Experimental and theoretical investigation of drying of a solid particle in an inert medium fluidized bed assisted by infrared radiation

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Abstract
The application of combined electromagnetic radiation and hot air is gaining momentum in food processing. A combined infrared and hot air heating system was developed for the drying of vegetables. Set of coupled heat and mass transfer equations are developed to predict the effect of infrared radiation (IR) in a fluidized bed with inert particles for drying of a single sphere solid. A two layer models were introduced for green peas, a penetration layer and a conduction layer model. Comparison of the results showed that the predicted model agreed well with the experimental results with a maximum error of 5% and 9% for average moisture content and temperature respectively. The model is capable of reasonably predicting temperature, moisture content and shrinkage distribution inside a particle.

Key words: modeling، drying, infrared, fluidized bed, inert particles

Introduction
Moisture content in food is eliminated during dehydration processes, thus achieving better microbiological preservation, as well as retarding many undesirable reactions (Ibarz et al 2000) due to the reduction in water activity. Since temperature is one of the major factors in achieving high product quality, therefore increasing the input air temperature may improve the rate of heat transfer which can provide significant benefits to the drying process.
A large number of dryer types have been used for drying in practice. The use of a fluidized bed dryer for granular material is now well established and widely used in industry. In fluidized bed drying processes, the product to be dried is homogenously

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dispersed in the bed and an isothermal operation is carried out, using the fluidization of material in the dryer (Panda, R. C. et al 1991, Hovmand, S. 1994).

Low thermal conductivity and case hardening of the material are the main factors responsible for slowing the hot air drying process (Afzal et al 1999). The application of infrared processing has gained momentum due to its inherent advantages over hot air heating (fluidized bed dryer), and combined with infrared processing has been tried in baking, rousting, thermal treatments and drying of food stuffs (Sandu, C. 1986).

In this work for the drying system a combined sources of convection and infrared heating are used to improve the quality of the dried products. The emission spectrums of infrared wave used in the drying processes are in the range of 0.1 to 100 micrometers (Metaxas, A. C. 1996).

In the case of an opaque material, the penetration depth reaches a few microns thus inducing a superficial heating. The heat is then transmitted by conduction through the material. The absorbed heat flux is given by the following equation:

$$(1)\quad Q_{Abs} = aQ_{Rad}$$

The absorption coefficient α depends on the superficial moisture content and wavelength of the incident lighting. By applying the law of Kirrocshof the case will be assimilated to a grey body with diffuse emission.

Experimental studies on infrared drying of various food products including vegetables have been reported by Ginzburg (1969). The application of combined electromagnetic radiation and hot air heating is considered to be more efficient over radiation or hot air heating alone as it gives the synergistic effect (Hebber, H. U. et al 2004). Energy and quality aspects were studied during the combined far infrared and convective drying of barley (Afzal et al.1999).

The combination of infrared heat source with a fluidized bed by inter particles provides the synergistic effect, resulting in an efficient drying process. When the material is exposed to infrared radiation it impinges on the material surface, penetrates through it and increasing molecular vibration (Sakai et al1994). Due to the absorption of radiation which generates heat in the material both at the surface and the inner layer simultaneously. The rapid heating of the material increases the rate of moisture movement towards the surface. The convective flow of air removes the moisture from the surface, hence lowering the temperature of the surface which results in increased mass transfer.

Tractate et al., (1985) used a fluid bed of inert particles for granulation and drying of pharmacologically active tablets. Abid et al, (1990) studied the kinetics of the drying of corn grains in a fluidized bed of inert particles and found that the limiting mechanisms of heat and mass transfer are primarily of an internal nature. Chen et al. (1996) carried out an experimental investigation on the drying of five kinds of materials such as concrete admixtare in a fluidized bed with inert particles and established a correlation to calculate the volumetric heat transfer coefficient. Combined convection and infrared heating in a fluidized bed contained inert particles, as a heat carrier, is distinguished by its high heat transfer coefficient. The objective of this work is to study the rate of drying of a porous particle and to develop a mathematical model for this system. Experimental works were carried out with spherical samples of green peas in which the drying process was considered to be one-dimensional diffusion in the radial direction. The effect of the main parameters affecting the drying process such as: air flow rate, air temperature, particle diameter and the amount of inert materials was investigated. Also, the shrinking effect, density and diffusivity variation during the drying process were taken into account for the purpose of simulation.

Mathematical modeling

The main assumptions made in the formulation of the model are stated as follows:

-Heat and mass transfers within the particle simultaneously take place in the radial direction.

-Coupled heat and mass transfer models are used to describe the drying process of a single kernel.

-Moisture evaporation takes place on the surface of the green peas

-The amount of energy loss by the IR lamps is negligible

-Inert material (glass beads) is transparent to infrared radiation.

According to the theory of infrared irradiation (Sandu, 1986), infrared energy from heaters suddenly impinges upon a grain surface, and directly penetrates into the grain approximately 1 mm under the surface(Ginzburg, 1969, Nindo et al, 1995) therefore, all of the IR energy is completely absorbed from the penetrating layer. This layer is considered to be the location of the heat-conversion. The interior of the grain from the depth of 1mm through to the grain core is called the conduction layer. Heat is transferred by conduction from the surface to the core of the particle, and moisture diffuses out to the surface particle. Moisture inside the particle grain is transferred from the core to the grain surface. Besides, heat and moisture at the grain surface take away by the air medium within the column. In the development of the model, heat is transferred to the surface of the particle by forced convection, and then into the interior of a grain by conduction (Jumah, (2006), Hatamipour, Mowla 2003). Therefore heat and mass transfer equations are written for the layers as follows:

For the conduction layer:

$$\frac{\partial(r_p X)}{\partial t} = D_{eff}\left[\frac{\partial^2(r_p X)}{\partial r^2} + \frac{2}{r}\frac{\partial(r_p X)}{\partial r}\right] \quad (2)$$

$$\frac{\partial(r_p C_p T)}{\partial t} = K\left[\frac{\partial^2(r_p C_p T)}{\partial r^2} + \frac{2}{r}\frac{\partial(r_p C_p T)}{\partial r}\right] \quad (3)$$

For the penetration layer

$$\frac{\partial(r_p X)}{\partial t} = D_{eff}\left[\frac{\partial^2(r_p X)}{\partial r^2} + \frac{2}{r}\frac{\partial(r_p X)}{\partial r}\right] \quad (4)$$

$$\frac{\partial(r_p C_p T)}{\partial t} = K\left[\frac{\partial^2(r_p C_p T)}{\partial r^2} + \frac{2}{r}\frac{\partial(r_p C_p T)}{\partial r} + Q_r\right] \quad (5)$$

The initial and boundary conditions are as follows:

Initial condition for mass transfer:

At $t=0$ $\quad 0 \le r \le R$ $\quad X=X_0$ (6)

Initial condition for heat transfer:

At $t=0$ $\quad 0 \le r \le R$ $\quad T=T_0$ (7)

Boundary condition for mass transfer:

At $t>0$ $\quad r=0$ $\quad \frac{\partial X}{\partial r} = 0$

At $t>0$ $\quad r=R_P$ $\quad$ (I) $\quad X=X_0$

(II) $\quad -D_{eff}\frac{\partial(r_p X)}{\partial r}\Big|_{r=R_p} = K_m(Y_i - Y_e)$ (8)

Boundary condition for heat transfer

At t > 0 r=0 $\frac{\partial T_p}{\partial r} = 0$

At t > 0 r=R_P $-K_p A_p \frac{\partial T}{\partial r}\Big|_{r=R_p} = hA_p (T_\infty - T_p) + r_g V_g h_{fg} \frac{\partial X}{\partial t}$ (9)

The second term on the right hand side of eq. (5) is due to infrared heat generation. The value of X is obtained by the volume average moisture content of the particle.

It is simply assumed that the special distribution of infrared energy absorption in an exponential decay from the surface into the inside of a spherical grain is according to Lambert's law (Eric Wessteins world of physics, 2005). The amount of infrared heat generated is calculated by the energy delivered to particle per unit volume of the penetration layer by Lambert's law which describes the conversion of infrared energy to thermal energy in a semi infinite lossy body:

$$Q_r = Q_{Abs} \exp(-K\Delta r(n-1) \quad (10)$$

Where Q_{Abs} is the initial radiant heat absorbed by the food sample on the surface, K is the extinction coefficient (m-1) and Δr is the grid size (m) (Jun and Irudayaraj, 2003).

The quantity of infrared energy delivered to the particle by IR heater written as follows:

$$Q_{Abs} = \frac{s(T_e^4 - T_{sur}^4)}{\frac{1-e_{IR}}{e_{IR} A_{IR}} + \frac{1}{F_{gp-IR} A_{IR}} + \frac{1-e_{gp}}{e_{gp} - A_{gp}}} \quad (11)$$

Where the values of e_{IR} and e_{gp} are 0.9 from the manufacturer (Sung Chai Meter Co., Ltd .Thailand, 2004) and 0.7(Arinze Schenw and Brigsby, 1984) respectively. The convective mass and heat transfer coefficients are obtained from the heat and mass transfer analogy as follows (Incorpera and Dewitt, 1996), (Naret Mees et al, (2006)):

$$\frac{h_t}{K_m} = r_a C_{pa} Le^{\frac{2}{3}} \quad (12)$$

Where $Le = \frac{a_a}{D_{eff}}$

The convective heat transfer coefficients are obtained from the following relation.

$$\overline{Nu}_D = 2 + (0.4\,\mathrm{Re}^{\frac{1}{2}} + 0.06\,\mathrm{Re}^{\frac{2}{3}})\,\mathrm{Pr}^{0.4}(\frac{m_a}{m_g})^{\frac{1}{4}} \quad (13)$$

Where $\mathrm{Pr} = \frac{m_a C_{pa}}{K_a}$

The above physical properties of air are obtained from (Pakowsk, Bartczak, Strymilo and Stenstorm 1991)

The moisture diffusion coefficient which is based on the exponential type equation is obtained from the partial differential equation for a wide range of temperature and moisture content as follows (Honarvar, Mowla, 2007):

$$D_{eff} = A - \exp\left(\frac{-E}{RT_{abs}}\right)\exp[(CT + F)X] \quad (14)$$

Equilibrium moisture content of green peas can be calculated from Laithong (1987)

$$1 - RH = \exp[-4.723\times10^{-6} T_a (100 M_e)^{2.386}] \quad (15)$$

The finite differences obtained from equations (4-9) provided a tri-diagonal matrix, suitable for solving by the implicit method. The computation program converged quickly to the final solution and the model is compared with the experimental data.

Materials and method

Materials

In this work, which is designed for drying agro food products, fresh green peas (Pisum Sativum) from Shiraz were chosen as the drying products, the size of the sample was measured by using a micro meter with an accuracy of 0.01 mm. These vegetables have a natural moisture content of about 75-80% and during drying, them maintains their shape, although the shrinkage resulted from the great water loss of samples during the process, cannot be ignored.

All peas were obtained from a single region and kept in a refrigerator at 4 C for more than 24hr to obtain equilibrium moisture content before carrying out the experiments.

Experimentation

A pilot scaled fluidized bed dryer with inert particles assisted by an infrared heating source was set up for performing the drying experiments. The schematic diagram of the experimental apparatus is shown in Figure 1.

The dryer was a 77.5mm cylindrical Pyrex column equipped with a perforated plate as an air distributor. The column was supplied with inert particles and infrared lamps placed around the column as a means of heating. It contained three emitters of a standard industrial type, each with a power of 250 W and working in the infrared ranges. Drying air was supplied from a high pressure source and a pressure regulator used to adjust its pressure. Air was passed through a rotameter before being heated by a controlled electrical heater. A temperature controller was used for regulating the temperature of drying air and the relative humidity was determined by an electronic humidity meter.

A given amount of inert material was placed inside the column and then a single particle of green peas hanged in the column by a thread. In each run the weight of the sample, surface and central temperature of the sample, air velocity and power of the infrared heater were measured at different times, then the sample was replaced with new ones to carry out the experiments for other intervals of time. The center of the sample has the maximum moisture content while the outer layer is in equilibrium with drying air. In each run, the volume of the dried sample was determined by immersing it in toluene and measuring the changes in the volume.

RESULTS AND DISCUSSION

In order to show the effect of various parameters such as air velocity, air temperatures, diameter of sample and amounts of inert particle on the drying time several set of experiments were preformed. Figures 2 and 3 compare the predicted and experimental values of average moisture content and surface temperature of green peas during the drying processes. Results indicate that good agreement between the experimental data and calculated values of different parameters obtained by the proposed model are existed. *The obtained results by the model agreed well with the experimental data where maximum errors of 5% for average moisture content and 9% for the temperature of the particle on a dry basis were obtained for the drying processes. Model indicates that infrared radiation was more effective in reducing the moisture content of the green peas rather than the dry green peas. The temperature of the penetration zone is also increased with an increased in the input power of infrared heat source.

The operating conditions and physical properties of the inert particles are summarized in tables 1 and 2 respectively.

From the obtained experimental data, the effect of various parameters could be investigated. The calculated values are those obtained from the numerical calculations. Figure 3 shows the moisture content for different layers of spherical drying material for different times. The predicted moisture content and temperature distributions across the product thickness during drying are shown in figures 4 and 5 respectively. Evaporation of liquid moisture takes place from the product surface by absorbing the heat of vaporization, as well as the heat of adsorption when removing the bond moisture. The initial moisture content at the surface is high therefore it can evaporate at a higher rate at the beginning of the drying process .

The evaporation rate is controlled by the internal mass transfer rate of moisture. It is worthwhile to note that the decrease of internal moisture content is mainly confined to the drying surface and slowly progresses to the interior, because of the low moisture diffusivity of the product.

A decrease in the temperature of the product during the initial period of drying indicates that the heat supplied by the drying air, inert particle and infrared heat source to the product surface cannot sustain the higher evaporation rate of the moisture. The vapor pressure at the drying surface increases with the increase in surface temperature. The diffusion coefficient increases with an increase in the product temperature that leads to enhanced internal mass transfer as well.

Effect of air velocity

Figures 6 and 7 show the effect of air velocity on the drying rate of green peas for glass beads of diameter 5mm, in a fluidized bed contained inert particles and being assisted with and without infrared heat sources. Figure 6 shows that the air velocity has an appreciable effect on the drying rate in a well fluidized bed system, where as figure 7 indicates that decreasing air velocity increases drying rate.

Effect of air temperature

Figures 8 and 9 shows the experimental and theoretical drying curves for spherical particle of green peas and inert material of diameter 5mm for systems of FBD and FBD+IR at different temperatures of 35, 40, 50 and 60C. As it was expected, a rise in the air temperature lead to an increase in the drying rate and a decrease in the moisture content of the sample.

Effect of sample diameter

Figures 10 and 11 shows the experimental and theoretical drying curves for spherical particles of green peas at different sample diameters of about 3 mm. Analysis of the results show that decreasing the diameters of the drying samples would increase the drying rate for the system of FBD and FBD+IR. However temperature and moisture content of the samples of the lower diameters reaches their final values more rapidly.

Effect of amount of inert material

Figures 12 and 13 shows the variations of the drying rates verses time for various amounts of inert materials. It could be concluded from these figures that although the amount of inert material has no pronounced effect on the sample temperature in a well fluidized system, the drying rate is increased slightly with increasing the amount of inert materials. Results indicate that good agreement between the experimental data and calculated values of different parameters obtained by the proposed model are existed.

The above investigation revealed that the addition of infrared heat source and inert particles to a fluidized bed would enhance the rate of drying and also by filling the interstitial spaces between the particles it would facilitate their fluidization [14, 25].The effect of increasing air temperature is clearly to increase the particle temperature and hence the drying rate .

*The plateau on the temperature curves reflects the equilibrium between internal heat generation and heat losses due to convection and evaporation. To prevent condensation of the evaporated moisture on the surface of the particle, it is necessary to heat the fluidizing air to improve its moisture – carrying capacity.

Conclusion

A mathematical model has been developed for the drying of a single particle in a fluidized bed contained inert particles with combined sources of convection and infrared heating. Simultaneous heat and mass moisture content and temperature of transfer equations were solved using the finite difference scheme to predict the changes in the green peas.

The obtained results by the model agreed well with the experimental data where maximum errors of 5% for average moisture content and 9% for the temperature of the particle on a dry basis were obtained for the drying processes. Model indicates that infrared radiation was more effective in reducing the moisture content of the green peas rather than the dry green peas. The temperature of the penetration zone is also increased with an increased in the input power of infrared heat source.

Figures

Fig.1. schematic diagram of the experimental apparatus

Fig.2. moisture distribution across the product during drying using infrared heat source assisted by fluidized bed with inert materials

Fig. 3. Temperature distribution across the product during drying

Fig. 4. The effect of air velocity on drying rate in fluidized bed with inert materials.

Fig.5. the effect of air velocity on drying rate in fbd assisted by infrared.

Fig.6. drying curve for 3.02 mm green peas diameter, 400 gr inert, 7 m/s air velocity in fbd.

Fig .7. Drying curve for mm green peas diameter, gr inert, m/s air velocity in fbd assisted by infrared source.

Fig.8. The variation of sample temperature with time in fbd with and without infrared heat source.

Fig.9. Effect of sample diameter on drying curve in fbd.

Fig.10. Effect of sample diameter on drying curve in fbd assisted by infrared heat source .

Fig.11. the effect of amount inert materials on drying rate with time by fbd

Fig.12. the effect of amount inert materials on drying rate with time by fbd assisted by infrared.

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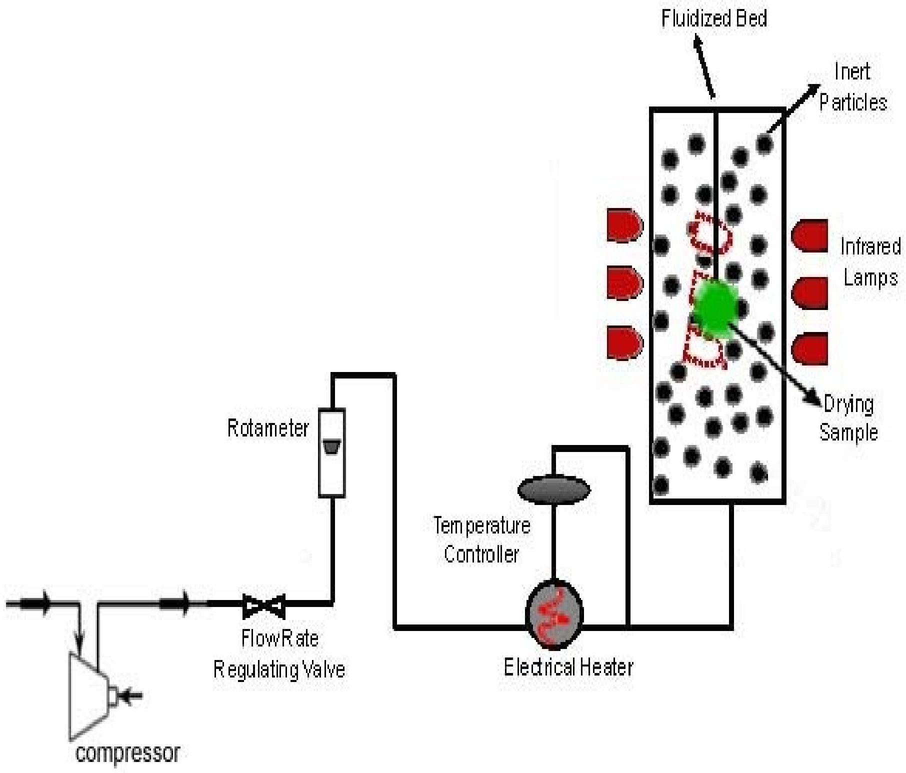

Figure 1. Schematic of pilot plant fluidized bed dryer with inert particles assisted by inferared heat source (single particle drying).

The operating conditions for drying of green peas in a fluidized bed of inert particles assisted by infrared heat source

Exp. #	Diameter of Samples, mm	Amount of Samples, gr	Number of Samples,	Air Velocity, m/sec	Inlet Air Temperature °C	Type of Inert	Amount of Inert, gr	Type of Experiment
1	9.24	0.481	1	7	50	Glass	No inert	FBD
2	9.24	0.481	1	7	50	Glass	150	FBD
3	9.23	0.487	1	7	50	Glass	150	FBD
4	9.24	0.483	1	7	50	Glass	300	FBD
5	9.22	0.479	1	7	50	Glass	300	FBD
6	9.24	0.482	1	7	50	Glass	400	FBD
7	9.24	0.478	1	7	50	Glass	400	FBD
8	9.23	0.492	1	7	50	Glass	150	FBD with IR
9	9.22	0.482	1	7	50	Glass	150	FBD with IR
10	9.25	0.482	1	7	50	Glass	300	FBD with IR
11	9.50	0.486	1	7	50	Glass	300	FBD with IR
12	9.50	0.476	1	7	50	Glass	400	FBD with IR
13	9.05	0.491	1	7	50	Glass	400	FBD with IR
14	9.05	0.462	1	5	60	Glass	150	FBD with IR
15	9.15	0.462	1	5	60	Glass	150	FBD with IR
16	9.14	0.457	1	5	50	Glass	150	FBD with IR
17	9.14	0.461	1	5	50	Glass	150	FBD with IR
18	9.12	0.457	1	5	40	Glass	150	FBD with IR
19	9.12	0.463	1	5	40	Glass	150	FBD with IR
20	9.13	0.459	1	5	30	Glass	150	FBD with IR
21	9.15	0.460	1	5	30	Glass	150	FBD with IR
22	9.13	0.460	1	5	60	Glass	150	FBD
23	9.14	0.464	1	5	60	Glass	150	FBD
24	9.13	0.461	1	5	50	Glass	150	FBD
25	9.14	0.467	1	5	50	Glass	150	FBD
26	9.14	0.472	1	5	40	Glass	150	FBD
27	9.13	0.463	1	5	40	Glass	150	FBD
28	9.15	0.470	1	5	35	Glass	150	FBD
29	9.14	0.462	1	5	35	Glass	150	FBD
30	9.14	0.461	1	2	50	Glass	400	FBD with IR
31	9.13	0.457	1	2	50	Glass	400	FBD with IR
32	9.13	0.463	1	5	50	Glass	400	FBD with IR
33	9.14	0.459	1	5	50	Glass	400	FBD with IR
34	9.12	0.460	1	7	50	Glass	400	FBD with IR
35	9.13	0.460	1	7	50	Glass	400	FBD with IR
36	9.13	0.464	1	8	50	Glass	400	FBD with IR
37	9.14	0.461	1	8	50	Glass	400	FBD with IR
38	9.12	0.467	1	2	50	Glass	400	FBD
39	9.14	0.472	1	2	50	Glass	400	FBD
40	9.15	0.463	1	5	50	Glass	400	FBD
41	9.15	0.470	1	5	50	Glass	400	FBD
42	9.14	0.462	1	7	50	Glass	400	FBD
43	9.14	0.465	1	7	50	Glass	400	FBD
44	9.14	0.470	1	8	50	Glass	400	FBD
45	9.13	0.461	1	8	50	Glass	400	FBD

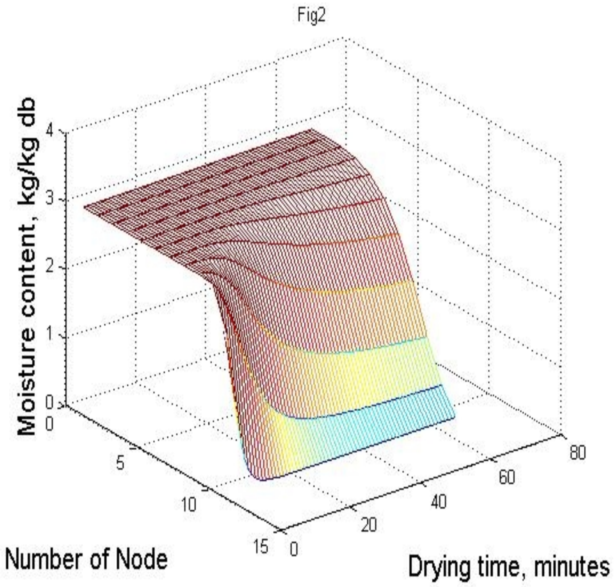
Fig2
Moisture content, kg/kg db
Number of Node
Drying time, minutes

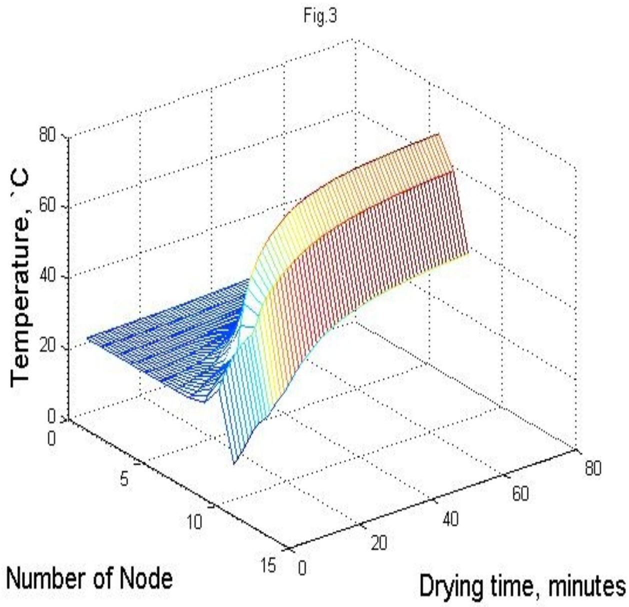
Fig.3
Temperature, `C
Number of Node
Drying time, minutes

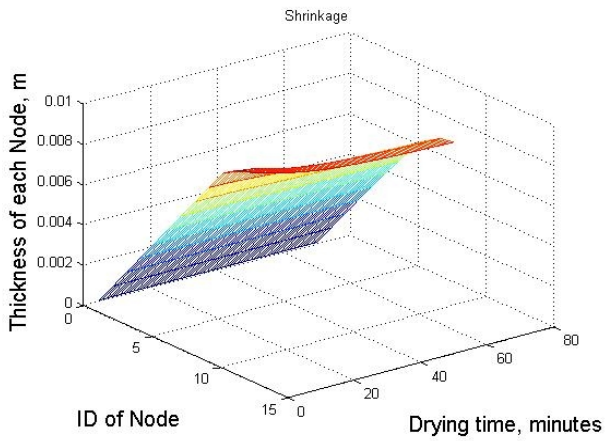
Shrinkage
Thickness of each Node, m
ID of Node
Drying time, minutes

Fig4

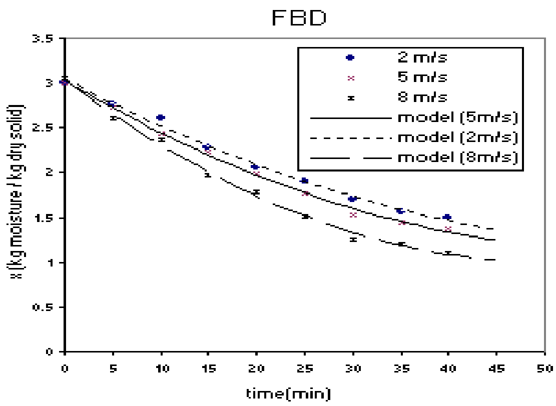
FBD
2 m/s
5 m/s
8 m/s
model (5m/s)
model (2m/s)
model (8m/s)
x (kg moisture / kg dry solid)
time(min)

fig.4

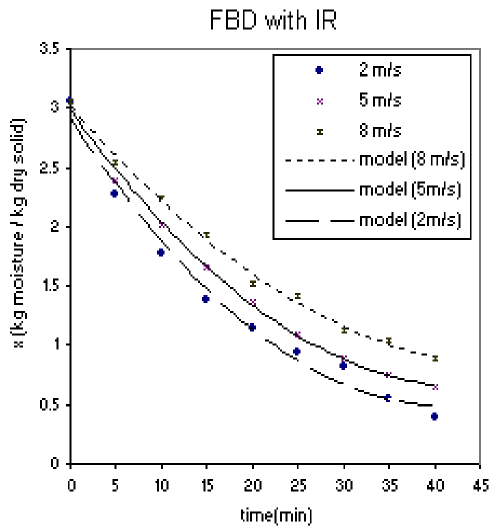

fig.5

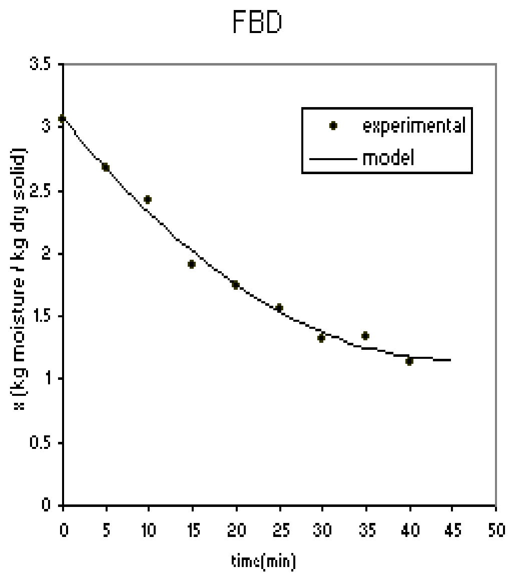

Fig.6

drying curve for9.02 mm green peas diameter,400 gr inert,7 m/s air velocity in fbd.

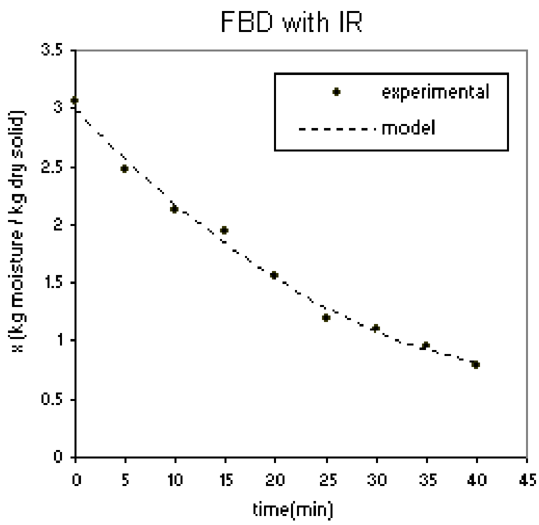

Fig .7

Drying curve for9.03mm green peas diameter,400gr inert,7 m/s air velocity in fbd assisted by infrared source

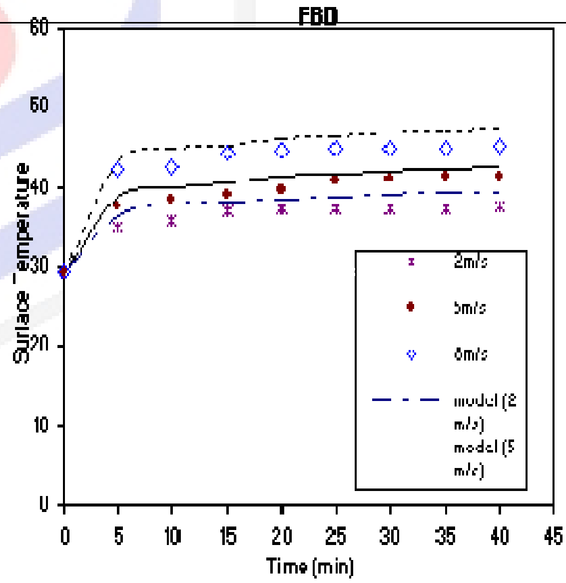

FIG.8

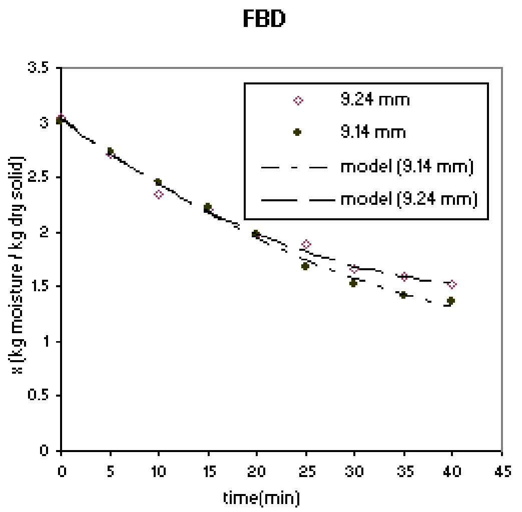

fig.9

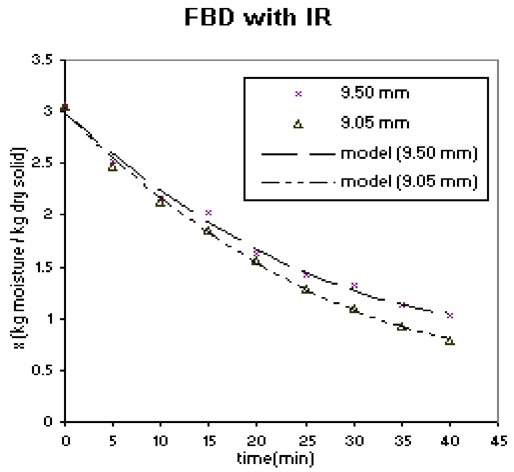

fig.10

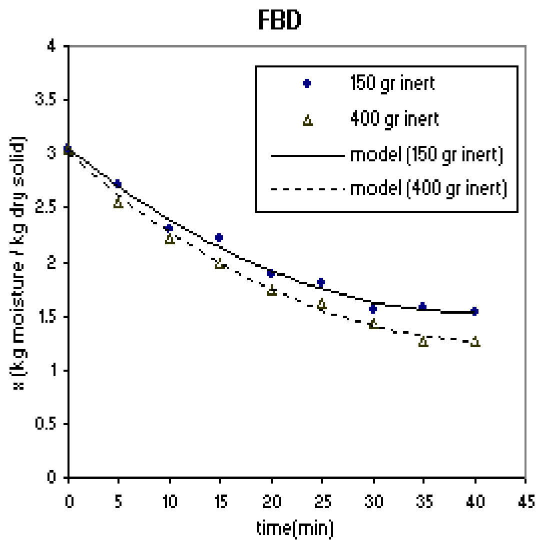

fig.11

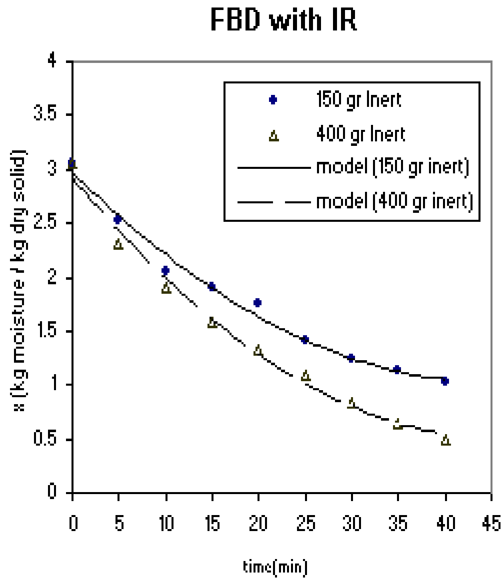

fig.12