ABSTRACT. The drying of welsh onion by a far-infrared (FIR) heater under reduced pressure and convective conditions were studied to understand the drying characteristics. The effects of radiant power input and vacuum levels on the drying phenomenon were investigated. In addition, drying rate as a function of moisture content was studied vis-a-vis drying qualities such as rehydration potential, shrinkage, and color change. When onion samples were dried from about 10.1 to 0.05 wb dry basis moisture content, the three characteristic periods, namely, rising, constant, and falling rate periods, were obtained. The drying rate increased with increasing radiant power input and was higher in a reduced-pressure environment than under a convective condition. With 0.17 W/cm² radiant power input, the drying rate was 50% higher in the vacuum operation than under the convective condition. There was a higher shrinkage with a concomitant higher rehydration potential and superior quality of onion at lower radiant power input with the FIR-vacuum system than with the FIR-convection system.

Keywords. Combined drying, Drying rate, Rehydration, Shrinkage, Color, Welsh onions.
100°C, should achieve this goal. A vacuum condition coupled with the FIR heater could speed up the drying process and further improve quality.

The infrared heater with a uniform distribution of high spectral emissivity in the full wavelength range has a high efficiency and can be deemed similar to a black body that emits a maximum radiation heat flux (Ratti and Mujumdar, 1995). This heater radiates infrared maximally even at low temperatures and should be suitable for use with a reduced pressure where high temperature in an enclosed chamber is undesirable.

In Pacific Asia, especially in Japan, Welsh onion in a dried form is a major spice in instant foods such as noodle and curry sauce. Its high initial moisture content and hence energy cost in drying has been a concern to many instant food companies. There is, therefore, a need to develop a cost-effective way of drying this important food ingredient. The leafy part of Welsh onion is hollow and thin (approximately 1 mm in thickness) and could lend itself to the FIR method of drying.

The objective of this paper is to compare the effectiveness of an FIR heater under a reduced pressure to that in combination with a convective condition in the drying of the leafy part of Welsh onion.

Material and Methods

Experimental Setup for FIR-Vacuum Drying

The experimental setup for the combined FIR-vacuum drying is shown in figure 1. A drying chamber of 40 × 30 × 40 cm internal dimensions was made from a transparent acrylic resin and with walls built to withstand 133 Pa absolute pressure. The inner walls were covered with a polished aluminum sheet to facilitate reflection of the infrared rays (Ratti and Mujumdar, 1995). A metal frame was placed inside the drying chamber to facilitate height adjustment of the heater above the drying material. A coated florine resin plastic board infrared heater, measuring 23 × 18 cm in area with a spectral peak height of 6 to 7 μm and emissivity of 0.9, was then attached to the metal frame. An aluminum plate was placed on top of the heater to prevent heat loss. The heater was small in thickness, and hence heat loss through the backsides was assumed to be negligible.

Air was discharged from the drying chamber using a vacuum pump, and this caused the water within the material being dried to vaporize at low temperature. A vacuum pressure controller was connected to the system for adjustment of pressure. A desiccator with about 2 kg of silica gel was connected between the vacuum pump and the drying chamber to absorb moisture from the drying process. The silica gel was replaced after each drying run.

A thermocouple was placed in the middle of the chamber to monitor the air temperature in the chamber. To record the material temperature, three type-T thermocouples, each of 0.1 mm diameter, were randomly inserted into the material to be dried. The experimental data was collected by a personal computer via a data logger (model GK-88Gn, ESD Co., Ltd., Tokyo, Japan) through an A/D converter interface.

The radiant power was regulated by adjusting the voltage and hence outputs of the radiant power from 0.10 to 0.24 W/cm² at increments of 0.02 W/cm². The W/cm² in this case is the nominal radiant power per unit area of infrared heater surface. The distance between the heater and the sample was fixed at 10 cm, and the absolute pressure kept in the neighborhood of 2.5 kPa. To study the influence of absolute pressure on drying, at a fixed radiant power input of 0.17 W/cm², the pressure was varied from a low vacuum level of 20 kPa to a high vacuum level of 2.8 kPa. The vacuum pump was turned on simultaneously with the heater, and after 10 minutes of vacuum operation, a steady state of between 2.8 and 20 kPa was attained. Each treatment was replicated for five drying runs.

Experimental Setup for FIR-Convection Drying

The experiment for the combined FIR-convection drying was carried out according to Alzal and Abe (1997) as shown in figure 2. The heater used was the same as in the FIR-vacuum drying system. The distance between the FIR heater and sample surface was fixed at 10 cm. Thermocouples were used to measure the temperature of the heated air entering and leaving the drying chamber. Five thermocouples, similar to those used in the FIR-vacuum setup, were used to record the material temperature. The temperature, relative humidity (RH), and velocity of heated air leaving the chamber were measured with a portable velocity meter. The radiant power input to the FIR heater was regulated by varying the power between 0.12 and 0.46 W/cm² in increments of 0.05 W/cm² with the convective conditions fixed at a constant inlet air temperature of 40°C and an average outlet air velocity of 0.54 m/s (approximately 0.033 m/s over sample surface).

![Figure 1. Schematic diagram of the FIR-vacuum drying system.](image-url)
RESULTS AND DISCUSSION

Effect of Radiant Power Input

FIR-Vacuum Test

Drying rate, defined as the rate of moisture loss per unit time, was calculated as the amount of moisture evaporating per min per kg of original Welsh onion. The drying rate of Welsh onion under the combined FIR-vacuum condition at 2.5 kPa is shown in Figure 3. It is evident from the figure that the rates increase with increasing radiant power input. The drying rate has a characteristic parabolic shape at all levels, as noted by Mongprün et al. (2002). Each curve seems to have three distinct periods: a rising-rate (I), a constant-rate (II), and a falling-rate period (III) (fig. 3). The rising-rate period was steep from the onset of drying (10 g H₂O/g dry matter) to moisture content of about 9.5 g H₂O/g (dry matter). This is because the samples were put into the drying chamber at atmospheric pressure, after which the chamber was evacuated and concurrently the heater was turned on. These conditions resulted in a rapid rise in the onion temperature to its boiling point, and hence the sharp rise in the drying rate. A constant-rate period from 9.5 g H₂O/g dry matter to approximately 1.8 g H₂O/g dry matter was attained thereafter. This was as a result of moisture evaporation from the onion being almost equal to water vapor removal from the product surface. The constant rate is broader at the low radiant power levels (0.10 and 0.12 W/cm²) with the highest drying rate being attained at 0.24 W/cm² (approximately 18 g H₂O/kg onion/min). The broad constant-rate per moisture content at lower radiant power inputs (0.10 and 0.12 W/cm²) might have been due to a slower loss of moisture from the onion. Once the moisture at the surface had evaporated, the drying process was controlled by diffusion of moisture within the material. Consequently, the drying rate decreased non-linearly with moisture content up to the end of drying, constituting the falling-rate period. This falling-rate period in the FIR-vacuum drying exhibited similar patterns as in the conventional drying methods. However, the typical second falling-rate period in the conventional drying systems was not observed with onion in the current combined system.

Figure 3. Drying rates at different radiant power inputs of the FIR heater at 2.5 kPa.

EXPERIMENTAL MATERIAL

About 50 g of the leafy part of Welsh onion (Allium fistulosum L.), stored at 5°C, was chopped into pieces, each of about 5 mm in length, and equilibrated to room temperature. The onion pieces were then spread in one or two layers in the tray (21 x 21 x 4 cm) on the electric balance in the drying chamber in such a way that the weight loss could be continuously monitored without taking the sample out of the chamber and without altering any of the experimental conditions. Weight loss was monitored from the initial moisture content until 0.05 w/w dry basis moisture content was attained. The initial moisture content of the cut onion, which varied between 10.1 and 12.8 w/w dry basis, was determined gravimetrically by drying at 65°C for 5 hours (Sugahara and Maekawa, 2000).

PRODUCT QUALITY ANALYSES

The rehydration ratio of the whole 50 g Welsh onion after drying from each treatment was determined according to the method of Ihoh and Han (1995). The volume of Welsh onion before and after drying was determined by close packing of the 50 g of onion in a 500 mL graduated cylinder. The close packing was achieved by vigorous shaking, and the difference in volume was used as an estimation of shrinkage.

Changes in color as a result of radiant power input and reduced pressure were investigated. The wet material was wrapped with a Saran Wrap film and the color measurements taken according to Feng et al. (1999). The fresh onion and dried onion were each milled, and the milled fresh onion covered with a Saran Wrap film to avoid direct contact of moisture with the equipment. The tristimulus color values (L*, a*, and b*) of plastic-covered fresh and dried onion were then determined on a Minolta CM-2600d spectrophotometer. The milled dried onion was then soaked in distilled water for 2 hours, after which the water was squeezed out. It was then covered with the plastic wrap, and the tristimulus values were taken again.

Figure 2. Schematic diagram of the FIR-convection drying system.
FIR-Convection Test

It is reported in the literature that inlet air temperature between 30°C and 40°C has no effect on drying rates (Afzal and Abe, 1997). In addition, preliminary investigations in our laboratory showed that the optimum drying rate was attained at 0.54 m/s outlet air velocity. In FIR-convection drying, therefore, a constant inlet air temperature of 40°C and outlet air velocity of 0.54 m/s were used throughout the experiment. Figure 4 shows the drying rate curves of welsh onion by an FIR-convection heater. The effect of radiant power input on drying of welsh onion was similar to that in the FIR-vacuum system. However, the rising (I) and constant rate (II) periods were shorter. This is because the emitted radiation and the convective air within the chamber resulted in a more rapid loss of moisture from the onion surface. Thus, the actual drying took place mostly in the falling-rate period, prolonging this phase (Khraisheh et al., 1995).

![Drying rates at different radiant power inputs of the FIR-convection drying.](image)

A comparison of drying rate curves of the two drying techniques is shown in figure 5. The 0.12, 0.17, and 0.22 W/cm² radiant power input levels were chosen for ease of comparison. The drying rates are conspicuously higher under reduced pressure than in the convective condition. There is also an obvious relation between the rates and the radiant power input vis-à-vis the drying condition. Increasing radiant power input from 0.12 through 0.17 to 0.22 W/cm² brought about an approximately 30%, 50%, and 60% respective increase in the drying rates of the FIR-vacuum system compared to its FIR-convection counterpart. The corresponding drying times to reach the desired final moisture content (0.05 w/w dry basis) were 77, 96, and 123 minutes in the case of FIR-vacuum drying and 160, 189, and 236 minutes for FIR-convection drying (fig. 6). The increases in drying rates were a result of the high heat flux provided by the infrared heating (Sandu, 1986; Therien et al., 1991), which culminated in a rapid rise of the onion temperature toward the end of the drying process (fig. 6). This is significantly different from hot air convection drying, in which product temperature is well controlled by the hot air temperature. This may be also a major technical issue that needs to be addressed when implementing the technology in industrial process. Lu et al. (1999) have observed a similar phenomenon with microwave drying. Measures to control the material temperature may, therefore, be required to avoid overheating and scorching of the product at this stage. Intermittent drying and cooling techniques may be applied to enhance the moisture diffusion to the surface. Not all the energy from the radiant heater was used for evaporation in the FIR-convection system due to convective losses. This led to a lower onion temperature (fig. 6), culminating in the lower drying rate in the FIR-convection system. It also in part explains why drying under convection took twice as much time as under vacuum at any given power input.

![Drying rate of welsh onion from the two drying systems at 0.12, 0.17, and 0.22 W/cm² radiant power inputs.](image)

Figure 5.

![Onion temperature-time curves of the two drying systems at 0.12, 0.17, and 0.22 W/cm² radiant power inputs.](image)

Figure 6.

**PRODUCT QUALITY**

**Reconstitution**

Dried onion is normally rehydrated before consumption. The ability of the dried product to be reconstituted to its former state upon addition of boiling water has, therefore, been used as a measure of quality (Cenkowski and Sosulski, 1998; Maskan, 2001; Ratti, 2001). If rehydrability is low, it implies bad quality (Ratti, 2001). Figure 7 shows the effect of radiant power input on the rehydration potential. Recovery upon reconstitution of the dried onion in boiling water was negatively correlated with the level of radiant power input supplied to the FIR heater under reduced pressure; however, under convection, the correlation was positive.
In the case of reduced pressure, the surface temperature of the onion was very high during the last phase of drying, especially at high radiant power input levels (fig. 6). This might have led to casehardening, culminating in a decreasing rehydration capacity of the material. The implication of this negative correlation in industrial processes is that to achieve a high reconstitution, drying should be carried out at lower radiant power input levels.

In the convective condition, however, the falling rate period, which is related to the radiant power input, directly controls the rehydration potential. That is, prolonged drying duration resulted in poor reconstitution. It is, therefore, imperative to dry at higher radiant power input levels for better reconstitution.

Shrinkage that led to higher rehydrability implied superior product quality (Nsonzi and Ramaswamy, 1998; Maskan, 2001). There was a positive correlation \( R^2 \geq 0.82 \) between rehydration and shrinkage for both systems in drying of the leafy part of welsh onion. This positive correlation implies that higher shrinkage promoted higher rehydrability and hence superior product quality. However, this positive correlation is at variance with other drying systems in the drying of more compact agricultural produce (Nsonzi and Ramaswamy, 1998; Maskan, 2001; Torringa et al., 2001). Nevertheless, in the drying of the leafy part of welsh onion, which is hollow, the FIR-vacuum system has higher shrinkage, rehydrability, and hence superior product quality at lower energy inputs. It is therefore more energy efficient and should be preferred in the drying of the produce.

Figure 7. Rehydration potential of onion under FIR-vacuum drying and FIR-convection drying.

Shrinkage has been used as a measure of quality in the drying of agricultural materials (Wang and Brennan, 1995; Nsonzi and Ramaswamy, 1998; Maskan, 2001; Ratti, 2001). A ratio of volume of dried onion \( V_d \) to volume of fresh onion \( V_f \) was used as an index of shrinkage. A lower \( V_d/V_f \) ratio denotes a higher shrinkage and vice-versa. The effect of radiant power input on volume change/shrinkage of dried welsh onion is depicted in figure 8. The shrinkage of onion was higher in the FIR-vacuum drying system than in the FIR-convection drying system. This is because the extensive heat generation under vacuum resulted in a faster and higher loss of moisture. Similar high shrinkages due to high moisture loss in some agricultural produce have been noted by Sjöholm and Gekas (1995) and Torringa et al. (2001).

In the FIR-vacuum system, higher shrinkage indices were obtained at lower radiant power input levels (fig. 8). This is due to the fact that at lower radiant inputs, the change in the internal structure of the onion was minimal because of the low onion temperature. There was a gradual but effective loss of moisture from the onion. As a result, the onion shrank gradually from the surface and down fully with time. In the FIR-convection system, however, a higher shrinkage was observed at higher energy inputs. This was due to the prolonged drying time, which was more than double that in the FIR-vacuum system (fig. 6).

Color Change

Color changes of fresh onion after drying and upon rehydration have also been used as a measure of quality. The tristimulus values, which denote the degree of lightness \( (L^*) \), the degree of greenness \( (a^*) \), and the degree of yellowness \( (b^*) \), were used as indices of color change and are presented in figures 9, 10, and 11. A more negative \( a^* \) value denotes a deeper green color. A more yellow and lighter color are, on the contrary, denoted by higher \( b^* \) and \( L^* \) values, respectively. Welsh onion dried by the two systems showed a general decrease in greenness with an accompanying increase in yellowness. In addition, dehydration made the onion lighter in color (fig. 11). These changes were, however, more pronounced in the FIR-convection system because of its prolonged drying period. This is in agreement with the findings of Gunasekaran (1999). The changes in \( a^* \) values in the two techniques were greater than those of \( b^* \), and these changes tended to increase with increasing radiant power inputs. The highest greenness of dried onion was obtained at 0.19 and 0.31 W/cm² radiant power inputs under the absolute pressure and convective conditions, respectively. At these radiant power input levels in the respective systems, the dried onion is most appealing to the eye. The dried onion upon rehydration also showed a general decrease in \( a^* \), \( b^* \), and \( L^* \) values. These are indicative of the browning effect of drying (Krokida et al., 2000). In addition, it could be due to the
higher moisture contents of the fresh and rehydrated onion, which tend to lower the three qualities of color.

![Graph of a* and b* parameters of onion under FIR-vacuum drying.](image)

**Figure 9.** The a* and b* parameters of onion under FIR-vacuum drying.

![Graph of a* and b* parameters of onion under FIR-convection drying.](image)

**Figure 10.** The a* and b* parameters of onion under FIR-convection drying.

![Graph of L* parameter of onion under the two drying systems.](image)

**Figure 11.** The L* parameter of onion under the two drying systems.

**EFFECT OF VACUUM TREATMENT**

Figure 12 shows the drying rates of welsh onion by the FIR heater at a 0.17 W/cm² radiant power input and at various operating pressures. It is clear that lowering the operating pressure in the drying chamber increased the drying rate. This is because reduced pressure enabled the material to be dried at a lower temperature (fig. 5) than would have been required at atmospheric pressure and thereby improved the drying rate (Wadsworth et al., 1990; Gunasekaran, 1999). During the first 70 minutes of drying, onion temperature was lower at high operating pressure, especially between 2.8 and 4.5 kPa pressure (fig. 13). After 70 minutes, the amount of water in the material was so small that operating pressure no longer controlled product temperature. Instead, the sensible heat supplied by the FIR heater became the dominant factor influencing the material temperature, resulting in a rapid rise in the onion temperature (fig. 13) and leading to a decrease in infrared absorptivity. This is in agreement with the findings of Perre and Turner (1997) and Hashimoto and Kameoka (1999). A radiation control or an intermittent technique would be required at this stage to help prevent the material temperature from rising too high.

![Graph of drying rate on drying rate of onion at 0.17 W/cm² radiant power input.](image)

**Figure 12.** Effect of reduced pressure on drying rate of onion at 0.17 W/cm² radiant power input.

![Graph of moisture content and temperature gradients of onion at 0.17 W/cm² radiant power input.](image)

**Figure 13.** Effect of reduced pressure on moisture content and temperature gradients of onion at 0.17 W/cm² radiant power input.

The effect of reduced operating pressure on rehydration potential is shown in figure 14. Rehydration potential increased with increasing absolute pressure. The shrinkage of dried onion was higher at higher absolute pressure. This must have led to the effective loss of moisture on the onion surface. In addition, because of the low product temperature during the first 70 minutes of drying, the moisture content at the center of a piece was never much higher than at the surface, minimizing internal stresses in the onion; a consequence of this was increased rehydration capacity of the material upon drying. The other drying quality indicators had no relation with vacuum levels.
CONCLUSION

Welsh onion drying in the FIR-vacuum and FIR-convocation systems showed the three characteristic drying rate features: a rising-rate, constant-rate, and falling-rate periods. Drying rate increased with increasing radiant power input and was higher under the reduced-pressure environment than under the convective condition, as was greenness.

At 0.17 W/cm² radiant power input, the drying rate was 50% higher in the vacuum operation than in the convective condition. Lowering the operating pressure in the drying chamber increased the drying rate. Shrinkage was higher with a concomitant higher rehydration potential of onion, and hence superior quality at lower radiant power input under the reduced pressure. For optimum drying rates vis-à-vis product quality and energy savings in the drying of Welsh onion, it is recommended that FIR-vacuum operation at 0.17 W/cm² radiant power input be used. In the convective condition, drying should be done at higher radiant power input levels for better reconstitution.

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