11

Infrared heating

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11.1 Introduction; principle and uses

Sir William Herschel discovered in the 1800s infrared – or heat-radiation when he was attempting to determine the part of the visible spectrum with the minimum associated heat in connection with the astronomical observations he was making. In 1847 A.H.L. Fizeau and J.B.L. Foucault showed that infrared radiation has the same properties as visible light. It was being reflected, refracted and capable of forming an interference pattern (Encyclopedia Internet 2000). There are many applications of infrared radiation. A number of these are analogous to similar uses of visible light. Thus, the spectrum of a substance in the infrared range can be used in chemical analysis much as the visible spectrum is used. Radiation at discrete wavelengths in the infrared range is characteristic of many molecules. The temperature of a distant object can also be determined by analysis of the infrared radiation from the object. Medical uses of infrared radiation range from the simple heat lamp to the technique of thermal imaging, or thermography. It has also been used for drying of dye and lacquer for cars, drying of glue for wallpaper, drying of paper in a paper machine, drying of dye to plastic details, shrinkage of plastics, activation of glue in the plastic industry, etc.

The electromagnetic spectra within infrared wavelengths can be divided into three parts: long waves (4 μm–1 mm), medium waves (2–4 μm) and short waves (0.7–2 μm). The short waves appear when temperatures are above 1000°C; the long waves appear below 400°C and medium waves between these temperatures. The electromagnetic spectrum is shown in Fig. 11.1.

For food the technique has been used in many applications, as the long waves are one of the main heat transfer mechanisms in ordinary ovens or other heating
equipment. However, using short waves is new to the food industry. In the 1950s in the Soviet Union Lykow and others reported in general terms the results of their theoretical and experimental studies of infrared drying (Ginzburg 1969). In the 1960s in East Germany, Jubitz carried out substantial work on infrared heating and in France Déribéré and Leconte did some work on different applications on infrared irradiation in various industries. During this time Pavlov in the Soviet Union carried out a lot of work on infrared heating and food. On an industrial scale long wave radiation was already being used in the United States during the 1950s in many industrial food processes.

During the early 1970s there were many discussions about finding new methods for industrial frying/cooking of meat products (Skjöldebrand 1986). Deep fat frying, the process most often used in industrial frying, was criticised because of the fat and flavour exchange and surface appearance. Also environmental and nutritional aspects had to be considered. The consumer also wanted products more like the ones cooked at home. One of the new techniques that was discussed was near infrared heating (NIR) or short-wave infrared heating. This technique is used in the car industry for drying of coatings. Also the paper and textile industry use it for drying. Thus, like many other processes in the food industry, infrared heating was transferred from other industries. Why, then, has short wave infrared radiation not been used before? The answer is that there was a lack of knowledge about many of the factors concerning this process. On the one hand the radiators, the reflectors and the different systems for cassettes were developed during the 1960s; on the other hand there was not very much knowledge about the optical properties of the foodstuffs and how these develop during processing. Other problems then were braking of the radiators and cleaning of the equipment.

**Fig. 11.1** The electromagnetic spectrum (from Anon. 1974).
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During the 1970s and 1980s most of the research work on food in Sweden was carried out at SIK the Swedish Institute for Food and Biotechnology (Dagerskog and Österström 1979; Skjödebrand 1986; Skjödebrand and Andersson 1989). New knowledge was gained after a lot of studies.

In this chapter the following topics of infrared heating for food processing will be covered:

- theories and infrared properties
- technologies
- infrared heating equipment
- applications and case studies
- future trends
- sources of information and advice.

11.2 Theories and infrared properties

The basic concepts of infrared radiation are high heat transfer capacity, heat penetration directly into the product, fast process control and no heating of surrounding air. These qualities indicate that infrared radiation should be the ideal source of energy for heating purposes. The penetration characteristics are such that a suitable balance between the surface and body heating can be achieved, which is necessary for an optimal heating result.

The following factors are critical to control to get an optimal heating result (Ginzburg 1969; Hallström et al. 1988):

- radiator temperature
- radiator efficiency
- infrared reflection/absorption properties
- infrared penetration properties.

11.2.1 Radiators

The main component of IR equipment for heating is the radiator, of which there are various types and shapes. They may be divided into the following main groups

- gas heated radiators (long waves)
- electrically heated radiators
  - tubular/flat metallic heaters (long waves)
  - ceramic heaters (long waves)
  - quartz tube heaters (medium, short waves)
  - halogen tube heaters (ultra short waves).

There is more information about radiators in Section 11.4.
11.2.2 Heat transfer

As indicated earlier electromagnetic radiation having a wavelength in the range from $75 \times 10^{-6}$ cm to $100,000 \times 10^{-6}$ cm (0.000075–0.1 cm) covers the infrared spectra (Fellows 1988). Infrared rays thus occupy that part of the electromagnetic spectrum with frequency less than that of visible light and greater than that of most radio waves although there is some overlap. The name infrared means ‘below the red’, i.e. beyond red, or lower-frequency (longer wavelength) end of the visible spectrum. Infrared radiation is thermal for objects whose temperature is above 10 K. The radiation gives up its energy to heat materials when it is absorbed. The rate of heat transfer depends on

- the surface temperature of the heating and receiving materials
- the surface properties of the two materials
- the shape of the emitting and receiving bodies.

The amount of heat emitted from a perfect radiator (termed black body) is calculated using the Stefan-Boltzmann equation

$$Q = \sigma A T^4$$  \[11.1\]

where $Q$ (Js$^{-1}$) is the rate of heat emission, $\sigma$ ($= 5.7 \times 10^{-8}$ J s$^{-1}$ m$^{-2}$ K$^{-4}$) the Stefan-Boltzmann constant, $A$ (m$^2$) the surface area and $T$ (K = °C + 273) the absolute temperature. This equation is also used for a perfect absorber of radiation, again known as a black body.

Figure 11.2 shows the spectral characteristics of black body radiation from objects at different temperatures. These curves give the maximum possible radiation that can be emitted by any body for the temperatures shown. A black body produces maximum intensity according to Planck’s law

$$ Q = C_1 \lambda^{-5} \left( \frac{\epsilon_\lambda}{T} - 1 \right)^{-1} $$ \[11.2\]

Here $Q$ is the radiant flux emitted per unit area per unit increment of wavelength w/m$^2$/microns. $C_1 = 3.740 \times 10^{-12}$ W cm$^2$ and $C_2$ is 1.438 cm, K.

It should be remembered that Wien’s law states that the product of the wavelength corresponding to maximum emittance and the emission temperature of the black body is constant if $\lambda$ is expressed in microns

$$ \lambda_{max} \times T = 2900 \mu m K $$ \[11.3\]

Table 11.1 shows some data for different IR radiators. The wavelength distribution is important both for penetration, since it is not a distinct wavelength, and for the energy transfer. However, radiant heaters are not perfect radiators and foods are not perfect absorbers, although they do emit and absorb a constant fraction of the theoretical maximum. To take account of this, the concept of grey bodies is used, and the Stefan-Boltzmann equation is modified to

$$ Q = \varepsilon \sigma A T^4 $$ \[11.4\]
Here \( \varepsilon \) is the emissivity of the grey body expressed as a number from 0 to 1. Emissivity varies with the temperature of the grey body and the wavelength of the radiation emitted.

**Table 11.1** Some data for IR radiators

<table>
<thead>
<tr>
<th>IR radiator</th>
<th>( \lambda_{\text{max}} ) (( \mu \text{m} ))</th>
<th>Temp (K)</th>
<th>Max energy flux (kW/m(^2))</th>
<th>Radiation ( &lt;1.25 \mu \text{m} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra short wave</td>
<td>1.0</td>
<td>2627</td>
<td>4010</td>
<td>41.1</td>
</tr>
<tr>
<td>Short wave 1</td>
<td>1.12</td>
<td>2316</td>
<td>2547</td>
<td>32.9</td>
</tr>
<tr>
<td>Short wave 2</td>
<td>1.24</td>
<td>2066</td>
<td>1697</td>
<td>25.8</td>
</tr>
<tr>
<td>Medium wave</td>
<td>1.8</td>
<td>1338</td>
<td>1697</td>
<td>7.0</td>
</tr>
<tr>
<td>Long wave</td>
<td>3.0</td>
<td>694</td>
<td>50</td>
<td>0.2</td>
</tr>
</tbody>
</table>
11.2.3 Optical properties/IR reflection

When infrared waves hit a material they are reflected $r$, transmitted $t$ or absorbed $\alpha$ (see Fig. 11.3). The amount of radiation absorbed by a grey body is termed the absorptivity $\alpha$ and is numerically equal to the emissivity. Radiation, which is not absorbed, is reflected and this is expressed as the reflectivity $1 - \alpha$. The amount of absorbed energy, and hence the degree of heating, varies from zero to complete absorption. This is determined by the components of food, which absorb radiation to different extents, and the temperature of the source determines the wavelength of infrared radiation. Higher temperatures produce shorter wavelengths and greater depth of penetration. The net rate of heat transfer to a food therefore equals the rate of absorption minus the rate of emission:

$$Q = \varepsilon\sigma A(T_1^4 - T_2^4) \quad [11.5]$$

where $T_1$ (K) is the temperature of emitter and $T_2$ (K) the temperature of absorber.

The absorbed waves are transformed to heat and the temperature of the material increases. When the waves penetrate the material the vibrations and rotation of the molecules are changed. The two fundamental vibrations that occur are stretching and bending. Stretching means a decrease or an increase of the distance between atoms and bending means a movement of the atoms. When the infrared light hits a molecule, energy is absorbed and the vibration changes. When the state of the molecule returns to the absorbed, energy will be transformed to heat (Fig. 11.4).

The infrared absorption properties of foodstuffs are not as easy to describe. Regular reflection takes place on the surface of a material and is approximately 4% for most organic materials. In the case of body reflection the light enters the material, diffuses because of the scattering, and undergoes some absorption (Dagerskog 1978). Regular reflection produces only the gloss or shine of the material.

Fig. 11.3 The total energy ($E$) is either reflected ($r$), absorbed ($\alpha$) or transmitted ($t$).
polished surfaces while body reflection produces the colour and patterns that constitute most of the information we obtain visually. For materials with rough surfaces, both regular and body reflection will become diffuse. The reflection at short wavelength ($\lambda < 1.25\mu m$) is generally high, approximately 50% and at longer wavelengths is long: less than 10%. It is important to remember this fact in order to choose the right type of infrared radiators. The actual reflection has to be measured for each foodstuff at different stages of the process and translated into what it means at the actual lamp distribution when calculating heat transfer.

The penetration properties are important for optimising the system. The penetration depth is defined as 37% of the unabsorbed radiation energy. For short waves, the penetration ability is ten times higher than for long waves. The

**Table 11.2** The calculated penetration depths for crust and crumb for radiators used in baking ovens (Skjöldebrand et al. 1988)

<table>
<thead>
<tr>
<th>Power level (%)</th>
<th>Maximum energy wavelength</th>
<th>Spectral range (nm)</th>
<th>Penetration depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Crumb</td>
</tr>
<tr>
<td>100</td>
<td>1300</td>
<td>800–1250</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1250–2500</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>800–2500</td>
<td>1.9</td>
</tr>
<tr>
<td>75</td>
<td>1320</td>
<td>800–1250</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1250–2500</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>800–2500</td>
<td>1.9</td>
</tr>
<tr>
<td>50</td>
<td>1410</td>
<td>800–1250</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1250–2500</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>800–2500</td>
<td>1.8</td>
</tr>
</tbody>
</table>

**Fig. 11.4** Molecular vibrations.
The direct penetration ability of infrared radiation makes it possible to increase the energy flux without burning the surface and thus reduce the necessary heating time that conventional heating methods require. This is especially true for thin products. In a special study a method was developed to determine optical properties of bread at different degree of baking (Skjöldebrand et al. 1988). The results were that the transmission by the crust is less than the crumb. Even the thinnest dough sample did not transmit any radiation.

Reflection curves for crust and dough are very similar while the reflection for the crumb is about 10–15% less. Table 11.2 shows calculated penetration depths for crust and crumb for radiators used in baking ovens. Measurements have been carried out for other foods and Table 11.3 shows some examples (Dagerskog and Österström 1979).

| Product | Radiation source $\lambda_{\text{max}} /\mu m$ | Penetration depth | Wavelength range $\mu m$ | $\lambda < 1.25$ | $1.25 < \lambda < 1.51$ | $\lambda > 1.51$
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Potato</td>
<td>1.12</td>
<td>4.76</td>
<td>0.48</td>
<td>0.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potato</td>
<td>1.24</td>
<td>4.17</td>
<td>0.47</td>
<td>0.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pork</td>
<td>1.12</td>
<td>2.38</td>
<td>0.28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bread</td>
<td>1.12</td>
<td>6.25</td>
<td>1.52</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

11.3 Technologies

In IR heating, heat is transferred by radiation, the wavelength of which is determined by the temperature of the body – the higher the temperature, the shorter the wavelength. Present interest in industrial heating applications centres on short wave IR (wavelengths around 1 $\mu m$) and intermediate IR (around 10 $\mu m$), since these wavelengths make it possible to start up and reach working temperatures in seconds, while also offering rapid transfer of high amounts of energy and excellent process control. In some food materials, moreover, short wave IR demonstrates a penetration depth of up to 5 mm (see Section 11.1).

The best known industrial applications (for non-food uses) are in the rapid drying of automobile paint and drying in the paper and pulp industry (see Section 11.1). For paper drying IR has superseded microwaves because it offers superior process control and economy.

IR technology has long been under-estimated in the food field, despite its great potential. The main commercial applications of IR heating are drying low moisture foods (examples are drying of breadcrumbs, cocoa, flours, grains, malt, pasta products and tea). The technique is often used as one part of the whole process very often at the start to speed up the first increase of the surface.
temperature. Such processes are frying, baking and drying. Radiant heating is used in baking or roasting ovens and is also used to shrink packaging film.

In a recent search in the literature it was found that there is some use of the IR technique on drying of fish products (Wei-Renn-Lein and Wen-Rong-Fu 1997). A lot of research in recent years has been done in Taiwan, China and Japan (Afzal and Abe 1998; Wen-Rong-Fu and Wei-Renn-Lien 1998). They have studied drying of fish, drying of rice, rice parboiling and potato.

The basic characteristics of infrared radiation are the high heat transfer capacity, heat penetration directly into the product, fast regulation response and good possibilities for process control. These qualities indicate that infrared radiation should be an ideal source of energy for heating purposes. As distinguished from microwave heating the penetration properties are such that suitable balance for surface and body heating can be reached which is necessary for optimal heating (see Section 11.1). Some empirical work in this field can be found in the literature by, for example, Ginzburg (1969). Suggestions have been made that radiant heating elements should be operated at temperatures between 1200 and 1800°C as only wavelengths longer than 2 μm are effective in developing colour. Successful results have been reported for several frying applications (Dagerskog 1978). Asselberg et al. (1960) used quartz tube heaters (1000–1300°C) at 2.2 W/m² for braising of beef stew. For the parboiling procedure, for a similar degree of heat treatment as compared with conventional technology, the infrared treatment required a shorter time (83%) with lower weight losses (50%). The flavour, colour and texture of the infrared braised meat were claimed to be superior.

An industrial process for pre-cooking of bacon in a continuous infrared oven at Swift & Company has been investigated by Hlavacek (1968). Electric resistance heaters below the seamless stainless steel belt supplemented the 288 kW of infrared radiant heating from overhead quartz lamps. The frying time was 2–3 minutes and pre-cooked bacon was found to taste as good or better than freshly fried bacon.

Several studies have been reported by Soviet investigators concerning the frying of meat with infrared radiation, but the only work published in English is that of Bolshakov et al. (1976) on the production of baked pork meat products. By analysing transmittance spectrographs of lean pork they showed that the maximum transmission of infrared radiation is for the wavelength region of 1.2 μm. For wavelengths longer than 2.5 μm the transmission was negligible. Consequently, it is necessary to use sources with the maximum radiation falling in the region of maximum transmission to achieve deep heating of pork. For heat treatment of the pork surface radiators in the region of maximum transmittance and reflectance (λ_{max} > 2.3 μm) must be used. The authors therefore designed a two-stage frying process. In the first stage surface heat transfer was bought about by a radiant flux with λ_{max} at 3.5–3.8 μm. In the second stage the product was subjected to an infrared radiation flux with λ_{max} at 1.04 μm providing deep heating of the product. The result showed that the final moisture content and sensory quality of the product heated by the two-stage process were higher than those heated by conventional methods.
The effect of radiation intensity (0.125; 0.250; 0.375 and 0.500 W/cm² and slab thickness (2.5, 6.5 and 10.5 mm) on moisture diffusion coefficient of potato during far IR drying have been investigated by Afzal and Abe in 1998 in Japan. They found that the diffusivity increased with increasing radiation intensity and with slab thickness. In contrast activation energy for moisture desorption decreased with increasing slab thickness and resulted in higher drying rates for slabs of greater thickness. In Taiwan also far IR has been used for dehydration of fish. Over 90% of the far IR dried products had higher quality than currently marked sun dried product (Wei-Renn-Lein and Wen-Rong-Fu 1997).

11.4 Equipment

IR ovens or equipment of various sizes and constructions have been developed and tested in many countries. The main component – the radiator – may be of various types and shapes.

Early tests with tube heaters revealed that successful radiant cooking required both the quality and quantity of energy used should be suitably balanced. As described in Section 11.2.1 the radiators may be divided into the following main groups:

1. Gas-heated radiators (long waves)
2. Electrically heated radiators
   – tubular/flat metallic heaters (long waves)
   – ceramic heaters (long waves)
   – quartz tube heaters (medium- and short wave)
   – halogen heaters (ultra short waves)

Various reflector systems are also used (see Fig. 11.5) (Hallström et al. 1988):

- individual metallic/gold reflectors
- individual gilt twin quartz tube
- flat metallic/ceramic cassette reflector.

Some of the high intensity radiators need water or compressed air cooling to avoid overheating. Table 11.4 shows the infrared emitter characteristics.

IR equipment may be either of batch or continuous type. The radiator cassettes are positioned above the transport belt, which usually are wire mesh as indicated in Fig. 11.6. Some equipment also uses IR heating from below if the product allows this from a contamination point of view. The equipment shown in Fig. 11.7 has been used in reheating and frying in catering, utilises individual pans for the product to avoid fat dripping. In other equipment the IR system is combined with air convection to control the surrounding air temperature and humidity. On most equipment the degree of heating is controlled by thyristor systems. The simplest way is to use pure on/off systems where the number of radiators/tubes operating at any one time is controlled by switches. Advantages
Fig. 11.5  (a) Individual reflector (b) Individual gilt twin quartz tube (c) flat metallic ceramic cassette reflector.

Fig. 11.6  Continuous process infrared oven.

Fig. 11.7  Infrared oven in which heating is from above and below the product: this oven utilises individual pans for the product.
<table>
<thead>
<tr>
<th>Type of emitter</th>
<th>Maximum running temperature (°C)</th>
<th>Maximum intensity (kW/m²)</th>
<th>Maximum process temperature (°C)</th>
<th>Radiant heat (%)</th>
<th>Convection heat (%)</th>
<th>Heating-cooling time (s)</th>
<th>Expected life</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Short wavelength</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat lamp</td>
<td>2200</td>
<td>10</td>
<td>300</td>
<td>75</td>
<td>25</td>
<td>1</td>
<td>5000 h</td>
</tr>
<tr>
<td>IR gun</td>
<td>2300</td>
<td>2</td>
<td>1600</td>
<td>98</td>
<td>2</td>
<td>1</td>
<td>–</td>
</tr>
<tr>
<td>Quartz tube</td>
<td>2200</td>
<td>80</td>
<td>600</td>
<td>80</td>
<td>20</td>
<td>1</td>
<td>5000 h</td>
</tr>
<tr>
<td><strong>Medium wavelength</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz tube</td>
<td>950</td>
<td>60</td>
<td>500</td>
<td>55</td>
<td>45</td>
<td>30</td>
<td>Years</td>
</tr>
<tr>
<td><strong>Long wavelength</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Element</td>
<td>800</td>
<td>40</td>
<td>500</td>
<td>50</td>
<td>50</td>
<td>&lt;120</td>
<td>Years</td>
</tr>
<tr>
<td>Ceramic</td>
<td>700</td>
<td>40</td>
<td>400</td>
<td>50</td>
<td>50</td>
<td>&lt;120</td>
<td>Years</td>
</tr>
</tbody>
</table>
of microcomputer control systems over convection ovens include:

- very short heating time
- fast heating due to penetration of radiation into the product
- easy to pre-program and regulate the heating cycle for different products
- high energy efficiency.

At SIK, the Swedish Institute for Food and Biotechnology, two types of equipment were tested. The first one was built by Infrared Teknik in Sweden. This equipment was constructed as a baking oven. It was $4.3 \times 1 \, \text{m}$ (see Fig. 11.8), continuous, i.e. it had a conveyor that transported the bread through the

![Fig. 11.8 Infrared Teknik oven.](image)
oven, and the speed of the conveyor could be varied, and the oven is divided into three zones with different effects of IR radiators. All the lamps installed are of short waves. The lamps were placed in cassettes that in turn were placed both above and under the conveyor. The total input was 125 kW and this was distributed in the three zones as follows:

<table>
<thead>
<tr>
<th>Zone</th>
<th>Cassette above kW</th>
<th>Cassette under kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>32</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>8</td>
</tr>
</tbody>
</table>

The radiators at the top are placed at an angle to the conveyor belt so the radiation falls on the side of the bread.

Each radiator can be switched on or off separately. The IR effect and the speed of the conveyor can be varied and controlled from the control panel. The top cassette can be regulated to have different distances between the product and the radiators. The distance is varied between 24 and 41 cm. The cassettes below the product are at a distance of 18 cm and the baking time can be varied between 2 to 30 minutes. There is a steam zone before the radiating zones. The oven has been used for baking in a bakery as well as in the laboratory.

The second baking oven was built by a Swedish company (TRIAB = TRI Innovation AB) in collaboration with SIK (see Fig. 11.9) (Skjöldebrand and Andersson 1987). The oven is semi-continuous, which means that the bread is transported on a conveyor into the oven chamber. The conveyor stops during the baking procedure. The oven has two cassettes, which have 24 radiators each. One of the cassettes is placed at the bottom and one at the top of the oven. 12 of the 24 radiators emit electromagnetic waves mainly within the medium range of the infrared spectrum and 12 within the short wave range. The size of the oven cabinet is 1800 mm × 500 mm. A fan is placed in one of the walls, which makes it possible to combine the infrared heating with convection. The air temperature can be varied between 90°C and 300°C and the air velocity between 0 and 2 m/s.

Fig. 11.9 The research oven at SIK.
The maximum temperature of the short wave radiators is 2228 K which corresponds to a $\lambda_{\text{max}}$ of 1.3 $\mu$m. The corresponding temperature for medium infrared radiation is 1113 K which corresponds to a $\lambda_{\text{max}}$ of 2.7 $\mu$m. Also the power level per unit surface area can be varied continuously between 0 and 100%. The wavelength distribution of the short wave radiators and the corresponding power are shown in Fig. 11.10.

The cassettes can be moved to create different distances between product and radiator. The parameters that can be varied are wavelength, level of power, air velocity and temperature. A computer-based system is connected to the oven, which will aid in giving reproducible experiments. Similar equipment from the same manufacturer is sold to the food industry. These often form only part of the process, for example the first step in a biscuit-baking process or in a meat frying process.

### 11.5 Applications: case studies and modelling

In this section some applications with the most important results will be summarised. Also some examples of modelling of the heating procedure will be described.

Most applications of IR within the area of food came during the 1950s to 1970s from the United States, the Soviet Union 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. More recently work has also been carried out in Japan, Taiwan and other countries. Most of this work is still of an experimental nature. Applications are mainly from the following areas.

![Wave length distribution of the lamps in the research oven.](image-url)

Fig. 11.10  Wave length distribution of the lamps in the research oven.
• drying of vegetables, fish
• drying of pasta, rice
• heating of flour
• frying of meat
• roasting of cereals
• roasting of coffee
• roasting of cocoa
• baking of pizza, biscuits and bread.

The technique has also been used for thawing, surface pasteurisation of bread and pasteurisation of packaging materials.

11.5.1 Baking

When baking with irradiation it seems that short-wave radiators should be used. The short-wave infrared radiation may be combined with convection for drying out the surface with good results.

Ginzburg divided the baking process using infrared radiation into three periods:

• The first phase is characterised by an increase of the surface temperature (1–2 mm) to 100°C. Very little weight loss occurs during this period.
• The second period is characterised by the start of mass transfer. An evaporation zone forms, which moves towards the central parts. Energy is used to evaporate water and to heat the dough.
• In the third and final period the central parts have reached 90°C and the temperature increases further about 8° at the end of baking. The duration of this period amounts to about 25% of the total time of baking.

When comparing time-temperature relations between infrared radiation and conventional baking it is clear that IR radiation is more efficient both at the surface parts and the central sections.

Using the baking oven at SIK mentioned in Section 11.4, the following results were achieved using short wave infrared heating (Skjödebrand et al. 1994):

• the baking time was 25–50% shorter compared to an ordinary baking oven, depending on the thickness of the product
• energy consumption was comparable to ordinary baking
• weight losses were 10–15% lower
• quality was comparable.

These results show that infrared heating for bakery products is very promising compared to other heating techniques.

Further studies at SIK have shown that baking of bread using the short-wave infrared heating technique is a very interesting alternative to traditional baking (Skjödebrand and Andersson 1987). The baking time can be reduced by 25%
but in some cases 50%. The reduction depends on the thickness of the product. This is due to penetration of the waves into the product. The penetration properties of the bread change during baking: at the start they are almost zero and the crust has poorer penetration depth than the porous water-rich breadcrumb. The baking time reduction is also due to the more effective heat transfer to the surface than convection or conduction heating. Using short wave infrared radiation may reduce the weight losses. In some of the experiments it was found that the water content in the centre had increased during baking causing better and longer storage. The sensory quality does not seem to be poorer for bread baked in an infrared oven.

The advantages of using short wave infrared radiation were found to be

- high and effective heat transfer
- heat penetration/reduction of baking time
- no heating of air in the oven
- quick regulation and control
- compact and flexible ovens.

11.5.2 Mathematical modelling

Several attempts have been made to model infrared heating of foods. To calculate temperature distribution during combined infrared and convection heating, the heat conduction equation was solved using the finite difference method where the material is divided into a number of layers. For calculation of heat generated by infrared radiation an exponential penetration was assumed. The following discussion shows the principal equations of the finite difference solution to the heat transport by combined conduction and infrared radiation.

The first attempt to find a mathematical model for infrared heating was done by Dagerskog (1978). Skjöldebrand and Falk (1990) made some further developments to the program. The computer program enables us to simulate the time-temperature relation at different points in the food process. Radiation can be combined with convection in the program. The program was developed using the American developed scientific software called ‘Asyst’ originally developed for use in datalogging. The program calculates the temperature distribution in heated foods by solving the heat conduction equations using a numerical method based on the finite difference technique.

Theories and basic equations are developed for surface temperature, centre temperature and temperatures in the product between surface and centre. Since no pure conduction occurs, so-called effective or apparent thermal properties have been used. Energy balances are used for the calculations. Three different energy balances are made up for the following volume increments:

- at the surface of the product
- in the product
- in the centre.
The program consists of three main parts:

1. initiation of the calculations
2. calculations
3. results of the calculations.

The program was tested on three cases:

1. baking in conventional ovens
2. baking using short wave infrared radiation
3. grilling of meat.

The results for baking in a short wave infrared oven were that it was possible to simulate the temperature and these showed the same tendency as the ones measured, but the values are somewhat lower. The explanation for the deviation is complex since there could be errors in the thermal properties as such, but also other assumptions such as the volume changes in time or temperature of the thermal properties and the chain in the rate of heat transfer during the baking. For grilling it was easier to simulate the temperature curves as no calculation is needed for the surface thermal properties. The air temperature rose to quite a high level, no crust was formed on the meat and the surface temperature was below 100°C.

Skjöldebrand et al. (1994) looked at the ratio between the radiate and the convective heat transfer of the total heat flux under different process conditions in a baking oven. Bread and a ‘dummy’ food were studied. An energy balance was set and the time-temperature relation was studied. It was found that

- it is appropriate to assume that the radiate energy at low temperatures (100–150°C) is transferred to the product at an infinitesimal surface layer
- the radiate heat transfer coefficient was 16–43 W/m²K at the radiant source temperature of 250 and 370°C.
- the proportion of radiate to convective energy is correlated to time more than correct surface temperature
- the ratio of radiation and convective heat transfer (free or forced) ranges from 0.65 to 8. The convective coefficient ranges from 5–10 (free) to 30–40 W/mK
- for dry bread the proportion of radiation to total amount of energy is 53% to 83%
- attempts to simulate the temperature inside the bread with the developed model did not give any satisfactory results.

### 11.6 Future trends

I will describe future developments on infrared heating in the following vision of the future. Let us visit a small town in Europe in the year 2003. Both households and small companies are located in the town. One of the companies is a small enterprise called 'Local Food'. It produces fresh bread and convenience foods based on bread. About 400 different articles are produced. The products are
distributed to households close to ‘Local Foods’, i.e. the country where the production is carried out. The products are filled French rolls, crepe, and pies pizza. New products are developed now and then. These new products are often developed based on the technique used, available raw material properties and wanted product properties. The company has just started producing ‘functional foods’ based on bread and fillings. The customers can buy and order their food via the Internet. The ordered product will be sent out at the time the customer has indicated. If he/she wants something special this is possible. The order goes directly to the production computer that controls the processes.

The production unit is fully automated and the process line is based on flexible automation and is tailor-made to the product to be produced. New heating techniques like short wave infrared radiation and microwaves are used frequently and where it is appropriate. The aim is minimal processing based on knowledge about wanted product properties and its interaction with the processes. A computer is installed to provide decision support for the operator. It is possible to trace components or foreign substances throughout the whole production line. Sensors on-line are installed to measure product properties and feed forward process control is used. When the product is ready, the processes stop and the product is sent to the customer. The operators have good knowledge about their processes.

This scenario shows the different developments that are reality in present time and will influence the future application of, for example, infrared heating techniques. To be able to fulfil this scenario the following are important points for future developments.

- More knowledge about the interaction between processes and products needs to be gained. The relationship between raw material properties and how these are affected by the process to obtain the desired properties in the end product should be studied. These are necessary for the success of using new techniques like NIR or short wave infrared heating equipment.
- IR heating should be particularly useful for continuous baking, drying and grilling as well as for surface pasteurisation.
- As different heating techniques have their own limitations, areas of application and possibilities, good background knowledge may combine these in an optimal way. More knowledge is important for the success of the heating technique.
- The use of IR technology in the food industry today is quite limited, and the available equipment is not optimised for the various heating operations along the processing lines for baking, drying, etc. Its application is certain to grow as food equipment manufacturers begin to realise its full potential.
- Along with the development of process control and information technology the IR technique will show its full potential with fast regulation of radiators and rapid heat transfer.
- IR heating certainly will fulfil its role in the requirement of flexible production units.
With the development of new products the heating technique used will be important. New flavours can be created via both the recipe and the heating technique.

11.7 References


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