Correlations for Shrinkage and Moisture Diffusivity for Drying of Green Peas in a Fluidized Bed with Inert Particles Assisted by Infrared Heating

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Abstract
Drying behavior of green peas is investigated in a pilot scaled fluidized bed dryer with inert particles assisted by an infrared heating source. The variations of shrinkage and moisture diffusivity with temperature and moisture content were investigated. The variations of shrinkage are a function of moisture content. It was found that shrinkage was a function of moisture content and moisture diffusivity was also dependent on temperature. The values of moisture diffusivity which obtained are in the range of 5E-10 to 30E-10. Some correlations were proposed for these properties.

Keywords: fluidized bed, drying, inert particle, diffusivity, shrinkage

Introduction
Drying is one of the most energy intensive unit operations because of the high latent heat of vaporizations and the inherent specific heat capacity of the drying materials. Design of the dryers to produce dried products of the desired quality with minimum energy consumption and maximum throughput, still remain as a challenge. The drying process couples the heat and mass transfer operations which must be analyzed carefully for efficient design and operation of a dryer. Many authors have applied it successfully for a range of solids dried in a variety of dryers [1]. A grate deal of works were done to study the drying of different foodstuffs by air drying [2], sun drying [3], convection, microwave drying [4] and drying in a fluidized bed [5,6].
Infrared drying is another drying method whose mechanism is different from the fluidized bed or conventional drying, which has been used as a potential method for obtaining high quality dried foodstuffs, including fruits, vegetables and grains [7]. However, infrared processing has the disadvantage of non homogenous distribution in an infrared cavity, creating problems of non-uniform heating [8]. In this method, as the temperature inside the material approaches the boiling point of water, pressure development becomes significant. This pushes moisture from inside towards the surface leading to Darcy’s flow. Generally, this results in a much higher surface moisture level than due to the diffusion alones [9]. A mechanism for moisture diffusivity during drying was proposed by [10]. According to this approach, at first, by internal heating, liquid water movement from the interior to the surface of the particle by Darcy’s law is started. As the temperature inside the material approaches the boiling point of water, the pressure developed pushes the moisture towards the surface, from where it is vaporized into the air. As drying proceeds, the internal liquid water supply cannot maintain the evaporation rate at the surface. Afterwards, the water starts to evaporate inside the particle

and in this period Darcy's flow and the vapor diffusion are the two major mechanisms for the moisture transport in the particle. In the last period, the moisture content near the surface decreases below the critical moisture content. Darcy's flow disappears so that liquid water has to be evaporated and then transported to the particle surface only by vapor diffusion.

Fluidized bed drying with infrared heating compensates for some of the drawbacks of each method. Temperature uniformity of the particles can be provided by good mixing due to fluidization [11] and at the same time diffusion period of drying can be reduced by the utilization of infrared energy [12].

Use of inert particles in a fluidized bed of combined sources of convection and infrared heating may give rise to higher mass and heat transfer coefficient, reducing minimum fluidization velocity and uniform temperature distribution.

One of the undesirable changes which occur simultaneously with moisture diffusion is shrinkage; modifying physical properties, heat and mass exchange area and in particular affecting the diffusion coefficient of the materials. In general shrinkage occurs as a result of volume reduction due to evaporation of the moisture contained in the solid.

Another important parameter in drying is the moisture diffusivity which knowledge of that is essential in simulation and optimization of the drying process, since water vapor transfer rates inside the materials is controlled by diffusion of moisture toward the outer surface. Then the water vapor concentration on outer surface of the material becomes at equilibrium or very close to equilibrium values. Drying rate increases as a result of equilibrium concentration of the water vapor on the surface of the materials at higher temperature. 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, analysis of the mass transfer phenomenon is based on the assumption that the effective moisture diffusivity represents all parameters influencing the process rate.

In this work it is expected to study the properties of shrinkage and mass diffusivity of green peas during their drying in a fluidized bed dryer containing inert particles which equipped with sources of convection and infrared heating.

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. Drying air was supplied from a high pressure source and a pressure regulator is used to adjust its pressure. Air was passed through a rotameter before heated by a controlled electrical heater. A temperature controller was used for regulating the temperature of drying air and the humidity was determined by an electronic humidity meter. Green peas with initial moisture content of 75% on a wet basis were obtained from local market and stored in a refrigerator for 24 hours at 4 ± 1 °C. Prior to the drying experiment, the weight of green peas was determined by means of an electronic balance.

A given amount of inert material of glass beads was placed inside the column and then a given amount of green peas was added to the drying column. In each run the weight of the bulk samples, surface and central temperature of the sample, air velocity and power of infrared heater were measured at different times. In each run, the volume of dried sample was determined by immersing it in toluene and measuring the volume change.

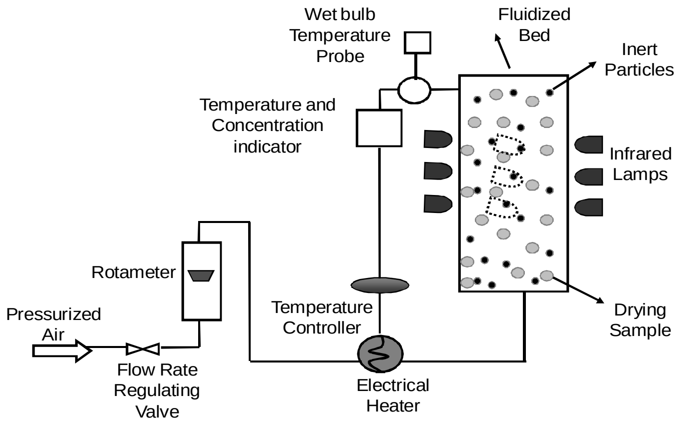

Figure 1. Schematic of pilot plant fluidized bed dryer with inert particles assisted by infrared heating (Bulk drying materials).

Experiments to determine the influence of process variables on the shrinkage and moisture diffusivity in a fluidized bed with and without the source of infrared heating were performed. In the case of shrinkage the variables taken in to consideration were the air velocity, air temperature, characteristic size of the sample and the amount of the materials.

The effect of moisture content on shrinkage

In many cases for simplicity it can be assumed that there is no shrinkage, nonetheless, shrinkage is not negligible during drying. Most foods shrink during drying, some of them shrinking more than 50 % of their original dimensions, depending upon the degree of drying [13]. Food shrinkage produces a variation in the distance required for the movement of water molecules, therefore making that effective diffusivity be overestimated when obtained from analytical solution. For this reason, it is desirable to obtain a simple model taking into account dimensional changes due to shrinkage. The changes in volume of the solid could be monitored for most cases.

In this research the analysis of the experimental data proved that changes in (V/V_0) and $(D/D_\circ)^2$ during the drying of spherical green peas, in a fluidized bed with inert heat carriers and combined heat sources of convection and infrared could be well correlated as linear functions of moisture content of the sample, in the forms of:

$$(V/V_0) = aX + b \qquad (1)$$

$$(D/D_\circ)^2 = aX + b \qquad (2)$$

Where V and V_0 are respectively the original volume of the particle and its volume after shrinkage; D and $D_\circ$ are respectively initial diameter of the particle and its diameter after shrinkage.

Analysis of the experimental data revealed that the correlations for V/V_0 and $(D/D_\circ)^2$ against X could be written as:

$$(V/V_0) = 0.285486\,X + 0.28006 \qquad R^2 = 0.9866 \qquad (3)$$

$$(D/D_\circ)^2 = 0.22283\,X + 0.3952 \qquad R^2 = 0.9866 \qquad (4)$$

Effect of Temperature on Moisture Diffusivity

In the last period of drying Fick's law of diffusion may be applied with the following assumptions to write the partial differential equation defining the moisture transfer from the particles.

1- The fluidized bed is well mixed.

2- Green peas are uniform in size, homogeneous, and can be approximated as isotropic spheres.

3- Conduction of heat and moisture between bed particles and heats losses are negligible.

$$\frac{\partial(r_s X)}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D^{eff}\,\frac{\partial(r_s X)}{\partial r}\right) \qquad (5)$$

Where X (kg water/kg of dry solid) is the moisture content, t(s) is time and D^{eff} (m^2/s) is the effective diffusivity of moisture in both liquid and vapor form.

The solution of this equation for a sphere assuming constant moisture diffusivity and no shrinkage is (Crank, 1975):

$$\frac{X_t - X^*}{X_0 - X^*} = \frac{6}{p^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-n^2\frac{p^2 D^{eff} t}{r^2}\right) \qquad (6)$$

where, X_t is the moisture content at time t, X^* is the equilibrium moisture content, $X_\circ$ is the initial moisture content and $r(m)$ is the radius of the particle. When the Fourier number, $(D^{eff} t/r^2)$, is greater than about 0.1, the terms other than the first on the right hand side can be neglected and by taking log from both side of equation 4, resulting in [14]:

$$\ln\left(\frac{X_t - X^*}{X_0 - X^*}\right) = \ln\left(\frac{6}{p^2}\right) - \frac{p^2 D^{eff}}{r^2}t \qquad (7)$$

When the experimental values of $\ln\left(\frac{X_t - X^*}{X_\circ - X^*}\right)$ are plotted against t, one can obtain the effective diffusivity from the slope of the linear portion of the curve.

In this work an exponential type of equation is assumed for effective moisture diffusivity [15]:

$$D^{eff} = D_{\circ} \exp\left(\frac{-E_a}{RT}\right) \quad (8)$$

Where E_a is the activation energy (kJ/kg mol), T is temperature (K), R is the gas law constant (kJ/kg mol K) and $D_{\circ}$ is a constant. Eq. (6) can be rearranged into the form of:

$$\ln(D^{eff}) = \ln(D_{\circ}) - \frac{E_a}{RT} \quad (9)$$

For system of FBD (Drying material in a fluidized bed contained inert materials convection heating)

$$D^{eff} = 1.85E - 5.0 \exp(-\frac{3400}{T}) \quad (10)$$

For system of FBD+IR (Drying materials in a fluidized bed contained inert materials with sources of convection and infrared heating)

$$D^{eff} = 1.0E - 5.0 \exp(-\frac{3100}{T}) \quad (11)$$

Results and discussion

Figures 2 and 3 show the variations of moisture content against time for different temperatures, and for the cases of FBD and FBD+IR. The result of experiment indicates that for both cases, by increasing temperature, the amount of moisture content is decreased. The result also shows that when IR is used, the decrease of moisture content is faster.

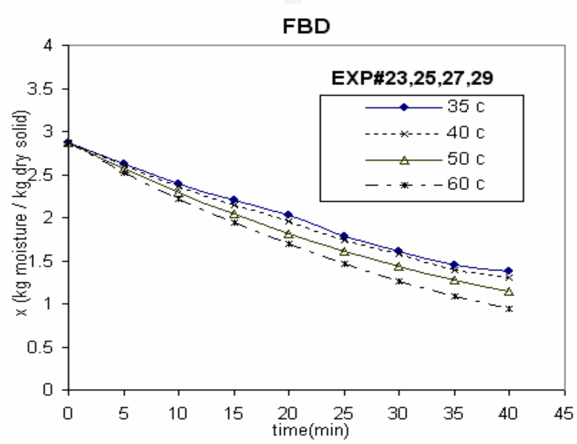

FIG.12

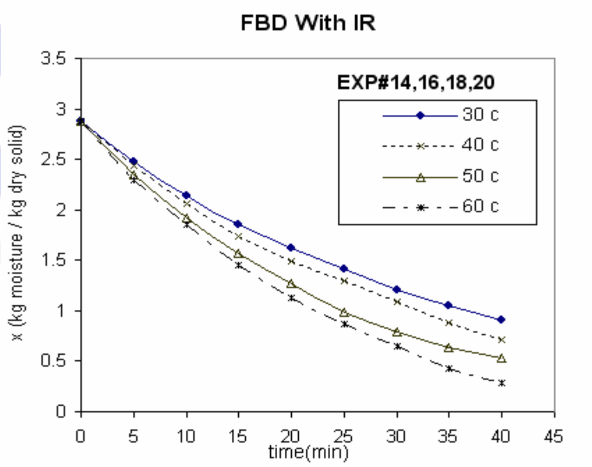

FIG.13

Figures 4 and 5 show the variations of drying rate (dX/dt) against time for different input air temperatures. As expected, there is an acceleration of the drying rate due to the increase of the temperature in both cases of FBD and FBD+IR. However in the case of FBD+IR, the rate of drying is faster due to the higher power of infrared heat source.

Figures 6 and 7 show the variations of $(V/V_{\circ})$ verses moisture content at different velocities. Figure 4 shows that by decreasing velocities, shrinkage is increased, but in figure 5 for the case of FBD+IR increasing air velocities resulted in higher shrinkage.

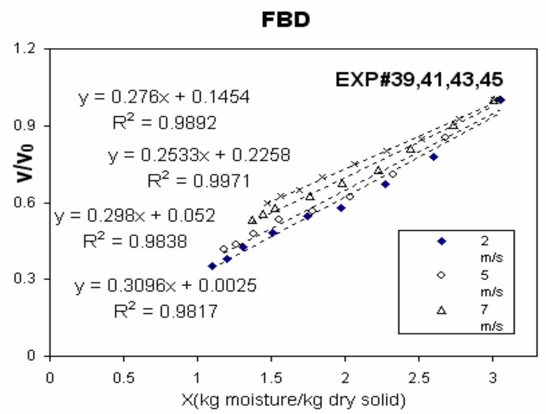

FIG.2

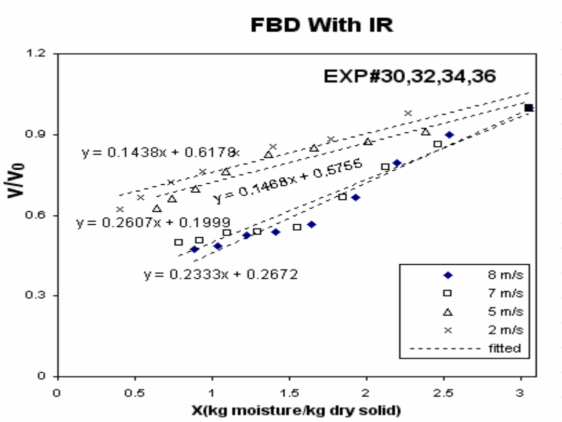

FIG.3

Analysis of data revealed that a linear relationship between shrinkage $(V/V_{\circ})$ and moisture content for systems of FBD and FBD+IR are existed.

Figures 8 and 9 show the variations of $(V/V_{\circ})$ verses X for different temperatures. The result indicates that by increasing air temperature, a lower amount of shrinkage for both systems of FBD and FBD+IR is expected, however in the case of FBD+IR shrinkage is increased by a slower rate.

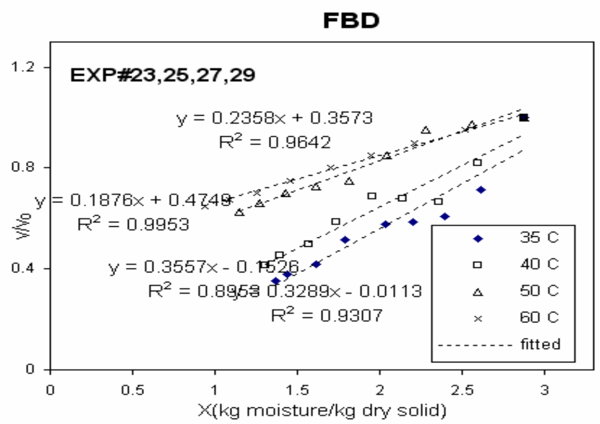

FIG.4

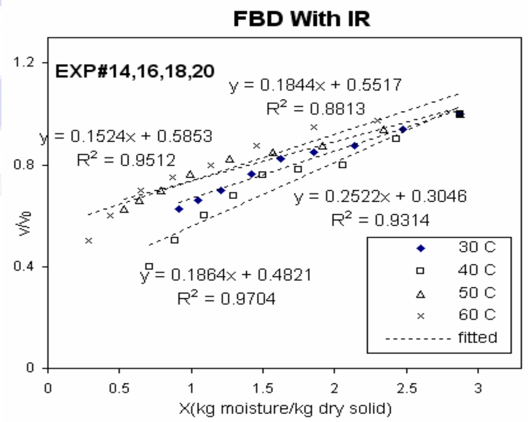

FIG.5

The variations of $(D/D_{\circ})^2$ against moisture content for different amounts of inert materials are shown in diagrams of 10 and 11. The results indicate that there is no effect on the variations of shrinkage by increasing the amount of inert particles. The figures also show that there exist a linear relationship between $(D/D_{\circ})^2$ and moisture content.

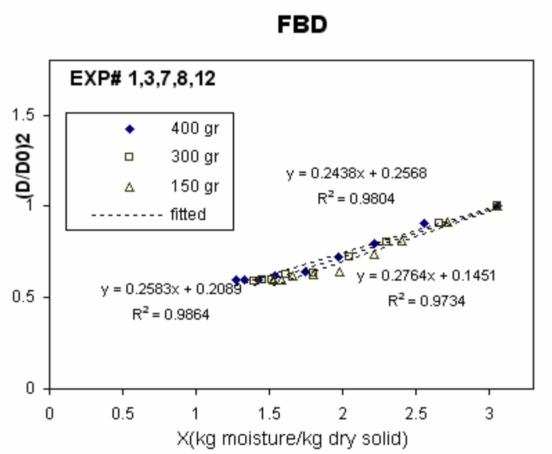

FIG.8

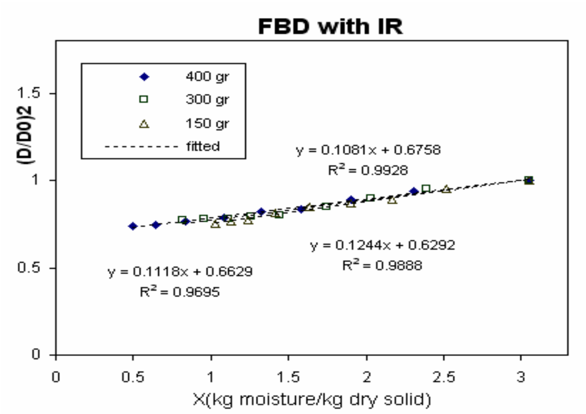

FIG.9

The variations of $\ln D^{eff}$ against 1/T for cases of FBD and FBD+IR are shown in figures 12 and 13. Analysis of the experimental data revealed that linear relationships between these parameters are existed. For systems of FBD and FBD+IR the obtained correlations are given in equations 10 and 11 respectively. The values of activation energies for FBD and FBD+IR are obtained as 28.26 and 25.77kj/kmol respectively.

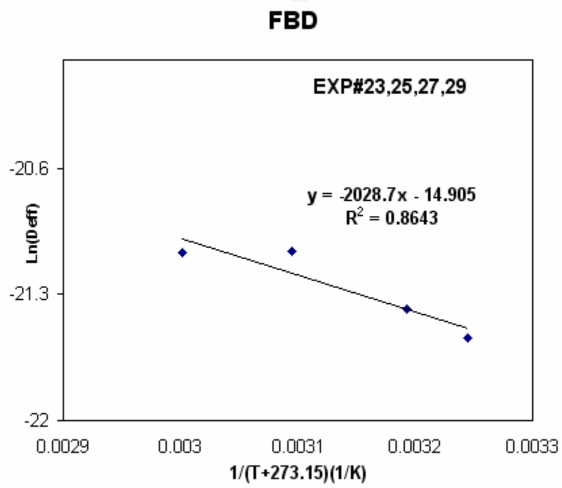

FIG.14

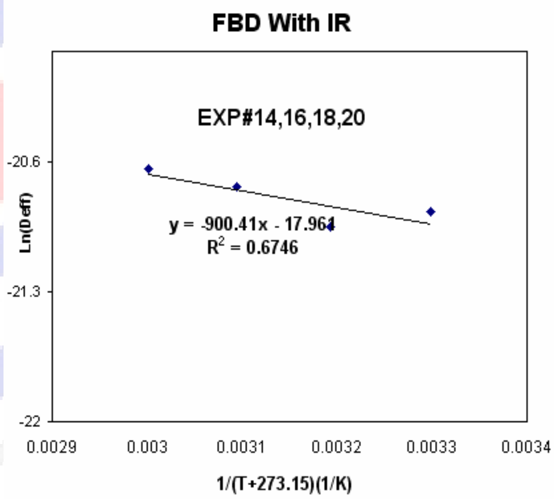

FIG.15

Conclusion

Shrinkage of green peas during drying in a fluidized bed with inert particles and assisted by infrared drying depends on its moisture content. Moisture diffusivity is a function of temperature. By increasing the power of the infrared heating, the temperature of the drying particles is increased which resulted in a higher of moisture diffusivity**.** The values of moisture diffusivity which obtained are in the range of 5E-10 to 30E-10. Some correlations were proposed for these properties. The values of activation energies for FBD and FBD+IR are obtained as 28.26 and 25.77kj/kmol respectively.

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Table (1). 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, g	Number of Samples,	Air Velocity, m/sec	Inlet Air Temperature °C	Type of Inert	Amount of Inert, g	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