Journal of Food Engineering 104 (2011) 571–576

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

The effect of moisture content on short infrared absorptivity of bread dough

Tzvetelin Dessev *, Vanessa Jury, Alain Le-Bail

ONIRIS – GEPEA – UMR CNRS 6144, BP 82225, F-44322 Nantes Cedex 3, France

ARTICLE INFO

Article history:
Received 11 July 2010
Received in revised form 29 November 2010
Accepted 19 January 2011
Available online 28 January 2011

Keywords:
Infrared
Baking
Absorptivity

ABSTRACT

The main objective of the study was to assess the influence of moisture content on short infrared absorptivity of bread dough. Weight loss, surface temperature and short to medium infrared absorptivity of dough were measured in a series of radiant heating experiments. A strong positive correlation between surface temperature and total heat flux absorbed by the dough samples was observed. The variation of infrared absorptivity of the dough is explained with the state of the water in the samples – vapor or liquid.

1. Introduction

The development of innovative baking process (Patel et al., 2005; and Skjöldebrand et al., 1988) addresses the use of different heating technologies as described by Sumnu et al. (2007). Microwave (MW), Infrared (IR), jet impingement (JET) are the most cited technologies. Radiating technologies are particularly interesting in heating operations as they allow immediate and significant energy input to the product to be processed. IR offers several advantages, when is used for heating of bakery products, in particular, the possibility to reach high heat flux and heating at distance with a better control than in the case of convective heat transfer. However, the high power density applied to the material can significantly alter the usual drying kinetics and bring about important processes (Salagnac et al., 2004). In the case of microwave, several properties have been identified and there are quite an abundant literature that describes the dependency of moisture and of the degree of baking on dielectric constant and dielectric loss factor (Ozmutlu et al., 2001; Sahin et al., 2002; Sumnu et al., 2007, 1999). Beside, the amount of literature available regarding IR technology is not so common. Infrared heating of foods have been studied by Ginzburg (1969); Il'yasov and Krasnikov (1991); Ratti and Mujumdar (1995); Sakai and Hanzawa (1994); Sandu (1986). Il'yasov and Krasnikov (1991) provided detailed discussion on infrared energy absorption in foods, but did not include energy or mass transport. Ginzburg (1969) and Datta and Ni (2002) applied an exponential decay model with a finite penetration depth and predicted temperature profiles for such infrared heating. They showed that resulting internal infrared heat dissipation had considerable effect on surface moisture content of the food. For the heat transfer only, Sakai et al. (1993) found no significant difference between two formulations of infrared absorption by foods – one with zero penetration depth and the other with finite penetration depth.

Baking of bread using IR has been studied by several authors such as Keskin et al. (2004); Olsson et al. (2005); Skjöldebrand and Andersson (1987). Keskin et al. (2004) showed that short IR radiation combined to microwave can be used to bake bread with quality similar to conventional baking process. A halogen lamp was used as IR emitter. However, increasing the halogen lamp power reduced specific volume and increased weight loss, firmness and total color difference of the crust. Additionally, Skjöldebrand et al. (1988) found that as energy levels increase too high white spots occur on the bread surface, due to ungelatinized starch. Also, big pores or even holes in the crumb can occur when too high energy levels are used in a baking oven based on infrared heating. However, as there is a fast response when changing energy levels, the heat transfer may be controlled to get an optimized color on the bread surface.

It has been found that dough-based products baked by means of IR radiation have better textural qualities, have a thinner crust and a finer crumb structure which are characteristics that can be desirable for some consumers. Skjöldebrand and Andersson (1987) and Skjöldebrand et al. (1988) reported that using shortwave infrared radiation may reduce weight losses and increase volume compared to a conventional oven. The products tested were sweet rolls, buns, baguettes, white bread loaves and rye bread loaves. In some of the experiments they found that the water content in the centre of the products had increased during baking, resulting in a prolonged shelf life.

In the case of IR heating, the efficiency of the heat treatment depends on the amount of energy effectively transferred to the food

* Corresponding author.
E-mail address: dessev@mail.bg (T. Dessev).

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doi:10.1016/j.jfoodeng.2011.01.019

Nomenclature

Roman letters

E	energy emitted (W m^{-2})
F_{ij}	view factor (dimensionless)
I_0	incident radiant flux intensity (W m^{-2})
J	radiosity (W m^{-2})
$\dot{q}$	heat flux (W m^{-2})
T	temperature (K)

Greek letters

α	absorptivity (dimensionless)
ε	emissivity (dimensionless)
λ	wavelength (μm)
ρ	reflectivity (dimensionless)
σ	the Stefan–Boltzmann constant, $\sigma = 5.669 \times 10^{-8}$ W m^{-2} K^{-4}

stuff. It is known in the art that when making a determination as to whether to use IR radiation to heat food, it is necessary to first determine which wavelength band is most efficiently absorbed by food being heated. The absorbance of the food depends on several parameters such as the wavelength, specific surface characteristics, moisture content, chemistry composition and physical properties. In the case of bakery products, the moisture tends to decrease during the baking process, which results in a complex situation. The evaluation of the absorbance of a given food stuff toward IR radiation can be done with a spectral approach (at selected wavelength) or globally as a total absorbance. Shortwave radiation is expected to reach high specific power due to a higher depth of penetration. However, the reflection can be higher than in the case of long-wave radiation especially in the case of white surface. The balance has to be found between the reflection and the absorbance to control the amount of heat (heat flux) that is transferred to the food surface. There is controversy in the literature regarding the absorbance of radiation in function of the wavelength. Some authors Skjöldebrand et al. (1988); Lentz et al. (1995) found that the depth of penetration was higher for short vs. long IR, whereas the opposite was observed by Cavada and Noriega (2008). Salagnac et al. (2004) reported that in the case of an opaque porous material, the penetration depth reaches just a few microns for the tested wavelength range of 0.8–10 μm. Some authors reported that the most suitable wavelength band for deep heating of a dough-based product is the band 0.8–1.3 μm (Lentz et al., 1995). Skjöldebrand et al. (1994) reported that only wavelengths longer than 2 μm are effective in developing of crust coloration.

The penetration depth of infrared energy, like that of the microwave is primarily a function of the moisture content and of the wavelength. If the infrared penetration depth is high, infrared energy is absorbed quite similar to microwave energy and thus moisture accumulation at the food surface, caused by the pressure-driven flow exists (Datta and Ni, 2002). The heat and mass transfer modeling of Parroufe et al. (1992) and Fasina et al. (1998) considered all infrared energy to be absorbed at the surface, i.e., no penetration into material and noted that infrared had no special influence beyond increased heat flux, as compared to convective heating. However, in the literature there is a lot of information indicating that infrared radiation can penetrate significantly into the material. Such penetration can have dramatic effect on moisture migration toward surface.

The optical properties of bread in the near infrared range were measured by Skjöldebrand et al. (1988) and Skjöldebrand and Andersson (1987). They found that the penetration properties of bread change during baking. At the start they indicated that the penetration depth is close to zero, with the crust having poorer penetration depth than the porous water rich crumb. The penetration depth into the crust was 2.5 mm for the spectral range 0.8–1.25 μm, and 0.6 mm for the spectral range 1.25–2.5 μm. The penetration depth into the crumb was 3.8 mm for the shorter wavelength region, and 1.4 mm for the longer wavelength region.

The literature review has evidenced the lack of data on the total absorbance of IR by bread dough with different moisture content. The present study aims at evaluating the total absorbance of bread dough with respect to short and medium infrared wavelength.

2. Materials and methods

2.1. Dough formulation

A bread dough was prepared using soft wheat flour supplied by Moulins Soufflet Pantin – Pornic, France with the following characteristics: 0.53% ash content, 14% moisture, 10.58% protein on dry matter, falling number 402 s, Zeleny 38, alveograph parameters W = 183, Pm/L = 0.62. The composition of the dough was formulated on a flour weight basis : for 100 g flour, 2 g salt (sodium chloride – Esco, Levallois-Perret, France S.A.) and 1 g improver comprising a mix of alpha-amylase, vital gluten (confidential proportion – PURATOS – Groot-Bijgaarden – Belgium). The amount of water was adjusted at selected levels to mimic different dehydration of the dough during baking. Dough hydration levels of 75, 52 and 16 (in g water for 100 g of flour) were used corresponding to 1.0 (50% wb), 0.74 (43% wb) and 0.34 (25% wb) g of water per g of dry matter. No yeast was added to prevent fermentation and expansion of the dough during the test. Ingredients were mixed in a SP10 spiral mixer (VMI, Montaigu, France) for 2 min at 100 rpm and 7 min at 200 rpm. At the end of the mixing, dough temperature was controlled and found to be between 18 and 20 °C. Dough was then rested (15 min) and was chilled at 4 °C to prevent any biochemical reaction before testing. A small layer of dough was sampled from the dough pieces and was laminated using a roller until a thickness of 2 mm was reached. The dough sheet was folded and a heat flux sensor 30 × 30 × 0.4 mm with sensitivity of 7.56 μV/(W m^{-2}) (Captec, France) was installed between the two dough sheets as shown in Fig. 1.

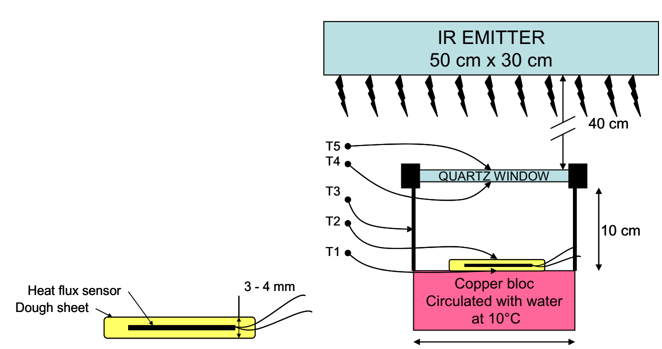

Fig. 1. Folded dough sheet with the heat flux sensor embedded inside the dough piece and scheme of the system used to measure the effective absorbance of dough vs. IR emitter.

2.2. Radiative heat transfer

Radiative properties of foods depend on the wavelength of radiation incident on the food, which in turn depends on the emission characteristics of the source of the radiation. Thus, it is important to know the characteristics of common sources (emitters) used for thermal radiation. A halogen lamp provided by Heraeus (Heraeus, Germany) was used as a radiation source. The bulb of the lamp was made of quartz and a gold reflector was installed in the upper part of the bulb to reflect the radiation emitted by the filament. The nominal peak wavelength of the bulb was 1.35 μm, according to the Heraeus specifications, corresponding to a temperature of the filament of 2147 K (first Wien's law) and nominal power of 2500 W. Three lamps spaced of 5 cm were installed in a metallic bloc that was refrigerated by a fan (system designed by Heraeus). A power rheostat was used to control the power emitted by the lamps. Four power levels were chosen (1100, 1800, 2500 and 3200 W) which result in four different peak wavelengths (1.62, 1.45, 1.35 and 1.27 μm) according to the Heraeus specifications. The lamp assembly was placed above the system that was used to measure the absorbance (Fig. 1). A copper bloc (10 cm diameter) was circulated by water at 20 °C. The dough assembly was contacted onto the surface of the copper bloc which was gold plated. The system was surrounded by a steel cylinder painted in black (internally) and coated with aluminum foil (externally) to act as a reflector toward external radiation. A sapphire window was installed on the systems' top. The sapphire window (single-crystal aluminum oxide Al_2O_3) is known to be transparent to the short infrared radiation but opaque to the long one. The heat flux signal delivered by the sensor as well as 5 temperatures (T_1–T_5), as shown in Fig. 1, were logged during each experiment (SA32 Data Logger – AOIP – France). The temperature of the different surfaces in the baking chamber of the experimental set up (Fig. 1) was measured by calibrated miniature *T*-type thermocouples with a sensitivity of ±0.3 °C (Omega Engineering, USA). The surface temperature of the dough samples (T_2) was measured by a miniature thermocouple inserted just under the surface of the sample (approximately 0.7 mm below the surface). Special attention was paid to ensure the right position of the sensor, as this greatly affects the temperature measured. This experimental set up allows the determination of the absorbance of the dough with respect to radiation emitted by the bulbs in well defined conditions. One of the advantages of the system is that the dough was maintained at quasi constant moisture thanks to the confinement ensured by the window and the walls. However, moisture loss of the dough was checked before and after each experiment using a scale with 0.05 g sensitivity (Sartorius, France).

When the material is considered opaque to radiation, the assumption is that the impinged radiation which is not reflected is converted to heat at the surface according to the Stefan–Boltzmann law (Sandu, 1986). According to Skjöldebrand et al. (1988), who reported that even the thinnest dough samples (2 mm) do not transmit any infrared radiation, the transmission through the dough in our calculations was assumed as negligible.

The total infrared absorptivity of bread dough in our study is calculated as the fraction of the incident radiation that is absorbed by the sample:

$$\alpha_{calc} = \frac{MHF_{dough}}{THF(I_0)} \tag{1}$$

where: MHF_{dough} is the measured total heat flux inside the dough by the inserted heat flux sensor, (W m^{-}2); THF (I_0) is the total incident radiation (irradiation) on the surface of the dough, (W m^{-}2).

The net heat flux effectively transmitted through the sapphire window was previously measured using a heat flux sensor painted in black and mounted on a copper bloc circulated by water at 20 °C (Fig. 1).

As the internal surfaces of the experimental set up are heated, they emit a long-wave infrared radiation. Therefore, an exchange of long-wave infrared radiation between the surface of the sample and the interior of the baking chamber exists during heating. The net long-wave radiative flux delivered to the product being baked should be taken into account when considering the short infrared absorbance. According to Fig. 1, which represents our pilot system, the measured total heat flux MHF_{dough} must be corrected to take into account the long-wave radiation emitted by the heated interior surfaces, which include – sapphire glass (surface 4), steel cylinder (surface 3), dough sample (surface 2) and gold coated copper block (surface 1). For this purpose a mathematical model of the system was used in order to recalculate the long-wave infrared radiative exchange. The measured total heat flux MHF_{dough} is defined as:

$$MHF_{dough} = NHF_s + NHF_L, \tag{2}$$

where, NHF_S – net short-wave radiative flux, (W m^{-2}); NHF_L – net long-wave radiative flux, (W m^{-2}).

The net long-wave radiative flux is calculated using Eqs. (3) and (4). For this purpose the radiosity method was applied to the closed loop system (Fig. 1) (considering the sapphire glass as opaque to long-wavelength radiation) and the radiosity of each surface was calculated using Eq. (5), according to the procedure given from Lienhard (2006) and Mohammed (2006).

$$\dot{q}_1 = \epsilon\sigma T^4 - \alpha E \tag{3}$$

or

$$\dot{q}_j = \frac{\epsilon_j}{1-\epsilon_j}(\sigma T_j^4 - J_j) \tag{4}$$

$$J_i = E_i + \rho \Sigma J_j F_{ij} \tag{5}$$

where, J_i is the radiosity of surface *i*, E_i the emitted energy of surface *i*, ρ the reflectivity of surface *i*, J_j the radiosity of surface *j* and F_{ij} the view factor of surface *j* relative to surface *i*. Excel Visual Basic macro, based on inversion of the matrix of a system of radiosity equations was used according to Mohammed (2006). Once the mathematical model has been formulated and solved, the experimental results need to be corrected in term of the short infrared absorptivity of the bread dough (Eq. (6)). Corrected values of the absorptivity were approximately 4–5% lower than the experimental ones.

$$\alpha = \frac{MHF_{dough} - NHF_L}{THF(I_0)} \tag{6}$$

For calculation of radiative heat transfer the parameter that is mainly used is the total hemispherical emissivity. Spectral emissivity measurements are difficult and require great care. This is largely because there are so many factors that can influence a measurement, among them: temperature measurement (sample surface, blackbody), temperature control (uniform, stable temperatures), low signal-to-noise and possible material sample variability. Moreover the emissivity coefficient for some materials varies with their temperature. All this leads to a complex situation with determination of the exact coefficients. The surface temperature and emissivity for each element (surface) used in the radiosity calculations are represented in Table 2. The emissivity coefficients for the different surfaces that we used in the calculations (Table 2) were gathered from a bibliographic survey (Lienhard, 2006).

2.3. Statistical analysis

All experimental data reported in this work were triplicated, and data are expressed as the mean ± standard deviation of the mean. Data were subjected to analysis of variance (ANOVA) and mean comparisons at 5% significance level. Statistical analysis was performed using Microsoft Excel 2007. Correlations among variables were assessed by means of the Pearson's correlation test. Determination coefficients are reported.

3. Results and discussion

Dough samples with different moisture content were used in a series of radiant heating experiments designed to test the total absorbance of short infrared by bread dough. Surface temperature, total heat flux and weight loss were measured for a range of radiant flux intensities. Statistical analysis (ANOVA) was performed to study the individual effect of the incident radiation and initial moisture content of the dough samples on their surface temperature and delivered heat flux inside. ANOVA revealed that these effects were significant ($p < 0.05$) at the 5% significance level. Additionally, ANOVA was applied to study the effect of these factors on the weight loss of the dough during baking. The analysis showed that the irradiation level (I_0) has statistically significant effect ($p < 0.05$) on the weight loss, at the 5% significance level, while the other factor (initial moisture content of dough) is significant ($p < 0.05$) just in case of higher irradiation levels ($I_0 = 4600\ W\ m^{-2}$ and $I_0 = 5500\ W\ m^{-2}$, Fig. 3).

As the heating started, the temperature of the dough surface increased rapidly and then leveled off to approach slowly a constant value (Fig. 2). A similar tendency is reported by Datta and Ni (2002), Tanaka et al. (2007), Sumnu et al. (2005) and Salagnac et al. (2004). The samples that were exposed to an infrared flux of 5500 W m^{-2} reached a surface temperature of 100 °C after 200 s of heating and these exposed to infrared flux of 1050 W m^{-2} reached a final temperature of 40 °C after 400 s (Fig. 2). Surface temperature increased steadily up to 100 °C for an incident flux of 5500 W m^{-2} followed by a slower heating rate with final reached temperatures of 110, 103, and 101 °C for dough samples with initial moisture content of 25%, 43% and 50% on wb, respectively. The highest dough surface temperatures corresponded to samples with the lowest moisture content (Table 1). The temperature differences among dough samples for a given incident radiation could be explained by the correlation that exists between surface reflection, surface moisture and surface temperature. The surface moisture affects the surface reflectance leading to changes in surface temperature. According to Dagerskog and Österström (1979), drier samples have larger dissipation coefficients, resulting in higher surface temperatures. Another explanation is that evaporating moisture from the dough facilitates cooling of the surface (evaporative cooling). Thus, the samples with higher moisture content and enhanced moisture loss (Fig. 3) have lower surface temperature (Table 1). Moreover, it is well known in the literature that water has much higher specific heat capacity than the dry matter of the dough. Dough samples with lower moisture content are therefore easier to heat, since less heat is required to change their temperature.

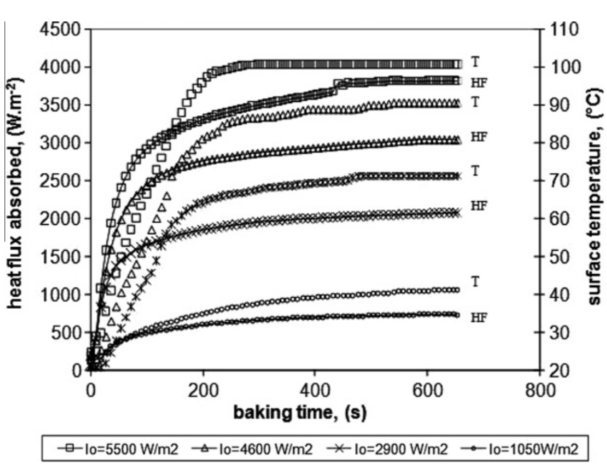

Fig. 2. Heat flux absorbed (HF) and surface temperature (T) of the samples vs. baking time (time of exposure to irradiation) for different irradiation levels I_0 (for a dough sample with 50% moisture content on wb).

Table 1
Dough surface temperature* (T_2 according to Fig. 1) and measured total heat flux inside the dough* (MHF_{dough}). These data were obtained after 10 min of baking.

Incident radiation, I_0, (W m^{-2})	Initial moisture content of dough on wb, (%)					
	25		43		50	
5500	110 °C	3950 W m^{-2}	103 °C	3837 W m^{-2}	101 °C	3784 W m^{-2}
4600	103 °C	3337 W m^{-2}	95 °C	3040 W m^{-2}	92 °C	2957 W m^{-2}
2900	79 °C	2081 W m^{-2}	74 °C	1976 W m^{-2}	72 °C	1915 W m^{-2}
1100	45 °C	745 W m^{-2}	42 °C	727 W m^{-2}	47 °C	760 W m^{-2}

*Values are mean of three determinations.

The surface temperature of the dough in our study did not reach 100 °C for lower incident flux levels. Since surface temperature did not reach 100 °C for some of the experimental sets, no crust was formed. In reality, moisture evaporates from samples despite the fact that the sample surface did not reach 100 °C. Moisture loss at temperatures below 100 °C has been observed in literature as a result of surface evaporation, diffusion, and pressure-driven flow (Datta and Ni, 2002; Fasina et al., 1998; Salagnac et al., 2004). According to their studies, high intensity radiant flux also leads to faster evaporation of moisture from the crust core interface, and compared with this mechanism of moisture loss, diffusivity and evaporation under 100 °C are negligible.

The rapid rise of the surface temperature significantly increases the saturation steam pressure and this in turn increases surface evaporation, as shown by Datta and Ni (2002), Salagnac et al. (2004). In our study the weight loss (an index of moisture loss) of the dough samples with different moisture content baked in the IR pilot oven increased linearly with the irradiation levels (Fig. 3), which is in agreement with the results reported by other researchers for heating in conventional, microwave, infrared and infrared – microwave combined oven (Sahin et al., 2002; Sumnu et al., 1999; Sumnu et al., 2005; Keskin et al., 2004). The weight loss corresponds to a quasi moisture equilibrium that was reached after some time (typically 10 min) from the start of the experiment. The moisture released by the sample was trapped in the cavity of the experimental system; after some time equilibrium was obtained between the dough sample and the moisture in the cavity, allowing the measurement of absorptivity in steady state conditions.

According to Datta and Ni (2002), as infrared penetration depth is increased, surface moisture increases due to the enhanced moisture transport to the surface. They assumed that liquid water reaching the surface from inside is due to the capillary-pressure effect and water vapor reaching the surface is due to diffusion-

Table 2
Surface temperature (°C) and emissivity (ε) of each element (surface) of the baking chamber (according to Fig. 1).

I_0, (W m^{-2})	Gold coated copper block (T_1) $\varepsilon = 0.1$	Steel cylinder (T_3) $\varepsilon = 0.98$	Quartz window-lower side (T_4) $\varepsilon = 0.9$	Quartz window-upper side (T_5) $\varepsilon = 0.9$
5500	20	140	160	150
4600	20	110	130	112
2900	20	77	90	88
1100	20	46	55	49

pressure combined effect. For low penetration depth infrared heat can reduce surface moisture and increase surface temperature; in this case, increasing infrared power flux facilitates surface moisture removal.

As can be seen from Fig. 3, the moisture loss increased with increased moisture content of the dough samples. The highest moisture losses of 14% and 12% were observed for samples with the highest initial moisture content (50% wb and 43% wb respectively) exposed to high irradiation (5500 W m^{-2}).

Infrared induces a surface heating and the heat diffuses inside the material. Once the radiant energy is converted to thermal energy according to Beer's law, conductive heat transfer occurs. In term of conduction, heat flux delivered to the dough interface depends on the temperature difference between the crust and crumb domains. The higher the difference in temperature, the higher the resulting heat flux. The effect of the incident radiation level on the delivered heat flux to the samples is shown in Fig. 2. The total heat flux inside the sample, caused mainly by the penetrating IR radiation and conductive heat transfer, ranged from 700 to 4000 W m^{-2} depending on incident radiation on the sample surface (Fig. 2). At lower incident radiation I_0 = 1050 W m^{-2}, the delivered heat flux and surface temperature were lower than those obtained at I_0 = 5500 W m^{-2}, where both were significantly increased ($p < 0.05$). These results show that the rate of increasing of the total heat flux inside the sample is very high during the first 60 s of baking. This is because the flux intensity primarily affects the surface temperature at the beginning of the baking process, resulting in high temperature gradient in the sample interface. For longer baking times (i.e., more than 200 s), the growth rate of the heat flux diminished and the heat flux finally leveled off. Higher incident flux resulted in higher heating rate, and higher final temperatures. After 10 min of baking, a final heat flux and surface temperature were reached for all irradiation levels (Fig. 2).

In general, the heat flux curves correlate with the surface temperature (Fig. 2). Statistical analysis was performed to determine if there was a correlation between each pair of heat flux delivered and dough surface temperature for a given irradiation level (Fig. 2 and Table 1). In all cases a strong positive correlation was observed ($R^2 > 0.85$).

The major dough components are protein, starch and water. These spectra have a number of absorption bands, and the bands are not clearly isolated. Not only do the protein bands overlap each other, but they overlap the starch bands. However, protein and starch absorb NIR radiation much more weakly than water (Williams and Norris, 2001). Throughout the infrared spectral region, water exhibits a strong absorption and weak scattering of radiation. The absorption bands are due to the presence of a hydroxyl group held through hydrogen bonding. According to Williams and Norris (2001), the main features of the water spectrum are the two absorption bands that peak at 1.43 and 1.94 μm. The last absorption band is isolated from the bands of the other absorbers.

The state of water also affects the interaction in the infrared range. Water molecules exhibit very different behavior in the vapor and liquid states. In vapor state, the molecules have enough energy to avoid intermolecular interaction and are therefore allowed to rotate. In the liquid state, the molecules are still in movement, but they do not have energy to avoid intermolecular hydrogen bonding and they are caused to vibrate. For liquid water, the absorption bands are centered around 1.19, 1.43, 1.94, 2.93, 4.72, 6.10 and 15.3 μm, but for water vapor they are centered at 1.14, 1.38, 1.87, 2.7 and 6.3 μm (Rao et al., 2005; Williams and Norris, 2001).

The absorption coefficient depends on the surface moisture content and on the wavelength range of the incident lighting (Salagnac et al., 2004). Similar conclusions were also reported by Datta and Ni (2002) regarding the penetration depth of infrared energy – the penetration depth is primarily a function of moisture content and wavelength. Fig. 4 represents the absorption peaks for different wavelengths and dough moisture content. A statistical dispersion analysis with Fisher's F-test was performed in accordance with ANOVA procedure for detecting the effect of each individual factor (peak wavelength and dough moisture content) on the variable response (absorptivity). Effects were statistically significant at the 5% significance level.

Results show two clearly distinguished regions of infrared absorptivity with a threshold at peak wavelength $\lambda_{peak} \approx 1.4$ μm. Thus, the studied spectral range can be divided into two parts, one for wavelengths up to 1.4 μm and the other for wavelengths above 1.4 μm. For an incident radiation with a peak wavelength $\lambda_{peak} < 1.4$ μm, higher absorptivity is observed for dough samples with low moisture content (25% wb). The absorption peak (0.72) corresponds to $\lambda_{peak} \approx 1.35–1.39$ μm. In contrast, for a longer wavelength domain ($\lambda_{peak} > 1.4$ μm) the absorption peaks of 0.73, 0.708 are observed for dough samples with high moisture content – 50% wb and 43% wb, respectively. Both these peaks correspond to $\lambda_{peak} \approx 1.43–1.5$ μm. This could be explained by the state of the free water in the samples. For drier samples (25% wb) exposed to a higher irradiation levels (4600–5500 W m^{-2}) with $\lambda_{peak} < 1.4$ μm, a higher surface temperature is generated (Table 1) and causes a water vapor state in the bread dough. For this state, the absorption peak of the water is well known (Williams and Norris, 2001) and it is centered at 1.38 μm, which corresponds to our results. For a lower irradiation level, the surface temperature is below the water boiling point, and liquid water absorbs infrared radiation. The liquid water absorption band is well known in the literature and it is centered at 1.43 μm (Williams and Norris, 2001; Nielsen, 2003).

4. Conclusions

A series of radiant heating experiments were designed to test the total infrared absorptivity of bread dough samples with

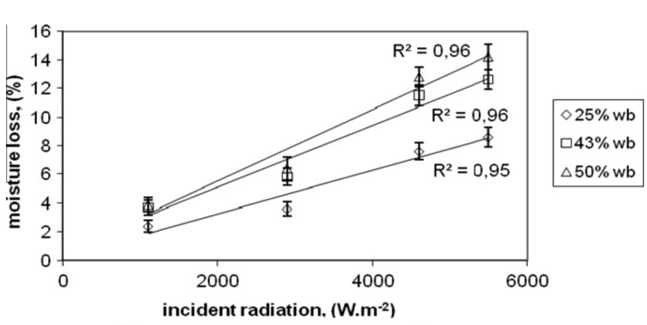

Fig. 3. Moisture loss vs. incident radiation for dough samples with different moisture content.

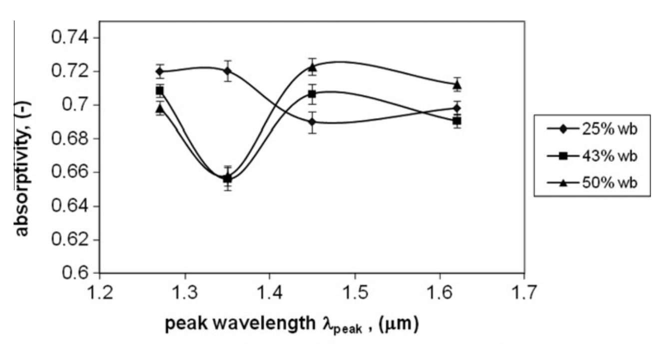

Fig. 4. Absorptivity vs. peak wavelength for dough samples with a different moisture content.

different moisture contents. Weight loss, surface temperature, and total heat flux were measured for a range of radiant flux intensities. The obtained experimental data were corrected in terms of long wavelength infrared radiation generated by the interior of the baking chamber.

The data showed that the weight loss of the dough samples increased linearly with the irradiation level. The highest weight losses corresponded to dough samples with high initial moisture content exposed to high irradiation.

The highest levels of the total heat flux absorbed by the dough and highest dough surface temperature were measured for dough samples with low initial moisture content. A strong positive correlation between the surface temperature of the dough and the total heat flux absorbed was observed for each irradiation level.

In term of the infrared absorptivity, two clearly distinguished regions were observed with a wavelength break point of 1.4 μm. The observed variations in the dough infrared absorptivity are explained in terms of the state of the water in the dough during baking. The highest absorptivity of the drier dough samples was observed at peak wavelength of 1.38 μm (water vapor absorption peak), while those dough samples with higher moisture content exhibited strong infrared absorptivity at peak wavelength of 1.43 μm (liquid water absorption peak).

Acknowledgements

This study has been carried out with financial support from the Commission of the European Communities, FP6, Thematic Area "Food quality and safety", FOOD-2006-36302 EU-FRESH BAKE. It does not necessarily reflect its views and in no way anticipates the Commission's future policy in this area. Tzvetelin DESSEV is a post doc co-funded by the region Pays de Loire and EU-FRESHBAKE. Thanks to Mohamed Fadhel BEN AISSA, Christophe COUEDEL and Luc GUIHARD for the technical support.

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