

# Effect of Particle Size Distribution on Ammonium Sulphate Dried in a Rotary Dryer

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**Abstract**—The aim of this work is to study theoretically, by mathematical model development, the effect of particle size distribution on the performance of rotary dryer to dry ammonium sulphate fertilizer assuming plug flow with axial dispersion pattern (PFDA model) for solid particle flow. The mathematical model development was carried out by combining the drying processes model with particle size distribution model. Particle size distribution models used are Rosin-Rommler model and Gamma distribution model. For simplicity, the model of drying processes of solid particles in the rotary dryer was developed by assuming of uniform air conditions (temperature and humidity) along the rotary dryer as in the entry conditions. The resulting differential equations were solved analytically under Matlab 6.1 facility. Since this model, solid hold up, and axial dispersion number were obtained from empirical correlations in the literatures. The drying rate of ammonium sulphate fertilizer in rotary dryer was estimated using isothermal diffusion model with effective diffusivity of moisture in the particle obtained from previous study [2]. Using Gamma function distribution, this research showed that for the value of the coefficient of variance (CV) less than 0.5, particle size distribution does not have significant effect on dryer performance. For the value of CV greater than 0.5, the dryer performance increase (or outlet solid moisture content decrease) with increasing the value of CV. The application of Rosin-Rammler model gives lower prediction of outlet solid moisture content compared to the application of Gamma function model.

**Keywords**—Particle size distribution, coefficient of variation, moisture content, analytical solution

## I. INTRODUCTION

Drying which occurs in the rotary dryer is a process that has long been used in industry. For example, the fertilizer industry uses a rotary dryer to dry ammonium sulphate (ZA), superphosphate, and NPK. Rotary dryer is an equipment commonly used in the drying process of material that is not easily broken and not sensitive to heat. Fundamental events that include simultaneous transfer of heat from the drying medium (usually air) to the solid and the mass transfer of water from the solids to the drying medium occurred during the drying process in the RD [22]. The process occurring in rotary dryer is very complex and still less well understood. Describe drying process in rotary dryer is described by Fuzzy modeling [16, 23].

To enhance the effectiveness of contact between solid and gas, the rotary dryer is equipped with flights, which are placed along the cylinder. Volume of materials transported by the flights is between 10 to 15% of the total volume of material contained in a rotary dryer [15]. The mechanism is as follows, as the dryer rotates solid

is taken up by the flights, up to a certain distance and then the solid is poured over the air. Most of the drying occurs at this time, where the solid contacts with the gas. Flights also serves to transport the solid through the cylinder [25].

To be able to analyze and design a rotary dryer properly, the information concerning heat transfer, mass transfer, and solid transport in rotary dryer is needed. This has been explored by previous researchers experimentally, as Friedman & Marshall [5] who developed the research to find a correlation of volumetric heat transfer coefficient in rotary dryer. Friedman and Marshall [5] conducted a research to estimate the amount of solid material resides in a dryer that affect the heat transfer rate. Hold up correlations have been obtained both for cocurrent flow or counter-current. Friedman and Marshall [6] conduct research on the influence of air speed, feed rate, rotation speed, slope, and the number of flight on heat transfer rate that occurs in the rotary dryer. Research on solid hold up or the average residence time of solid in a rotary dryer has been carried out by Pan *et al* [18], Purutyan *et al* [20], Kemp [12]. Kemp [12] examined the particle motion in cascade rotary dryers and he obtained a new formula to replace the existing formula and this formula is used for early design. Pan *et al* (2006), have created a model for the granule transport based on motion analysis and have obtained a method for calculating the mean residence time of granule. Theoretical studies are needed to predict rotary dryer performance based on heat and mass transfer process and solid transport mechanism.

The drying process is influenced both by external conditions, such as temperature, velocity, humidity of drying air and particle size distribution and by internal drying mechanism inside the solid which depends on the solid particle characteristic including pore structure, hygroscopic characteristic, shape and size of the particles. A number of theories (models) that describe the process of drying of solid particles has been developed by previous researchers such as Akpınar and Dincer [1], Haghi and Angiz [8], Haghi [9, 10]. These researchers estimate theoretically the rate of drying with the diffusion model. Meanwhile, theoretical studies for the performance of the drying process in the rotary dryer (for some specific materials) has been developed by several researchers, including the Yliniemi [25] uses the assumption of uniform particle size and makes the flow of solid particles in a rotary dryer a mixed flow (lump-parameter model); and Wang *et al* [24], Kiranoudis *et al* [13], Pacheco & Stella [19], Menshutina *et al* [17] which also used the uniform particle size assumption but the solid and gas flow inside the rotary dryer is assumed plug flow (distributed parameter model).

Fernandes *et al* [4] and Schofield and Glikin [21] studied the mathematical modeling of industrial fertilizer rotary dryer using uniform particle size and plug flow of

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solid assumption. In industrial dryer, the particle size is generally not uniform and when the solids in the rotary dryer was taken up by the flight at a certain height and then dropped into the bottom of the rotary dryer, back mixing occurs in solid flow, so that the solid and gas flow characteristics are non-ideal in the real process (not a plugflow or mixed flow). Besides, the previous researchers assumed uniform particle size in their mathematical model development.

This study aims to examine theoretically (by mathematical model development) the influence of particle size distribution on rotary dryer performance by considering solid backmixing. Rosin-Rammler and gamma function modeling were used to describe particle size distribution.

## II. METHOD

This study was carried out experimentally and theoretically to study drying process of ammonium sulphate fertilizer in rotary dryer. The rotary dryer system under study is that used in PT. Petrokimia Gresik. The dryer is cylindrical shaped with a diameter of 2.418 m and a length of 12.2 m. The rotary dryer is placed with the slope of 4.5% and the cylinder rotated at 3.5 rpm. The inside of the cylinder is equipped with 20 flight. Hot air was used as the drying media. The rotary dryer was operated cocurrently. The experimental work was carried out to measure particle size distribution parameter of particle and the simulation work was carried out by developing mathematical model of drying process in rotary dryer by considering non-uniform particle size.

The particle size distribution was measured using a set of screens with size: 20, 30, 35, 40, 45, 50, 60, 70, and 80 mesh or 841, 600, 500, 425, 355, 300, 250, 212, 180, and 150  $\mu\text{m}$  to obtain mass fraction of solid particles with mean diameter of 720.5, 550, 462.5, 390, 327.5, 275, 231, 196, 165  $\mu\text{m}$ . The measurement results were analyzed using Rosin-Rammler and Gamma distribution model to determine the model parameters. Rosin-Rammler and Gamma distribution model can be represented in Equation (1) and (2) respectively.

$$p(D_p) = \frac{n}{D_p^n} D_p^{n-1} \exp\left[-\left(\frac{D_p}{D_p}\right)^n\right] \quad (1)$$

$$p(D_p) = \frac{1}{\beta^\alpha \Gamma(\alpha)} D_p^{\alpha-1} \exp\left(-\frac{D_p}{\beta}\right) \quad (2)$$

The value of Rosin-Rammler parameter,  $n$ , called spread parameter, was determined using the following exponential relation between particle diameter  $D_p$ , and mass fraction of particle with diameter greater than  $D_p$ , that is  $M_D$ ,

$$M_D = \exp\left(-\left(\frac{D_p}{\bar{D}_p}\right)^n\right) \quad (3)$$

where  $\bar{D}_p$  is mean diameter and  $n$  is spread parameter.

The value of Gamma distribution parameters,  $\alpha$  and  $\beta$ , was determined using Equation (4) and (5).

$$\alpha = \left(\frac{\mu}{\sigma}\right)^2 \quad (4)$$

$$\beta = \frac{\sigma^2}{\mu} \quad (5)$$

The spreadness of distribution of both model can be measured using parameter coefficient of variance (CV) defined as follows,

$$CV = \frac{\sigma}{\mu} \quad (6)$$

The mathematical model of drying process in rotary dryer with non-uniform particle sizes was developed by combining the uniform particle size drying process model with particle size distribution models: Rosin-Rammler and Gamma distribution model where coefficient of variation (CV) becomes an important parameter.

Uniform particle size drying process model was developed by assuming steady state condition, plug flow with axial dispersion pattern for solid flow, uniform drying air condition throughout the dryer. The model consist of differential mass balance of moisture in solid particle in the rotary dryer that can be represented in Equation (7).

$$-\frac{\partial X}{\partial \xi} + \frac{1}{P_e} \frac{\partial^2 X}{\partial \xi^2} = \phi_1 \quad (7)$$

where,

$$\xi = \frac{z}{L}, \phi_1 = \frac{LR_w}{u}, P_e = \frac{Lu}{D_z} \quad (8)$$

The boundary conditions for Equation (7) are shown in Equation (9) and (10).

$$\text{BC 1: } \xi = 0, X = X_0 \quad (9)$$

$$\text{BC 2: } \xi = 1, dX/d\xi = 0 \quad (10)$$

The Peclet number, or the inverse of axial dispersion number, in Equation (8) was determined using an empirical correlation by Liang Tseng Fan (1961) shown in Equation (11) and (12).

$$\frac{D_z}{uL} = (2.46 \times 10^{-12}) \left(\frac{F}{\text{DiSN}}\right)^{-2.02}, \frac{F}{\text{DiSN}} < 0.287 \quad (11)$$

$$\frac{D_z}{uL} = (1.79 \times 10^{-10}) \left(\frac{F}{\text{DiSN}}\right)^{1.415}, \frac{F}{\text{DiSN}} > 0.287 \quad (12)$$

Where the linear solid velocity,  $u$ , was obtained as follows,

$$u = \frac{L}{t} \quad (13)$$

Solids residence time in the rotary dryer ( $t$ ) was estimated from the empirical correlation [20], shown in Equation (14)

$$t = \frac{0.3464 L}{S N^{0.9} Di} - 0.5904 \frac{LG}{F_s' D_p^{0.5}} \quad (14)$$

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$$\frac{\partial X}{\partial t} = \frac{D_{eff}}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial X}{\partial r} \right) \quad (15)$$

with the following initial condition and boundary conditions,

$$IC : t = 0, X(r,0) = X_0 \quad (16)$$

$$BC1 : r = 0, \frac{\partial X}{\partial r} = 0 \quad (17)$$

$$BC2 : r = R, \frac{\partial X}{\partial r} = -\frac{k_G (P_A^{sat} - P_A)}{\rho_s D_{eff}} \beta \quad (18)$$

Parameter  $\beta$  in Equation (18) is called partition factor defined in Equation (19) to account for surface resistance of mass transfer while gas side mass transfer coefficient in Equation (18) was estimated using empirical correlation [7].

$$\beta = e^{-\left( \frac{X_0 - X}{X_0} \right)} \quad (19)$$

The partial differential equation represented in Equation (15) with initial and boundary conditions represented in Equation (16), (17) and (18) were discretized using implicit finite difference method with Crank Nicholson scheme to obtain a set of linear algebraic equations solved by matrix inversion method. The solution represents the values of solid moisture content at various position in the particle and at any instant. Then, the average moisture content of the solid at any instant can be obtained by the following equation,

$$\bar{X}(t) = \frac{3}{R^3} \int_0^R X r^2 dr \quad (20)$$

The predicted result of  $\bar{X}(t)$  was fitted into a simple exponential model,

$$\bar{X}(t) = K e^{-Bt} \quad (21)$$

where the value of constants K and B can be obtained using least square method. Finally rate of drying per unit mass of dry solid can be obtained as follows,

$$R_w = -\frac{d\bar{X}}{dt} = -KB e^{-Bt} = B\bar{X} \quad (22)$$

Differential Equation (6) with boundary conditions (8) and (9) was solved analytically to obtain moisture content of solid particle as a function of axial position in the rotary dryer and particle diameter,  $\bar{X}(D_p, z)$ .

The result of analytical solution was coupled with particle size distribution model to obtain the average moisture content in solid particle as a function of axial position in the dryer ( $\bar{X}(z)$ ) expressed in Equation (23).

$$\bar{X}_{avg}(z) = \int_0^\infty p(D_p) \bar{X}(D_p, z) dD_p \quad (23)$$

### III. RESULTS AND DISCUSSIONS

The most important information needed in mathematical model development of rotary dryer is rate of solid drying. Rate of drying of ammonium sulphate particles was obtained from Equation (22), where the value of B was obtained by fitting the predicted results, from Equation (20), with the simple exponential model, Equation (21). The value of B was determined for various drying conditions or for different value of air temperature, humidity and velocity shown in Table 1. Then, the following correlation was obtained, using linear regression, to relate constant B with operating variable

$v, T$  and  $D_p$ .

$$B = 3.34368 \times 10^{-12} v^{0.75719} H^{-0.01773} T^{4.87650} D_p^{-1.27485} \quad (24)$$

And the rate of drying was obtained by substitution B from Equation (24) into Equation (22) as follows,

$$R_w = 3.34368 \times 10^{-12} v^{0.75719} H^{-0.01773} T^{4.87650} D_p^{-1.27485} \frac{X}{X} \quad (25)$$

This study explored the effect of particle size non-uniformity, expressed as Coefficient of Variance, on rotary dryer performance using Rosin-Rammler and Gamma distribution. The particle size non-uniformity was measured using a set of screens. Table 2 shows the experimental results of particle size distribution measurement. The average particle diameter, standard deviation, coefficient of variance, Rosin-Rammler distribution parameter, and Gamma distribution parameter can be obtained using data from Table 2 as follows:  $\mu = 330.22 \mu\text{m}$ ,  $\sigma = 144.36 \mu\text{m}$ ,  $CV=0.437$ ,  $n = 2.3$ ,  $\alpha = 5.24$ ,  $\beta = 63$ .

The mathematical model was developed to account for the effect of particle size non-uniformity on rotary dryer performance. In this case, the drying process model in rotary dryer with uniform particle size  $D_p$  was combined with the particle size distribution model. The drying process model with uniform particle size was obtained by solving analytically Equation (6) with boundary conditions (8) and (9) as follows,

$$\bar{X} = f(D_p, z) = X_0 \left( 1 - \frac{\phi_1}{P_c} \exp(-P_c) [1 - \exp(P_c \xi)] - \phi_2 \xi \right) \quad (26)$$

This solution gives moisture content in solid particle with diameter  $D_p$  at axial position,  $z$ , in rotary dryer. While mass fraction of particles with diameter  $D_p$  in a group of particles with various sizes was represented with Rosin-Rammler model shown in Equation (1) and Gamma distribution model shown in Equation (2). Then, the average moisture content at axial position,  $z$ , in rotary dryer can be obtained from Equation (23), where  $f(D_p, z)$  was found from Equation (26).

The integration in Equation (23) was carried out numerically using Simpson rule, where the higher limit of integration was replaced with  $D_{p,max}$  obtained from Equation (27).

$$\int_0^{D_{p,max}} \frac{n}{D_p^n} D_p^{n-1} \exp \left[ -\left( \frac{D_p}{D_p} \right)^n \right] dD_p \geq 0.999 \quad (27)$$

The simulation results are presented graphically in Fig. 1 and Fig. 2. Fig. 1 shows the average moisture content in solid at axial position in rotary dryer with Coefficient of Variance (CV) as parameters. This figure depicts that for the value of CV less than 0.5, the non-uniformity of particle sizes does not give significant effect on the predicted moisture content profile and the predicted moisture content in solid particle effluent from rotary dryer. The effect of CV on the rotary dryer performance is significant for the value of CV greater than 0.5. The moisture content in the solid effluent decrease (or the performance of rotary dryer increase) with increasing the value of CV. Increasing CV means that the mass fraction of particles with diameter is significantly less than or more than the average of diameter increase. Increasing the fraction of fine particle will increase the drying rate due to large surface area. This is the explanation why the dryer performance increases with increasing the value of CV.

TABLE 1.  
THE EFFECT OF V, H, T AND DP ON THE VALUE OF B

No.	Rate of Air (m <sup>3</sup> /hr)	v (cm/s)	H (gr H <sub>2</sub> O/gr dry air)	T (°C)	Dp, μm	B
1	7000	42.37	0.015	110	185	0.00036
2	9000	54.47	0.015	110	185	0.00043
3	11000	66.57	0.015	110	185	0.00049
4	7000	42.37	0.02	110	185	0.00036
5	9000	54.47	0.02	110	185	0.00043
6	11000	66.57	0.02	110	185	0.00049
7	7000	42.37	0.025	110	185	0.00036
8	9000	54.47	0.025	110	185	0.00042
9	11000	66.57	0.025	110	185	0.00049
10	7000	42.37	0.015	115	185	0.00044
11	9000	54.47	0.015	115	185	0.00052
12	11000	66.57	0.015	115	185	0.00062
13	7000	42.37	0.02	115	185	0.00044
14	9000	54.47	0.02	115	185	0.00052
15	11000	66.57	0.02	115	185	0.00061
16	7000	42.37	0.025	115	185	0.00043
17	9000	54.47	0.025	115	185	0.00052
18	11000	66.57	0.025	115	185	0.00061
19	7000	42.37	0.015	120	185	0.00053
20	9000	54.47	0.015	120	185	0.00066
21	11000	66.57	0.015	120	185	0.00081
22	7000	42.37	0.02	120	185	0.00053
23	9000	54.47	0.02	120	185	0.00065
24	11000	66.57	0.02	120	185	0.0008
25	7000	42.37	0.025	120	185	0.00053
26	9000	54.47	0.025	120	185	0.00065
27	11000	66.57	0.025	120	185	0.0008
28	7000	42.37	0.020	110	150	0.000495
29	7000	42.37	0.020	110	200	0.000326
30	7000	42.37	0.020	110	300	0.000193
31	7000	42.37	0.020	110	400	0.000134
32	7000	42.37	0.020	110	500	0.0001

TABLE 2.  
PARTICLE SIZE DISTRIBUTION

No	Mesh	Size, μm D	Mean Diameter, μm	Mass Percentage, %	Diameter D, μm	M <sub>D</sub> %
1	-20+30	-841 + 600	720.5	30.92	600	30.92
2	-30+35	-600 + 500	550	20.97	500	51.89
3	-35+40	-500 + 425	462.5	16.37	425	68.26
4	-40+45	-425 + 355	390	10.99	355	79.25
5	-45+50	-355 + 300	327.5	10.50	300	89.75
6	-50+60	-300 + 250	275	3.53	250	93.28
7	-60+70	-250 + 212	231	3.40	212	96.68
8	-70+80	-212 + 180	196	1.74	180	98.42
9	-80+100	-180 + 150	165	1.59	150	100.01

TABLE 3.  
VALIDATION OF SIMULATION PREDICTIONS WITH A ROTARY DRYER OPERATING DATA IN PT.PETROKIMIA GRESIK

No	X(%)	Ts(°C)	Fs(ton/h)	Tg(°C)	X out (%)			Error (%)	
					RR	GM	Pilot	RR	GM
1	0.615	70	36	114	0.05	0.06	0.045	11.11	33.33
2	1.175	70	33	113	0.06	0.07	0.095	36.84	26.32
3	0.985	70	30	117	0.05	0.06	0.075	33.33	20
4	0.655	65	36	117	0.05	0.05	0.075	33.33	33.33
5	0.675	70	33	115	0.05	0.06	0.075	33.33	20

Fig. 2 shows the effect of the application of distribution model (Rosin-Rammler and Gamma distribution) on the solid moisture content profile in the rotary dryer. The application of Rosin-Rammler distribution model gives the smaller prediction of solid moisture content in rotary dryer compared to the application of Gamma distribution model. This is due to the Rosin-Rammler model that gives higher prediction of small particle size mass fraction compared to the Gamma distribution model.

The prediction results either using Rosin-Rammler or Gamma distribution model was compared to rotary dryer operating data in PT Petrokimia Gresik and the comparison is shown in Table 3. The application of Rosin-Rammler and Gamma distribution model give the prediction with average deviation of 29.6% and 26.6% (compared to the operating data) respectively based on the moisture content in the solid product.

#### IV. CONCLUSIONS

This work has studied the effect of particle size distribution on rotary dryer performance and expressed as the profile of moisture content in solid along the dryer by assuming uniform condition of air along the dryer as the inlet condition. In this case, the moisture balance in the rotary dryer is coupled with particle size distribution model. The particle size distribution model considered is Rosin-Rammler and Gamma function model. Using Gamma function distribution, the study shows that for the value of the coefficient of variance less than 0.5, particle size distribution does not have significant effect on dryer performance.

For the value of CV greater than 0.5, the dryer performance increases (or outlet solid moisture content decrease) with increasing the value of CV. The application of Rosin-Rammler model gives lower prediction of outlet solid moisture content compared to the application of Gamma function model. The deviation of product moisture content is predicted from the drying model with application of Rosin-Rammler and Gamma distribution was 29.6% and 26.6% respectively, but still acceptable by the industry.

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Notation		Unit
B	= Constant in Equation (21)	
CV	= Coefficient of Variance	-
$D_z$	= Axial dispersion coefficient	$m^2 s^{-1}$
$D_{eff}$	= Effective diffusivity of moisture in solid particle	$m^2 s^{-1}$
$D_i$	= Rotary dryer diameter	m
$D_p$	= Particle diameter	m
$\overline{D_p}$	= Average particle diameter	m
$D_{p,max}$	= Maximum particle diameter	m
F	= Solid volumetric rate per drum cross sectional area	$m s^{-1}$
$F_s'$	= Dried solid mass velocity in axial direction	$kg m^{-2} s^{-1}$
$F_s$	= Solid flow rate	ton/h
G	= Air mass velocity per cross-sectional area of RD	$kg m^{-2} s^{-1}$
H	= Air humidity	-
K	= Constant in Equation (21)	
$k_G$	= Gas side mass transfer coefficient	
L	= Length of dryer	m
$M_D$	= Fraction of particles with diameter greater than $D_p$	
n	= Rosin-Rammler parameter	
N	= Rotation speed of rotary dryer	$s^{-1}$
$p(D_p)$	= Particle size density function	
$P_A$	= Partial pressure of water vapour in air	Pa
$P_A^{sat}$	= Saturated vapor pressure of water	Pa
$P_e$	= Peclet Number	-
r	= Radial position in solid particle	-
R	= Particle radius	-
$R_w$	= Drying rate per unit mass of dry solid	$s^{-1}$
S	= Slope of the drum	$\square$
t	= Time	s
$\underline{t}$	= Residence time of solid in drum	s
T	= Temperature	K
$T_g$	= Gas temperature	K
$T_s$	= Solid temperatur	K
u	= Linear velocity of solid in the drum	$m s^{-1}$
X	= Local moisture content in solid particle	-
$\overline{X}$	= Average moisture content in solid particle	-
$\overline{X}_{avg}$	= Average moisture content in a group of solid with various diameter	-
z	= Axial position in rotary dryer	m
		-
Greeks symbols		
$\alpha$	= Parameter of Gamma distribution	-
$\beta$	= Parameter of Gamma distribution	-
$\beta^*$	= Partition coefficient	-
$\phi_1$	= Defined in Equation (8)	-
$\mu$	= Mean diameter of solid particle	m
$\xi$	= Dimensionless axial position in rotary dryer	-
$\rho_s$	= Density of solid particle	$kg m^{-3}$
$\sigma$	= Standard deviation of particle diameter	m

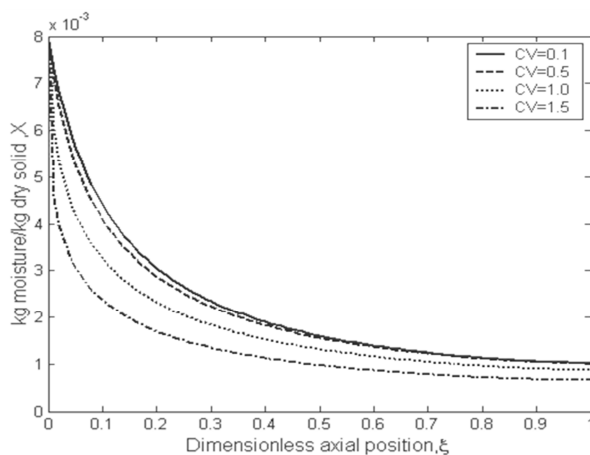


Fig. 1. The effect of particle size distribution on the profile of solid moisture content in rotary dryer using Gamma function distribution model.

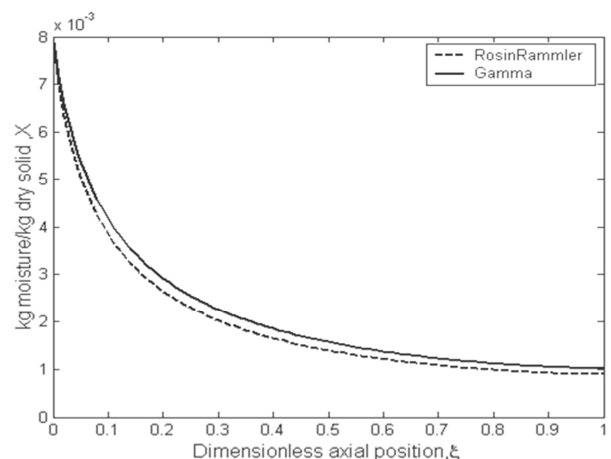


Fig. 2. The effect of distribution model (Rosin-Rammler and Gamma distribution) application on the profile of solid moisture content in rotary dryer.  $\mu = 330.22 \mu m$ ,  $CV = 0.437$ .

