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Effect of Microwave, Infrared and Infrared-assisted Microwave Heating on the Drying Rate of Bread Dough

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Abstract: The present study was aimed to determine the contribution of microwave and infrared drying mechanims in infrared-assisted microwave drying. Bread dough samples were dried from 40.9 to 8% moisture content (wet basis) with microwave, infrared and infrared-assisted microwave drying by using halogen lamp-microwave combination oven. Microwave and/or halogen power levels of 30, 50 and 70% were used. It was found that in the infrared-assisted microwave drying, microwave energy was the dominant mechanism with about nine times greater contribution than that of infrared. An estimation for the change in the relative drying rate of infrared-assisted microwave drying was found by using the relative drying rate values and the fractional contributions of both drying mechanisms.

Key words: Microwave, infrared, near-infrared-assisted microwave, relative drying rate, dough

Introduction

Drying is a simultaneous heat and mass transfer operation in which the water activity of a material is lowered by the removal of nearly all the water normally present by evaporation into an unsaturated gas stream (Karel, 1975). Large quantities of food products are dried to improve shelf life, reduce packaging costs, lower shipping weights, enhance appearance, encapsulate original flavour and maintain nutritional value in many agricultural countries (Chou and Chua, 2001).

Earlier attempts by Ginzburg (1969) and Yagi and Kunii (1951) to apply infrared radiation to drying process of agricultural materials have been reported in the literature. Combined infrared radiation and convection or vacuum drying has also been reported (Hasatani *et al*., 1988; Abe and Afzal, 1997; Dontigny *et al*., 1992). Far infrared drying of potato achieved high drying rates with infrared heaters of high emissive power (Masamura *et al*., 1988). Far infrared and near infrared drying using three types of granular bed and their quantitative comparison to hot air drying from the view point of the heat transfer has been studied by Hashimoto *et al*. (1991). Datta and Ni (2002) reported the application of combined infrared, microwave and hot air heating food materials. Hebbar *et al*. (2004) have developed a combined infrared and hot air heating system for drying of vegetables. Thin layer infrared radiation drying of onion slices was studied by Sharma *et al*. (2005) and their study have showed that drying time reduced by about 2.25 times on increasing power from 300 to 500 W. Nowak and Lewicki (2004) had studied the drying of apple slices and Sumnu *et al*. (2005) dried carrots by near infrared radiation. Infrared drying found also application in the food analysis for the purpose of measuring moisture content in food products (Hagen and Drawert, 1986; Anonymous, 1995).

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It has been recognized that microwave drying can lead to potentional economic, engineering and social benefits over the last few decades (Sanga *et al*., 2000). According to Feng (2000), it is the disadvantages of the conventional drying methods that provide microwave heating vast opportunity as a new drying method for improving both energy efficiency and product quality. Prabhanjan *et al*. (1995) reported a reduction in drying time up to 25-90% in microwave drying of foods when compared to convective drying. The earliest example of microwave drying process is the finish drying of potato chips (Schiffmann, 2001). Microwave drying has been used in drying of pasta (Anonymous, 1972; 1974; Al-Duri and McIntyre, 1992), milk and milk products (Al-Duri and McIntyre, 1992; Kim and Bhowmik, 1995), meat products (Brighenti *et al*., 1982), cereal products such as rice, maize, wheat, barley (Fanslow and Saul, 1971), potato (Bouraout *et al*., 1994), macaroni beads (Goksu *et al*., 2005), raisins (Tulasidas *et al*., 1996; Kostaropoulos and Saravacos, 1995), apple and mushroom (Funebo and Ohlsson, 1998), diced apples (Feng and Tang, 1998), carrots (Prabhanjan *et al*., 1995; Litvin *et al*., 1998; Lin *et al*.,1998; Sumnu *et al*., 2005), herbs (Giese, 1992), tomato (Chin *et al*., 1985), strawberry (Hemphill and Martin, 1992), banana (Maskan, 2000), cranberries (Yongsawatdigul and Gunasekaran, 1996), egg yolk paste (Faillon *et al*., 1977; 1978), fish protein (Rosenberg and Boegl, 1987) and American ginseng roots (Ren and Chen, 1998). According to Beaudry *et al*., (2004), an advantage of using microwave technology is the possibility of combining diverse drying methods with microwaves.

Infrared-assisted microwave drying is a new technology, which is the combination of two different heating mechanisms: microwave heating and infrared heating. Infrared-assisted microwave drying combines the time saving advantages of microwaves with surface moisture removal advantages of infrared heating. Datta and Ni (2002) showed how the excess moisture that may accumulate on the food surface from microwave drying can be removed by combining microwave heating with infrared power of small penetration depth. Sumnu *et al*. (2005) studied drying of carrots in microwave and halogen lamp-microwave combination ovens.

There is still a lack of understanding on the fundamentals of heat and mass transport when drying is done by infrared-assisted microwave drying. Microwaves modify the transport processes due to internal heat generation which leads to an increase in internal vapor generation promoting liquid flow towards the surface and leads to higher internal temperatures, both of which increase the drying rate. The hardness to solve transport process when coupled with infrared drying becomes more complex. In a such process, power level and penetration of infrared energy are expected to be the significant parameters, however the effects of these parameters have not been identified quantitatively (Datta and Ni, 2002).

There is only one study on infrared-assisted microwave drying in scientific literature. Hence, the objective of the study was to understand the mechanism of this new drying method and to find out the individual contributions of microwave and infrared drying of bread dough in terms of relative drying rate values. In addition, it was aimed to compare infrared, microwave and infrared-assisted microwave drying on drying rate of bread dough.

Materials and Methods

Preparation of Dough

Flour containing about 32% wet gluten, 13.1% moisture and 0.55% ash was used. The composition of the prepared dough as mass per 100 mass of flour was 100% flour, 4.3% sugar, 1.9% salt and 64.4% water. Firstly, the flour, sugar and salt were mixed for 2 min by a mixer at 58 rev/min (Kitchen Aid, 5K45SS, St. Joseph, USA). Then, water was added to the dry mixture and mixed again for 2.5 min with the same mixer at the same speed. At the end of the second mixing, the dough was punched in order to make the dough be ready for the rolling step and to have an efficient moulding process. Punched dough was then rolled into a sheet having a thickness of 3.02±0.009 mm with the help of a pasta machine (Otello, Italy). Additional flour (on dough basis; 100% dough, 0.8% additional flour) was used to avoid sticking of dough sheet to the equipment. Moulding was done by cutting the dough sheet to have a circular shape with a diameter of 8.9±0.01 cm and weight of 20.8 g. Prior to the drying step, initial moisture content of the dough was determined by weighing 10 g of dough sheet with an electronic balance (Adventurer™ OHAUS, China) and drying in 100°C oven (Dedeoğlu, TS-5050, Turkey) until a constant weight value was reached. Initial moisture content was determined as 40.925±0.0250% (wet basis).

Drying

Cut dough sheets were dried by using microwave, infrared and infrared-assisted microwave drying methods up to a final moisture content of about 8% (wet basis). Weight and time data were recorded during the drying process and time intervals were adjusted according to the drying method.

Microwave Drying

Halogen lamp-microwave combination oven (Advantium Oven™, General Electrics, Louisville, KY, USA) was used by operating only the mode of microwave heating for the purpose of microwave drying. The power of the oven was found as 706 W by the IMPI 2 L Test (Buffler, 1993). Microwave drying experiments were carried out at 30, 50 and 70% microwave powers. During drying, weight of the dough was recorded with 15 sec of time intervals.

Infrared Drying

Infrared drying was achieved by operating only the mode of halogen lamp heating (near-infrared heating with a wavelength range of 0.7-1.1 μm) in halogen lamp-microwave combination oven (Advantium Oven™, General Electrics, Louisville, KY, USA). There are two 1500 W halogen lamps at the top of the oven and one 1500 W halogen lamp at the bottom of the oven. During halogen lamp drying, upper and lower halogen lamps were operated at the same power. Drying experiments were performed at 30, 50 and 70% halogen powers respectively. Weight data were taken with a time interval of 60 sec.

Infrared-assisted Microwave Drying

Halogen lamp-microwave combination oven (Advantium Oven™, General Electrics, Louisville, KY, USA) combines two different heating mechanisms, microwave and near-infrared heating. Samples were dried at 30, 50 and 70% halogen lamp powers and at 30, 50 and 70% microwave powers in halogen lamp-microwave combination oven. Weight of the dough samples was measured for every 15 sec.

Relative Drying Rate

Weitz ***et al***. (1989) defined the relative rate of drying as:

$$\zeta = \frac{t_c}{t_s} \qquad (1)$$

where, ζ is the relative drying rate, t_c is the drying time of control sample (s) and t_s is the drying time of treated sample (s) for the same initial and final moisture contents.

In this study, drying time of control sample (t_c) was determined by drying the sample in a conventional oven (Arçelik ARMF 4 Plus, Turkey) at 75°C. Drying times are defined as the time to reach a final moisture content of 0.08 g g^{-1} from 0.409 g g^{-1} (wet basis).

Results and Discussion

Moisture content decreased linearly with drying time during microwave drying after about an initial period of 30 sec, where this initial period may be considered as the adaptation period of the material to the drying conditions (Fig. 1). The coefficient of determination, r^2 of the fitted line was 0.99 for all of the microwave powers used. This behaviour is in agreement with the reported findings (Sahin *et al.*, 2002; Keskin *et al.*, 2004).

For all of the infrared drying treatments, the drying time was found to decrease with increase in the halogen lamp power (Fig. 2). Similar results have already been reported in the earlier studies on drying with infrared energy (Abe and Afzal, 1997; Afzal and Abe, 1999; Das *et al.*, 2004). As expected with increasing halogen lamp powers, food was exposed to more radiative heat and have greater mass transfer driving force resulted in faster drying and consequently less drying time.

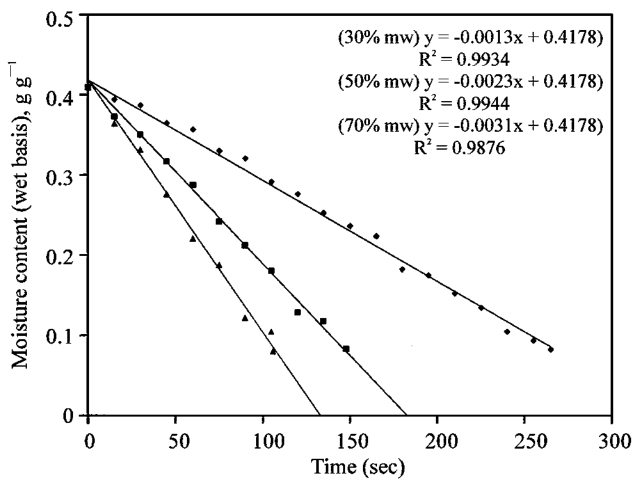

Fig. 1: Drying curves for microwave drying and the fitted lines for t>30 s. ♦ 30% mw ■ 50% mw ▲ 70% mw

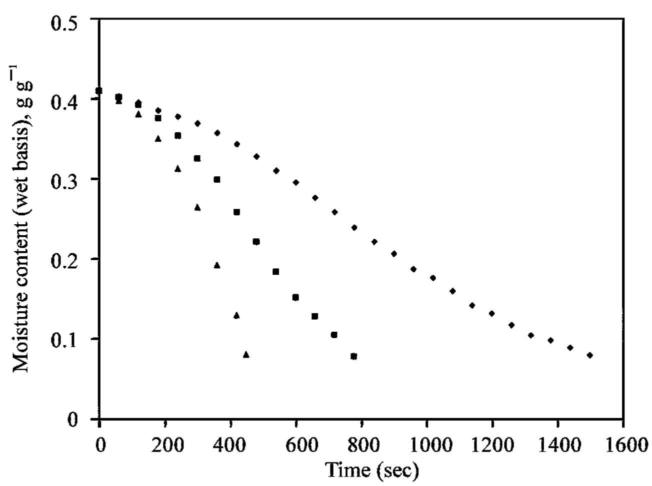

Fig. 2: Drying curves for infrared drying. ♦ 30% halogen ■ 50% halogen ▲ 70% halogen

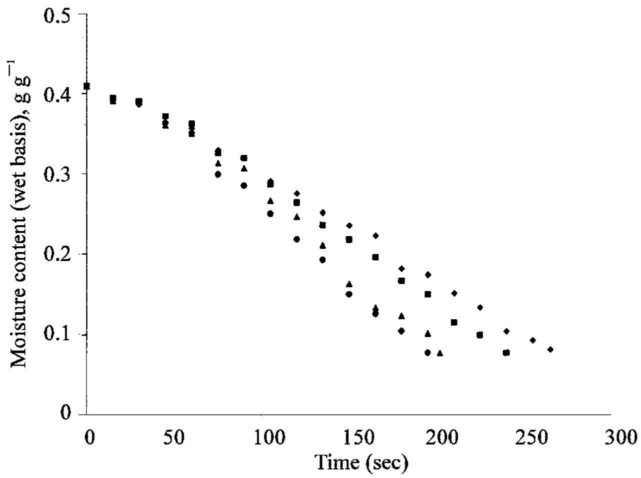

Fig. 3: Drying curves for microwave and infrared-assisted microwave drying at 30% microwave power. ♦ 30% mw only ■ 30% mw + 30% halogen ▲ 30% mw + 50% halogen ● 30% mw + 70% halogen

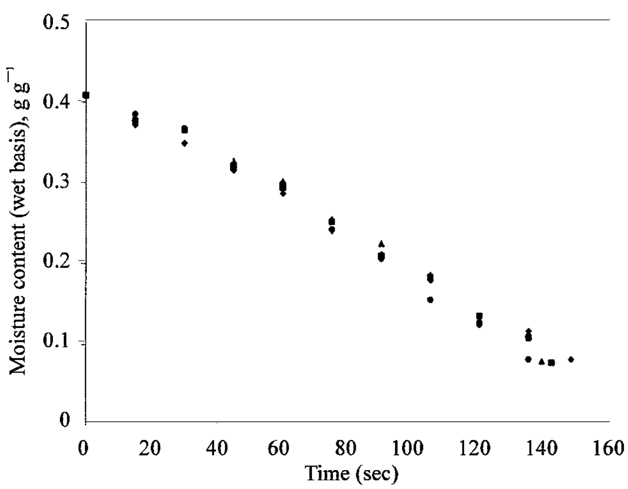

Fig. 4: Drying curves for microwave and infrared-assisted microwave drying at 50% microwave power. ♦ 50% mw only ■ 50% mw + 30% halogen ▲ 50% mw + 50% halogen ● 50% mw + 70% halogen

Figure 3-5 show the comparison of microwave and infrared-assisted microwave drying. It can be seen that microwave heating was the dominant mechanism affecting moisture loss in the infrared-assisted microwave drying at medium and high microwave powers. Since infrared-assisted microwave drying curves were very similar to the microwave drying curves at 50 and 70% fixed microwave powers, the effect of halogen lamp power could not be clearly observed as the data points coincided (Fig. 4 and 5). Microwave heating being the dominant mechanism was also reported by Keskin *et al.* (2004) in infrared-assisted microwave baking of breads when weight loss was concerned. A similar behaviour at 30% fixed microwave power was seen up to about 60 sec of drying. However, after this period the contribution of infrared power was seen clearly as the data points for the different ratings

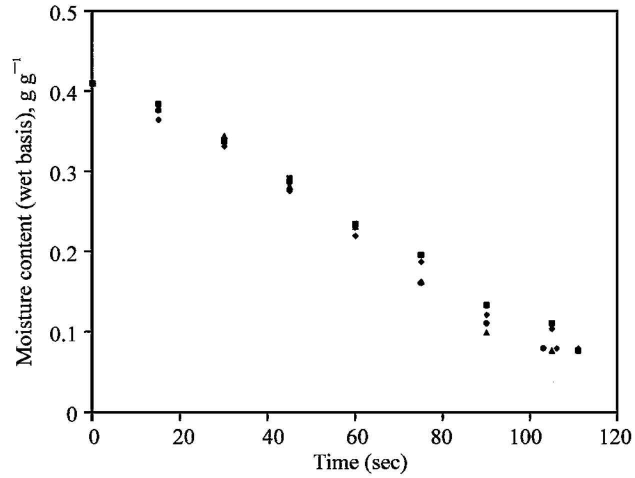

Fig. 5: Drying curves for microwave and infrared-assisted microwave drying at 70% microwave power. ♦ 70% mw only ■ 70% mw + 30% halogen ▲ 70% mw + 50% halogen ● 70% mw + 70% halogen

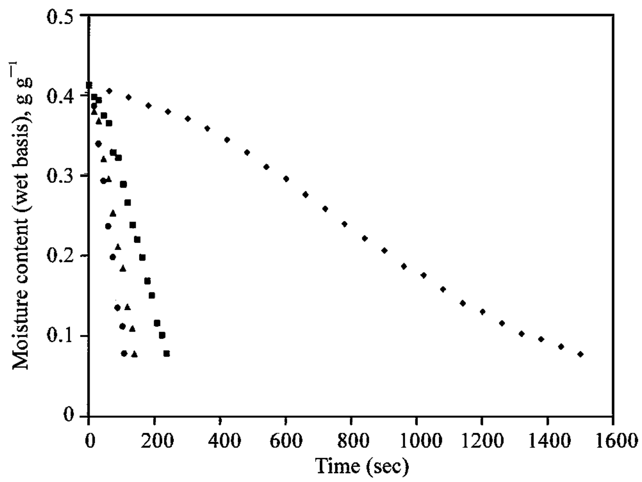

Fig. 6: Drying curves for infrared and infrared-assisted microwave drying at 30% halogen lamp power. ♦ 30% halogen only ■ 30% mw + 30% halogen ▲ 50% mw + 30% halogen ● 70% mw + 30% halogen

separated from each other showing that the increase in the halogen lamp power caused more moisture loss and hence faster drying (Fig. 3).

Figure 6-8 show the role of microwave heating in the infrared-assisted microwave drying more clearly. Reduction in drying time due to the increase in microwave power was observed as quite similar to the microwave drying (Fig. 1, 6-8). This also shows that the contribution of microwave heating mechanism is more pronounced in the infrared-assisted microwave drying as earlier discussed above.

The results indicate that the drying behaviour under infrared-assisted microwave drying and microwave drying highly resemble each other. However, a difference for the drying behaviour under infrared drying in both when working at the same microwave power only and the combined powers could be seen (Fig. 9-11). Hence, the fact that microwave heating dominated in the infrared-assisted

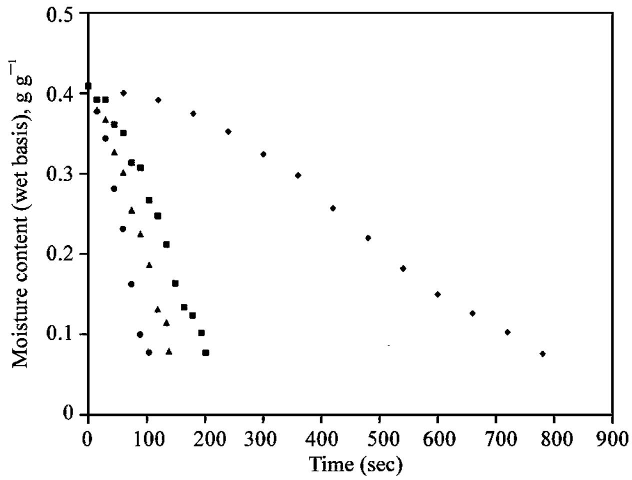

Fig. 7: Drying curves for infrared and infrared-assisted microwave drying at 50% halogen lamp power. ♦ 50% halogen only ■ 30% mw + 50% halogen ▲ 50% mw + 50% halogen ● 70% mw + 50% halogen

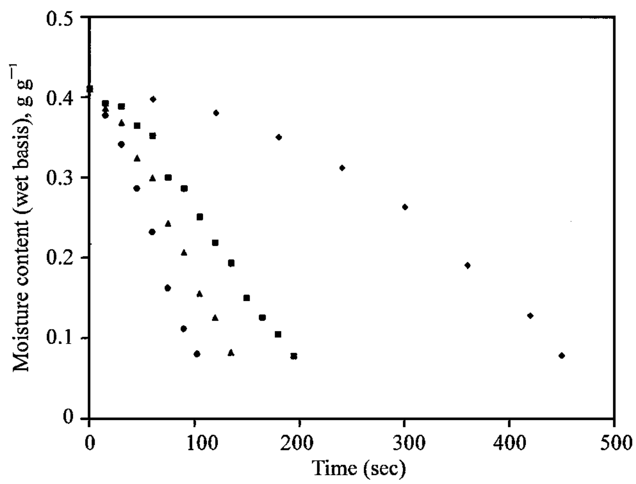

Fig. 8: Drying curves for infrared and infrared-assisted microwave drying at 70% halogen lamp power. ♦ 70% halogen only ■ 30% mw + 70% halogen ▲ 50% mw + 70% halogen ● 70% mw + 70% halogen

microwave drying was encountered once more. Figures 9-11 also designated that microwave energy was more effective on the moisture removal resulting in reduction in drying time. This might be owing to the increased internal temperatures causing higher vapor pressure hence the driving force of the microwave energy as compared to the infrared drying.

When infrared-assisted microwave drying was conducted at 30% and 50% fixed microwave powers, the drying rate of the dough samples increased and hence drying time decreased as compared to using only infrared or only microwave energy (Table 1). This was an expected result since with the coupled drying mechanism it was possible to reach higher internal temperatures due to microwave heating and higher surface temperatures due to infrared heating (Ni *et al*., 1999; Sumnu *et al*., 2005).

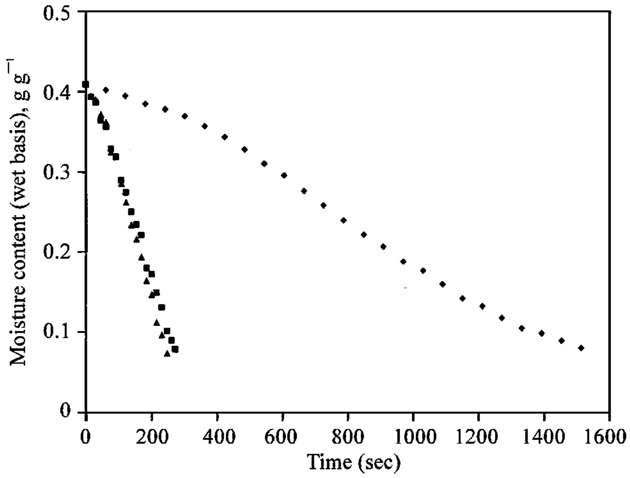

Fig. 9: Drying curves for microwave, infrared and infrared-assisted microwave drying at 30% values of each. ♦ 30% halogen only ■ 30% mw only ▲ 30% mw + 30% halogen

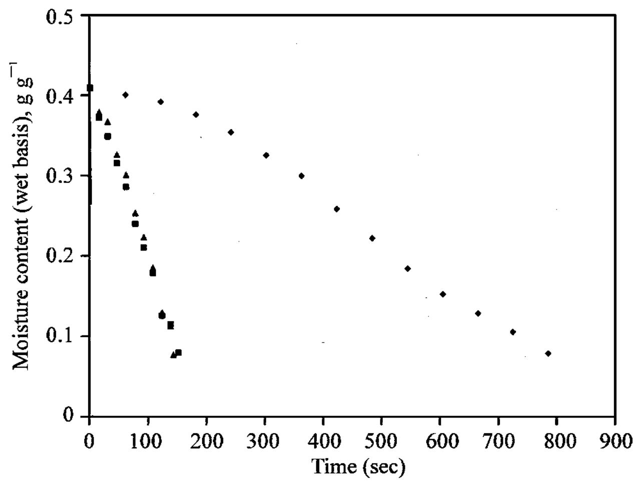

Fig. 10: Drying curves for microwave, infrared and infrared-assisted microwave drying at 50% values of each. ♦ 50% halogen only ■ 50% mw only ▲ 50% mw + 50% halogen

The relative drying rates calculated from Eq. 1 (Table 1) varied from 5.04 to 73.40 (excluding 0% microwave and 0% halogen lamp power combination representing conventional oven drying), the highest being obtained with the infrared-assisted microwave drying at 70% microwave and 70% halogen lamp power combination. Infrared only drying gave smaller rates when compared with the other drying methods. This is to a high degree due to the fact that by microwave heating internal resistance to moisture diffusion is more effectively reduced when compared to infrared heating. On the other hand, removal rate of the moisture reaching the surface is due to the infrared energy. Thus, for the drying methods used in this study, an increase in microwave power and/or infrared power resulted with an increase in the relative drying rate. In addition, microwave power was found to be more effective on increasing the relative drying rate when compared with halogen lamp power (Table 1), which is another evidence of microwave heating being the dominant mechanism in the infrared-assisted microwave drying.

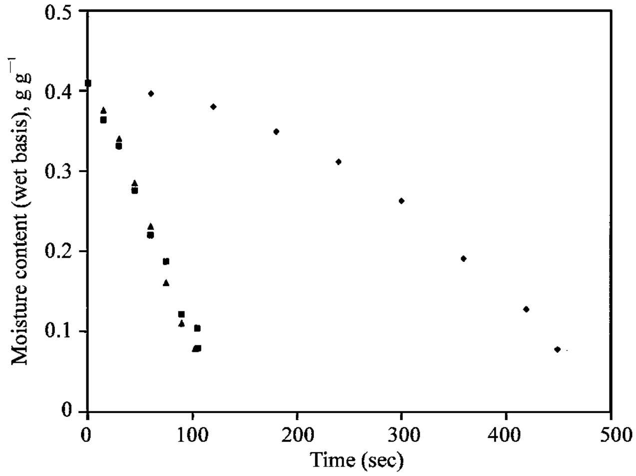

Fig. 11: Drying curves for microwave, infrared and infrared-assisted microwave drying at 70% values of each. ♦ 70% halogen only ■ 70% mw only ▲ 70% mw + 70% halogen

Table 1: Relative drying rate of dough (s s^{-1}) for different drying methods in reaching a moisture content of 0.08 g g^{-1} (wet basis) according to Eq. 1

Halogen power (%)	Microwave power (%) 0	30	50	70
0	1	28.53	51.08	71.32
30	5.04	31.50	53.24	68.11
50	9.69	37.43	54.39	72.00
70	16.80	38.77	56.00	73.40

As a rough quantitative estimate for the fractional contributions, Table 1 can be inspected both column-wise and row-wise. It can be seen that for 20% increments in the powers the increase in the relative drying rate is about 16.81 s s^{-1} for the microwave and 1.88 s s^{-1} for the infrared power. Thus, contributions of the powers to the drying rate as microwave:infrared is in the order 9:1. So by having the relative drying rate results of microwave only and infrared only and the estimated fractional contributions, the change in the relative drying rate of infrared-assisted microwave drying for this study can be estimated from:

$$\Delta\zeta = (\Delta\zeta_i^* \times 0.1) + (\Delta\zeta_j^* \times 0.9) \quad (2)$$

where,

$$\Delta\zeta_i^* = \zeta_{i_2,1} - \zeta_{i_1,1} \quad (3a)$$

$$\Delta\zeta_j^* = \zeta_{1,j_2} - \zeta_{1,j_1} \quad (3b)$$

It should be noted that Table 1 is prepared in matrix notation, i.e., $\zeta_{i,j}$ indicates the relative drying rate for the ith row and the jth column combination of halogen lamp (infrared) and microwave powers in Eq. 3a and 3b. i and j values represent power levels as 1 = 0%, 2 = 30%, 3 = 50% and 4 = 70%. Thus, $\Delta\zeta_i^*$ is the change in the relative drying rate between two halogen lamp powers in infrared drying only and similarly $\Delta\zeta_j^*$ is the change in the relative drying rate between two microwave powers in microwave drying only.

Equation 2 gives good estimates of the relative drying change for infrared-assisted microwave drying, i.e., $i_1, j_1 > 1$. Several examples comparing $\Delta\zeta$ according to experimental and calculated values are given in Table 2.

Table 2: Several examples showing experimental and calculated values of $\Delta\zeta$

Powers	$\Delta\zeta$ (experimental)	$\Delta\zeta$ (calculated)
$i_1 = j_1 = 2$ $i_2 = j_2 = 3$	$\Delta\zeta = \zeta_{3,3}-\zeta_{2,2}$ $= 54.39-31.50 = 22.89$	$\Delta\zeta = (\Delta\zeta_i^* \times 0.1) + (\Delta\zeta_j^* \times 0.9)$ $\Delta\zeta_i^* = \zeta_{3,1}^*-\zeta_{2,1} = 6.69-5.04 = 4.65$ $\Delta\zeta_j^* = \zeta_{1,3}^*-\zeta_{1,2} = 51.08-28.53 = 22.55$ $\Delta\zeta = (4.65\times0.1) + (22.55\times0.9) = 20.76$
$i_1=3, j_1=2$ $i_2=4, j_2=3$	$\Delta\zeta = \zeta_{4,3}-\zeta_{3,2}$ $= 56.00-37.43 = 18.57$	$\Delta\zeta = (\Delta\zeta_i^* \times 0.1) + (\Delta\zeta_j^* \times 0.9)$ $\Delta\zeta_i^* = \zeta_{4,1}-\zeta_{3,1} = 16.80-9.69 = 7.11$ $\Delta\zeta_j^* = \zeta_{1,4}-\zeta_{1,3} = 51.08-28.53 = 22.55$ $\Delta\zeta = (7.11\times0.1) + (22.55\times0.9) = 21.01$
$i_1 = 2, j_1 = 3$ $i_2 = j_2 = 4$	$\Delta\zeta = \zeta_{4,4}-\zeta_{2,3}$ $=73.40-53.24 = 20.16$	$\Delta\zeta = (\Delta\zeta_i^* \times 0.1) + (\Delta\zeta_j^* \times 0.9)$ $\Delta\zeta_i^* = \zeta_{4,1}-\zeta_{2,1} = 16.80-5.04 = 11.76$ $\Delta\zeta_j^* = \zeta_{1,4}-\zeta_{1,3} = 71.32-51.08 = 20.24$ $\Delta\zeta = (11.76\times0.1) + (20.24\times0.9) = 19.39$
$i_1 = 3, j_1 = 2$ $i_2 = 4, j_2 = 2$	$\Delta\zeta = \zeta_{4,2}-\zeta_{3,2}$ $= 38.77-37.43 = 1.34$	$\Delta\zeta = (\Delta\zeta_i^* \times 0.1) + (\Delta\zeta_j^* \times 0.9)$ $\Delta\zeta_j^* = \zeta_{4,1}-\zeta_{3,1} = 16.80-9.69 = 7.11$ $\Delta\zeta_j^* = \zeta_{1,2}-\zeta_{1,2} = 28.53-28.53 = 0$ $\Delta\zeta = (7.11\times0.1) + (0\times0.9) = 0.71$
$i_1 = j_1 = 2$ $i_2 = 2, j_2 = 4$	$\Delta\zeta = \zeta_{2,4}-\zeta_{2,2}$ $= 68.11-31.50 = 36.61$	$\Delta\zeta = (\Delta\zeta_i^* \times 0.1) + (\Delta\zeta_j^* \times 0.9)$ $\Delta\zeta_j^* = \zeta_{2,1}-\zeta_{2,1} = 5.04-5.04 = 0$ $\Delta\zeta_j^* = \zeta_{1,4}-\zeta_{1,2} = 71.32-28.53 = 42.79$ $\Delta\zeta = (0\times0.1) + (42.79\times0.9) = 38.51$

Conclusions

The drying time of bread dough was found to decrease with increase in power (microwave and/or halogen lamp) in all of the drying treatments. Owing to a high degree of reduction in the internal resistance to moisture diffusion, usage of microwaves reduced the drying time of bread dough significantly. It was concluded that contribution of microwave drying was about nine fold of that of infrared drying showing that microwave heating is the dominant mechanism in the infrared-assisted microwave drying.

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