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Modeling of Alomina Drying Process in Spray Dryer

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ABSTRACT

Spray dryers are one of the most important dryers and have many applications in the food, drug and chemical industries. In this investigation, a model is suggested to predict the product temperature, drying time and the dryer height In order to evaluate the dryer performance in different operational conditions. To achieve this, knowledge of the drying kinetics and the transfer phenomenon are necessary. The main aim in this project is, modeling of the spray drying of Alumina Slurry in a co current dryer.In this modeling Mass, heat and momentum transfer equations on droplets and hot air have been written. By writing a computer program for the simultaneous solution of mass, energy and momentum balances, a mathematical model is introduced. In order to evaluate the accuracy of the model, the experimental data were used and results showed good agreement between the theory and the experiments. By using the results of the model, the change in the dryer input parameters and their effect on final product characterizations have been studied.

1. Introduction

Mineralogical researchers have been always searched for solid material with regular crystal structure and composition capabilities with other materials, scientists have been considered the alumina crystal Perhaps as much about these comments [1-5]. The most important current applications of alumina powder are to provide powder for ceramic [6, 7]. Today, for making ceramic coating with different uses and applications, large factory are using this powder [8]. This powder also used increasingly in ceramic industry especially in pipe industry and valve and also is used very pervasive in pipes which coated with alumina to prevent heat exchange and heat-resistant high [9-12]. Present alumina are used widely in industries like paints, inks, coatings of various Posts glue rubber, pharmaceutical industry, tiles, refractory bricks, kitchen, electronics, accessories, accessories, and dental plastics [13-17]. Material drying with spraying feed into the tower, which called spray dryer briefly, has definition as the following: Transformation of feed flow from fluidity to the solid state and dry using hot air spraying into the food inside a tower [18-22]. Spraying operation occurs with spray (Atomizer) which liquid feed broken to a large number of small droplets and as a result of this action large level of liquid occurred that causes accelerate in mass and heat transfer and due to high humidity evaporation rate, surface temperature of drops have been always below and can use high temperature gas without affected product from drying gas [23-26]. Feed could be a solution, suspension, or paste form and grout dried product as powder, granule or lump. Progresses In this field cause model to compete very high level with other drying methods [27-30].General steps that feed passed during Spray dryer unit to convert to the desired product include four stages, which are:

1 - Spraying and feed conversion to drops
2 - Contact droplets with air or drying gas (mixing and flow)
3 - drying droplets (moisture evaporation)
4 - product recycling

In each of the above steps, according to the dryer design and operating conditions alongside the physical and chemical properties of dried feed, product characteristics determine [31-36]. The most consistent of the countercurrent flow is for dried sensitive material to temperature. In this case, the hot air treat with the most humid drop and drying speed got higher, Hot air temperature will drop quickly and the outlet temperature is low enough that no damage enters to the product [37-

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42]. In this method, High speed evaporation of drops moisture, cause porosity in dry product and naturally high surface of contact in product. Rapid evaporation of drops moisture causes cooling of hot air and reduced drying evaporation time [43-47]. In this system, the product usually not shared with exposed thermal analysis and the evaporation of moisture on the droplets, Product temperature is usually low and is at the range of wet limit temperature [48-52]. When the desired amount of product moisture was content, each product particle affected with colder air and so increasing in much product temperature is not tangible [53-58].

2. Modeling

For choosing a model for modeling for a unit, some parameters must be noted, including follows parameter:

1 - Selected model must be answered the required accuracy.
2 - The model must be selected into computer algorithms and solved by numerical methods.
3 - Acceptable model solving speed with personal computers.
4- Different parameters of model could calculated by the internal algorithms are practical with not experiences user. Model presented in this article, extraction model based on thermal, mass and momentum balance and the use of comments and studies by researchers ([7], [8] and [9]) on different models. In fact, the presented model contained three different models for the three types of flow countercurrent, concurrent, and is complex, These models have many common basic equations, but their solving algorithm are different. For converting a physical or chemical phenomenon, a mathematical model first a series of assumptions simplifier required, for this modeling some assumptions also considered which are as follows:[7]and [10]

1 - Droplets from spraying have same diameter and are homogenized.
2 – Neglected any crush, incorporate, neighborhood effects, gathering and deforming of particles.
3 - Droplets are spherical shape.
4 - There is no radial direction on moisture and temperature gradient inside the container.
5 –force heat and mass convection between drops and air required.
6 – The effect of droplets movement neglected on the hot air speed.
7 - Model is steady state
8 - Heat loss from through of body dryer neglected.

2.1. Mass (moisture) and energy balance on droplets

Sprayed droplets which get out of bed dryer to get the heat, loose their moisture and drop's mass change over time which is proportional to the drying drop amount. Droplet drying process could split into two stages drying with constant intensity and the second stage descending intensity drying. Since conditions in every drop of this two-step are quite different from each other therefore, each stage equations are studied separately.

2.2. First stage drying

During the first stage, as surface water evaporation is performed and penetration of moisture drops into the surface, keeps saturation level of drops conditions and during this stage, evaporation intensity will be constant. Regardless of the heat transfer by radiation, mass and energy balance for the drop with diameter and temperature RP and TP (drops temperature at this stage is considered constant for the entire drops) can be considered as follows:

Mass balance (moisture) [7]

Moisture Moved from the drops = drop gathering intensity moisture

$$W_D = \frac{dm_p}{dt} = -k_g \,.\, A_p.(y_{eq} - y_g) \tag{1}$$

At the above relationship, evaporation rate drops with time WD; mass transfer coefficient Kg, transfer area AP, equilibrium moisture level of the gas in drops temperature according kg moisture per kg dry gas Yeq and drying gas moisture in each moment yg.

Drop energy balance [7]

Amount of heat transmitted to the drop with hot air= Amount of energy required for raising the temperature drops+ Amount of energy required for evaporation in the temperature drop

$$m_s\left[C_{Ps} + x\,C_{PL}\right]\frac{d\,T_p}{dt} = -\Delta H\,\frac{d_{mp}}{dt} + h\,.\,A_p(T_g - T_p) \tag{2}$$

At the above relationship, evaporation latent heat , convection heat transfer coefficient h, temperature gas Tg and the temperature drop is TP. If equation (2) rewrite with the reference temperature, will have:

$$m_s\frac{d}{dt}\left[(C_{Ps} + x\,C_{PL})(T_p - T_{ref})\right] = h\,.\,A_p.(T_g - T_p) \tag{3}$$
$$-\left[\Delta H_{ref} + C_{PV}(T_p - T_{ref})\right]W_D$$

Also CP or specific heat of drop moisture could obtain by following equation:

$$C_p = \frac{C_{ps} + x\,C_{pl}}{1 + x} \tag{4}$$

And ms or a solid level in the every drop is constant whole process so will have:

$$M_s = \frac{\rho_p.V_p}{1 + x} \tag{5}$$

Finally, will have:

$$\frac{dT_p}{dt}=\frac{\dfrac{6h.(T_g-T_p)-6\left\lfloor W_D(\Delta H_{ref}+C_{pv}(T_p-T_{ref})\right\rfloor}{\pi d_p^2}}{d_p\rho_p C_p} \tag{6}$$

Drop diameter changes:

$$\frac{d_{Rp}}{dt}=\frac{1}{4\pi\rho_L R_p^2}\frac{d_{mp}}{dt} \tag{7}$$

$$m_p=m_s+m_L \tag{8}$$

Second stage drying (descending intensity) [7] and [8]

This stage started when humidity drops begins to critical moisture. Final moisture content could achieve through the experiment and tests performed. During this stage the moisture could not penetrate from core to surface so saturated conditions do not maintained so, a dry layer will be formed at the drops surface, Increasing its thickness, moisture penetration got difficult from core to drops surface, evaporation rate decreased and drying rate goes a downtrend. Drops mass and heat transfer rate is a function of temperature, humidity, drop's size, temperature, relative humidity and speed between the air and drops. In this section, for writing equations of mass and energy, first steam infiltrate between a porous dry media (Assumed that produced shell is a porous media, and it follows the rules)[9] and discharged from drops after penetration in air. During this period rate was fixed but rate increased in length and time. Considering the above assumptions the equations of drops mass and energy transfer will be as follows.

Mass transfer equations

Influence the spherical shell (assuming porous media) [9]

$$\frac{dm_p}{dt}=\left\{\frac{D_V P_T}{RT_{ave}}Ln\frac{P_T-P_{Vi}}{P_T-P_{Vo}}\right\}\Bigg/\left\{\frac{1}{4\pi\alpha_m}\left(\frac{1}{R_o}-\frac{1}{R_i}\right)\right\} \tag{9}$$

Which:

D_V = Penetration of steam in dryer

(V_L/V_L+V_s) Void fraction = α_m

$\left((\frac{1}{2}(T_o+T_i)\right)$ Average temperature = T_{ave}

P_{Vi}, P_{Vo} = shell inside and outside saturation vapor pressure

Mass transfer (moisture) to the air dryer environment:

$$\frac{dm_p}{dt}=K_m.4\pi R_\circ^2(C_{V\circ}-C_{Vi})$$

Or

$$\frac{d_{mp}}{dt}=k_g.4\pi R_\circ^2\left(y_{eq}-y_g\right) \tag{10}$$

With combining two equations (9) and (10), will have:

$$\frac{dm_p}{dt}=\frac{1}{[\frac{1}{R_\circ}-\frac{1}{R_i}]}\frac{4\pi\alpha_m D_V P_T}{RT_{ave}}Ln\left[\frac{P_T-P_{Vi}}{P_T-\dfrac{RT_\circ}{km4\pi R_\circ^2 M_w}\dfrac{dm_p}{dt}-\dfrac{P_{V\infty}.T_\circ}{T_\infty}}\right] \tag{11}$$

Also will have:

Steam penetration in porous media: $D_c=\alpha^m D_V$

Wet sphere radius calculated equation:

Assuming that ratio of the total amount of solid to liquid in drops is the same, will have:

$$\frac{m_{li}}{m_{l\circ}}=\frac{d_i^3}{d_\circ^3}\quad\Rightarrow\quad\frac{di}{d\circ}=\frac{m_{li}^{\frac{1}{3}}}{m_{l\circ}^{\frac{1}{3}}}=\frac{m_l^{\frac{1}{3}}}{m_{l\circ}^{\frac{1}{3}}} \tag{12}$$

So will have:

$$\frac{dR_i}{dt}=\frac{0.333R_\circ}{m_{L_\circ}^{\frac{1}{3}}m_L^{\frac{1}{3}}}\frac{dm_L}{dt} \tag{13}$$

m_L = Mass moisture (solvent) in slurry drop

$m_{l\circ}$ = Initial moisture content drops when second phase starts

Equation to obtain drops external temperature [12] and [13]

First heat transferred with air convection to drops and then with conduction of porous layer. Assuming the drop is in Steady state will have:

$$T_\circ=T_\infty-\frac{\dfrac{1}{h_c 4\pi R_\circ^2}}{\dfrac{1}{h_c 4\pi R_\circ^2}+\dfrac{R_\circ-R_i}{4\pi R_\circ R_i k_{ps}}}(T_\infty-T_i) \tag{14}$$

Conduction heat transfer coefficient in porous shell (kPS) is calculated by the following equation:[15]

$$k_{ps}=k_a\left(\frac{k_s}{k_a}\right)^{0.280-0.757Log\zeta-0.057Log(Ks/Ka)} \tag{15}$$

In equation number (14), porosity and solid conduction heat transfer coefficient, Ka is heat transfer coefficient of air (or gas drying).

Equation calculated for porous shell internal surface temperature

$$\frac{T_\infty - T_i}{\frac{1}{h_c \pi R_\circ^2} + \frac{R_\circ - R_i}{4\pi R_\circ R_i k_{ps}}} = -\Delta H - \frac{dm_L}{dt} + (C_{PL} m_L + m_{SK} C_{PS}) \frac{d\,T_i}{dt} \qquad (16)$$

Amount of $(C_{PL} m_L + m_{SK} C_{PS})$ shows core wet heat capacity (formation of suspension moisture (water) and solid particles) if the assumption of evaporation rate ratio does not change the porosity drops msk can be calculated from the following equation**:**

$$m_{sk} = \frac{d_i^3}{d_\circ^3} m_s \qquad (17)$$

Mass and energy balance of dryer gas:

Mass balance of dryer gas:

With calculating drops moisture evaporation rate and drying gas flow rate, increase in drying gas humidity can be calculated.

Energy balance of dryer gas:

As discussed, heat and mass transfer occurred between air and drops. This exchange of temperature and humidity causes changes in temperature and humidity drops and hot air in dryer. In the previous section, changes in drops temperature and humidity and the drying gas moisture changes were studied and their governing equations derived. In this section to determine changes in temperature between the air and drops, write energy balance of drying gas. To obtain gas temperature variations, small height of the Spray dryer dx observed. It should be mentioned that in steady state droplets number in each section of height according to its distance to automiser is constant, The fact that changes in gas volume enthalpy due to solvent evaporation from drops surface and heat transfer due to thermal gradient existing between the surface temperature drops and the gas volume, so enthalpy gas drying could calculate from following equations and the reference temperature:

$$H_{gas} = C_{Pg}(T_g + 273) + \left[\Delta H_{ref} + C_{PV}(T_g - T_{ref})\right] y_g \quad (Kj/Kg) \qquad (18)$$

The transferred steam enthalpy of gas from a drop surface, the following relationship is obtained:

$$H_{vaper} = \left[\Delta H_{ref} + C_{PV}(T_P - T_{ref})\right] . w_D \qquad (19)$$

And the rate of heat transfer from the surface of drops per gas volume and or vice versa, using the following equation is obtained:

$$q = h.\pi d_p^2 .(T_g - T_P) \qquad (20)$$

Therefore, enthalpy changes for the small gas volume in short length dx, will have:

$$w_g \frac{d(H_g)}{dt} = \sum_{i=0}^{i} N_i . H_i - \sum_{i=0}^{i} N_i . q \qquad (21)$$

And for drop, energy changes in the drying gas at each time per tangible energy changes and drops evaporation rate could calculate with following equations:

$$w_g \frac{d(H_g)}{dt} = \left(\Delta H_{ref} + C_{PV}(T_P - T_{ref})\right) w_D - h.\pi d_p^2 (T_P - T_g) \qquad (22)$$

With differentiation of equation (18) according to time, will have:

$$\frac{dH_g}{dt} = C_{Pg} \frac{dT_g}{dt} + \left[\Delta H_{ref} + C_{PV}(T_g - T_{ref})\right] \frac{dy_g}{dt} + y_g \left[C_{PV} . \frac{dT_g}{dt} \right] \qquad (23)$$

Instead of obtained equation gas specific heat is [59-63]:

$$C_{Pg,wet} = \frac{(C_{Pg} + y_g . C_{PV})}{(1 + y_g)} \qquad (24)$$

Finally will have:

$$\frac{dT_g}{dt} = -\left[\frac{\Delta H_{ref} + C_{PV}(T_g - T_{ref})}{C_{Pg,wet} .(1 + y_g)} \right] \frac{dy_g}{dt} + \frac{\Delta H_{ref} + C_{PV}(T_g - T_{ref}) . w_D}{w_g . C_{Pg,wet} .(1 + y_g)} - \frac{h.\pi d_p^2 .(T_g - T_p)}{w_g . C_{Pg,wet} .(1 + y_g)} \qquad (25)$$

3. Simulation

Since the used Spray Dryer in experimental studies has been co-current, so this alumina Spray dried simulated and co-current simulation results were compared with Spray dryer test results in the laboratory. For co-current state a computer program written that is able to model equations as mentioned consecutive solved and provide moisture profiles, temperature, speed, retention time, height, dryer high, air outlet temperature and outlet dryer temperature of alumina.

At first try to keep test environment at a constant temperature and moisture as possible. Then after weighing, put the test material (slurry alumina) to oven at time .

Then, after each interval time, the amount of dried materials weight and recorded per spent time.

Weighing continued until have no changes in sample weight. Then dryer temperature raise to 120 , after an hour or more, moisture-free dry matter and weighing and amount of dry matter (ms) obtained.

Defined X:

X = (dry weight - wet weight of material) / (Dry weight)

With T and X value can be calculated.

The important parameters that prove correct conditions in laboratory are temperature, humidity and interval weighing time. In addition, important point is that drying material thickness have not very deep that penetration considered and not too low that during drying some parts of surface dried and other parts still remain wet which cause changes in surface. Usually predict the behavior of a process model, that model accuracy, error model and error causes are identified. As for adjusted simulation accuracy, simulation results required to compare with a series of experimental data. For this purpose, information obtained from Spray dryer method compared with data obtained from experimental software designed. Tables (1) and (2) shows results of relevant tests at 65 and 75 degrees C.

Designed Software after receiving the required input data with selected interval time when starting to solve equations and finally gives profiles, drops and air temperature, drops speed, air and drops humidity per time and dryer height that user can make required analysis to perform obtained information. This software also allows the user to change control parameter corresponding to desired conditions. The results of computer simulation at 65 degrees C temperature show by graphs (1) to (12).

$$A = 9.498*10^{-3}(m^2)\ m_s = 12.4*10^{-3}(kg)$$

Table 1. Experience results for 65 $^\circ C$

T(Sec)	X(kg Water/ kg Dry Solid)	W(kg/m^2.Sec)*10E-4
0	11.500	0.00
1800	9.143	3.171
3000	7.460	3.40
4200	5.876	3.20
5400	4.345	3.09
6600	2.900	2.92
8400	1.546	1.82
9600	0.875	1.35
10800	0.598	0.56
12000	0.435	0.33
13200	0.345	0.18
15000	0.275	0.09
16200	0.234	0.08

$$A = 9.765*10^{-3}(m^2)\ m_s = 17.39*10^{-3}(kg)$$

Table 1. Experience results for 75 $^\circ C$

T(Sec)	X(kg Water/ kg Dry Solid)	W(kg/m^2.Sec)*10E-4
0	6.321	
3600	5.681	3.164134949
7200	5.049	3.124583262
10800	4.411	3.154247027
14400	3.775	3.144359106
18000	3.14	3.139415145
21600	2.57	2.818057689
25200	2.13	2.175342777
28800	1.799	1.636451044
32400	1.5	1.478244297
36000	1.27	1.142054958
39600	1.067	0.998680093
43200	0.896	0.845417307
46800	0.765	0.647658872
50400	0.678	0.430124595

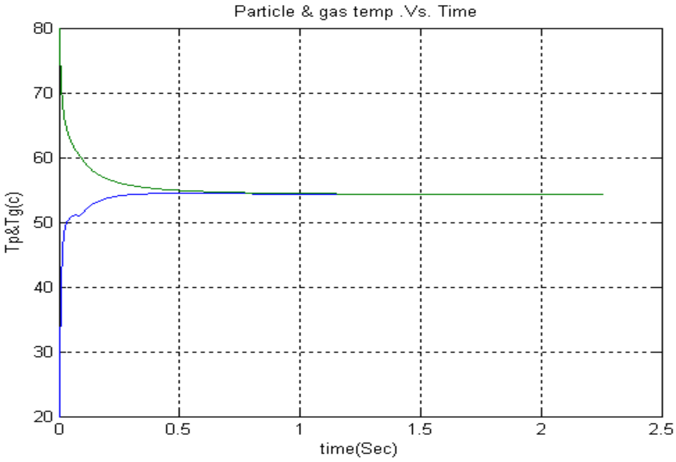

Figure 1. Particles and gas temperature variation per time

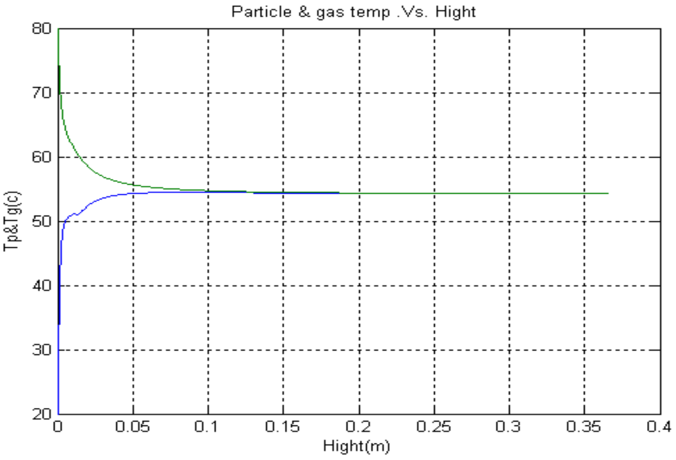

Figure 2. Particles and gas temperature variation per height

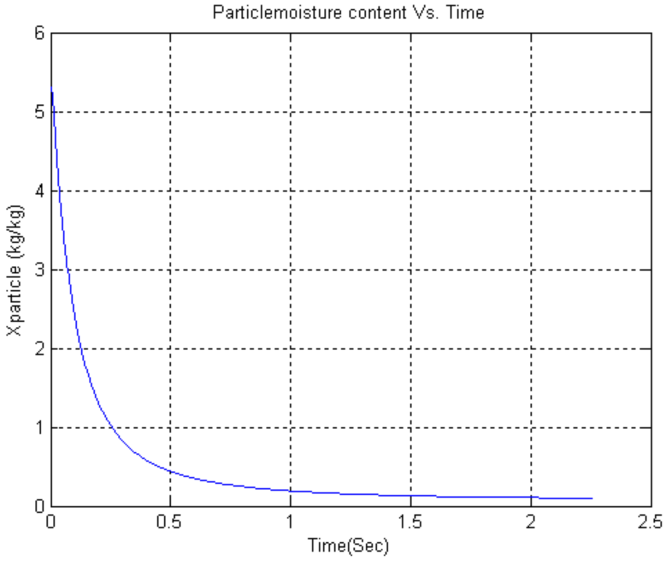

Figure 3. Particles moisture variation per time

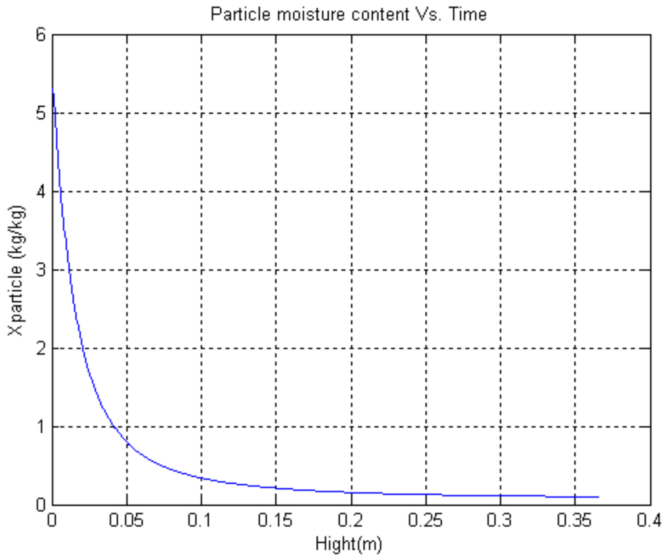

Figure 4. Particles moisture content per height

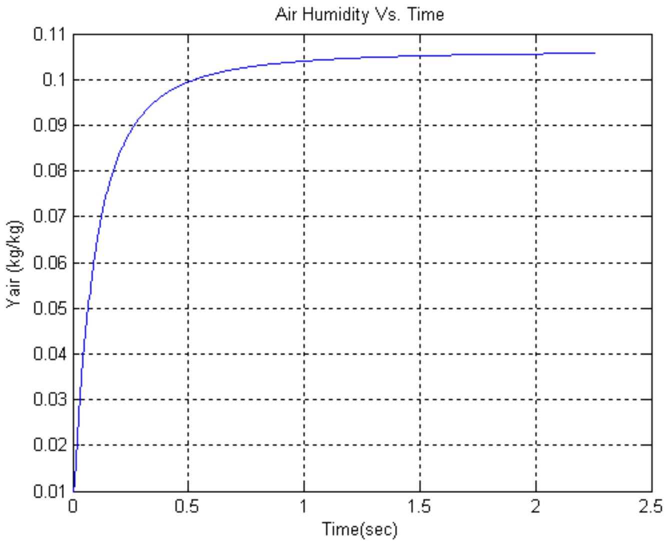

Figure 5. Air humidity variation per time

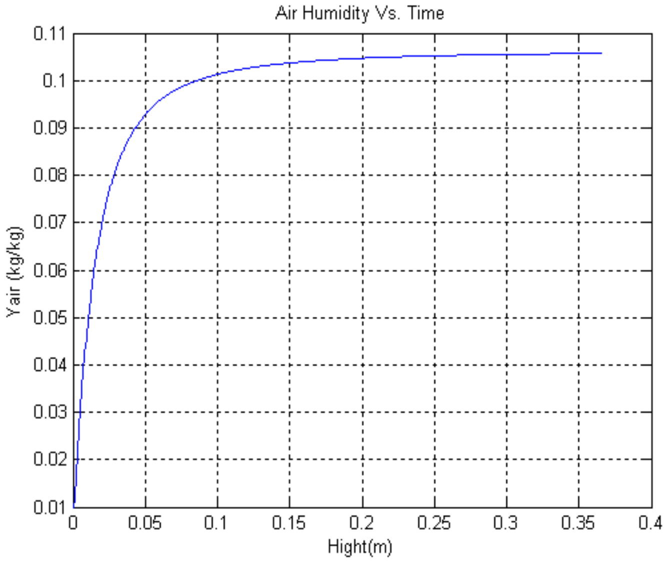

Figure 6. Air humidity variation per height

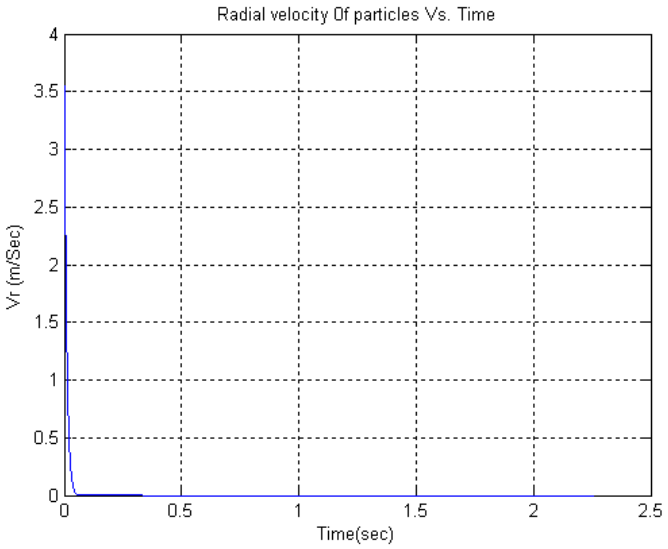

Figure 7. Radial particle velocity variation per time

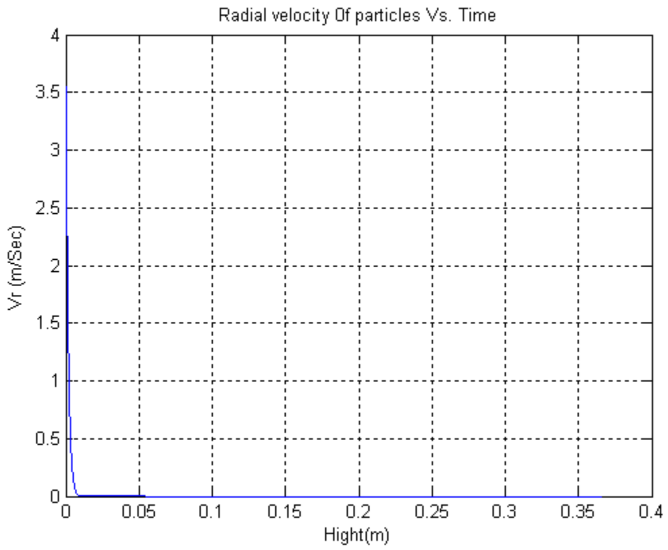

Figure 8. Radial particle velocity variation per height

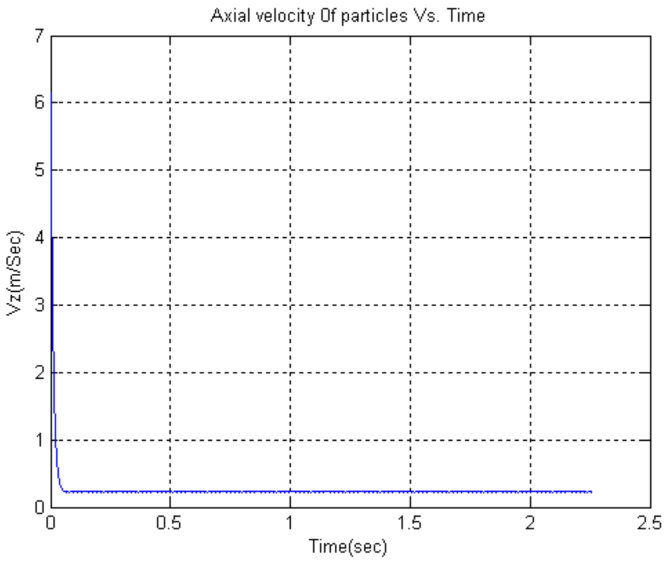

Figure 9. Axial particle velocity variation per time

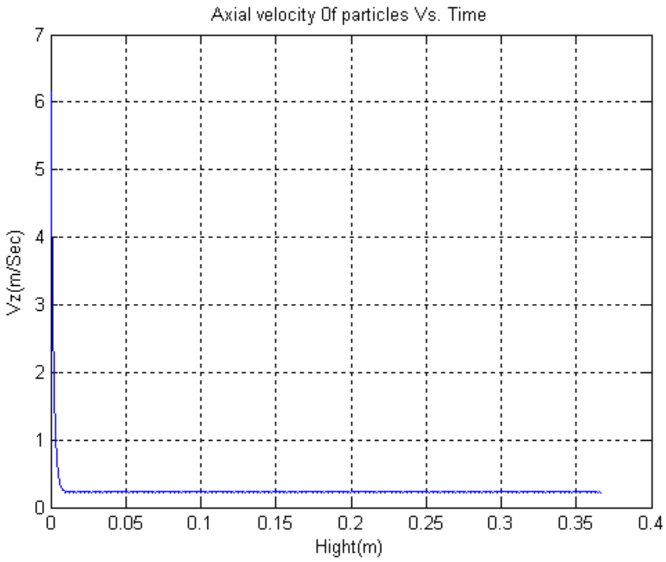

Figure 10. Axial particle velocity variation per height

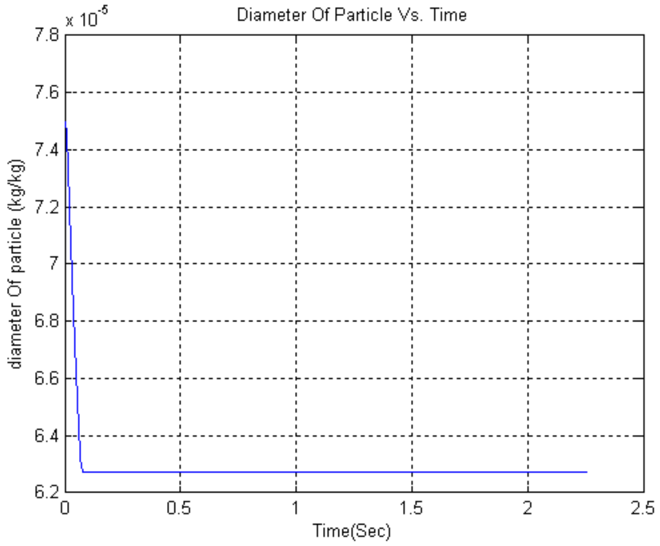

Figure 11. Particle diameter variation per time

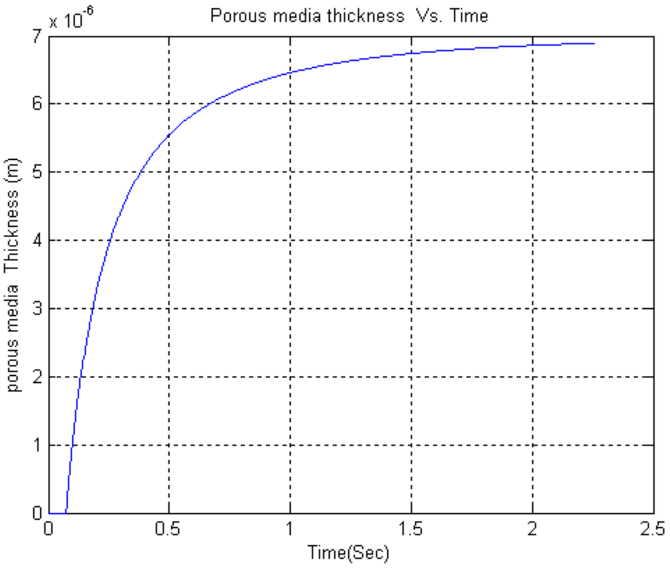

Figure 12. Porous media thickness variation per time

4. Conclusion

The following point's can construct from charts:

1 - with changes of temperature and humidity in gas chamber dryer which is the same as trend expected, i.e. changes in moisture or gas and increases in air flow, due to droplets moisture evaporation and enter the moisture to gas observed and gas temperature decreasing which is also due to required energy supplied for evaporation of droplets moisture in gas flow.

2 - At the simulation beginning or droplet evaporation starting due to drops low temperature $(20^{c}C)$ heat transferred from warm air to the droplets, only droplets temperature increased, so at this short time, no tangible change occurred in rate of drops relative humidity. Therefore, in drops relative humidity curves in first 0.1 sec of simulation, a small direct line observed that drop's moisture do not changes and therefore no change in droplets diameter and density.

3 -initial increase in drops temperature curves observed due to temperature gradient between gas flow and droplet surface and also enhance the overall heat transfer coefficient, but reduced in thermal gradient and resuming drops surface evaporation, drops temperature decreased till drops moisture got close to critical moisture and Convection heat transfer between gas and droplets, will control the drops temperature.

4- Due to obtained drying curve in this simulation and droplets critical moisture, two stages are accepted for droplets evaporation. In the first stage, evaporation rate is steady per time and reduction is uniformity in relative drops humidity, which obtained curves for drops relative humidity is well in the relevant forms. When drops moisture reach to critical moisture, drops evaporation rate with time will reduce. After this step, solid crust on the surface of droplets will formed thicker with time and humidity and evaporation rate of droplets affiliated on moisture penetration rate between this crust and solid external surface crust.

5 - Output air temperature from simulation in first experiment at laboratory is 54.27 degrees C, while the experiment's temperature is 49.3 degrees Celsius which is about 5 degree and the difference is about 10% error. Second experiments error has the same error that this error is due to heat loss neglecting in tower, but in practice due to heat loss, outlet air temperature is lower. Simulated tower height obtained 37.3 cm, while the laboratory Spray dryer height is 40 cm which provides % 2.6 difference errors that this error is because of drying operation efficiency assumed one hundred percent, while because smaller operation efficiency, greater length is required.

Nomenclature

P	pressure	A	surface
P_v	Vapor pressure	c_V	Mass concentration
R_p	Drop radius	C_p	Heat capacity at constant pressure
R_i, R_o	Internal and external radius of porous shell	C_D	Drag coefficient
S	Drops surface	D_C	Steam penetration coefficient at porous shell
t	Time	D_v	Steam penetration coefficient at air
T	Temperature	d_p	Drop diameter
T_{ave}	Mean Temperature	g	gravity
V_l	Liquid volume inside the drop	h_c	Convection heat transfer coefficient
V_s	Solid volume inside the drop	k_m	Mass transfer coefficient
$,U_{pf}\ U$	Velocity, relative velocity of air and drop	k_a	Air conduction heat transfer coefficient
X	Solid moisture per dry solid	k_{ps}	Shell conduction heat transfer coefficient
α	Void fraction	k_g	Mass transfer coefficient(base on moisture)
ε	Porosity	m	Mass
$\lambda, \Delta H_{lv}$	Water evaporation latent heat	m_{sk}	Solid mass at wet particle
ρ	Density	M	Molecular weight

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