COMPREHENSIVE
REVIEWS
IN FOOD SCIENCE AND FOOD SAFETY

Infrared Heating in Food Processing: An Overview

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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. Combinations of IR heating with microwave heating and other common conductive and convective modes of heating have been gaining momentum because of increased energy throughput. This article reviews aspects of IR heating and presents a theoretical basis for IR heat processing of food materials and the interaction of IR radiation with food components. The effect of IR on food quality attributes is discussed in the context of samples and process parameters. Applications of IR heating in food processing operations and future research potential are also reviewed.

Introduction

Energy conservation is one of the key factors determining profitability and success of any unit operation. Heat transfer occurs through one of 3 methods, conduction, convection, and radiation. Foods and biological materials are heated primarily to extend their shelf life or to enhance taste. In conventional heating, which is achieved by combustion of fuels or by an electric resistive heater, heat is generated outside of the object to be heated and is conveyed to the material by convection of hot air or by thermal conduction. By exposing an object to infrared (IR) radiation (wavelength of 0.78 to 1000 μm), the heat energy generated can be absorbed by food materials. Along with microwave, radiofrequency (RF), and induction, IR radiation transfers thermal energy in the form of electromagnetic (EM) waves and encompasses that portion of the EM spectrum that borders on visible light and microwaves (Figure 1). Certain characteristics of IR heating such as efficiency, wavelength, and reflectivity set it apart from and make it more effective for some applications than others. IR heating is also gaining popularity because of its higher thermal efficiency and fast heating rate/response time in comparison to conventional heating. Recently, IR radiation has been widely applied to various thermal processing operations in the food industry such as dehydration, frying, and pasteurization (Sakai and Hanzawa 1994).

Food systems are complex mixtures of different biochemical molecules, biological polymers, inorganic salts, and water. The infrared spectra of such mixtures originate with the mechanical vibrations of molecules or particular molecular aggregates within a very complex phenomenon of reciprocal overlapping (Halford 1957). Amino acids, polypeptides, and proteins reveal 2 strong absorption bands localized at 3 to 4 and 6 to 9 μm. On the other hand, lipids show strong absorption phenomena over the entire infrared radiation spectrum with 3 stronger absorption bands situated at 3 to 4, 6, and 9 to 10 μm, whereas carbohydrates yield 2 strong absorption bands centered at 3 and 7 to 10 μm (Sandu 1986; Rosenthal 1992).

IR radiation can be classified into 3 regions, namely, near-infrared (NIR), mid-infrared (MIR), and far-infrared (FIR), corresponding to the spectral ranges of 0.75 to 1.4, 1.4 to 3, and 3 to 1000 μm, respectively (Sakai and Hanzawa 1994). In general, FIR radiation is advantageous for food processing because most food components absorb radiative energy in the FIR region (Sandu 1986).

Over the past several years, IR heating has been predominantly applied in the electronics and allied fields with little practical application in the food processing industry. However, in the last few years significant research efforts have been made in the area of IR heating of foods. The present review is in line with the current developments in the area of IR heating and a base for its widespread upcoming practical applications in food processing. Therefore, the aim of this review is to evaluate existing knowledge in the area of IR heating, provide insight for the relation between product properties and engineering processes, and present an up-to-date view on further research. Along with the sound theoretical background on IR heating, the review also encompasses application of IR heating in food processing operations such as drying, dehydration, blanching, thawing, pasteurization, sterilization, and other miscellaneous food applications such as

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roasting, frying, broiling, and cooking, as well as in-depth assessment of pathogen inactivation. The effect of IR heating on sensory, physicochemical, nutritional, and microstructural quality of foods and its comparison with other existing common methods of heating such as convection and microwave heating are discussed as well.

Basic laws of infrared radiation

The amount of the IR radiation that is incident on any surface has a spectral dependence because energy coming out of an emitter is composed of different wavelengths and the fraction of the radiation in each band, dependent upon the temperature and emissivity of the emitter. The wavelength at which the maximum radiation occurs is determined by the temperature of the IR heating elements. This relationship is described by the basic laws for blackbody radiation such as Planck's law, Wien's displacement law, and Stefan–Boltzman's law, as summarized in Table 1 (Dagerskog and Österström 1979; Sakai and Hanzawa 1994).

Interaction of IR radiation with 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 2. Absorption intensities at different wavelengths differ by food components. 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 0.7 μm (ultraviolet and visible rays), (2) changes in the vibrational state corresponding to wavelength range 2.5 to 1000 μm (FIR), and (3) changes in the rotational state corresponding to wavelengths above 1000 μm (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 2.5 μm (Sakai and Hanzawa 1994). Sandu (1986) reported that most foods have high transmissivities (low absorptivities) smaller than 2.5 μm.

Due to a lack of information, data on absorption of infrared radiation by the principal food constituents can be regarded as approximate values. The key absorption ranges of food components are as visualized in Figure 3 (Sandu 1986). It depicts the principal absorption bands of the major food components compared to the absorption spectrum of water, indicating that the absorption spectra of food components overlap with one another in the spectral regions considered. Water effect on absorption of incident radiation is predominant over all the wavelengths, suggesting that selective heating based on distinct absorptivities for

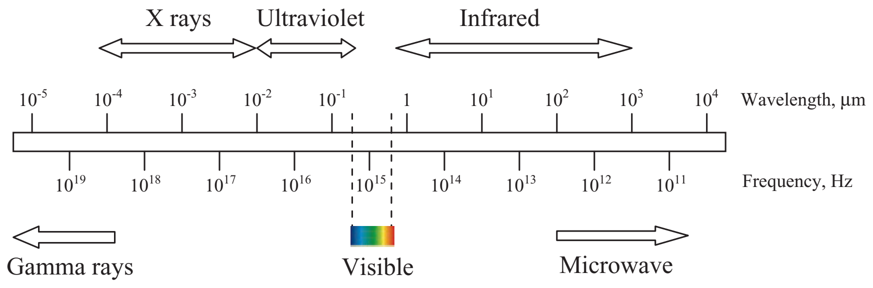

Figure 1 — Electromagnetic wave spectrum.

Table 1 — Basic laws pertaining to infrared radiation.

Basic laws	Aspects addressed/explanation
Planck's law $E_{b\lambda}(T,\lambda) = \dfrac{2\pi h c_0^2}{n^2\lambda^5[e^{hc_0/n\lambda kT} - 1]}$	Gives spectral blackbody emissive power distribution $E_{b\lambda}(T, \lambda)$
Wien's displacement law $\lambda_{\max} = \dfrac{2898}{T}$	Gives the peak wavelength ($\lambda_{\max}$), where spectral distribution of radiation emitted by a blackbody reaches maximum emissive power
Stefan–Boltzmann's law $E_b(T) = n^2\,\sigma T^4$	Gives the total power radiated ($E_b(T)$) at a specific temperature from an infrared source
Modified Beer's law $H_\lambda = H_{\lambda 0}\exp(-\sigma_\lambda^* u)$	Gives the transmitted spectral irradiance (H_λ W/m$^2\cdot\mu$m) in nonhomogeneous systems
$\rho + \alpha + \tau = 1$	Reflectivity (ρ): ratio of reflected part of incoming radiation to the total incoming radiation, absorptivity (α): ratio of absorbed part of incoming radiation to the total incoming radiation, and transmissivity (τ): ratio of transmitted part of incoming radiation to the total incoming radiation (Figure 2)

k: Boltzmann's constant (1.3806 × 10^{-23} J/K), n: refractive index of the medium (n for vacuum is 1 and, for most gases, n is very close to unity), λ: the wavelength (μm), T: source temperature (K), c_0: speed of light (km/s), h: Planck's constant (6.626 × 10^{-34} J·s), σ: Stefan–Boltzmann constant (5.670 × 10^{-8} $\frac{W}{m^2 K^4}$), $\lambda_{\max}$: peak wavelength, $H_{\lambda o}$: incident spectral irradiance (W/m$^2\cdot\mu$m), u: mass of absorbing medium per unit area (kg/m^2) and σ_λ^*: spectral extinction coefficient (m^2/kg).

a target food material can be more effective when predominant energy absorption of water is eliminated. The infrared absorption bands for chemical groups and relevant food components are summarized in Table 2 (Rosenthal 1992).

Interactions of light with food material and the crucial optical principles such as regular reflection, body reflection, and light scattering were discussed by Birth (1978). Regular reflection takes place at the surface of a material. 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 ($\lambda < 1.25$ μm), 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).

The infrared optical characteristics of different media are also theoretically discussed demonstrating the necessity of the scattered radiation during measurements (Krust and others 1962). It was experimentally observed that as the thickness of the layer increases, a simultaneous decrease in transmittance and increase in reflection occurs. However, no theoretical explanation of this phenomenon was presented.

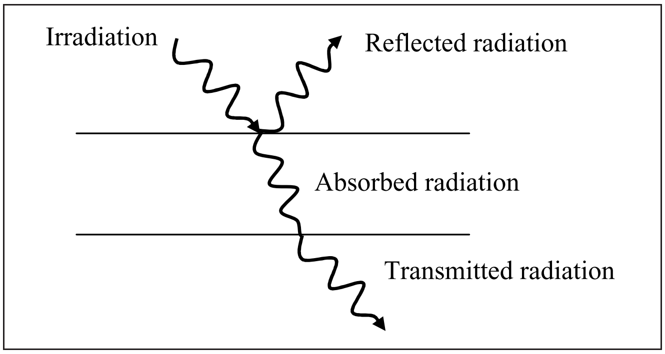

Figure 2—Extinction of radiation (absorption, transmission, and reflection).

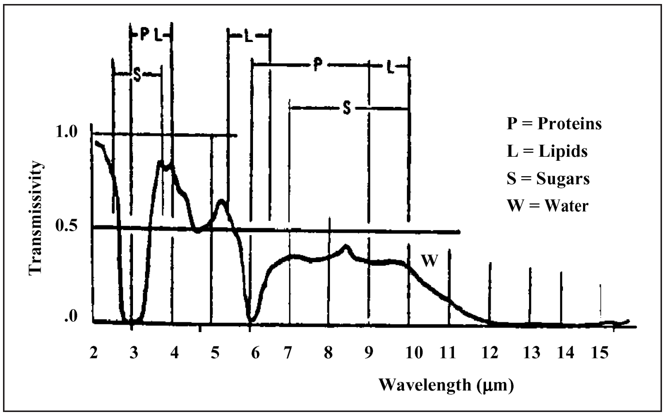

Figure 3—Principal absorption bands of the main food components compared with water (Sandu 1986).

Applications of IR heating in food processing operations

The application of infrared radiation to food processing has gained momentum due to its inherent advantages over the conventional heating systems. Infrared heating has been applied in drying, baking, roasting, blanching, pasteurization, and sterilization of food products.

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.

Factors affecting IR drying kinetics have been studied by several researchers. Masamura and others (1988) confirmed increased

Table 2—The infrared absorption bands for chemical groups and relevant food components (Rosenthal 1992).

Chemical group	Absorption wavelength (μm)	Relevant food component
Hydroxyl group (O-H)	2.7 to 3.3	Water, sugars
Aliphatic carbon-hydrogen bond	3.25 to 3.7	Lipids, sugars, proteins
Carbonyl group (C=O) (ester)	5.71 to 5.76	Lipids
Carbonyl group (C=O) (amide)	5.92	Proteins
Nitrogen–hydrogen group (-NH-)	2.83 to 3.33	Proteins
Carbon–carbon double bond (C=C)	4.44 to 4.76	Unsaturated lipids

drying rates of potatoes with increasing surface temperature of the radiator. Optimization of the FIR heating process for shrimp dehydration found that the effect of plate distance on the drying rate was not significant, whereas the drying rate increased monotonically with an increase in the plate and air temperature (Fu and Lien 1998). Nowak and Levicki (2004) reported that infrared drying of apple slices was an effective and much faster method of water removal than convective drying under equivalent parameters. Exploring the IR convective drying of onion slices, Sharma and others (2005) observed that the drying time increased with the increase in air velocity at all infrared powers applied; however, it reduced with an increase in infrared power and the drying took place in the falling drying rate period.

Integrated drying technologies: IR and convective drying. Even though 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, but its penetrating powers are limited (Hashimoto and others 1990; Sakai and others 1993). Prolonged exposure of a biological material to IR heat results in swelling and ultimately fracturing of the material (Jones 1992). Fasina and others (1996) showed that IR heating changes the physical, mechanical, chemical, and functional properties of barley grains. IR heating of legume seeds to 140 °C caused cracking on the surface (Fasina and others 1997). However, a combination of intermittent infrared heating and continuous convection drying of thick porous material resulted in better product quality and energy efficiency (Dostie and others 1989). Thus, IR radiation can be considered as surface treatment similar to other radiation technologies.

Application of combined electromagnetic radiation and conventional convective heating is considered to be more efficient over radiation or convective heating alone, as it gives a synergistic effect. Afzal and others (1999) reported that during the combined convective and IR heating process of barley, the total energy required was reduced by about 156%, 238%, and 245% as compared with convection drying alone at 40, 55, or 70 °C, respectively. Datta and Ni (2002) discussed the application of combined infrared, microwave, and hot air heating food materials. Mongpreneet and others (2002) evaluated the dehydrating synergy generated when using ceramic-coated radiators and a high-vacuum environment to study drying of welsh onion.

Development of a continuous drying apparatus equipped with FIR heaters, NIR heaters, and hot air blast can reduce the economic costs, drying time, and operating temperature. However, vegetable size should be restricted to no more than 5 mm in thickness to improve drying efficiency (Sakai and Hanzawa 1994). Hebbar and others (2004) developed a continuous combined infrared and convective dryer for vegetables. The synergistic effect of infrared and hot air led to rapid heating of the materials, resulting in a higher rate of mass transfer. The evaporation of water took 48% less time and 63% less energy consumption in combined mode drying as compared to convective drying.

Recently, the concept of FIR heating immediately after convective drying (approximately 40 °C) for drying of paddy has been utilized in the paddy industry in Japan (Bekki 1991; Inst. of Agricultural Machinery 2003). Gabel and others (2006) compared the drying and quality characteristics of sliced high-solids onions dried with catalytic infrared (CIR) heating and forced air convection (FAC) heating. CIR both with and without air recirculation had higher maximum drying rates, shorter drying times, and greater drying constants than FAC at moisture contents greater than 50% (d.b.).

A combination of IR heating with freeze-drying in sweetpotatoes could reduce the processing time by less than half (Lin and others 2005). The effect of NIR on reduction of freeze-drying time of beef was investigated by Burgheimer and others (1971). The authors concluded that shorter wavelength resulted in rapid drying and thus reduced drying time. Drying time with infrared heating was reduced to 7 h, as opposed to 11 h with convectional drying.

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.

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).

Effect of peak wavelength and bandwidth: As indicated earlier, food and microbial components absorb certain wavelengths of infrared radiation. Therefore, it is beneficial to investigate the absorption pattern of key components in order to ensure pathogen inactivation and minimize changes in food quality. It would be feasible to selectively heat the M/Os present in food products without adversely increasing the temperature of sensitive food components. Jun and Irudayaraj (2003) utilized selective infrared heating in the wavelength range of 5.88 to 6.66 μm using optical bandpass filters for inactivation of *Aspergillus niger* and *Fusar-*

ium proliferatum in corn meal. The selected wavelength denatures the protein in microorganisms, leading to a 40% increase in inactivation of *A. niger* and *F. proliferatum* compared to normal IR heating. For instance, a 5-min treatment with nonselective and selective heating resulted in approximately 1.8 and 2.3 $\log_{10}$ CFU/g reduction of *A. niger.* Similarly, reductions of 1.4 and 1.95 $\log_{10}$ CFU/g of *F. proliferatum* were obtained with 5 min of nonselective and selective heating, respectively. Although the sample temperatures after selective or nonselective infrared heating were identical, absorption of energy by fungal spores increased in selective heating, leading to a higher lethal rate (Jun and Irudayaraj 2003).

Total energy decreases as the peak wavelength increases. Therefore, NIR radiation with short wavelength has a relatively higher energy level than FIR radiation with longer wavelength. Hamanaka and others (2006) studied the inactivation efficacy of *Bacillus subtilis* treated with 3 infrared heaters (A, B, and C) having different peak wavelengths (950, 1100, and 1150 nm) and radiant energies (4.2, 3.7, and 3.2 μW/cm^2/nm), respectively. Air-dried *Bacillus subtilis* solution placed on a stainless steel petri dish was treated with infrared heating after water activity adjustment using a desiccator. Surface temperature of petri dish was 100 °C after a 2-min exposure for all the heaters. Pathogen inactivation was higher with heater A than those of heaters B and C, although temperature was the same for all the heaters. For example, at water activity of 0.7, decimal reduction times of heaters A, B, and C were approximately 4, 12, and 22 min, respectively. Therefore, it is obvious that inactivation efficiency is associated with the radiation spectrum (Hamanaka and others 2006).

Effect of sample depth: The penetration depth of IR radiation is very low. An increase in the sample depth slows down the bulk temperature increase of the food sample (Sawai and others 1995). A 90% reduction in IR power was observed within a thin layer of 40 μm in bacterial suspension (Hashimoto and others 1991). Therefore, the effect of IR radiation on the microbial inactivation diminishes as the sample thickness increases. Decreasing the sample depth also accelerates the inactivation of spores (Sawai and others 1997) and *E. coli* and *S. aureus* (Hashimoto and others 1992a). The ratio of number of injured cells to the number of survivors increased as the depth decreased. For example, *S. aureus* population was reduced by approximately 2 and 5 $\log_{10}$ CFU/mL at 321 °K, when the sample depths were 2.9 and 0.9 mm, respectively. Similarly, *E. coli* population in the samples with 1.3 and 2.2 mm in depth showed approximately 1.33 and 1.66 $\log_{10}$ CFU/mL at 321 °K.

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. If inactivation occurs in sequence, there will be tailing and shoulder effects. An initial increase in *B. subtilis* population was caused by heat shock germination of spores. A 10-min treatment with infrared heating resulted in more than 90% reduction in *B. subtilis* population (Daisuke and others 2001). 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. The irradiation helped in activation of spores into vegetative cells and the second irradiation effectively inactivated spore formers. Furthermore, intermittent treatment can minimize the quality changes, as continuous treatment longer than 50 s resulted in discoloration of wheat surface (Hamanaka and others 2000).

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. As the peak wavelength of the IR heating was short, the initial values of water activity leading to maximum *D* values for bacterial spores also increased.

Physiological phase of M/Os: Physiological phase of M/Os can be classified as lag phase (M/Os adapt to new environment before replicating), exponential phase (the number of M/Os increases exponentially), stationary phase (no further increase in M/O population), and death phase (the number of dead cells is higher than live cells). The chemical composition and resistance of the M/Os in various growth phases are different. Exponential phase cells are more sensitive to IR heating than stationary phase cells. In other words, exponential phase cells will have more injuries than stationary phase cells under IR heating. Sawai and others (1997) reported that IR radiation at 3.2 kW/m^2 resulted in reductions of approximately 1.8 and 3.9 $\log_{10}$ CFU/mL for stationary and exponential phase cells after 5-min treatment, respectively. It was also found that the pasteurization effect of FIR irradiation was much higher than conductive heating on exponential phase cells under the same conditions.

Inactivation mechanism: Inactivation of M/Os by IR heating may include inactivation mechanism similar to that of ultraviolet light (DNA damage) and microwave heating (induction heating) in addition to thermal effect, as infrared is located between ultraviolet and microwave in the electromagnetic spectrum (Hamanaka and others 2000). Thermal inactivation can damage DNA, RNA, ribosome, cell envelope, and proteins in microbial cell. Sawai and others (1995) investigated the inactivation mechanism of *E. coli* treated with infrared radiation in phosphate buffer saline. They proposed that sublethally injured cells will become more sensitive to an inhibitory agent which has an inhibitory action on the damaged portion of the cell. Four inhibitory agents, namely, penicillin (PCG; inhibits cell wall synthesis), chloramphenicol (CP; inhibits protein synthesis), rifampicin (RFP; inhibits RNA synthesis), and nalidixic acid (NA; inhibits DNA synthesis), were used for the enumeration of pathogens. An 8-min infrared radiation at a wattage of 3.22 kW/m^2 resulted in approximately 1.8, 1.9, 2.7, and 3.2 $\log_{10}$ reduction of *E. coli,* when NA, PCG, RFP, and CP enriched agars were used for enumeration, respectively. When no inhibitory agents were present, a 1.8 log reduction was obtained. This observation implies that approximately 0.1, 0.9, and 1.4 log reductions were caused by inhibitory actions of PCG, RFP, and CP, respectively. With conductive heating, similar damages were observed; however, RNA, protein, and cell wall showed more vulnerability to IR heating than conductive heating. The order of magnitude of infrared damages was as follows: protein > RNA > cell wall > DNA. RFP inhibits RNA polymerase in *E. coli* and CP binds ribosomal subunits and inhibits peptidyltransferase reactions (Sawai and others 1995).

Sawai and others (1997) reported that for both stationary and exponential phase cells, sensitivity to NA increased as the sample temperature increased. However, there was only a small increase, indicating that minimal damage occurred in the DNA. In particular, exponential phase cells had more cell wall and membrane damage than stationary phase cells. However, more serious injuries to RNA polymerase occurred for stationary phase cells compared to exponential phase cells (Sawai and others 1997). Transmission electron microscopic observation and infrared spectroscopy of IR-treated *S. aureus* cells clearly verified cell wall damage, cytoplasmic membrane shrinkage, cellular content leakage, and mesosome disintegration (Krishnamurthy 2006).

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. A summary of the study pertinent to pathogen inactivation in different types of food materials such as solid, liquid, and nonfood materials is given in Table 3.

IR heating in other miscellaneous food processing operations. The usefulness of IR heating has also been demonstrated in various other food processing applications such as roasting, frying, broiling, heating, and cooking meat and meat products, soy beans, cereal grains, cocoa beans, and nuts.

With the growing interest in flame-broiling and rapid cooking methods, conveyorized IR broiling is a unique and innovative method. Khan and Vandermey (1985) prepared ground beef patties by IR broiling in a conveyorized broiler. The results showed that due to high temperatures and short cooking times, the infrared broiler could produce more servings per hour compared to conventional gas heating. In addition, it was found that ground beef patties broiled by tube broiler did not have any adverse effects on the cooking quality (number of samples cooked/min, % shrinkage, number of servings/h) or sensory quality (appearance, flavor, texture, juiciness, and overall acceptability), as compared to conventional gas broiling method. Sakai and Hanzawa (1994) reported on the performance of infrared-based systems with conventional ovens for baking rice crackers and for roasting fish pastes. The comparative study indicated energy savings of 45% to 70% with infrared heating. Abdul-Kadir and others (1990) conducted imbibition studies and cooking tests to evaluate the effect of IR heating on pinto beans (*Phaseolus vulgaris*) heated to 99 and 107 °C. IR-heating was found to improve rehydration rate and degree of swelling of pinto beans; however, cooking time of pinto beans significantly increased.

Studies on color development during IR roasting of hazelnuts were reported by Ozdemir and Devres (2000). Olsson and others (2005) found that infrared radiation and jet impingement, as compared with heating in a conventional household oven, increased the rate of color development of the crust and shortened the heating time of parbaked baguettes during postbaking. Furthermore, the fastest color development was obtained by combining infrared and impingement heating. The rate of water loss increased due to a higher heat transfer rate, but the total water loss was reduced because of a shorter heating time. In general, the formed crust was thinner for IR-treated baguettes.

Sources of IR 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 (Hung and others 1995): 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% (Hung and others 1995). 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. Studies to investigate the superiority of FIR to NIR radiation have also been found in the literature. 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 λ_{max} of 2.7 μm (MIR) and at λ_{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.

FIR energy penetration into the food has gained ceaseless concern. Hashimoto and others (1990, 1994) studied the penetration of FIR energy into sweetpotato 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. Table 4 shows the penetration depth of NIR energy into food products (Ginzburg 1969).

Selective heating by infrared radiation

Very few attempts have been made to study selective heating in the food industry as well as in nonfood research areas. Certain studies have been found in the literature applied to electronics (Bischorf 1990; Sakuyama and others 1995). These studies on electronics showed the accessibility of selective heating based on the relation between the optical properties of objects and the spectral distribution of the radiative source. However, the studies did not elaborate on the details or its implementation.

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 ac-

Table 3 – Inactivation of pathogenic microorganisms by infrared heating

Pathogen	Food/nonfood material	Temperature/energy	Time	Log reduction[a]	References
Solid foods					
Monilia fructigena	Strawberry	approximately 50 °C[d]	10 s	2.5 to 5.2 log (estimated)	Tanaka and others (2007)
Natural microflora	Wheat	2.0 kW	63 s	approximately 2.0 log	Uchino and others (2000)
Total bacterial count	Wheat or soybean surface	1.5 kW	10 s	approximately 3.0	Daisuke and others (2001)
Total aerobic plate count	Onion	80 °C (average 2226 W/m^2)	approximately 24 min	1.72 ± 0.45 log$_{10}$ CFU/10g	Gabel and others (2006)
Coliform counts	Onion	80 °C (average 2226 W/m^2)	approximately 24 min	4.04 ± 0.47 log$_{10}$ CFU/10g	
Yeast and mold	Onion	80 °C (average 2226 W/m^2)	approximately 24 min	1.26 ± 0.14 log$_{10}$ CFU/10g	
Natural bacterial microflora	Wheat surface	2.0 kW	60 s	approximately 1.9 log$_{10}$ CFU/g	Hamanaka and others (2000)
Listeria monocytogenes	Turkey frankfurters	70 °C[d]	82.1 s	3.5 ± 0.4 log$_{10}$ CFU/cm^2	Huang (2004)
		75 °C[d]	92.1 s	4.3 ± 0.4 log$_{10}$ CFU/cm^2	
		80 °C[d]	103.2 s	4.5 ± 0.2 log$_{10}$ CFU/cm^2	
Salmonella enteritidis	Shell eggs	70 °C[d]	1.5 s	Up to 6 log (estimated)	James and others (2002)
Aspergillus niger spores	Corn meal	72 °C[e]	6 min	1.8	Jun and Irudayaraj (2003)
Aspergillus niger spores	Corn meal	68 °C[e] (with an optical filter: 5.45 to 12.23 μm)	6 min	2.3	
Fusarium proliferatum spores	Corn meal	72 °C[e]	6 min	1.4	
Fusarium proliferatum spores	Corn meal	68 °C[e] (with an optical filter: 5.45 to 12.23 μm)	6 min	1.95	
Listeria monocytogenes	Oil-browned deli turkey	399 °C around product surface	75 s	3.7 log$_{10}$ CFU/mL	Muriana and others (2004)
Liquid foods					
Yeast	Honey	0.2 W/cm^2	8 min	approximately 3.85 log$_{10}$ CFU/mL[c]	Hebbar and others (2003)
Nonfood materials					
Bacillus subtilis	Stainless steel plate at water activity of 0.7	4.2 μW/cm^2/nm (peak wavelength: 950 nm)	4 min[b]		Hamanaka and others (2006)
		3.7 μW/cm^2/nm (peak wavelength: 1100 nm)	22 min[b]		
		3.2 μW/cm^2/nm (peak wavelength: 1150 nm)	12 min[b]		
E. coli	Nutrient agar (depth = 0)	4.36×10^3	6 min	approximately 2.30 to 2.48 log$_{10}$ CFU/plate[c]	Hashimoto and others (1992b)
	(depth = 1 mm from surface)	4.36×10^3	6 min	approximately 0.70 log$_{10}$ CFU/plate	
	(depth = 2 mm from surface)	$4.36{\times}10^3$	6 min	approximately 0.66 log$_{10}$ CFU/plate	
Bacillus subtilis spores	Steel plate	180 °C	3.2 s[b]		Molin and Ostlund (1975)
E. coli	Phosphate buffer saline	3.22 kW/m^2	8 min	1.8 log$_{10}$ CFU/mL	Sawai and others (1995)
E. coli	Phosphate buffer	61 °C	2 min	0.98 log$_{10}$ CFU/mL	Sawai and others (2003)
Aspergillus niger spores	Physiological suspension	1.0 kW	40 s	4.0 to 5.0	Daisuke and others (2001)
Bacillus subtilis spores	Physiological suspension	1.0 kW	10 s	approximately 1.0	

[a] In (log$_{10}$ CFU/mL), unless specified.
[b] *D* value.
[c] No growth observed after treatment.
[d] Surface temperature.
[e] Temperature of corn meal.

curate 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 λ_{max} of 3.5 to 3.8 μm (FIR) and the 2nd stage for greater penetration of heat transfer by radiant flux with a λ_{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 λ_{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 λ_{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.

There seems to be a lack of consistent methods to explore the intrinsic selective heating process in the area of food engineering. It should be noted that Dagerskog and Österström (1979) first used a bandpass filter (Optical Coating Laboratory Inc., type nr L-01436-7) in their frying experiment of pork to transmit only the wavelength above 1.507 μm, which turned out be a good example for design of selective IR heating systems to emit the spectral regions of interest.

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. Applicability of this technique was demonstrated by selective heating of soy protein and glucose. Soy protein was heated about 6 °C higher than glucose after 5 min of heating, exhibiting a reverse phenomenon when heating without the filter. Simulation results from the developed models were consistent with experimental data, thus supporting the mechanism of selective IR heating.

Table 4—Penetration depth of NIR (0.75 to 1.4 μm) into food products.

Product	Spectral peak (μm)	Depth of penetration (mm)
Dough, wheat	1.0	4 to 6
Bread, wheat	1.0	11 to 12
Bread, biscuit, dried	1.0	4
	0.88	12
Grain, wheat	1.0	2
Carrots	1.0	1.5
Tomato paste, 70% to 85% water	1.0	1
Raw potatoes	1.0	6
Dry potatoes	0.88	15 to 18
Raw apples	1.16	4.1
	1.65	5.9
	2.36	7.4

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).

The evaluation of full-fat flour made from IR-heat treated soybeans maintained freshness similar to fresh flour for 1 y. However, untreated samples resulted in rancidity development (Kouzeh and others 1982). Compared to regular freeze-drying, IR-assisted freeze-drying of yam brought about lower color differences as well as faster dehydration. Furthermore, infrared heating leading to a higher dehydration ratio implies that infrared heating reduces serious product shrinkage (Lin 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). When menu servings of peas were held at 50 to 60 °C for 2 h by IR lamps, the quality of peas deteriorated and resulted in unacceptable products (Maxcy 1976). Bitterness and protein solubility of peas were reduced after IR heat treatment (McCurdy 1992). Furthermore, canola seeds had higher dehulling capacity after infrared heating (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.

Table 5 briefly summarizes the effect of IR treatment on nutritional quality of various food products. As the literature review substantiates, IR heating does not change the quality attributes of foods significantly, such as vitamins, protein, and antioxidant activities.

IR heat transfer modeling

Modeling of infrared heat transfer inside food has been a research-intensive area because of the complexity of optical characteristics, radiative energy extinction, and combined conductive and/or convective heat transfer phenomena.

Diffusion characteristics in relation to radiation intensity and thickness of slab were explored using the finite element method to explain the phenomenon of heat transfer inside food systems under FIR radiation. The radiation energy driving internal moisture movement during FIR drying of a potato produced the activation energy for diffusion inversely proportional to thickness of slab (Afzal and Abe 1998). Sakai and Hanzawa (1994) assumed that most FIR radiation energy would be absorbed at the surface of a food system due to the predominant energy absorption of water. Energy would thereafter be transported by heat conduction in the food. Based on this assumption, a governing equation and boundary conditions to explain heat transfer derived from energy balance in a food system were solved using Galerkin's finite element method. The measured temperature distribution in samples was in good agreement with model predictions, permitting

Table 5—Effect of infrared treatment on nutritional quality of food products.

Food product	Parameters effecting nutritional quality	Effect of treatment	Reference
Barley	Germination rate at 55 °C	25% increase by combination of IR heating and convectional heating	Afzal and others (1999)
Wheat	Germination rates (heat treatment for 63 s each)	Convectional heating: 90% to 97% Intermittent IR heating: 80% to 86% Continuous IR heating: 78% to 85%	Uchino and others (2000)
Lentils	Phytic acid content	Untreated: 2.34% High density IR heating (170 °C): 1.06%	Arntfield and others (2001)
Full fat soybeans	Protein solubility	Infrared heating: 84% Spouted bed drying: 82% Extrusion: 73%	Wiriyaumpaiwong and others (2004)
Lentils	Protein solubility	Untreated: 74.7% High-density IR heating (170 °C): 50.9%	Arntfield and others (2001)
Soymilk	Protein digestibility	Untreated: 83.2% IR heat treated (110 to 115 °C): 86.5%	Metussin and others (1992)
Crude canola oil	Phosphorus content	Untreated canola seeds: 46 ppm IR heat treated (123 °C): 273 ppm	McCurdy (1992)
	Sulfur content	Untreated canola seeds: 1.4 ppm IR heat treated (123 °C): 4.4 ppm	McCurdy (1992)
Soymilk	Available lysine content	Untreated: 4.64 g/16 g N IR heat treated (110 to 115 °C): 6.14 g/16 g N	Metussin and others (1992)
Fried chicken	Thiamine retention	Reheated by IR heating: 81% to 84% Convection heating: 86% to 96%	Ang and others (1978)
Orange juice	*D* values for vitamin C degradation at 75 °C	Convectional heating: 27.02 min Ohmic heating: 23.72 min Infrared heating: 23.76 min	Vikram and others (2005)
Full fat soybeans	Reduction in urease activity at 140 °C and 28% moisture (d.b.)	Infrared heating: 53% Spouted bed drying: 30%	Wiriyaumpaiwong and others (2004)
Peanut hulls	Antioxidant activities (total phenolic compounds in water extract, after 60 min) Radical scavenging activities	FIR irradiation: 141.6 μM FIR heating: 90.3 μM FIR irradiation: 48.83% FIR heating: 23.69%	Lee and others (2006)

control of the surface temperature to retain food properties without overtreatment.

Abe and Afzal (1997) investigated 4 mathematical drying models, namely, an exponential model, a Page model, a diffusion model based on spherical grain shape, and an approximation of the diffusion model to address the thin-layer infrared drying characteristics of rough rice. They found the Page model as most satisfactory for describing thin-layer infrared radiation drying of rough rice. Similarly, Das and others (2004) also reported that the Page model adequately fitted the experimental drying data while studying the drying characteristics of high-moisture paddy.

In general, numerical methods applied to solve the set of equations are finite elements, finite difference, and finite volume or the control volume method. It is often difficult to decide which solution strategy would give the best results and which would require the least computing time (Ranjan and others 2001). However, in a proposal suggested for the solution of heat transfer problems for food materials, it was recommended that if the solution region represents a simple rectangular domain, then the traditional finite difference methods should be the preferred discretization strategy (Turner and Perre 1996).

Tsai and Nixon (1986) investigated the transient temperature distribution in a multilayer composite, semitransparent or transparent, absorbing and emitting medium exposed to a thermal radiative heat flux. The governing conditions with the initial and boundary conditions in consideration of the effects of both thermal radiation and conduction within each layer and convection on both exterior surfaces were solved by a hybrid numerical algorithm, using a 4th-order explicit Runge–Kutta method for the time variable and a finite difference method for the space variable.

The experimentally measured temperature distribution of slices of beef during IR frying was successfully predicted by the model developed based on combined infrared radiation and convection heating (Dagerskog 1979). Heat conduction equation was solved numerically using the finite difference method. The infinitesimal differentials were replaced by differences of finite size and the degree of accuracy of the representation was determined by the step size of these differences.

A control volume formulation for the solution of a set of 3-way coupled heat, moisture transfer, and pressure equations with an IR source term was presented in 3 dimensions. The solution procedure uses a fully implicit time-stepping scheme to simulate the drying of potato during infrared heating in 3-dimensional Cartesian coordinates. Simulation indicated that the 3-way coupled model predicted the temperature and moisture contents better than the 2-way coupled heat and mass transfer model. The overall predictions agreed well with the available experimental data and demonstrated a good potential for application in grain and food drying (Ranjan and others 2002).

Togrul (2005) investigated infrared drying of apple to create new suitable models, including combined effects of drying time and temperature. In order to explain the drying behavior of apple, 10 different drying models (Newton, Page, modified Page, Wang and Singh, Henderson and Pabis, logarithmic, diffusion approach, simplified Ficks diffusion [SFFD] equation, modified Page equation-II, and Midilli equation) were developed and validated. The variation of moisture ratio with time could be well described by the model developed by Midilli and others (2002). Sixty-six different model equations relating the temperature and time dependence of infrared drying of apple were derived wherein the model derived from modified Page II had lowest root mean squared error (RMSE), mean bias error (MBE), and chi-square along with the highest modeling efficiency and regression coefficient. Moreover, a single equation was derived to predict the moisture ratio change during infrared drying (0 to 240 min) of apple in the temperature range of 50 to 80 °C. The developed model is expected to predict drying behaviors of other vegetables and fruit.

Thermal death kinetics model

Hashimoto and others (1992b) developed a simple integrated model to predict the survivors of *E. coli* under predicted temperature distribution during FIR pasteurization. Analytical and numerical models of bacterial spores have been developed to predict microbial spore growth during sterilization. Stumbo (1965) first validated a model with 1st-order inactivation of uniformly activated spores during a sterilization process. To overcome limitations of traditional models to predict spore populations during treatment, especially under ultrahigh temperatures, new models including spore activation have been proposed (Rodriguez and others 1988). The populations in a suspension of bacterial spores subjected to lethal heat treatment were simulated using a composite model involving simultaneous, independent activation and inactivation of dormant but viable spores, and inactivation of activated spores.

Jun (2002) developed an integrated model that combined the thermal death kinetics with the IR heat transfer model and could predict the survivors of fungal spores based on temperature prediction. Selective IR heating was found to differentially deliver a higher degree of lethality to individual fungal spores. The denaturation of the protein band as a target spectral region of selective heating might also partially contribute to an increase in the lethality of fungal spores.

Recently, Tanaka and others (2007) combined Monte Carlo FIR radiation simulations with convection–diffusion air flow and heat transfer simulations to investigate the suitability of the method for surface decontamination in strawberries. The model was a powerful tool to evaluate in a fast and comprehensive way to address complex heating configurations that include radiation, convection, and conduction. Computations were validated against measurements with a thermographic camera. FIR heating obtained more uniform surface heating than air convection heating, with a maximum temperature well below the critical limit of about 50 °C. To improve the system functionality in terms of heating rate and temperature uniformity, several factors can be considered, that is, system rotation, optimized heating cycles, and different heater geometries. The projected modeling approach can be used to achieve such goal in a comprehensive manner, and the model should be extended to consider mass transfer and volumetric dissipation of the radiation power.

Conclusions and Future Research Potential

IR heating is a unique process; however, presently, the application and understanding of IR heating in food processing is still in its infancy, unlike the electronics and allied sector where IR heating is a mature industrial technology. It is further evident from this

Table 6 — Major advantages and disadvantages of IR heating as compared to convectional heating methods (Dostie and others 1989; Sakai and Hanzawa 1994; Mongpreneet and others 2002).

Advantages	Disadvantages
High thermal efficiency	Low penetration power
Alternate source of energy	Prolonged exposure of biological materials may cause fracturing
Fast heating rate	Not sensitive to reflective properties of coatings
Shorter response time	
Uniform drying temperature	
High degree of process control	
Cleaner working environment	
Possibility of selective heating	

review that IR heating offers many advantages over convection heating, including greater energy efficiency, heat transfer rate, and heat flux that results in time-saving as well as increased production line speed. Table 6 lists advantages and disadvantages of IR heating compared to other thermal processing techniques (Dostie and others 1989; Sakai and Hanzawa 1994; Mongpreneet and others 2002). IR heating is attractive primarily for surface heating applications. In order to achieve energy optimum and efficient practical applicability of IR heating 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.

Over the last 3 decades, several studies have been conducted to address various technological aspects of IR heating for food processing. However, research need for upcoming years may include the following:

1. Selective heating: There is not much literature on selective heating using IR radiation in foods. IR heating can be controlled or filtered to allow radiation within a specific spectral range to pass through using suitable optical band pass filters. Such a controlled radiation can stimulate the maximum optical response of the target object when the emission band of infrared and the peak absorbance band of the target object are identical. Such manipulations of IR radiation for selective heating of foods could be very useful.

2. Detailed insight into the theoretical explanation of IR effects, especially with regard to its interaction with food components, changes in taste and flavor compounds and living organisms.

3. Application of catalytic infrared (CIR) heating: CIR heating uses natural gas or propane, which is passed over a mesh catalyst pad to produce thermal radiant energy through a catalytic reaction. This reaction occurs below the ignition temperature of gas so that no flame is produced. The electromagnetic radiant energy from CIR has peak wavelengths in the range of medium- to far-infrared. The peak wavelengths match reasonably well with the 3 absorption peaks of liquid water, which could result in rapid moisture removal. Since CIR directly converts natural gas to radiant energy, it is more energy-efficient than typical infrared emitters using electricity.

4. 3D modeling of food products: Studies on IR heating have generally been applied to foods with a simple 1D or 2D geometry. There is a paucity of information in the area of advanced 3D radiation modeling. Most crucially, integrating microbial death kinetics with chemical kinetics due to IR heating will provide a holistic approach to the understanding of complex microbial and chemical process kinetics and interactions as well as system design.

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