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Design and Fabrication of a Low Cost Fluidized Bed Reactor

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Abstract

Many farmers now use the dryer as a part of their normal grain-harvesting system even during wet seasons. This helps in reducing spoilage. However, most available dryers are expensive to purchase and maintain. This work therefore is an attempt to develop a simple low cost drying bed that can lead to reduced drying time. The fluidized bed designed and fabricated in this work consists of the drying column, fluidized plate, the inlet and outlet unit, the heating unit and the fan. The evaluation considered the drying time and temperature in achieving quality. The drying efficiency and the amount of moisture reduced per time and were investigated using rice and wheat with moisture contents of 23% and 33% respectively. The dryer has shorter drying times and efficiencies of 89% and 90% for rice and wheat respectively.

Keywords: Fluidized Bed, Grain Drying, Low Cost Design.

1. Introduction

Grain drying is now common in many countries. Instead of drying only during very wet harvest seasons, many farmers now use a dryer as a part of their normal grain-harvesting system. This helps in eliminating spoilage in storage and improvement on early harvesting. The fluidized beds have been developed for different physical and chemical operations, such as transportation systems and chemical reaction processes (Baeyens and Geldart, 1986; Kunii and Levenspiel, 1991).Studies (Baeyens and Geldart, 1986; Kunii and Levenspiel, 1991) however show that the traditional and some commercial grain dryers consume considerable time and energy in their operations and available dryers are very expensive. Therefore, there is the need to develop dryers that would lead to time reduction of grain without compromising efficiency and also give reduced operating cost (Kunii and Levenspiel, 1991).

In this work an attempt is made to design and construct a low cost fluidized bed reactor that will be used in the drying of food products and its performance was also evaluated.

2. Overview

The drying process is an operation that aims at a reduction of the moisture content in most products, industrialized or not, to guarantee their preservation in storage and transport (Keey, 1992). The process of fluidization with hot air is highly attractive for the drying of powders and wet granular materials. This technique has been used industrially and is currently quite common in the drying of coarse materials, pharmaceuticals and food products among other solids in different countries of the world (Aberuagba et al, 2005). The major parts of the fluidized bed reactors are: the fluidization vessel, the solids discharge, dust separator for the exit gas, the air supply and heat supply.

A fluidized bed is a vessel containing a bed of solid particles, e.g. sand or catalytically active particles, and a method of introducing gas from below. It is a machine in which a continuous flow of wet granular material is dried. In this process the air velocity of the drying air is adjusted in such a way that the layer of product is maintained in a fluidized state (Sripawatakul, 1994).

Uniform processing conditions are achieved by passing a gas (usually air) through a product layer under controlled velocity conditions to create a fluidized state. Heat may be effectively introduced by heating surfaces (panels or tubes) immersed in the fluidized layer (Queiroz et al, 2005).

2.1.Some Advantages of Fluidized Bed Reactor

One advantage of using fluidized bed reactor as a dryer is the close control of conditions so that predetermined amount of free moisture may be left with the solids and to prevent dusting of the product during subsequent material handling operations (Perry and Green, 1998). Other advantages include:

- Uniform temperature throughout the material bed by enhanced heat transfer
- Improved gas-solid contact, which results in faster rate of reaction
- Uniform product quality from extensive bed mixing and controlled reaction conditions

Fluidized bed technology has been successfully applied to the synthesis of materials via gas-solid or solid-solid reactions, coating via chemical vapor deposition, calcinations, sintering, thermal decomposition, thermal treatment, and drying (Harper, 2005).

The disadvantages of fluidized beds are summarized below:

- Bubbling beds of fine particles are difficult to predict and are less efficient,
- Rapid mixing of solids causes non-uniform residence times for continuous flow reactors,
- Particle comminuting (breakup) is common,
- Pipe and vessel walls erode due to collisions by particles.

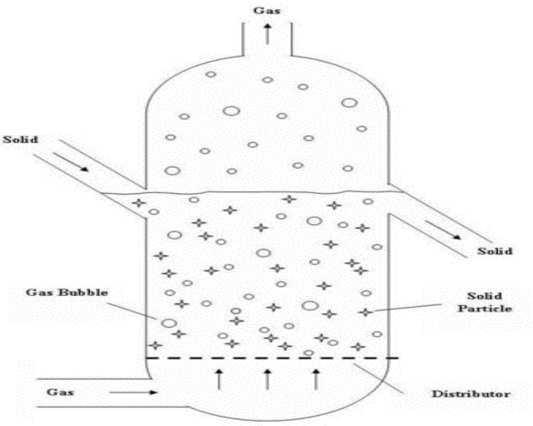

Figure 1: A typical fluidized bed reactor

Other factors that also affect the performance include: Bed temperature, particle size, fluidization velocity, bed height, tube location, heat transfer coefficient and pressure drop.

2.2 Design Parameters

A full listing of the terms and notations is presented in appendix 1. The design calculations for this work are based on the works of Levenspiel (1991), Sripawatakul (1994) and Soponronnarit (1999). Also the use of the conventional formula for the calculation of the volume (V) and cross sectional area (Ac) of a cylinder was adopted.. These and other relevant formulae are summarized below:

$V = \pi r^2 h$ Volume of the reactor 1

$Ac = \pi D^2/4$ = Cross sectional area (Ac) 2

The net gravitational force (Δp) needed in the fluidized vessel that would be exerted on the particles inside the vessel.

$$\Delta p = g\left(\rho_c - \rho_g\right)\left(1-\varepsilon\right)h \qquad 3$$

The emf is the void fraction at the point of the minimum fluidization. It appears in many of the equations describing the fluid-bed characteristics.

$$emf = 0.586\left(\psi\right)^{-0.072}\left(\frac{\mu^2}{\rho g\eta dp^3}\right)^{0.029}\left(\frac{\rho g}{\rho c}\right)^{0.021} \qquad 4$$

Reynolds number (Re): This is a dimensionless parameter that affects the characteristics of the two velocities involved in the study i.e. the minimum and the maximum fluidization velocity. This is expressed as: $\mathrm{Re} = \frac{124dpVp}{\mu}$ 5

Minimum fluidization velocity (umf): This is the velocity required to begin the fluidization at which the weight of particles’ gravitational force equals the drag on the particles from the rising gas.

$$umf = \frac{(\psi dp)^2}{150\mu}\eta\frac{emf^3}{1-emf}, \qquad where\cdot\eta = g(\rho c - \rho g) \qquad 6$$

Maximum fluidization velocity (Ut): The maximum fluidization velocity was calculated for the reactor so as to avoid chaotic situation where the particles will not be blown out of the reactor.

$$Ut = \frac{\eta dp^2}{18\mu} \qquad = [\frac{1.78\times10^{-2}\eta^2}{\rho g\mu}]^{\frac{1}{3}}dp \qquad 8$$

Inlet pipe flow (f_r): The expression adopted based on Eefisso for calculating different flow rates in a system (www.eefisso.com, 2007).

$$f_r = \frac{1}{4}\pi P_i^2 V \qquad 9$$

Mean residence time (τ): This is the mean time during with which the molecules remain on the surface of the bed .i.e. the mean time interval between impact and drying (IUPAC Compendium of Chemical Terminology, 1997 ; Sriparratakul, 1994).

$$\tau = \frac{V}{f} \qquad 10.$$

3. Methodology

In this section we give the major components, the design calculations and the fabrication of the fluidized bed.

3.1 Design Calculations

In this section we present the design parameters of the components of the bed, the design computations and performance tests carried out on the reactor.

3.1.1 The fluidizing vessel Requirements

The fluidization vessel was designed to have a volume of 100cm^3 so as to have a maximum bed height of 200mm (20cm). The height and the diameter chosen for this design were based on the fact that it was being designed on a small scale which will still bring appreciable outputs, and not to occupy much space when fully installed.

For the volume of the fluidizing chamber the use of the conventional formula $V = \pi r^2 h$ for volume determination was adopted.
$V = \pi r^2 h = 3.142 x 24^2$ x 56 m^3

3.1.2 Cross sectional Area of the reactor (Ac)

The cross sectional area of the empty vessel.
$Ac = \pi D\ ^2 r/4 = (3.142 \text{ x } 48\ ^2)\ /4 = 1809.79\ cm^2$

3.1.3 Net Gravitational force

The net gravitational force needed in the fluidized vessel bed reactor (dryer that would be exerted on the particles inside the vessel (Saponronnarit, 1999).

$\Delta p = g(\rho_c - \rho_g)(1 - \varepsilon)\ h = 9.81(1.3 – 0.00107)(1.\ 0.84)24$
$= 4.89 N/m^2$

3.1.4 emf for the reactor

The emf for the reactor needed in determining the minimum fluidization velocity for the reactor. This emf is the void fraction at the point of the minimum fluidization. It appears in many of the equations describing the fluid-bed characteristics (Saponronnarit, 1999).
is computed thus:
$Emf = 0.586(\Psi)^{-0.072}\ (\mu^2/\rho g \eta dp^3)^{0.029}\ (\rho g/\rho_c\ )^{0.021}$
$= 0.586(0.7)^{-0.072}\ (\{1.5x10^{-4}\}^2/(0.00107x12.7295x0.005^3))^{0.029}\ (0.0017/\ 1.3)^{0.021}$
$= 0.7202$
Ψ is the measure of particles not ideal in both shape and roughness (Wei and Yu, 1994). It is calculated by visualizing a sphere whose volume is equal to the particles and dividing the surface area of the sphere by the measured surface area of the particle.

3.1.5 Reynolds number

This is a dimensionless parameter that affects the characteristics of the two velocities involved in the study i.e. the minimum and the maximum fluidization velocity.
$Re = (124 dpVp)/\ \mu\ \ = (124 \text{ x } 0.05 \text{ x } 6.5458 \text{ x}10^{-5})\ /\ (1.5x10^{-4})$
$= 2.7$
Since the Re is less than 10, it gives the type of flow in the fluidizing vessel as a laminar flow and the type of maximum fluidizing velocity needed for the system.

3.1.6 Minimum fluidization velocity (umf).

Minimum fluidization velocity: This is the minimum velocity needed to blow the particles of the bed. It is the velocity required to begin the fluidization at which the weight of particles gravitational force equals the drag on the particles from the rising gas.
$Umf = [(\Psi dp)^2\ /\ (150\mu)]\ \eta\ [(emf)^3/(1\text{-}emf)]$, where $\eta = g(\rho c\text{-}\ \rho g) = 12.7295$
$= [(0.7x\ 0.05)^2\ /\ (150 \text{ x } 1.5x10^{-4})]\ 12.7295\ [(0.47)^3/(1\text{-}0.47)]$
$= 0.1357 m/s$

3.1.7 Maximum fluidization velocity.

The maximum velocity needed for the particles inside the reactor. The maximum fluidization velocity was calculated for the reactor so as to avoid chaotic situation where the particles will not be blown out of the reactor. The drag on the particles will surpass the gravitational force on the particle and the particles will be entrained in the gas.

Since the Re number is less than 10, we use the equation, $ut = (\eta dp^2)/[18\mu]$
$\quad$ Thus $ut = (\eta dp2)/ 18\mu = 12.795 \text{ x } 0.05^2/(18 \text{ x } 1.5 \text{ x } 10^{-4})$
$\quad\quad = 11.78$m/s

3.1.8 The inlet pipe

The feed inlet pipe was designed to supply feed at a rate of 1.988m^3/min, so as not to create a turbulent situation or flooding of the reactor. The pipe was attached to the reactor at an angle of 30 degrees$^{.}$ The expression used in the calculation of the pipe flow rate into the vessel was based on the work of Eefisso for calculating different flow rates (www.eefisso.com, 2007).

This is given as: $f_r = \frac{1}{4}\pi P_i^2 V$ = [3.142 x $(1.049)^2$ x 2.3] /4
$\quad\quad$ = 1.988m^3/s

3.1.9 Mean residence time for the chamber.

This is the mean time during with which the molecules remain on the surface of the bed .i.e. the mean time interval between impact and drying (IUPAC Compendium of Chemical Terminology, 1997; Sriparratakul, 1994).

$\tau = v/f = 101.248/1.988$
$\quad = 50.9799$s

3.1.10 Pressure drop in the equipment

ΔP, the pressure drop across the bed is closely related to drag force,
The pressure drop was calculated based on the work of Jayasuriya and Manrique (2005).
$\Delta P_g = hA\Delta t$
$\quad = h \text{ x } 0.00165\text{x } (413 - 353)$
$\quad = 0.099h$ N/m^2

3.1.11 Elutriation of Particles from fluidized bed reactor

The elutriation process causes a decrease in the particle concentration in the column and the concentration may be empirically modeled by an Arrhenius type expression
$C = C_o e^{-Mt}$; where C = concentration at time t C_o = the initial concentration M = empirical constant.

3.1.12 Power Requirement.

The power required for setting the designed fluidized bed into operation and the continuation of the operation was based on the suggestions of (Shott et al., 1975). They suggested horse power requirements for different types of flow actions and different reactions.

TABLE 1: Suggested Horse Power Requirements (hp/1000gal).

Type of flow	Power requirement	Types of operations
Mild	0.5 – 2	Mixing, blending
Medium	2 – 5	Heat transfer, suspension, gas absorption
Violent	5 – 10	Reactions, Emulsification,

3.2 Bill of Quantities

The quantities and price of material need for the work are summarized in Table 2.

Table 2: Bill of Quantities

(a) Construction cost					
s/n	Materials	Specifications	Quantity	Rate (Naira)	Cost (Naira)
1	Mild steel	G18 1.2×1.2 m	4	4000	16000
2	Mild steel	G16 1.2×1.2 m	2	3750	7000
3	Hacco pipe	100×4 m	1	5000	5000
4	Brim plate	4×4 m	1	2000	2000
5	Valves		2	600	1200
6	Electrode		2	1200	2400
7	Electric motor		1	8000	8000
8	Bolts and nuts		20	30	600
9	Electrode		100	10	1000
10	Paints		1	1850	1850
11	Miscellaneous				5000
Total		50,550.00			

Adding 10% contingency to the total cost give the total design cost to be 55605 Naira.
Adding 25% margin to the total design cost, the machine can be sold at a price of 69509.25 Naira which is still cheaper when compared to other commercial dryers of 126,556. Naira.

3.3 Fabrication of the Fluidize Bed

The fabrication of the Fluidize Bed was carried out using the data from the above computations. In addition to that, the following precaution are taken into consideration.

a. The fluidization vessel: the vessel was designed to have the capacity of receiving heated fluid (hot air) from the heat source and to house the porous disk.
b. The solid inlet feeders:
c. Solids discharge
d. Dust separator for the exit gas: The dust collector is usually designed to trap any solid, which might want to escape with the exit gas.
e. The air supply: the use of an electric motor fan was used to supply air to the system.
f. Heat supply: the heat was supplied by a heating element at a temperature of 115^0 Celsius.

3.4 Performance Tests

Tests were carried out on the designed machine to ascertain its performance. The analysis was carried out on the fluidization reactor to determine the moisture reduction of rice and wheat during the drying process.

Before the fluidization process, the weights of the rice and wheat were measured. The grains were fed manually into the equipment and the outputs from the grains outlet were subsequently collected and weighed. The temperature and pressure were kept constant at the heating chamber throughout the whole process and the time was varied between ten and thirty minutes for different quantities of food samples. The temperature inside the chamber was found to be 63 degrees centigrade.

The aim of the experiment was to monitor the reduction of moisture in food grains at different time intervals and constant temperature using rice and wheat as the samples.

For the evaluation process the following parameters were employed based on the work of Okoli (1991) and Ojediran and Jekayinfa (2002).

Sample evaluations were done using the following as the guide.
Moisture content in sample (mc) = original weight (Os) less final weight (Fs).
i.e. mc = Os – Fs 12

Drying time for samples
$(\tau) = (.x1 - xr)/N$ 13
% moisture content (Mc)

$$\frac{\text{Loss in weight}}{\text{Weight of the original sample}} \times 100$$

$$Mc = \frac{mc}{Os} \times 100 \qquad 14$$

Efficiency of the system (Eff):
1 –Mc = Eff 15

The results of the tests on the designed fluidized bed reactor were taken at 5 minutes interval to ascertain its efficiency; and also were compared with those of some commercial dryers. The results and the graphs are the discussions are presented in section 4.

4.0 Results and Discussion

4.1 Results of Performance Evaluation

Table 3: Percentage Moisture Reduction in Grain Samples

Time (minutes)	Rice (% moisture content reduced)	Wheat (% moisture content reduced)
10	4.774	3.212
15	4.896	5.576
20	5.682	7.114
25	7.550	8.605
30	8.048	9.420
35	11.178	9.670

For the results of efficiency of the designed equipment are presented in table 4.

Table 4: Efficiencies of the Fluid Bed Dryer

Time (minutes)	Rice efficiency	Wheat efficiency
10	0.95	0.97
15	0.95	0.94
20	0.94	0.93
25	0.92	0.91
30	0.92	0.91
35	0.89	0.90

Table 5: Performance Test Results Of Commercial Dryers At 20 Minutes

Drying air temperature (^oC)	Inlet moisture of grain (%)	Outlet moisture of grain (%)	Moisture reduction in grain (%)
115	22.0	20.1	1.9
115	26.0	22.5	3.5
115	28.7	22.5	6.2
115	30.6	23.0	7.6
115	27.0	21.0	6.0

Source: Soponronnarit (1999).

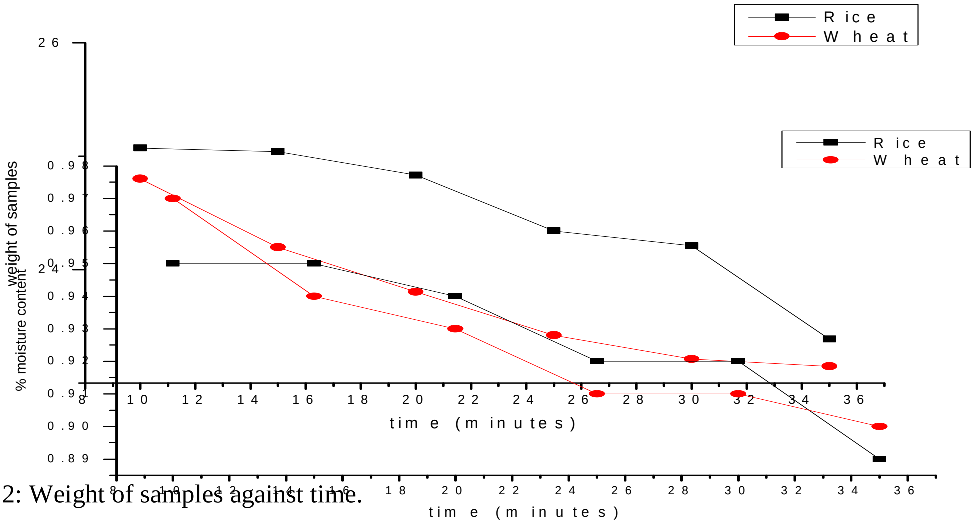

Figure 2: Weight of samples against time.

An examination of figure 2 shows that as the time in increased the moisture content in particles and their corresponding weights decreases because the moisture content contributed to the total weight of the particles. This shows that the fluidized bed dyer is a good medium for drying of rice and wheat.

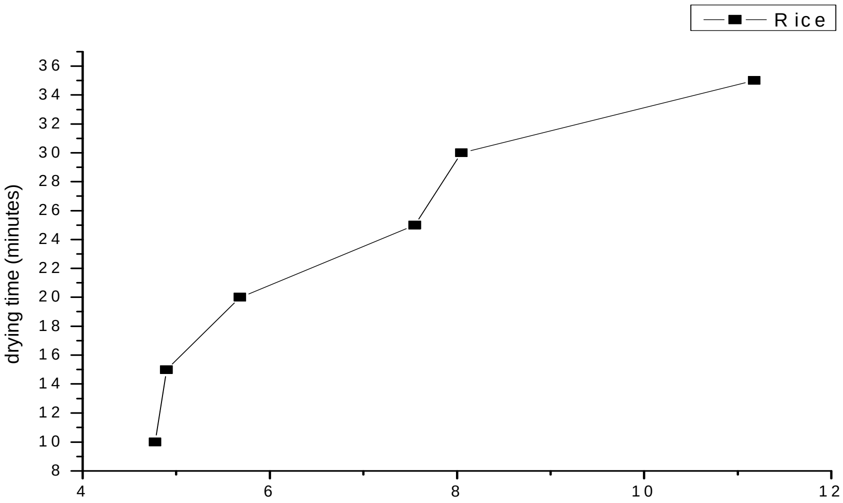

Fig 3: Drying time against Percentage moisture content in rice.

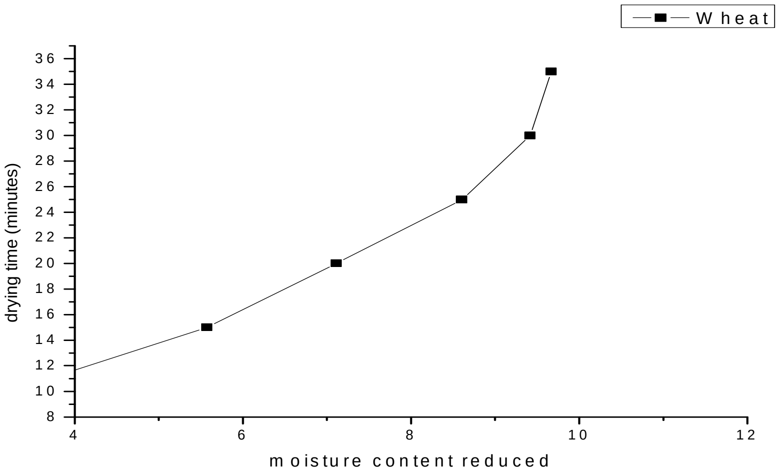

Fig 4: Drying time verses %age moisture in wheat

Figures 3 and 4 show the conformity of the fluidized bed dryer to the different drying principles in the literature. As the time is increased so also the moisture reduced until it gets to the equilibrium stage where no moisture will be removed from the grains. Wheat shows a better curve than rice since they are smaller in size and weight than rice. This is probably because the smaller seeds or grains have higher resistance to airflow and therefore reducing the action on fan outputs.

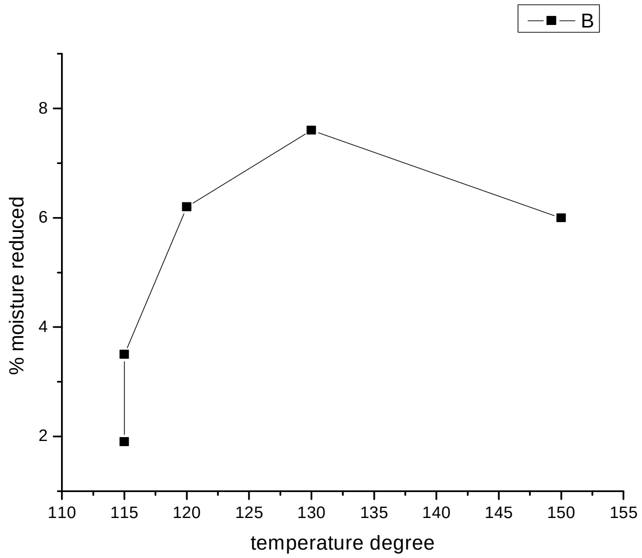

Fig 5: Percentage of moisture Commercial fluidized bed against Temperature (20 min)

Figure 5 shows the amount of moisture reduced at different temperatures at the time of 20 minutes. Comparing the efficiencies at the temperature of 115 degrees centigrade and at 20 minutes with the designed fluidized bed dryer, it was seen that the efficiencies is lower when compared with the designed dryer.

5.1 Conclusions

In this work the design and fabrication procedure for a low cost fluidized bed has been demonstrated. From the results obtained, it can be inferred that the weights of different samples affect the fluidization process, because grains with higher weights show less resistance to air flow in the system.

In addition to that, increasing the airflow speed increases the drying rate but also increases the power consumption in the system, smaller grains show high resistance to airflow therefore reducing the fan outputs and also increasing the amount of moisture reduced in the grains by the hot air giving higher power efficiency in wheat than in rice.

A fluidized bed dryer can be competitive with other convectional drying methods especially at high moisture level and low energy consumption. Drying on fluidized bed is a reliable and economical method for drying of light weighted grains.

Further work may investigate the energy consumption. Further research should be carried out on other food grains that have different weights and moisture content than the rice and wheat used in this study.

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NOTATIONS

Here we define the notations used in this work.
τ = drying time (seconds)
X1= initial moisture (kgh20kg-1.d.m)
xr = relative moisture (kgh20kg-1.d.m)
N = drying velocity (kgh20kg-1.d.m)
υ = velocity (ms-1)
υ1 = minimal fluidization speed (ms-1)
m.d.m = dry matter, mass (kg)
β = dimensionless coefficient
ρ = density (kg-3)
ρ1 = bulk density (kg-3)
Wost = water content in fresh material. (Kg/kg)
A = heating element area
D= Reactor diameter
H= Reactor height
P= Pressure
V= Air velocity
ε = porosity

g = Acceleration due to gravity
π = pi
ρg = 1.07× 10-3g/cm3
ψ = 0.7
μ = 1.5×10-4 poise
h = Bed height
Vp = Particle diameter
Pi = Pipe Diameter
Umf = minimum fluidization velocity
Ut = maximum fluidization velocity
Mc = % moisture content
Mc = moisture content
Ac = cross sectional area
V = volume

Plate 1: Constructed fluidized bed dryer.

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