Food Processing Operations Modeling

Design and Analysis

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Infrared Heating of Biological Materials

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1 INTRODUCTION

Infrared refers broadly to that portion of the electromagnetic spectrum starting at the deep red (the point at which light just begins to become visible, hence the name infrared) and extending to the microwave radar region. As shown in Figure 1, the relative position of infrared region of the electromagnetic spectrum is in the wavelength range of 0.75 to 1000 μm. Infrared waves are described as short, medium, or long wave. Short infrared waves (or near infrared) are closest to visible light. Because much of this energy is light, it is easily reflected. Short infrared waves occupy the region of the electromagnetic spectrum in the wavelength between 0.75 and 3.0 μm. The long infrared (or far infrared) waves, spanning the wavelength region of 25–1000 μm, are readily absorbed by most materials as heat. The medium waves (or middle infrared) occupy the region between the short infrared and long infrared regions [1].

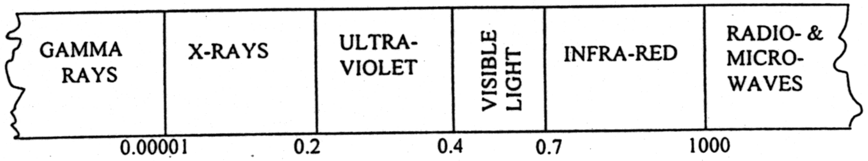

Figure 1 The electromagnetic spectrum.

When radiant electromagnetic energy impinges upon a food surface, it may induce changes in the electronic, vibrational, or rotational states of atoms and molecules [2]. The types of mechanisms for energy absorption are determined by the wavelength range of the incident energy. Changes in the electronic state correspond to wavelengths in the range between 0.2 and 0.7 μm (ultraviolet and visible rays); changes in the vibrational state correspond to wavelengths in the range 2.5–100 μm (part of infrared region); and changes in the rotational state correspond to wavelengths above 100 μm (microwaves). Infrared radiation causes molecular vibration changes; hence, heating occurs when biological materials are exposed to infrared radiation.

The fundamental relationships of infrared energy are established by three basic laws [Eqs. (1)–(3)] that determine the distribution and quantity of infrared energy. The laws are written for a blackbody, which assumes that a surface will absorb all and reflect none of the radiation falling on it. An ideal "blackbody" is a surface that absorbs and in turn radiates all the energy incident upon it.

Stefan–Boltzmann Law

$$W = \sigma T_{\mathrm{ab}}^4 \tag{1}$$

Wien's Displacement Law

$$\lambda_{\max} = \frac{2897.6}{T_{\mathrm{ab}}} \tag{2}$$

Planck's Equation

$$E = \frac{C_1 \lambda^{-5}}{\exp(C_2/\lambda T) - 1} \tag{3}$$

where the first (C_1) and second (C_2) radiation constants have values of $3.742 \times 10^8\,\mathrm{W\,\mu m^4/m^2}$ and $1.469\,\mu\mathrm{m\,K}$, respectively. The symbols are defined in Section 6 nomenclature.

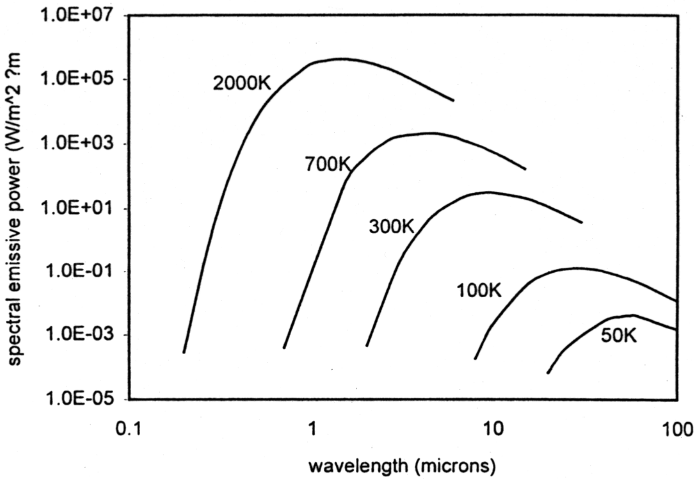

Figure 2 Spectral blackbody emissive power.

The Stefan–Boltzmann law and Planck's equation provide the means for determining the intensity and spectral distribution of the emission from a radiator. The Stefan–Boltzmann law shows that the intensity of heat at the surface of a body exposed to infrared radiation is proportional to the fourth power of temperature. The Wein's displacement law states that the peak wavelength ($\lambda_{\max}$) varies inversely with the absolute temperature of the radiating object. Figure 2 shows the emissive power curves of blackbody radiation versus wavelengths at different temperatures. The hotter the object, the shorter the wavelength of infrared radiation. The total emitted energy is the integral or the area under the curve shown in Figure 2 and can be calculated using the Stefan–Boltzmann relationship.

Because no object is a perfect emitter (i.e., a blackbody), real substances are characterized by an efficacy of radiant emission called emittance or emissivity (ε). The radiant energy flux for real objects is then calculated from

$$W = \varepsilon \sigma T_{\mathrm{ab}}^4 \tag{4}$$

Emissivity varies with wavelength and temperature. The common practice in engineering, however, is to represent the emissivity for the entire band of the electromagnetic spectrum involved rather than for a particular wavelength. Emissivity data for biological materials is scarce. Typical values of emissivity for agricultural crops vary from 0.7 to 0.9 [3,4]. Where there are no data for a particular application, an emissivity value of 0.9 is often used.

2 INFRARED HEAT GENERATION

Most generators of infrared energy are either electrically heated or gas fired. The electrical generators of infrared radiation include quartz lamp, tungsten arc lamp, xenon arc lamp, nonsheathed radiator, and resistance element (Table 1). For electrically heated radiators, infrared radiation is obtained by passing an electric current through an element [6]. Quartz, tungsten, and xenon lamps generally have maximum radiation at wavelength less than 1.3 μm. They are therefore referred to as light (short-wave) radiators. These lamps emit at temperatures of 1773–2073 K [7]. Resistance elements and gas-type generators are generally dark (long-wave) radiators because they have maximum radiation in the invisible infrared rays (> 1.3 μm). Gas-fired generators are made of perforated plate (metal or refractory) that is heated by gas flames in one of the surfaces, thereby causing the plate to rise in temperature and emits radiant energy [8]. The characteristics of commercially used infrared heat sources are compared in Table 1 [5].

3 APPLICATIONS TO BIOLOGICAL MATERIALS

Sun drying is the oldest method that has been used to dry agricultural products. Because most of the radiant energy of the sun is in the infrared region, infrared energy is indirectly the oldest and most traditional energy source for agricultural applications. Despite the historical nature of infrared energy in food preservation, the use of infrared radiation is mostly at the industrial level, such as in drying of coatings (powders, paints, inks, adhesives, films), in hazardous heating (space heating for oil and gas and petrochemical industries) and in electronics and metal processing applications.

Interest in the use of infrared heating in food processing has increased in the past few years due to recent developments in the design of infrared heaters that offer rapid and economical methods for production of food products with high organoleptic and nutritional value. The most significant advantage of infrared drying when used for drying is the reduction in drying time. Other advantages of infrared heating include the following [2,8]:

(a) High efficiency to convert electrical energy into heat when electric heaters are used.
(b) Efficient heat transfer to the food reduces processing time and energy costs.

TABLE 1 Characteristics of Commercially Used Infrared Heat Sources

Infrared source		Source temperature: Usual range (K)	Source temperature: Max (K)	Peak wavelength (μm)	Power (kW/m^2)
Electrically heated radiators					
Nonsheathed radiators	Sylite	1,750–1,800	2,200	1.65	Up to 80
	Graphite	2,300–2,800	3,500	1.2	Up to 1200
	Metallic–filament tungsten	1,900–2,200	2,700	1.2	$(1–1.4) \times 10^5$
	Metallic–molybednum	1,600–2,000	2,000	0.9	$(1–2) \times 10^5$
Sheathed radiators	Light bulbs	1,900–2,500	2,500	1.3	Up to 20
	Quarta lamp	1,900–2,500	2,800	1.0	30–400
	Plate radiators	700–1,200	1,200	4.0–9.0	4–14
	Xenon arc lamp	5,000–10,000	10,000	0.8–1.1	Up to 50
	Tungsten arc lamp	3,200–4,000	7,000	0.72	Up to 1400
Gas-heated					
Flame	Direct flame (Bunsen, Teclu, or Mecker burner)	500–1,600	1,800	2.8–4.3	20–30
	Indirect flame—ceramic element	600–800	1,500	4.0	50–60
	Indirect flame—metallic element	300–900	1,000	3.6	20–30
Flameless	Heated porous plate with internal burning	350–850	1,200	4.0	40–90
	Heated porous plate with external burning	1,000–1,700	2,000	1.5–2.0	160–2400

Source: Ref. 5.

(c) The air surrounding the equipment is maintained at ambient level.
(d) Infrared heaters are less expensive when compared to dielectric and microwave sources and they have longer service life and low maintenance.
(e) Surface irregularities on foods have insignificant effect on infrared heating—uniform heating of product is easily achieved.

Some of the disadvantages of infrared heating are (a) proper scaling up of heaters from laboratory model to full-plant model, and (b) infrared heating is essentially a surface heating method and is therefore best for thin materials.

Infrared heat is generally applied to biological materials in order to achieve thermal effects such as controlling insect infestation in stored product, inactivation of toxic and antimicrobial factors and degradative enzymes, reduction of microbial counts, enhancement of the dehulling of legume grains, and starch gelatinization in starch bearing materials [7,9–10]. The determination of appropriate equations to describe a process requires an understanding of the physical, chemical, and microbiological changes that occur when the process is applied to biological materials. In this section, some of the applications of infrared heating in food and agricultural industries are discussed. Examples of the various changes that occur in infrared heated foods are also presented.

3.1 Applications Involving Insect Disinfestation

Kirkpatrick [11] showed a 99% death rate of *Sitophilus oryzae* and a 93% death rate of *Rhyzopertha dominica* when insect-infested wheat samples were exposed to infrared radiation. The temperature of the wheat samples increased to 48.6°C. In another study, Kirkpatrick et al. [12] found that the natural infestations of stored wheat by the weevil *S. oryzae*, the grain borer *R. dominica*, *Crypolestes pusillus Schonh*, and *Tribolinum castaneum* were controlled by raising sample temperature to 55°C. Despite these encouraging results, there is no evidence that infrared heating is used commercially to disinfect food and agricultural materials. This is probably due to the limited use of infrared heating in the food industry at the time these studies were conducted. Due to the energy crisis of the 1970s, it was less expensive for food manufacturers then to use chemicals for food preservation.

3.2 Applications Involving Legume and Oil-Bearing Materials

Most of the commercial use of infrared heat processing in the food industry involves the inactivation of antinutritional factors in legume seeds (mostly soybeans) and enzymes that cause product degradation and development of rancidity. Several studies carried out by researchers at the Agricultural University in Wageningen, the Netherlands [13–16], showed that infrared heating can be used to improve the nutritive value of soybeans. The researchers, in addition to results from other published studies [17–19], found that infrared radiation can be used to inactivate lipoxygenase enzyme (that causes oxidative rancidity), reduce the trypsin inhibitor and other antinutritional factor levels, and increase the binding, emulsion power, water holding capacity, and shelf life of full-fat soybean flour. This has generally led to a longer shelf life of the product. Perhaps the most important conclusion made by the Wageningen researchers is that infrared treatment of soybeans offers the possibility for reducing energy requirements and production costs in comparison to the conventional steam-heating method used for soybean processing. The researchers showed that soybeans can be infrared heated to surface temperatures of 125–133°C for 60 sec. Steam heating is usually carried out at temperatures of 110–125°C for 20–30 min [20–22]. In addition, steam-heated samples have to be dried after treatment thus increasing processing cost.

When cocoa beans were infrared heated prior to dehulling, there was a significant improvement in winnowing performance during the separation of nib or beans from the shell. The shells became lighter due to expansion and are thus more effectively removed during air separation [20–22]. In addition, bacteria and contamination levels were reduced by 95%. The effect of infrared heating on the microbial counts of cocoa nibs is shown in Table 2 [9]. Infrared heating of the nibs was carried out for 10 sec under a ceramic plate heated to 970°C.

Cenkowski and Sosulski [23] investigated the effect of infrared heating on the physical and cooking properties of lentils. They found that cooking time was shortened from 30 mm for the controlled seeds to 15 mm for lentils adjusted to 25.8% moisture content and infrared heated to 55°C. Infrared

Table 2 Effect of Infrared Treatment of Cocoa Nibs on Microbial Counts

	Before infrared treatment (counts/g)	After infrared treatment (counts/g)
Total count	5×10^6	2×10^5
Enterobacteria	10^4	10
Yeasts	8×10^4	$<10^2$
Molds	6×10^4	$<10^2$

Source: Ref. 9.