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# Infrared Heating of Foods-A Review

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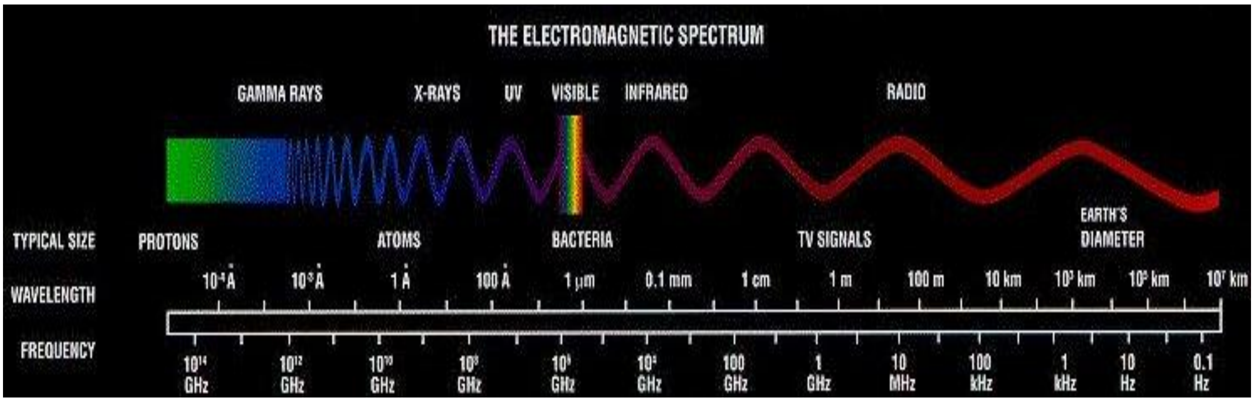
## ABSTRACT

*Infrared(IR) heating provides significant advantages over conventional heating, including reduced heating time, uniform heating, reduced quality losses, absence of solute migration in food material, versatile, simple, and compact equipment, and significant energy saving. Infrared heating can be applied to various food processing operations, namely, drying, baking, roasting, blanching, pasteurization, and sterilization. Infrared (IR) radiation heating has been considered as an alternative method for food and agricultural processing to improve product quality and safety, increase energy and processing efficiency and reduce water and chemical usage. Several novel IR based technologies have been developed recently by taking advantage of high heat transfer rate of IR radiation for blanching, dehydration and peeling of fruits and vegetables; production of healthy French fries; roasting and pasteurization of almonds and drying, disinfestation and enzyme inactivation of rice. It was found that IR heating achieved simultaneous blanching and dehydration eliminated the need for water or steam for blanching and reduced processing time and energy use. When IR is used for pasteurizing raw almonds, the treatment retains the characteristics of the raw commodity. IR heating also achieved simultaneous drying, disinfestation and partial enzyme inactivation of rough rice. The development and commercialization of IR-based food processing technologies should open new avenues to delivering safe and value-added foods desirable to consumers while reducing the consumption of natural resources during processing.*

## I.INTRODUCTION

Infrared (IR) radiation is one of the oldest ways to heat-treat foods. A traditional drying method for food products by exposure to intensive sunlight, it was aimed at reducing water activity and allowing longer periods of storage with minimal packaging requirements. It is known that IR radiation has some advantages over convective heating. Heat transfer coefficients are high, the process time is short, and the cost of energy is low. Since air is transparent to IR radiation, the process can be done at ambient air temperature. Equipment can be compact and automated with a high degree of control over process parameters (Nowak and Lewicki, 2004). Similar to other electromagnetic waves such as microwaves and radio frequencies, IR rays attain their unique radiative characteristics. 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. According to Jun and Irudayaraj (2004), 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 contents absorptivity decreases. From the food engineer's standpoint, it is very important to fully understand the above optic-thermal phenomena associated with IR and food products.

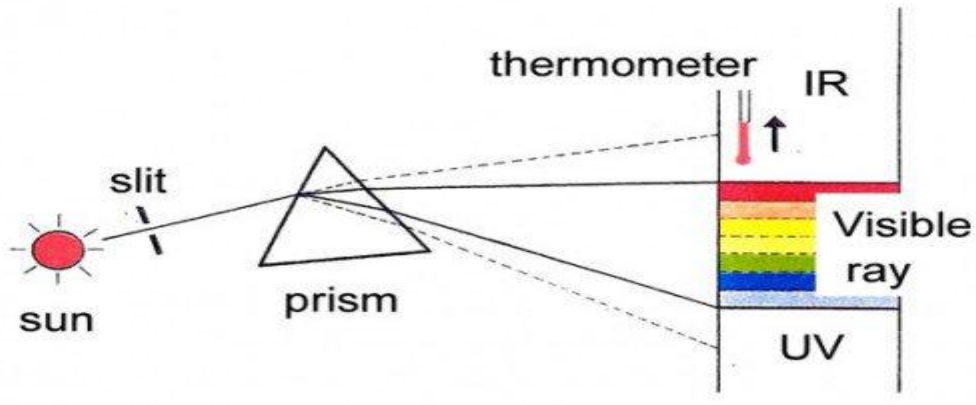
**Infrared radiation**, or simply **infrared** or **IR**, is electromagnetic radiation (EMR) with longer wavelengths than those of visible light, and is therefore invisible, although it is sometimes loosely called **infrared light**. It extends from the nominal red edge of the visible spectrum at 700 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.




The electromagnetic spectrum.

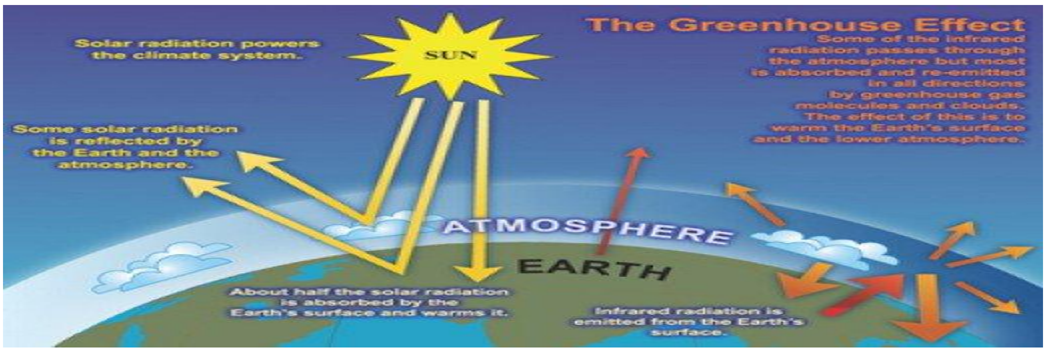
## II.DISCOVERY OF INFRARED RADIATION

Infrared radiation was discovered in 1800 by an English Astronomer called William Herschel. While Herschel was measuring the temperature of Sunlight that was split into a spectrum, he found that higher temperatures were felt beyond the visible red region of the spectrum, which he measured using a thermometer. So he confirmed that some invisible radiation existed beyond the red region of the spectrum that was responsible for this heat and he named it initially as "Calorific Rays." Calorific means "Heat generating." These were called infrared (*infra means below*) rays in the late $19^{th}$ century. Even though the wavelength of infrared radiation is higher than the visible red light, the frequency is lower than red, hence the name infrared.




## III.WHERE IS INFRARED FOUND?

Infrared red waves are emitted by all warm objects. They also heat up the objects on which they fall. When they fall on any substances, the molecules in the substances absorb this energy and get excited and as a result of this, the substance gets heated. A very good example is the earth. Earth gets heated up, due to the infrared radiation falling on it from the Sun.




## IV.HOW DOES INFRARED RADIATION WORK?

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 substances / objects, heat energy is released. This heat energy is not dependant on the temperature of the surroundings.

Examples of infrared radiation are, heat from the Sun, heat from fire, heat from radiator, etc.

In order to explain how infrared radiation works, the best example is the heating and cooling of the earth. During the day time when the Sun shines, the earth gets warm due to infrared radiation falling on it. In the night, after the Sun has gone down, the earth emits infrared radiation.

## V.WONDERS OF PHYSICS: INFRARED RADIATION

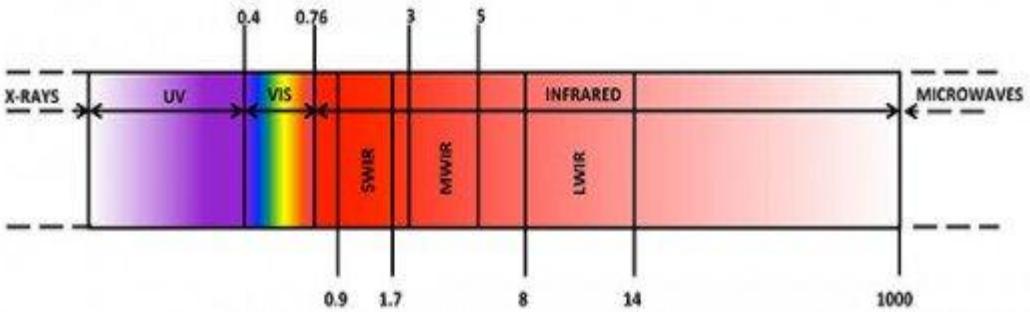
For example, on an extremely cold but sunny day, skiers, mountain climbers and people involved in similar activities or winter sports do not feel the cold because, they are heated up by the infrared radiation from the Sun and the infrared radiation reflected by the stones and other material in the environment. Heat energy is also emitted or released regardless of the surrounding temperature, when infrared rays fall on any surfaces or objects. So feeling warm or cold has got nothing to do with the temperature of the surrounding air, but it is to do with absorption of infrared radiation (*warming up*) or emission / releasing of infrared radiation (*cooling down when temperature around us is colder than our body temperature*).

Infrared rays travel through air and vacuum and they do not need a medium to travel through. They heat up any objects on which they fall and produce heat. For example surface of the earth, walls of the house, human body, etc.

The energy from the Sun that reaches the earth has a higher percentage of infrared radiation.

## VI.DIFFERENT REGIONS OF INFRARED

The infrared radiation is spread across a band (*spectrum*) of wavelengths (*0.75 micrometer to 1000 micrometers*) and hence it is divided into smaller sections. Sensors are very sensitive and do not detect all of these wavelengths and they will be built to sense a particular / small band of wavelengths. So infrared radiation of each region has different use or application. The different divisions of the infrared region are as follows and this is the most common subdivision scheme.




Different regions of the Infrared Source

- Near-infrared (NIR , IR-A) – This is the region near to the visible red region. This is used in fibre optic communication and night vision devices. It is also used in remote controls, astronomy, remote monitoring, material science, medical field and agriculture. The wavelength range is from 0.75 to 1.4 micrometers.

- Short wavelength infrared (SWIR, IR-B) – This is used for long distance telecommunications and the wavelength range is from 1.4 to 3 micrometers. It is also used in SWIR cameras, night vision goggles that play a major role for military purposes
- Mid wavelength infrared (MWIR, IR-C) – This is used in guided missile technology, infrared spectroscopy, communication, chemical industry, and the wavelength range is 3 to 8 micrometers. It also finds application in astronomy.
- Long wavelength infrared (LWIR, IR-C) – This is the thermal infrared region and is used to detect thermal emissions that require no illumination from other sources (thermal imaging). This finds extensive application in astronomical telescopes and optical fibre communication. The wavelength range of this division is 8 to 15 micrometers
- Far infrared (FIR) – These are used in infrared lasers, astronomy, infrared saunas and extensively used in the medical field and the wavelength range is 15 to 1000 micrometers. It also strengthens the immune system.

## PROPERTIES OF INFRARED RADIATION:

- Infrared radiation can travel in vacuum at the speed of light.
- Infrared radiation can travel through thick fog, thick smoke, dust and some other materials through which visible light cannot travel.
- Infrared radiation heats up objects on which they fall
- Infrared rays can be absorbed or reflected depending on the nature of the substance they fall on.
- Infrared has wavelength longer than visible light and shorter than microwaves.

## THE BASIC CONCEPTS OF INFRARED RADIATION ARE:

- High heat transfer capacity;
- Heat penetration directly into the product;
- Good possibilities for process control;
- No heating of surrounding air.

## VII.SOURCES OF INFRARED HEATING

Two conventional types of infrared radiators used for process heating are electric and gas-fired heaters. These 2 types of IR heaters generally fit into 3 temperature ranges : 343 to 1100 °C for gas and electric IR, and 1100 to 2200 °C for electric IR only. IR temperatures are typically used in the range of 650 to 1200 °C to prevent charring of products. The capital cost of gas heaters is higher, while the operating cost is cheaper than that of electric infrared systems. Electrical infrared heaters are popular because of installation controllability, ability to produce prompt heating rate, and cleaner form of heat. Electric infrared emitters also provide flexibility in producing the desired wavelength for a particular application. In general, the operating efficiency of an electric

IR heater ranges from 40% to 70%, while that of gas-fired IR heaters ranges from 30% to 50%. The spectral region suitable for industrial process heating ranges from 1.17 to 5.4 μm, which corresponds to 260 to 2200 °C (Sheridan and Shilton 1999).

Infrared radiation is transmitted through water at short wavelength, whereas at longer wavelengths it is absorbed at the surface (Sakai and Hanzawa 1994). Hence, drying of thin layers seems to be more efficient at the FIR region, while drying of thicker bodies should give better results at the NIR region. Sakai and Hanzawa (1994) have discussed the effects of the radiant characteristics of heaters on the crust formation and color development at the surfaces of foods such as white bread and wheat flour. Radiant heating with an NIR heater led to a greater heat sink into food samples, resulting in formation of relatively wet crust layers, compared to dry layers formed by FIR heaters. However, the rate of color development by FIR heaters was greater with NIR heaters, primarily due to a more rapid heating rate on the surface.

Sheridan and Shilton (1999) evaluated the efficacy of cooking hamburger patties using infrared sources at $\lambda_{max}$ of 2.7 μm (MIR) and at $\lambda_{max}$ of 4.0 μm (FIR). With a higher energy source (MIR), change in core temperature followed closely the change in surface temperature with a shorter cooking time. Fat content of the food was found to be independent of core temperature. However, with the lower energy source (FIR), the increasing rate of core temperature was dependent on the fat content, showing that targeted core temperature was achieved more quickly as fat content increased.

Hashimoto and others (1990, 1994) studied the penetration of FIR energy into sweet potato and found that FIR radiation absorbed by the vegetable model was damped to 1% of the initial values at a depth of 0.26 to 0.36 mm below the surface, whereas NIR showed a similar reduction at a depth of 0.38 to 2.54 mm. Sakai and Hanzawa (1994) reported the penetration depth of the FIR energy did not affect the temperature distribution inside the food. Further, they indicated that FIR energy penetrates very little, almost all the energy being converted to heat at the surface of the food, which was consistent with the study of Hashimoto and others (1993) evaluating FIR heating technique as a surface heating method.

## VIII.SELECTIVE HEATING BY INFRARED RADIATION

Most infrared heaters consist of lamps emitting the spectrum with 1 specific peak wavelength corresponding to a fixed surface temperature. The type of infrared emitter and control of the accurate wavelength should be considered for optimization of the process. In practice, the IR source emits radiation covering a very wide range. Hence, it is a challenge to cut off the entire spectral distribution to obtain a specific bandwidth.

In the context of food processing, wavelengths above 4.2 μm are most desirable for an optimal IR process of food system due to predominant energy absorption of water in the wavelengths below 4.2 μm (Alden 1992). Lentz and others (1995) discussed the importance of IR-emitting wavelength for thermal processing of dough. Excessive heating of the dough surface and poor heating of the interior was observed when the IR spectral emission was not consistent with the wavelengths best absorbed for dough. Excessive surface heating, in the absence of corresponding heat removal to the interior, gave rise to crust formation, thus inhibiting heat transfer.

From the earliest, Shuman and Staley (1950) discussed that orange juice has a minimum absorption at the range between 3 and 4 µm, whereas dried orange solids have a maximum absorption at the same region. When using an IR source with the maximum peak at wavelength of 4 µm, the radiation energy was not properly absorbed by orange juice; however, dried orange solids could absorb IR energy predominantly. Hence, the IR source was controlled to emit the spectral ranges between 5 and 7 µm to obtain desirable absorption of orange juice. Their work clearly shows the importance of spectral control of the IR source to manipulate the delivery of heat amounts to specific food materials.

A study by Bolshakov and others (1976) suggested that a maximum transmission of IR radiation should cover the spectral wavelength of 1.2 µm obtained by analysis of the transmittance spectrograms of lean pork for deep heating of pork. A 2-stage frying process they designed consisted of the 1st stage to aim surface heat transfer by radiant flux with $\lambda_{max}$ of 3.5 to 3.8 µm (FIR) and the 2nd stage for greater penetration of heat transfer by radiant flux with a $\lambda_{max}$ of 1.04 µm (NIR). Higher moisture content and sensory quality of the products was obtained using combined FIR and NIR heaters compared to the conventional method. A similar study explored by Dagerskog (1979) used 2 alternative types of infrared radiators for frying equipment, which were quartz tube heaters (Philips 1kW, type 13195X) whose filament temperature was 2340 °C at 220 V rating, corresponding to $\lambda_{max}$ of 1.24 µm as NIR region, and tubular metallic electric heaters (Backer 500W, type 9N5.5) at a temperature of 680 °C at 220 V, corresponding to $\lambda_{max}$ of 3.0 µm as FIR region. It was observed from the study that both penetration capacity and reflection increased as the wavelength of the radiation decreased, indicating that although the short-wave radiation (NIR) had a higher penetrating capability than the long-wave radiation (FIR), the heating effects were almost the same due to body reflection.

Recently, Jun (2002) developed a novel selective FIR heating system, demonstrating the importance of optical properties besides thermal properties when electromagnetic radiation is used for processing. The system had the capability to selectively heat higher absorbing components to a greater extent using optical band pass filters that can emit radiation in the spectral ranges as needed.

## IX.INTERACTION OF IR RADIATION EITH FOOD COMPONENTS

The effect of IR radiation on optical and physical properties of food materials is crucial for the design of an infrared heating system and optimization of a thermal process of food components. The infrared spectra of such mixtures originate with the mechanical vibrations of molecules or particular molecular aggregates within a very complex phenomenon in overlapping (Halford 1957). When radiant electromagnetic energy impinges upon a food surface, it may induce changes in the electronic, vibrational, and rotational states of atoms and molecules. As food is exposed to infrared radiation, it is absorbed, reflected, or scattered (a blackbody does not reflect or scatter), as shown in Figure 1.

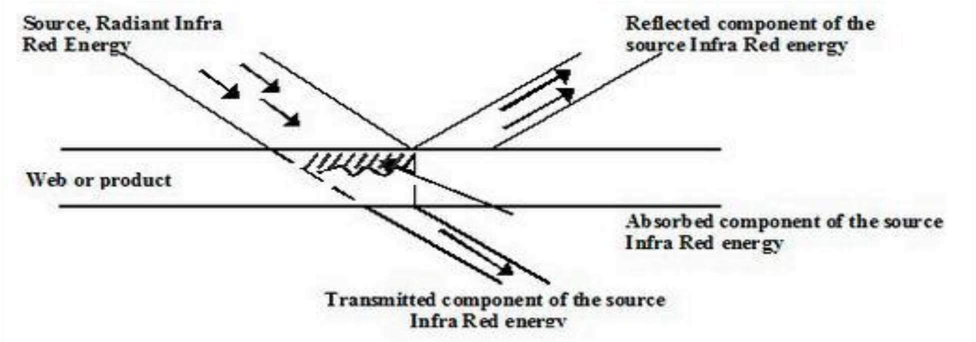



Figure 1. Schematic diagram of radiations falling on object surface.

The type of mechanisms for energy absorption determined by the wavelength range of the incident radiative energy can be categorized as:

(1) changes in the electronic state corresponding to the wavelength range 0.2 to 0.7µm (ultraviolet and visible rays),
(2) changes in the vibrational state corresponding to wavelength range 2.5 to 1000µm (FIR), and
(3) changes in the rotational state corresponding to wavelengths above 1000µm (microwaves) (Decareau 1985).

In general, the food substances absorb FIR energy most efficiently through the mechanism of changes in the molecular vibrational state, which can lead to radiative heating. Water and organic compounds such as proteins and starches, which are the main components of food, absorb FIR energy at wavelengths greater than 2.5µm (Sakai and Hanzawa 1994). Sandu (1986) reported that most foods have high transmissivities (low absorptivities) smaller than 2.5µm. Due to a lack of information, data on absorption of infrared radiation by the principal food constituents can be regarded as approximate values. For body reflection, the light enters the material, becomes diffuse due to light scattering, and undergoes some absorption; and the remaining light leaves the material close to where it enters. Regular reflection produces only the gloss or shine of polished surfaces, whereas body reflection produces the colors and patterns that constitute most of the information obtained visually. For materials with a rough surface, both regular and body reflection can be observed. For instance, at NIR wavelength region ($\lambda$<1.25µm), approximately 50% of the radiation is reflected back, while less than 10% radiation is reflected back at the FIR wavelength region (Skjoldebrand 2001).
Most organic materials reflect 4% of the total reflection producing a shine of polished surfaces. The rest of the reflection occurs where radiation enters the food material and scatters, producing different color and patterns (Dagerskog 1979).

## X.BASIC LAWS OF RADIATION

IR radiation is the part of the electromagnetic spectrum that is predominantly responsible for the heating effect of the sun. IR radiation can be divided into three different categories: near-IR (NIR), mid-IR radiation (MIR), and far-IR radiation (FIR; Sakai and Hanzawa, 1994). Since IR radiation is an electromagnetic wave, it has both a spectral and directional dependence. Spectral dependence of IR heating needs to be considered because energy coming out of an emitter is composed of different wavelengths, and the fraction of the radiation in each band is dependent on a number of factors such as the temperature of the emitter, emissivity of the lamp, etc. Radiation phenomena become more complicated because the amount of radiation that is incident on any surface does not have only a spectral dependence but also a directional dependence. The wavelength at which the maximum radiation occurs is determined by the temperature of the heater. This relationship is described by the basic laws for blackbody radiation, such as Stefan–Boltzmann's law, Wien's displacement law, Planck's law, and Kirchhoff's law (Sakai and Hanzawa, 1994; Dangerskog and Österström, 1979).

## 1. STEFAN–BBOLTZMANN LAW

It describes the power radiated from a black body in terms of its temperature. Specifically, the Stefan–Boltzmann law states that the total energy radiated per unit surface area of a black body across all wavelengths per unit time (also known as the black-body *radiant emittance* or *radiant exitance*), 'q', is directly proportional to the fourth power of the black body's thermodynamic temperature *T*:

$$q=\delta T^4$$

The constant of proportionality σ, called the Stefan–Boltzmann constant derives from other known constants of nature. The value of the constant is

$$\sigma = \frac{2\pi^5 k^4}{15c^2 h^3} = 5.670373 \times 10^{-8}\,\mathrm{W\,m^{-2}K^{-4}},$$

where k is the Boltzmann constant, h is Planck's constant, and c is the speed of light in a vacuum.

## 2.WIEN'S DISPLACEMENT LAW

It states that the black body radiation curve for different temperatures peaks at a wavelength inversely proportional to the temperature. The shift of that peak is a direct consequence of the Planck radiation law, which describes the spectral brightness of black body radiation as a function of wavelength at any given temperature. However, it had been discovered by Wilhelm Wien several years before Max Planck developed that more general equation, and describes the entire shift of the spectrum of black body radiation toward shorter wavelengths as temperature increases.

Formally, Wien's displacement law states that the spectral radiance of black body radiation per unit wavelength, peaks at the wavelength $\lambda_{max}$ given by:

$$\lambda_{\max} = \frac{b}{T}$$

where $T$ is the absolute temperature in kelvins. $b$ is a constant of proportionality called *Wien's displacement constant*, equal to $2.8977729(17)\times10^{-3}$ m·K, or more conveniently to obtain wavelength in micrometers, $b \approx 2900$ μm·K.

**3. PLANCK'S LAW**

It describes the spectral density of electromagnetic radiation emitted by a black body in thermal equilibrium at a given temperature $T$. The law is named after Max Planck, who proposed it in 1900. It is a pioneering result of modern physics and quantum theory.

The spectral radiance of a body, $B_\nu$, describes the amount of energy it gives off as radiation of different frequencies. It is measured in terms of the power emitted per unit area of the body, per unit solid angle that the radiation is measured over, per unit frequency. Planck showed that the spectral radiance of a body for frequency $\nu$ at absolute temperature $T$ is given by:

$$B_\nu(\nu, T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{k_B T}} - 1}$$

where $k_B$ the Boltzmann constant, $h$ the Planck constant, and $c$ the speed of light in the medium, whether material or vacuum.

**4. KIRCHOFF'S LAW:**

In heat transfer, **Kirchhoff's law of thermal radiation** refers to wavelength-specific radiative emission and absorption by a material body in thermodynamic equilibrium, including radiative exchange equilibrium.

or

*For an arbitrary body emitting and absorbing thermal radiation in thermodynamic equilibrium, the emissivity is equal to the absorptivity.*

$$\alpha_\lambda = \epsilon_\lambda$$

Where α = *absorptivity and* ε = *emissivity.*

## XI.THE MOST POPULAR INDUSTRIAL APPLICATIONS (FOR NON-FOOD USES) OF IR RADIATIONS

The most popular industrial applications (for non-food uses) are in the rapid drying of automobile paint and drying in the paper and pulp industry. For paper drying IR has superseded microwaves because it offers superior process control and economy. IR technology has long been underestimated in the food field, despite its great potential. Most applications of IR within the area of food came during the 1950s to 1970s from the USA, the

USSR and the eastern European countries. During the 1970s and 1980s SIK did a lot of basic work applying this technique within the area of food. In later years work was carried out in Japan, Taiwan and other countries.

## APPLICATIONS OF IR RADIATIONS IN FOOD PROCESSINGARE MAINLY IN THE FOLLOWING AREAS:

- Pasteurization,
- Baking, cooking, blanching and roasting,
- Thawing,
- Drying and dehydration
- Enzyme inactivation
- Pathogen inactivation

## 1.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 $W/m^2$-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). 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) developed an IR pasteurization process for inactivation of Listeria monocytogenes on hot dogs.

## 2. BAKING, COOKING, BLANCHING, AND ROASTING

As an industrial process, IR heating, using IR ovens, was reported by Dagerskog (1979), and many examples of baking, cooking, blanching, and roasting using IR energy can be found in the literature. Wade (1987) used quartz-tungsten tubes emitting radiation of peak wavelength of 1.2 μm to bake biscuits, and it was found that a wide range of biscuit products (crackers, semisweet, and short dough types) could be baked using IR heating in

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approximately half the time required in a conventional oven. Skjoldebrand and Anderson (1989) used IR heating as a bread-baking method and reported the advantages of higher heat transfer efficiency, reduction in baking time to attain a desired quality, and rapid control of oven parameters. Khan and Vandermey (1985) investigated the quality assessment of ground beef patties after IR processing in a tube broiler used for food service. 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) reported the use of FIR heating to make boiling eggs without requiring the use of hot water. Cenkowski and Sosulski (1997) investigated the effects of IR heating on physical and cooking properties of lentils. It was determined that the IR heating was effective in gelatinization and solubilization of starch, leading to reduced cooking times. Cenkowski and Sosulski (1998) determined the effects of high-intensity IR heating on water hydration rate and cooking time of Infrared Heating for Food and Agricultural Processing split peas and the changes in functional properties of the protein and starch. 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. Pan et al. (2005) evaluated the feasibility of MIR and FIR for blanching and dehydration of various fruits and vegetables. They determined IR radiation to be an effective method for dry-blanching of fruits and vegetables with high processing efficiency and significant processing time saving, leading to high-quality products without using any steam or water. Khir et al. (2006, 2007) studied the moisture removal characteristics of thin-layer rough rice heated by IR heating and cooled by natural and forced air. It was concluded that higher heating rates, faster drying, and better rice quality could be achieved by heating rough rice to about 60°C followed by tempering and slow cooling.

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.

## 3. THAWING

The quality of frozen products has been improved significantly with advancements in freezing technologies. With notable exceptions such as ice cream, most frozen foods must be thawed before further use or consumption, and the quality might deteriorate during thawing. In a number of food-manufacturing operations, it is a common practice to begin with frozen foods as a raw material. For example, in manufacturing sausages, frozen meat is used as the raw material. Similarly, large blocks of frozen fish are processed into fillets for further processing. Different thawing and tempering methods are used for preparing frozen foods for further processing, and each has its own advantages and disadvantages. The main goal of the thawing processes is to keep thawing time to a minimum so that the least damage is caused to the quality of the food product. However, during thawing, a number of quality attributes may be adversely affected by moisture (drip) loss, change in structure of proteins, microbial growth, and textural changes.

Microwave thawing is one possible method to reduce thawing time, but, due to the significant differences in the dielectric properties of frozen and unfrozen food products, runaway heating or overheating near the surface might occur.

In the IR region, the absorption coefficients of ice and water are approximately same (Sakai and Mao, 2005), and this prevents runaway heating, making IR heating a possible thawing method. Sakai and Mao (2005) refer to the studies found in the literature for thawing tuna using FIR heating without drip losses and discoloration, where commercial thawing equipments and a refrigerator with a partial defrosting system using IR energy were developed. Evolution of surface temperature due to absorption of IR energy is a significant parameter to control in thawing using IR energy. Liu et al. (1999) investigated the FIR thawing conditions on the temperature distribution of frozen tuna during thawing.

## 4. DRYING AND DEHYDRATION

Infrared heating provides an imperative place in drying technology and extensive research work has been conducted in this area. Most dried vegetable products are prepared conventionally using a hot-air dryer. However, 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). The use of IR radiation technology for dehydrating foods has numerous advantages including reduction in drying time, alternate energy source, increased energy efficiency, 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 (Dostie and others 1989; Navari and others 1992; Sakai and Hanzawa 1994; Mongpreneet and others 2002). Therefore, FIR drying operations have been successfully applied in recent years for drying of fruit and vegetable products such as potatoes (Masamura and others 1988; Afzal and Abe 1998), sweetpotatoes (Sawai and others 2004), onions (Mongpreneet and others 2002; Sharma and others 2005), kiwifruit (Fenton and Kennedy 1998), and apples (Nowak and Levicki 2004; Togrul 2005). Drying of seaweed, vegetables, 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 (Hagen and Drawert 1986; Anonymous 1995). 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 (Lampinen and others 1991). 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.

## 5. ENZYME INACTIVATION

Infrared heating can be effectively used for enzyme inactivation. Lipooxygenase, an enzyme responsible for deterioration in soybeans, was inactivated 95.5% within 60 s of IR treatment (Kouzeh and others 1982). Certain enzyme reactions (involving action of lipases and α amylases) were affected by infrared radiation at a bulk temperature of 30 to 40 °C (Kohashi and others 1993; Rosenthal and others 1996; Sawai and others 2003). 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 (van Zuilichem and others 1986), as well as other enzymes and bacteria in solution (Sawai and others 2003). Galindo and others (2005) 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.

## 6. PATHOGEN INACTIVATION

IR heating can be used to inactivate bacteria, spores, yeast, and mold in both liquid and solid foods. Efficacy of microbial inactivation by infrared heating depends on the following parameters: infrared power level, temperature of food sample, peak wavelength, and bandwidth of infrared heating source, sample depth, types of microorganisms, moisture content, physiological phase of M/Os (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 and others (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 $\log_{10}$ CFU/g total bacteria after a 60 s treatment, respectively.

***Temperature of food sample:*** Dry heat inactivation of *B. subtilis* spores by infrared radiation was investigated by Molin and Ostlund (1975). *D* values of *B. subtilis* at 120, 140, 160, and 180 °C were 26 min, 66, 9.3, and 3.2 s, respectively. Shorter treatment time was enough to inactivate pathogens at higher temperatures and the estimated *Z* value was 23 °C. *E. coli* population was reduced by 0.76, 0.90, and 0.98 $\log_{10}$ after 2 min exposure to IR radiation when the temperature of the bacterial suspension was maintained at 56, 58, and 61 °C, correspondingly (Sawai and others 2003).

***Types of M/Os:*** 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. Hamanaka and others (2006) also reported a shoulder effect where *B. subtilis* spores were germinated.

Cereal surface is often contaminated with spore formers like *Bacillus*, *Aspergillus*, and *Penicillium.* Wheat was treated with infrared heating at 2.0 kW for 30 s, followed by cooling for 4 h, and again treated for 30 s with infrared heating to obtain a 1.56 $\log_{10}$ CFU/g reduction. Naturally occurring yeasts in honey were completely inactivated with an 8-min infrared heat treatment (Hebbar and others 2003). 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 M/Os readily absorb infrared radiation. These water molecules are attached to polar groups such as $-NH_2$, -COOH, and -COO within the cell (Uedaira and Ohsaka 1990; 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 and others 2006). Maximum D values of *B. subtilis* spores inactivated by IR heat differed with initial water activities ranging from 0.6 to 0.9.

***Types of food materials:*** As described earlier, IR radiation has a poor penetration capacity. However, the surface temperature of food materials increases rapidly and heat is transferred inside food materials by thermal conduction. Typical thermal conductivities of solid foods are much lower than liquid foods. Convective heat transfer to occur inside liquid foods under IR heating can contribute to an increase in the lethality of microbes.

## XII.QUALITY AND SENSORY CHANGES BY IR HEATING

It is crucial and beneficial to investigate the quality and sensory changes occurring during IR heat treatment for commercial success. Several researchers have studied the quality and sensory changes of food materials during IR heating.

Application of infrared radiation in a stepwise manner by slowly increasing the power, with short cooling between power levels, resulted in less color degradation than with intermittent infrared heating (Chua and Chou 2005). Reductions in overall color change of 37.6 and 18.1% were obtained for potato and carrot, respectively. The quality of beef produced by infrared dehydration was similar to that of conventional heating as indicated by surface appearance and taste tests (Burgheimer and others 1971). Longer infrared heat treatments may darken the color of onion due to browning (Gabel and others 2006).

Hebbar and others (2003) suggested that 3 to 4 min infrared heat treatment was adequate for commercially acceptable products, with reduction in yeast cells and acceptable changes in hydroxymethylfurfural and diastase activity. Infrared heating raised the internal temperature of the strawberries not above 50 °C, while the surface temperature was high enough to effectively inactivate microorganisms. Therefore, infrared heating can be used for surface pasteurization of pathogens without deteriorating the food quality (Tanaka and others 2007).

IR heat-treated lentils were found to be darker than raw lentils, though there was no visible indication (Arntfield and others 2001). Cell walls of lentils were less susceptible to fracture after infrared heat treatment, in addition to having a more open microstructure, thus enhancing the rehydration characteristics (Arntfield and others 2001).

Sensory evaluation of ground beef patties treated by infrared heating and gas broiling in terms of flavor, texture, juiciness, and overall acceptability showed no significant difference between the 2 treatments (Khan and Vandermey 1985). However, the appearance of gas-broiled patties was rated higher than infrared heating, as seen by the scores of 10.94 and 9.62 for gas broiling and IR heating, respectively. Pungency of onions following infrared radiation decreased with reduction in moisture (Gabel and others 2006). Infrared heating of carrots provided less damage to the tissue than blanching, as observed by lower relative electrolyte leakage values and microscopic observations (Galindo and others 2005). Furthermore, infrared-treated carrots had higher tissue strength while effectively inactivating the enzymes on carrot surface.

Although infrared heat-treated turkey samples were slightly darker than the controls after treatments, refrigerated storage for an hour resulted in no significant difference in color values as measured by $L^*$, $a^*$, and $b^*$ values (Huang 2004). Bitterness and protein solubility of peas were reduced after IR heat treatment (McCurdy 1992). Head rice yield was improved by infrared heating and the whiteness of the rice was maintained (Meeso and others 2004).

Chlorophyll content of dehydrated onions treated by infrared increased with an increase in irradiation power (Mongpreneet and others 2002). Infrared heating provided a more appealing brown color and roasted appearance to deli turkey, in addition to effectively pasteurizing the surface (Muriana and others 2004). Infrared heating and jet impingement of bread resulted in rapid drying and enhanced color development, compared to conventional heat treatment (Olsson and others 2005). Though the thickness of bread crust increased faster, a short IR treatment time enabled the formation of thinner crust.

## XIII.CONCLUSION

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.

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