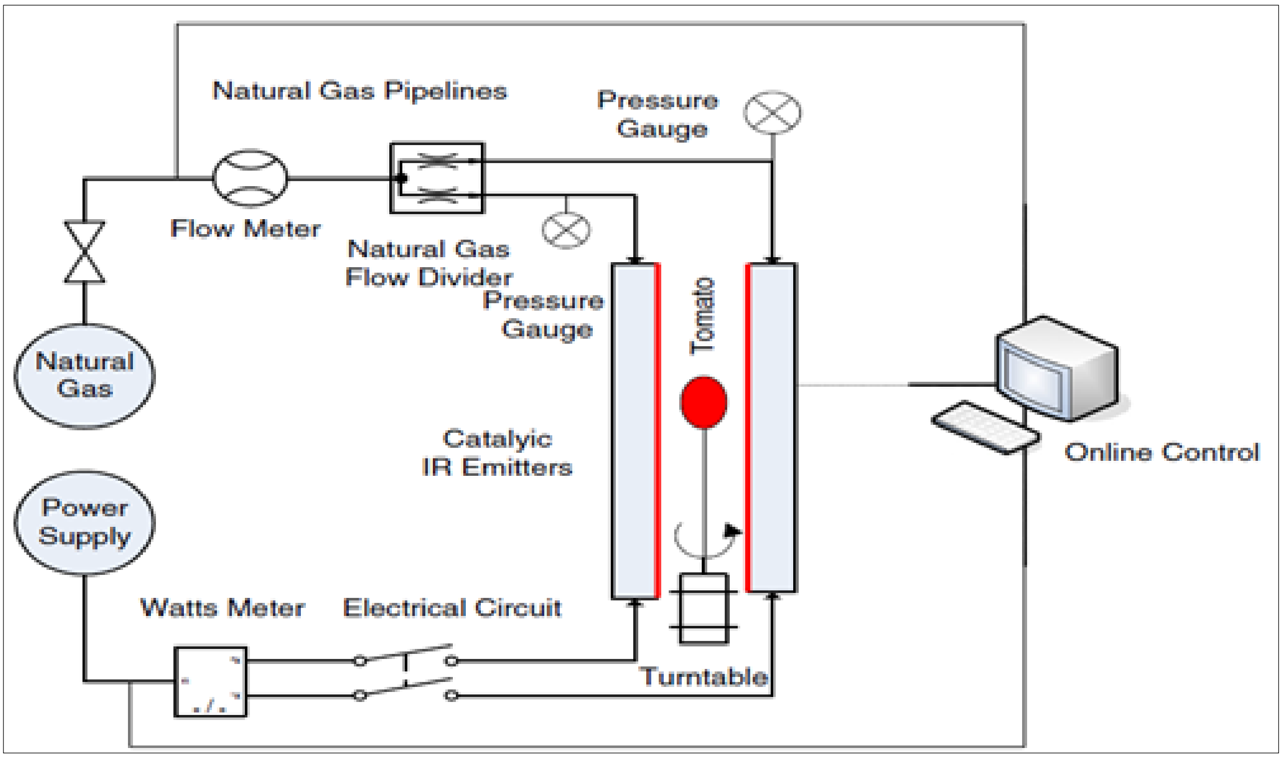


Fig 8: Setup of IR dry-peeling system of tomato with continuous rotary heating

Infrared peeling is best suitable in case of tomato peeling (figure 8) as peel has less intacted skin to it. Moreover thickness of peel is also very less. The surface of the peeled product remains firm and clean as compared to steam peeling. The emerging infrared dry-peeling technique offers a novel approach to eliminate the usage of chemicals and water in the peeling process while maintaining high quality peeled products.

Enzyme Inactivation

Infrared heating can be effectively used for enzyme inactivation. Lipooxygenase, an enzyme responsible for deterioration in soybeans, was inactivated 95.5% within 60s of IR treatment (Kouzeh and others 1982) [16]. Certain enzyme reactions (involving action of lipases and α amylases) were affected by infrared radiation at a bulk temperature of 30 to 40 °C (Sawai and others 2003) [43]. FIR radiation for 6 min resulted in a 60% reduction in lipase activity, while thermal conduction resulted in 70% reduction. FIR has been successfully used to inactivate enzymes responsible for the development of off-flavors in peas prior to the freezing process (Zuilichem *et al.*, 1986) [48], as well as other enzymes and bacteria in solution (Sawai and others 2003) [43]. Galindo *et al.*, (2005) [12] investigated the application of IR heating of carrot slices prior to freezing as compared to blanching in terms of carrot cell and tissue damage. Carrot slices heated by FIR radiation contained damaged cells only in the first half millimeter from the surface and exhibited the texture characteristic of the raw tissue, thus providing the potential of FIR energy technology in the frozen carrots industry.

Pathogen Inactivation

IR heating can be applied for inactivation of bacteria, spores, yeast, and mold in both liquid and solid foods. Microbial inactivation by infrared heating depends on the following parameters: infrared power level, peak wavelength, and bandwidth of infrared heating source, sample depth, temperature of food sample, types of microorganisms, moisture content, physiological phase of Microorganisms (exponential or stationary phase), and types of food materials. Therefore, several researchers have investigated the effects of these parameters on inactivation of pathogenic microorganisms as follows. Effect of power: Increase in the power of infrared heating source produces more energy and thus total energy absorbed by microorganisms (M/Os) increases, leading to microbial inactivation. Sterilization of wheat surface was investigated by Hamanaka *et al.*, (2000). Surface temperature increased rapidly as infrared rays directly heated the surface without any need for conductors. Therefore, irradiating powers of 0.5, 1.0, 1.5, and 2.0 kW resulted in 60, 80, 125, and 195 °C inside the experimental device, and 45, 65, 95, and 120 °C on the surface of wheat stack, obtaining 0.83, 1.14, 1.18, and 1.90 log10 CFU/g total bacteria after a 60s treatment, respectively. Correspondingly (Sawai *et al.*, 2003) [43]. Types of Microorganisms: Resistance of bacteria, yeasts, and molds to infrared heating may be different due to their structural and compositional differences. In general, spores are more resistant than vegetative cells. When Bacillus subtilis spores in physiological saline were exposed to infrared heating, a spore population increased up to 5 times in the first 2 min, followed by subsequent exponential reduction, resulting in shoulder and tailing effects. Upon infrared heat treatment, vegetative cells were inactivated followed by activation of spores. Then vegetative cells formed from spores will be activated and thus spores will be inactivated. An initial increase in B. subtilis population was caused by heat shock germination of spores. The temperature of the honey was raised to 110 °C after the treatment, resulting in microbial reduction of 3.85 $\log_{10}$ CFU/mL. Effect of moisture content: Water molecules inside microoganisms readily absorb infrared radiation. These water molecules are attached to polar groups such as $–NH_2$, -COOH, and -COO within the cell (Hamanaka and others 2006). State and amount of water inside spores, bonding conditions of water molecules, and location of water molecule within M/Os affect their responses to infrared heating (Hamanaka *et al.*, 2006). Maximum D values of B. subtilis spores inactivated by IR heat differed with initial water activities ranging from 0.6 to 0.9.

Baking

Baking is a very important step in the production of bakery products, which determines the quality, palatability, and consumability of final products. IR baking has several advantages over conventional hot air baking, including reduced baking time and energy consumption, better products with thin crust and softer crumb, and better quality in terms of color, texture, puffing, and rollability. Combination of heating technologies, such as IR microwave heating and IR jet impingement heating, have been investigated for baking processes to reduce processing time and improve product quality. In the combined IR–microwave heating method, microwave heating is used to accelerate the entire baking process, while IR heating is utilized to promote browning and crisping reactions on the product surfaces. Several patents have been registered on the use of combined IR and microwave heating method (Jung and Lee, 1992) [19]. Several studies reported the effect of the combination of IR–microwave baking on quality control and improvement (texture, volume, porosity, color) of breads and cakes (Sakiyan *et al.*, 2011) [44].

Cooking, blanching and roasting

Food is processed by various thermal treatments to attain specific color, texture, flavor and crispiness. Sheridan and Shilton (1999) evaluated the efficacy of cooking hamburger patties by IR heating at 2.7 and 4.0 µm. With a higher-temperature (lower-wavelength) energy source, a change in core temperature of patties was closer to the change in surface temperature, and cooking time was found to be shorter. In addition, roasting and browning of meat products‟ surfaces are significant processes in the meat process industry, and Sakai and Hanzawa (1994) [41] reported the use of FIR heating to make boiling eggs without requiring the use of hot water. While the water hydration rate increased by 7%, cooking time decreased by one third, and proteins were denatured and starch granules pregelatinized. IR heating was found to be an effective technique for making instant split peas and expanding dry pea-based food. Fasina *et al.* (2001) determined the effects of IR heating on the properties of legume seeds, and functional characteristics of flours of the IR-processed seeds were determined to be superior to those obtained from untreated seeds. Conventional roasters use hot air for roasting, and air may be heated to 350°C–450°C to roast; for example, coffee beans. For the case of coffee beans, the roasting process might take up to 20 min (Sakai and Mao, 2005) for bean temperatures of around 180°C to 230°C. Due to the requirement of higher temperatures, IR energy can be used as an alternative to roasting.

Pasteurization

Applying IR heating for surface pasteurization purposes has the potential to become a common industrial practice. Exposing a food product to an IR heating source results in an increase in the surface temperature, and the heat is conducted to the interior by conduction. Because food products have lower thermal conductivity (<0.6 W/m²-K in most cases), the rate of heat transfer through the food products is rather slow. Hence, an intense heat might accumulate on the surface, causing the surface temperature to increase rapidly. If the IR exposure time is properly controlled, the surface temperature can be preferentially raised to a degree sufficient to inactivate target pathogenic microorganism without substantially increasing the interior temperature. IR heating inactivates the pathogen microorganisms by causing damage in their intracellular components such as DNA, RNA, ribosomes, cell envelope, and/or cell proteins (Krishnamurthy *et al*., 2008) [17]. Absorption of IR radiation by water molecules in the microorganism is a significant factor in the inactivation since the water absorbs the IR radiation, resulting in a rapid increase in temperature (Hamanaka *et al*., 2006a). Rosenthal *et al*. (1996) used IR heating for surface pasteurization of cottage cheese. Hamanaka *et al*. (2000) investigated the sterilization of wheat surface by using IR heating. Jun and Irudayaraj (2004) applied IR heating for disinfection of fungal spores in agricultural materials. Huang (2004) used IR heating as a possible intervention technology to pasteurize the surface of turkey frankfurters contaminated with Listeria monocytogenes. Use of IR heating for pasteurization of oysters, Japanese noodles, and secondary pasteurization of boiled fish paste was reported by Sakai and Mao (2005). Huang and Sites (2008) [15] developed inactivation of Listeria monocytogenes through IR pasteurization process.

Conclusion

IR drying is a promising novel method, it is not a panacea for all drying processes. It appeals, because it is fast and produces heating inside the material being dried. Specialized manufacturers produce infrared radiators with efficiency of 80-90%, reduced overall dimensions and fairly narrow spectral distributions. The recovery of the heat dissipated in the radiators themselves and its proper use can increase the overall efficiency of infrared heating IR heating has attracted a lot of attention for surface heating applications such as prevention of growth of yeasts and fungi on cheese surfaces, pasteurization of the surface of eggs, as well as ready-to-eat meats such as hotdogs, arresting fungal spoilage of strawberry during storage as well as dry pasteurization of raw almonds. The development and implementation of IR technologies in the food and agricultural sectors as alternative and sustainable methods will benefit the environment and reduce energy and water use. Overall, efficient IR processes having environmental and economic benefits as compared to conventional thermal processes can be achieved by precise process control and a well-designed equipment and processing system. The need for improved product quality, safety, and energy and processing efficiency are expected to drive the industrialization of IR technologies for food and agricultural processing. IR heating is attractive primarily for surface heating applications. In order to achieve energy optimum and efficient practical applicability in the food processing industry, combination of IR heating with microwave and other common conductive and convective modes of heating holds great potential. It is quite likely that the utilization of IR heating in the food processing sector will augment in the near future, especially in the area of drying and minimal processing.

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