Physical Properties of Green Pea in an Inert Medium FBD Dryer Assisted by IR Heating

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ABSTRACT: *The drying behavior of green peas is investigated in a pilot scaled Fluidized Bed Dryer (FBD) with inert particles assisted by an Infra Red (IR) heat source. The variation of shrinkage and moisture diffusivity with temperature and moisture content were investigated. The experimental drying curves were adjusted to the diffusion model of Fick's law for spherical particles. The result was that, although the shrinkage was only a function of moisture content, the moisture diffusivity was dependent upon both temperature and moisture content. The effective diffusion coefficients were estimated at a temperature range of 35-70°C and a moisture content range of 0.25- 3.8 kg moisture/kg dry solids. Some correlations were proposed for these properties.*

KEY WORDS: *Moisture diffusivity, Shrinkage, Infrared, Fluidized bed, Drying, Inert particle, Green pea.*

INTRODUCTION

Drying is one of the most energy-intensive unit operations due to the high latent heat of vaporization and the inherent specific heat capacity of the drying materials. The design of the dryers to produce dried products of a desired quality with minimum energy consumption and maximum throughput still remains a challenge. The drying process couples the heat and mass transfer operations, which must be analyzed carefully for the efficient design and operation of a dryer. Many authors have successfully applied this process in different solids dried in a variety of dryers [1]. Many studies have been carried out to investigate the drying of different foodstuffs by air drying [2, 3], convection and microwave drying [4, 5] and drying in a fluidized bed.

Recently, a non-classical technique has been developed in which heating and drying in fluidized beds has been accomplished in the presence of particles. This method, which is known as inert medium fluidized bed drying, can be defined as a fluidized bed of drying solid samples and inert particles, whereby the inert particles serve as the heat carrier. In this type of dryer, the drying gas fluidizes both the inert particles and the drying solids

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in the bed. Mixing and heat transfer are quite rapid, as the inert particles can absorb heat from a heat source and transport it uniformly through the bed. In general, the presence of inert material would increase the rate of drying. This could be due to the fact that the presence of smaller inert materials in fluidized beds fills the interstitial space between the particles, hence facilitating their fluidization, which, in turn, causes more efficient contact between the drying materials, inert material, and drying air [6]. The thermal conductivity of inert material may have a significant effect on the drying rate. This subject has been of special interest in recent decades, for example, the works of *Abbasi & Mowla,* (2007,2008) *Grabowsk*,(1994),*Jariwara et al* (1970), and *Zhou et al*, (1998), to name just a few[7-11].

Everybody emits radiation electromagnetic waves because of heating or electric agitation due to temperature. The emission spectrum of industrial emitters is in the range of 0.8-10 μm. When radiant electromagnetic energy impinges upon a food surface, it may induce changes in the electronic, vibrational, or rotational states of atoms and molecules [12]. The mechanism of energy absorption depends upon the wavelength range of the incident energy. Infrared radiation causes molecular vibration changes; hence, heating occurs when food materials are exposed to an infrared region.

Absorptivity α varies with wavelength and temperature. Although emissivity data for biological materials is scarce, typical values of emissivity for agriculture crops vary from 0.7 to 0.9 [13]. Lambert's Law describes radiation power, resulting in the conversion of infrared energy to thermal energy within a semi-infinite loss body.

An undesirable change that occurs simultaneously with moisture diffusion or drying is shrinkage, modifying both physical and transport properties of the material. In general, shrinkage occurs as a result of volume reduction due to the evaporation of the moisture contained in the solid. The changes in the volume of the solid could be monitored for most cases. Shrinkage was found to be dependent on the amount of moisture content. Another important parameter in drying is moisture diffusivity. Since the rate of water vapor transfer in materials is controlled by the diffusion of moisture toward the outer surface, the water vapor concentration on the outer surface of the material is at equilibrium or very close to equilibrium values. The drying rate increases as a result of the equilibrium concentration of the water vapor on the surface of the materials at a higher temperature. As a result of heat transfer to a wet solid, a temperature gradient is developed within the solid, while moisture evaporation occurs from the surface. This produces a migration of moisture from within the solid to the surface, which occurs through one or more mechanisms namely, molecular diffusion, capillary flow, Knudsen flow, hydrodynamic flow, or surface diffusion. Therefore, the analysis of the mass transfer phenomenon is based on the assumption that the effective moisture diffusivity represents all parameters influencing the process rate. In the case of mass diffusivity, it is obvious that temperature and moisture content are the main factors in determining moisture diffusivity. Furthermore, mass diffusivity increases with an increase in air temperature and the power of infrared heating [14].

The objective of this study was to experimentally investigate the changes in different physical properties of green pea during drying in a conventional FBD with energy carriers and also the FBD with energy carriers assisted by IR heat source.

EXPERIMENTLAL SECTION

Materials

In the present work, which was designed for agro-food products, fresh green peas *(Pisum Sativum)* from Shiraz, situated in the south-west of Iran, were chosen as the drying product. Green peas were purchased from the same supplier to maximize the reproducibility of the results. Care was taken when selecting green peas to obtain only those which approximately resemble a spherical shape. Size was measured using a micrometer with an accuracy of 0.01 mm. Several measurements of the dimensions of the spherical samples were made and only samples within a 5% tolerance of the average dimensions were used. To equilibrate the moisture content, green peas were kept in a plastic container in a refrigerator at 4ºC for more than 24 h before experimentation. After the drying the green pea samples in an oven at 105-110ºC for 24h, the average initial moisture content was found to be 77% on wet basis. In the previous work by Wijitha Senadeera 2004, an initial moisture of 75-80% on wet basis for this agro product was reported [15].

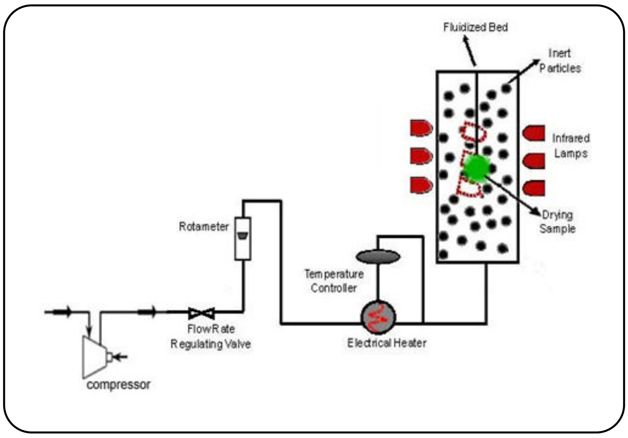

Fig.1. Schematic diagram of the experimental apparatus.

Fig. 2: Fluidized Bed Dryer assisted by infrared heating set up.

Experimentation work

A pilot-scaled fluidized bed dryer with inert particles assisted by an infrared heating source was set up to perform the drying experiments. The schematic diagram of the experimental apparatus is shown in Fig. 1, and a picture of the dryer section is shown in Fig. 2. The dryer was a 77.5 mm cylindrical Pyrex column equipped with a perforated plate as an air distributor. The column was filled with glass beads of 3.0 mm diameter as inert particles, and some infrared lamps were placed around the column as a heating instrument. Drying air was supplied from a high pressure source, and a pressure regulator was used to adjust its flow rate. Air was passed through a rotameter before being preheated by an electrical heater. Likewise, a temperature controller was used to regulate the temperature of air within ±0.1 ºC, and the humidity of the air was determined by an electronic humidity meter (Lutron, model: HT-301 S). A single sample of peas was hung in the fluidized bed of glass beads by means of a light string so that the sample could move freely with the inert particles. During the drying experiments, the weight of the green peas was determined at different times by means of an electronic balance with an accuracy of 0.001g (Radwag WAS 220/C/2). The weighing procedure took no more than 10 seconds after removing the sample from the column. In order to obtain accurate data, the reduction in the weight of the samples was measured independently for a fixed period of time by using several similar green peas each time. The infrared lamps were available at different powers and were placed in an oven space of 0.18 m^3. The surface as well as the central temperature of the sample and the velocity and the temperature of drying air were measured each time. In each run, the volume of the dried sample was measured by immersing it in toluene with pycnometers, and the change in the volume was measured. The effects of various parameters could be investigated considering the obtained experimental data. The operating conditions are summarized in Table 1.

RESULTS AND DISCUSSION

In order to propose some correlations for shrinkage, density and effective moisture diffusivity of green peas during the drying process, a non-linear regression method has been employed. In this method, the correlation coefficient R^2 and the Root Means Square Error (RMSE) were used to evaluate the accuracy of the fitting process. These parameters were calculated from the following equations:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(M^{pred,i} - M^{exp,i}\right)^2}{\sum_{i=1}^{N}\left(\bar{M}^{pred} - M^{pred,i}\right)^2} \qquad (1)$$

$$RMSE = \left[\frac{1}{N}\cdot\sum_{i=1}^{N}\left(M^{pred,i} - M^{exp,i}\right)^2\right]^{1/2} \qquad (2)$$

where $M^{exp,i}$ and $M^{pred,i}$ stand for the experimental and the predicted values of the parameter that is to be correlated respectively for the same operating conditions [16].

Drying Rate

The drying of green peas occurs only in the falling rate period, and the rate of moisture removal is limited by

Table 1: The operating conditions for drying of green pea in FBD and FBD+IR systems.

Exp. # No.	Diameter of Sample mm	Weight of Sample g	Air Velocity m/s	Inlet Air Temperature °C	Amount o f Inert g	Type of System	Infrared power W
1	9.24	0.461	7	50	150	FBD	0
2	9.24	0.462	7	50	400	FBD	0
3	9.24	0.468	8	50	400	FBD	0
5	9.50	0.476	8	50	400	FBD with IR	600
4	9.05	0.451	7	50	400	FBD with IR	600
6	9.05	0.452	5	60	150	FBD with IR	600
7	9.5	0.469	5	50	400	FBD with IR	600
8	9.14	0.461	5	50	150	FBD with IR	600
9	9.12	0.457	5	40	150	FBD with IR	600
10	9.13	0.459	5	30	150	FBD with IR	600
11	9.13	0.460	5	60	150	FBD	0
12	9.14	0.464	5	60	150	FBD	0
13	9.14	0.461	5	50	150	FBD	0
14	9.14	0.459	5	40	150	FBD	0
15	9.13	0.463	5	40	150	FBD	0
16	9.14	0.462	5	35	150	FBD	0
17	9.14	0.461	2	50	400	FBD with IR	600
18	9.12	0.458	5	50	400	FBD with IR	600
19	9.14	0.462	2	50	400	FBD	0
20	9.14	0.460	5	70	150	FBD+IR	600
21	9.14	0.465	5	70	150	FBD	0
22	8.61	0.417	3	40	400	FBD with IR	600
23	8.61	0.408	3	40	400	FBD with IR	500
24	9.46	0.477	3	40	400	FBD with IR	400
25	9.24	0.473	3	40	400	FBD with IR	200
26	9.51	0.471	3	40	400	FBD	0
27	9.15	0.415	3	40	400	FBD with IR	600
28	8.61	0.4085	3	40	400	FBD with IR	500
29	8.61	0.411	3	40	400	FBD with IR	400
30	9.1	0.458	3	40	400	FBD with IR	200
31	9.48	0.472	3	40	400	FBD	0

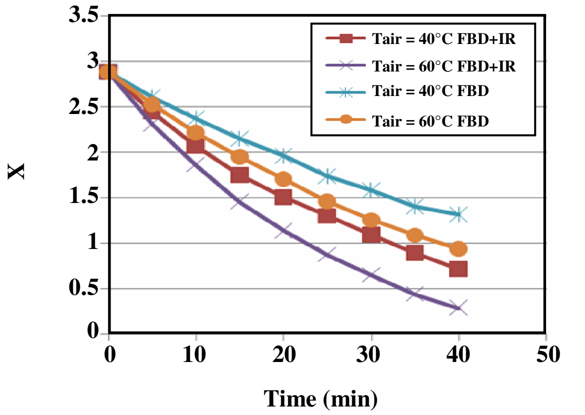

Fig. 3: Variation of moisture ratio with time at different air temperatures for both systems.

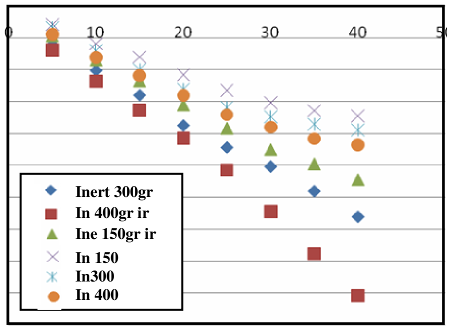

Fig. 5: Variation of moisture ratio with time at different amounts of inert particles for both systems.

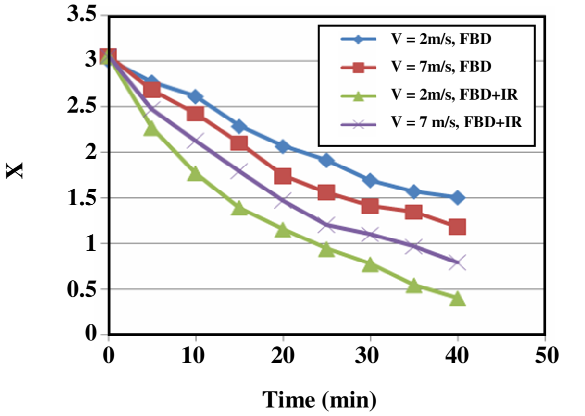

Fig. 4: Variation of moisture ratio with time at different air velocities for both systems.

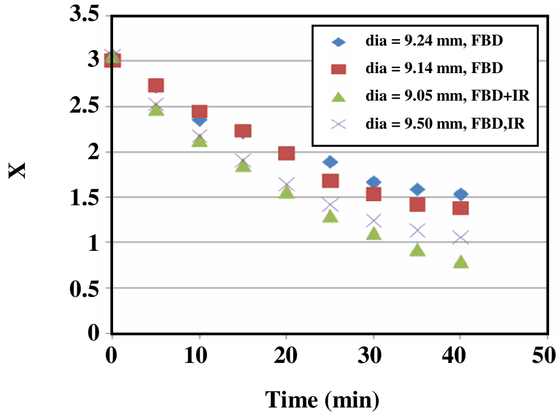

Fig. 6: Variation of moisture ratio with time at different diameters of drying sample for both systems.

the diffusion inside the product. Figs. 3-6 show the effects of air temperature, drying sample diameter, amount of inert particles and air velocity on the drying rate of green peas. It was found that air temperature (Fig. 3) is the main parameter having a significant effect on drying curve.

Drying rate decreases continuously with time and decreasing moisture content. In the present study as shown on the curves, the whole experiment occurs in the falling rate period. The values of the drying rate almost doubled when the drying temperature was increased from 40 to 60 °C.

It could be concluded that the amount of inert material has no pronounced effect on the drying rate. The drying rate (Fig. 4) is decreased by increasing the mass ratio of the drying solid to inert material. It could be seen that decreasing the diameter of the drying sample (Fig. 5) would increase the drying rate. Moreover, it is clear that samples with a smaller diameter would approach their final moisture content and temperature more rapidly than larger ones. Fig. 6 shows the variations of the dried sample moisture content with flowing air velocity for two different systems, while maintaining other parameters constant. In this case, the air velocity is changed from 2 m/s (minimum fluidizing velocity) to 7 m/s. For FBD with IR system at low air velocity, the rate of water content loss was higher, as expected. This can be attributed to the fact that at higher air velocities, more heat is lost due to forced convection. For the other system (FBD), increasing the velocity of air shows different results.

Shrinkage

In order to show the effects of various parameters on the shrinkage of the green peas, several experiments were carried out under different operating conditions. For each

Table 2: Calculated values of constants for shrinkage Equations (3&4).

FBD						
T	V	Mip	dia	a	b	R^2
50 °C	2 m/s	400 g	9.1 mm	0.051	0.847	0.990
50 °C	7 m/s	400 g	9.02	0.130	0.597	0.993
60 °C	5 m/s	150 g	9.14	0.082	0.792	0.959
40 °C	5 m/s	150 g	9.84	0.082	0.792	0.959
50 °C	5 m/s	150 g	9.24	0.159	0.512	0.968
50 °C	5 m/s	150 g	9.14	0.114	0.643	0.988
50 °C	5 m/s	400 g	9.24	0.139	0.580	0.982
50 °C	5 m/s	150 g	9.24	0.157	0.517	0.977
				a	$\bar{d}$	$\bar{d}$
FBD+IR						
T	V	Mip	dia	a	b	R^2
50 °C	2 m/s	400 g	9 mm	0.054	0.856	0.891
50°C	7 m/s	400g	9	0.098	0.699	0.961
60°C	5 m/s	150g	9.1	0.062	0.845	0.986
40°C	5 m/s	150g	8.625	0.075	0.813	0.966
50°C	5 m/s	150g	9.05	0.124	0.625	0.984
50°C	5 m/s	150g	9.05	0.098	0.699	0.961
50°C	5 m/s	400g	9.24	0.108	0.675	0992
50°C	5 m/s	150g	9.24	0.124	0.629	0.988
				$\bar{d}$	$\bar{d}$	$\bar{d}$

experiment, the changes in $D/D_\circ$ were determined at various moisture contents.

The analysis of the experimental data reveals that the changes of $D/D_\circ$ during the drying of samples in a fluidized bed of inert heat carriers with and without infrared heat source assistance could be well correlated as linear functions of the moisture content (X) of the samples as follows:

For FBD $\left(D/D_\circ\right) = 0.08287\ X + 0.7671$ (3)

R^2=0.9815

For FBD with IR (4)

$\left(D/D_\circ\right) = 0.076167\ X + 0.790467$ R^2=0.9786

Different constants in the above equations are determined for various operating conditions and summarized in Table 2, along with the R^2 for each case. The effects of various parameters on the shrinkage are outlined as follows:

Effect of Air Velocity

Referring to Table 1, some of the results of the experiments were used to analyze the effect of air velocity on $D/D_\circ$. Fig. 7 shows that as air velocity increases, the shrinkage of the drying particle decreases. Comparing the results obtained for the fluidized bed dryer systems with and without infrared (IR) assistance indicates a lower shrinkage when IR is used. This is due to the fact that when IR is used, the rate of drying is higher and, thus, the drying time is shorter, causing lower volume change.

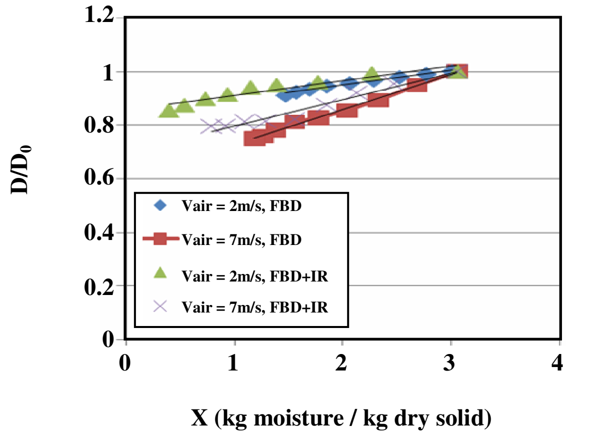

Fig. 7: The effect of air velocity on the shrinkage in FBD and FBD assisted by IR.

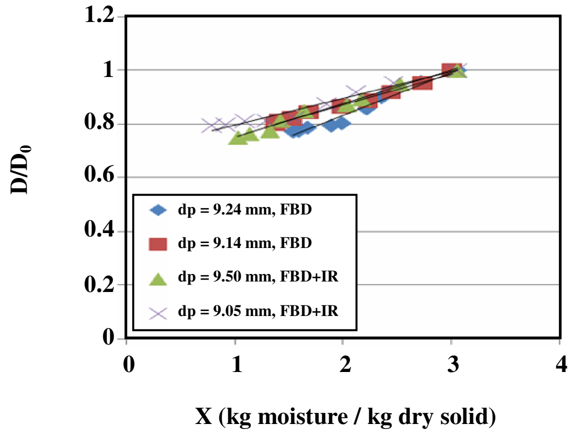

Fig. 9: The effect of particle diameter on the shrinkage in FBD and FBD assisted by IR.

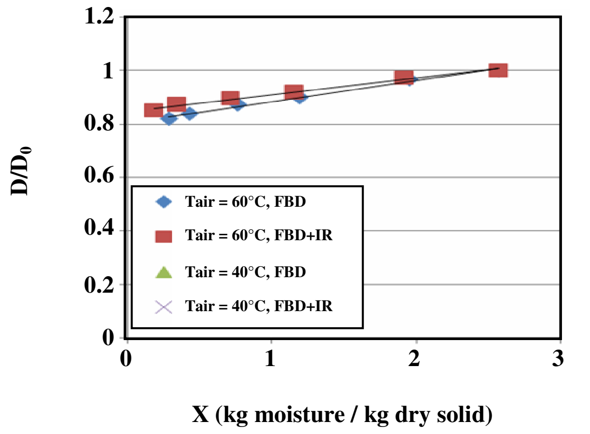

Fig. 8: The effect of air temperatures on the shrinkage in FBD and FBD assisted by IR.

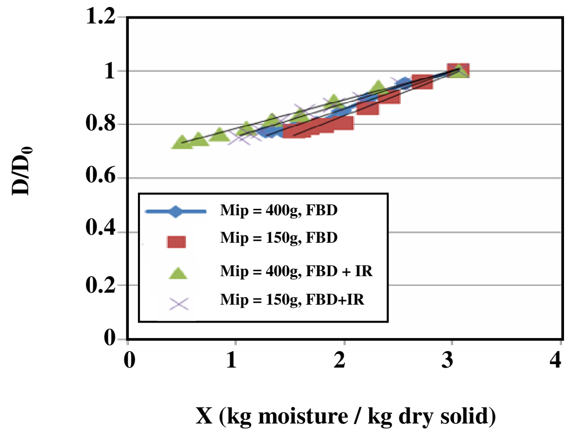

Fig. 10: The effect of amount of inert materials on the shrinkage in FBD and FBD assisted by IR

Effect of Air Temperature

Fig. 8 shows the variations in the shrinkage of the drying particle with the drying air temperature. These figures clearly suggest that as the temperature of the inlet air increases, the amount of shrinkage decreases. What is more, comparing both systems of FBD with and without IR, one would conclude that using IR source resulted in a lower shrinkage.

Effect of Drying Sample Diameter

Fig. 9 shows that as the diameter of the drying particle increases, the amount of shrinkage increases as well, and the variations of (D/D_0) versus particle moisture give a linear relationship.

Effect of Presence of Inert Material

Addition of some inert materials, which act as heat carriers, to the drying sample, is one of these improvement techniques. Inert particles can improve the fluidization behaviour of drying materials and increase convective heat and mass transfer coefficient. According to Fig. 10, the amount of inert materials has no significant effect on the particle shrinkage.

Particle Density

The density of foodstuffs with a given initial moisture content decreases during the drying process [17]. The density of a foodstuff is the ratio of the current total mass of the sample to its overall volume at any time.

Table 3: Calculated values of constants for density Equations (5&6).

FBD								
T	V	Mip	dia	a	b	c	d	R^2
40°C	5 m/s	150g	9.14 mm	36.83	-222.7	521.1	530.3	0.997
60°C	5 m/s	150g	9.14 mm	28.22	-198	504.1	537.8	1.0
70°C	5 m/s	150g	9.14 mm	22.66	-180.1	489.6	532.9	0.991
				$\bar{a}$ =29.2366	$\bar{b}$ =-200.267	$\bar{c}$ =504.933	$\bar{d}$ =533.66	R^2=0.996
FBD+IR								
T	V	Mip	dia	a	b	c	d	R^2
40°C	5 m/s	150g	9.14	10.47	-92.58	290.8	719	0.996
60°C	5 m/s	150g	9.14	56.53	-314.3	590.8	620.5	0.996
70°C	5 m/s	150g	9.14	21.94	-173.4	450.9	623.5	0.984
				$\bar{a}$ =29.6467	$\bar{b}$ =-193.427	$\bar{c}$ =444.167	$\bar{d}$ =654.333	R^2=0.992

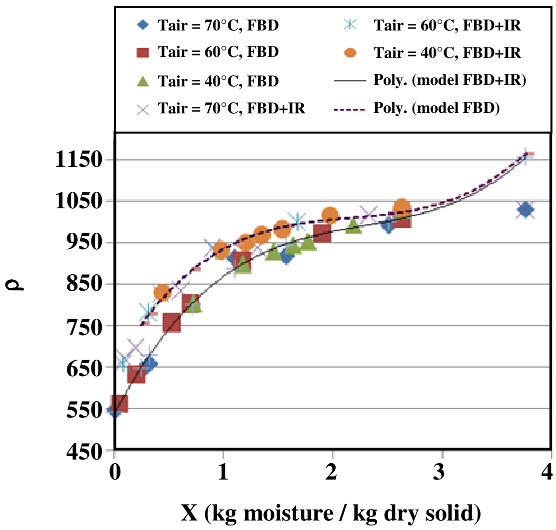

Fig. 11: The effect of air temperature on the particle density in FBD and FBD assisted by IR.

Several experiments were carried out under different operating conditions and in each experiment, the changes in ρ_p with moisture content were determined. Fig. 11 shows the variation of drying sample density with its moisture content at different operating conditions for both systems of FBD, with and without IR heat source. The following correlations were obtained for density by a non linear regression method:

For FBD (5)

$\rho_p = 29.2366X^3 - 200.267X^2 + 504.933X + 533.66$

R^2=0.996

For FBD with IR (6)

$\rho_p = 29.6467X^3 - 193.427X^2 + 444.167X + 654.33$

R^2=0.992

Different constants in the above equations are determined for various operating conditions and summarized in Table 3, along with the R^2 for each case. As shown by these correlations, the sample density variations showed similar behavior in both systems. Fig. 11 shows that as the drying air temperature increases, the amount of shrinkage decreases slightly, and a decrease in moisture content results in a decrease in particle density. The results show that the values of R^2 are greater than 0.992 and the values obtained for RMSE are in the range of 0.0052 to 0.031032, which show that the proposed correlation is acceptable.

Estimation of moisture diffusivity and activation energy

The determination of moisture diffusivity by the obtained experimental drying data was interpreted using Fick's diffusion model [18].

$$\frac{\partial(\rho_p X)}{\partial t} = D_{eff} \frac{\partial^2 (\rho_p X)}{\partial r^2} \quad (7)$$

In most situations, the food product is assumed to be one-dimensional and to have uniform initial moisture content. Therefore, the following initial and boundary conditions could be written for spherical particles:

I.C. at $t = 0$ $X = X_0$ $0 < r < R_p$ (8)

B.Cs. at $r = 0$ $\frac{\partial X}{\partial r} = 0$ $t > 0$ (9.a)

at $r = R_p$ $X = X_e$ $t > 0$ (9.b)

By neglecting shrinkage, the solution of a Fickian equation in such conditions for different geometries has been presented by *Crank* [19].

Equilibrium moisture content calculated by *Medeiros & Sereno* (1994) is as follows [20]:

$$X_e = \frac{0.0516 \times 1.41 \times 0.954 \times a_w}{\left[(1 - 0.954 \times a_w)(1 - (1 - 1.41) 0.954 \times a_w)\right]} \quad (10)$$

a_w of the surface can be expressed as $RH_{equilibrium}/100$. The solution of Fick's equation for a spherical particle is as follows:

$$MR = \frac{X - X_e}{X_o - X_e} = \frac{6}{\pi^2} \sum_{i=1}^{n} \frac{1}{n^2} \exp(-n^2 \pi^2 Fo) \quad (11)$$

By neglecting the terms beyond the first term of summations and replacing the Fouriers number with proper variables, the following equation can be obtained.

$$\ln MR = \ln \frac{X - X_e}{X_o - X_e} = \ln \frac{6}{\pi^2} - \left(\pi^2 \frac{D_{eff}}{R_p^2} \right) \quad (12)$$

Plotting the experimental values of $\ln \frac{X - X_e}{X_o - X_e}$ versus time, at a given temperature will result in a straight line of slope $\pi^2 \left(D_{eff} / R_p^2 \right)$ which could be used to obtain the effective moisture diffusivity. In the present study, an Arrhenius type equation in the form of Eq. (8) is assumed for the effective moisture diffusivity.

$$D_{eff} = D_0 \exp\left(\frac{-E_a}{RT_{abs}} \right) \exp\left[(AX + B) T_{abs} \right] \quad (13)$$

Empirical correlations for moisture diffusivity of green peas as a function of moisture content and temperature for systems of FBD and FBD with IR would be obtained by fitting some experimental data to Eq. (13), as will be seen later. A complication of such equations is given by *Zogzas et al.* [21]. Although different authors agree that the temperature dependence can be satisfactorily described by an Exponential-type relation, the moisture content dependence has not yet been formulated into a generally accepted model.

Based on the obtained experimental data for variation of the moisture content (in the range of 0.358-2.74) as a function of time for various temperatures (40-60 °C), the D_{eff} is calculated for different operating conditions using Eq. (12). Then the parameters D_o, E_a, A and B in Eq. (13) are determined by a fitting process. The results are shown in Table 4. In this table the Mean Average Errors (MEA) are also given at each operating conditions. This fitting process gives the following correlations as the best empirical correlations for the effective moisture diffusivity in green pea:

$$D_{eff} = 1.85 \times 10^{-5} \exp\left(-\frac{3400}{T} \right) \times \quad (14)$$

$$\exp\left[(-0.007T + 2.5) X \right] \quad \text{(FBD without IR)}$$

$$D_{eff} = 1 \times 10^{-5} \exp\left(-\frac{3100}{T} \right) \times \quad (15)$$

$$\exp\left[(-0.007T + 2.5) X \right] \quad \text{(FBD with IR)}$$

The results show that the values of RSME are in the range of 1.6E-11 to 7.06E-11 for FBD with IR system and in the range of 3.5E-11to 1.3E-10 for the FBD system, which shows that the proposed correlations are acceptable. Some typing variations of D_{eff} for green peas with moisture contents at different air temperatures are shown in Fig. 14 and 15. As shown, the effective moisture diffusivity increases with an increase in both temperature and moisture content. Comparison of Figs. 12 & 13 also shows that the effective moisture diffusivity increases by applying IR to the FBD system. D_{eff} values for each level of air velocity and temperature are reported in Table 4. The value of E_a for green peas varies from 25.45 to 28.4 kj/ mol. In general, E_a lies in the range of 12.7 – 110 kj/mol for food product.

The effective moisture diffusivity increased dramatically with an increase in infrared power .The typical variation in D_{eff} with moisture content at an air velocity of 3.0 m/s and temperature of 40ºc at infrared power of 400,500 and 600 W are shown in Fig.14. The increase in the temperature on the surface of the product resulted in an increase in the water vapor pressure inside the product, and thus, in a higher drying rate and D_{eff} . The effective moisture diffusivity D_{eff} increased from 5.99×10^{-10} to 1.05×10^{-9} m^2/s at 600 w, 5.56×10^{-10} to 9.25×10^{-10} m^2/s at 500 w, 5.50×10^{-10} to 8.15×10^{-10} m^2/s at 400 w and 4.82×10^{-10} to 6.79×10^{-10} m^2/s without infrared heat source combined fluidized bed dryer with moisture content of green peas.

Table 4: Comparison between the $(D_{eff})_{Exp}$ with the $(D_{eff})_{Cal}$ at various conditions.

T=60 ˚C, Vair=5 m/s, FBD+IR				T=50 ˚C, Vair=5 m/s, FBD+IR			
x	$(D_{eff})_{Exp}$	$(D_{eff})_{cal}$	MAE%	x	$(D_{eff})_{Exp}$	$(D_{eff})_{cal}$	MAE%
2.588	1.41E-09	1.37405E-09	-2.75222	2.611	1.29E-09	1.24035E-09	-4.02219
2.08	1.24E-09	1.26083E-09	1.391097	2.133	1.15E-09	1.10648E-09	-3.7984
1.655	1.18E-09	1.17349E-09	-0.21691	1.743	1.07E-09	1.00815E-09	-6.00477
1.292	1.07E-09	1.1037E-09	3.17047	1.416	1E-09	9.32265E-10	-6.91195
1	9.94E-10	1.05055E-09	5.734119	1.128	9.47E-10	8.70335E-10	-8.11038
0.757	9.53E-10	1.00822E-09	5.739617	0.889	8.95E-10	8.22026E-10	-8.103
0.54	9.47E-10	9.71942E-10	2.606886	0.712	8.25E-10	7.87979E-10	-4.46714
0.358	9.42E-10	9.42595E-10	0.105377	0.584	7.75E-10	7.6418E-10	-1.39081
T=40 ˚C, Vair=5 m/s, FBD+IR				T=60 ˚C, Vair=5 m/s, FBD			
x	$(D_{eff})_{Exp}$	$(D_{eff})_{cal}$	MAE%	x	$(D_{eff})_{Exp}$	$(D_{eff})_{cal}$	MAE%
2.655	1.08E-09	1.11015E-09	2.941922	2.699	8.64E-10	9.49723E-10	9.92162
2.248	9.8E-10	9.78934E-10	-0.10817	2.367	8.44E-10	9.03904E-10	7.09764
1.903	9.06E-10	8.79908E-10	-2.89251	2.08	8.18E-10	8.65986E-10	5.866315
1.619	8.21E-10	8.06185E-10	-1.76393	1.823	8.04E-10	8.33497E-10	3.668805
1.394	7.47E-10	7.51885E-10	0.708568	1.58	7.92E-10	8.03815E-10	1.491806
1.19	7.2E-10	7.06053E-10	-1.92122	1.358	7.75E-10	7.7775E-10	0.354792
0.987	6.85E-10	6.63014E-10	-3.17494	1.173	7.60E-10	7.56509E-10	-0.45935
0.796	6.74E-10	6.25158E-10	-7.25527	1.013	7.39E-10	7.38765E-10	-0.0318
T=50 ˚C, Vair=5 m/s, FBD				T=40 ˚C, Vair=5 m/s, FBD			
x	$(D_{eff})_{Exp}$	$(D_{eff})_{cal}$	MAE%	x	$(D_{eff})_{Exp}$	$(D_{eff})_{cal}$	MAE%
2.721	7.79E-10	8.3858E-10	7.602448	2.739	6.48E-10	7.26859E-10	12.15658
2.426	7.68E-10	7.86093E-10	2.33208	2.482	6.35E-10	6.749E-10	12.15658
2.165	7.44E-10	7.42411E-10	-0.234	2.252	6.35E-10	6.31481E-10	6.212789
1.929	7.36E-10	7.05039E-10	-4.24457	2.049	6.23E-10	5.95407E-10	-4.47745
1.712	7.24E-10	6.72345E-10	-7.16142	1.845	5.90E-10	5.61394E-10	-4.84853
1.522	7.08E-10	6.44905E-10	-8.90122	1.655	5.61E-10	5.31358E-10	-5.28381
1.354	6.93E-10	6.2159E-10	-10.2844	1.487	5.32E-10	5.06155E-10	-4.8581
1.212	6.66E-10	6.02611E-10	-10.2844	1.354	5.06E-10	4.87105E-10	-3.73417

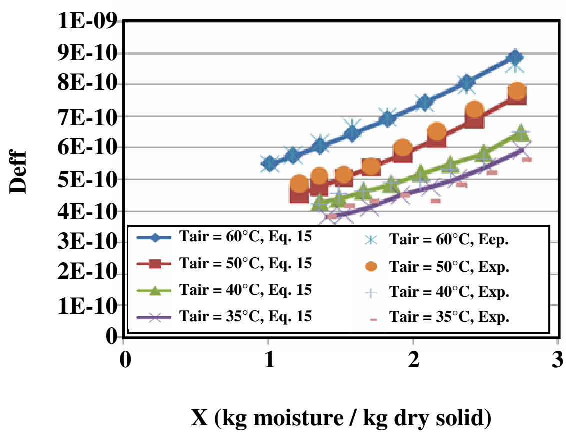

Fig. 12: Comparison of the experimental D_{eff} with the values predicted by the model in FBD.

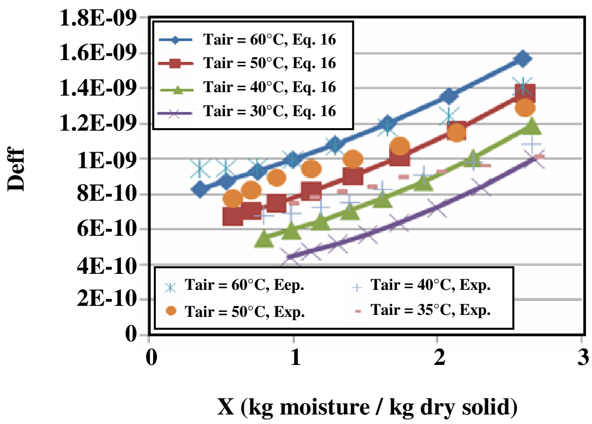

Fig. 13: Comparison of the experimental D_{eff} with the values predicted by the model in FBD assisted by IR.

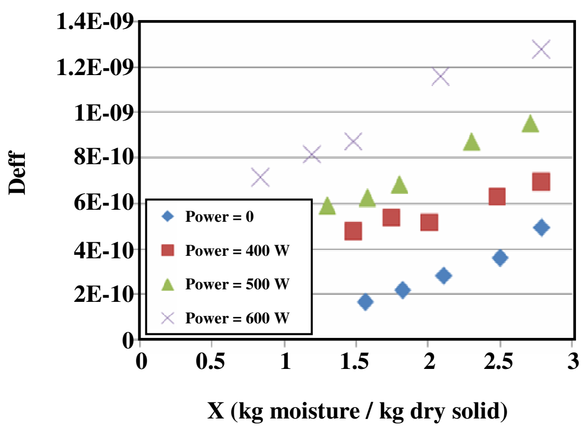

Fig. 14: Variation in effective moisture diffusivity with moisture content at different powers of infrared heat source.

CONCLUSIONS

Different physical properties of green peas during drying in FBD and FBD+IR systems with inert particles are investigated. The following points are noted for this case:

1- For both FBD and FBD + IR systems, shrinkage increases linearly with moisture content. However, the increase happened at a slower rate when IR heat source was used. In either case, shrinkage is less for a FBD + IR (with R^2=0.9786) system in comparison with the FBD (with R^2=0.9815) system alone.

2- The density increases with moisture content for both systems, and its variation is in the form of a polynomial function (R^2>0.9598 for both systems).

3- The D_{eff} increases with the temperature and moisture content of green peas. The effective diffusivity for a FBD + IR system is larger than a FBD system for the same temperature (MAE).

5- The energy of activation calculated for green peas in drying experiments varied between 25.45 to 26.46 kJ/mol.

6- The effective moisture diffusivity increases with an increase in the applied power of IR system.

7- Inert particles can improve the fluidization behaviour of drying materials and increase convective heat and mass transfer coefficient. Inert Particles have the added advantages of keeping local moisture and temperature approximately constant throughout the drying tests and decreasing the hot spot zone on the drying sample.

Nomenclature

A, A', a, a'	Constants in equations
B, B', b, b'	Constants in equations
D	Diameter of sample, m
D_0	Initial diameter of sample, m
D_{eff}	Effective diffusivity, m^2/sec
E_a	Activation Energy, kJ/mol
K	Extinction coefficient, m^{-1}
MAE	Mean Average Error
n	Node number, dimensionless
Q	Heat transfer rate, W
Q_{abs}	Initial radiant heat, W
Q_r	Average volumetric heat, W/m^3
R	Radius, m
R_p	Outer radius of solid to be dried, m
R_g	Universal gas constant, J/mol.K
t	Time, s
T_e	Emitor temperature, K

T_g Air temperature, K
T_p Particle temperature, K
X Moisture content, kg moisture/kgd.b
X_0 Initial moisture content, kg moisture/kgd.b
X_e Equilibrium moisture content, kg moisture/kgd.b

Greek symbols

δ_P Penetration depth, m
ε Emissivity
δ Stephan-Boltzmann, W/m^2K^4
ρ_p Particle density, kg/m^2

Dimensionless group

Fourier No $Fo = D_{eff}.t/\bar{R}^2$

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