Study on Heat and Mass Transfer During Urea Prilling Process

Ali Mehrez, Ahmed Hamza H. Ali, W. K. Zahra, S. Ookawara, and M. Suzuki

***Abstract*—Urea prills are produced in the prilling towers where a solidification-cooling process takes place. The ambient air is used as the cooling air stream for this process. In hot days, the temperature of the product at the bottom of the tower are hot that cannot be packed directly. In addition, in hot/ humid days, the prills form lamps and cakes with each other and on the scrubber. A mathematical model based on the hydrodynamics, heat, and mass transfer between the urea and the cooling air is developed. A numerical technique with an explicit scheme is used to solve the model. The model results describe the variation of the temperature and moisture along the radius of the particle. Hence, the model results introduce an interpretation of the problem of caking and lamps formation appears because of the incomplete solidification of the prills at the bottom of the tower. In addition, the results predict the quality of the product under different operating conditions of the ambient cooling air.**

***Index Terms*—Numerical simulation, urea solidification, Heat and mass transfer, mathematical modeling.**

I. Introduction

Urea is marketed as a solution or in the solid form. Urea in solid form is produced in the final process stage by either granulation or prilling. Transformation of urea from melt to solid prills takes place in the urea prilling tower. In the prilling process, urea melt is pumped to the top of 50 to 60 meter (above ground) cylindrical concrete tower where it is fed to the prilling device that called rotating bucket. The rotating bucket is a sieve-like cylindrical or conical drum that rotates about its axis. Liquid jets emerge from the various holes on the curved surface of the drum, and break up due to centrifugal and capillary instability. The liquid urea droplets formed fall downward the prilling tower. A countercurrent cooling air stream enters from intake openings located around the circumference of the tower at a height approximately 7 meters from the ground level of the tower.

Heat and mass transfer between the downward urea droplets and the upward cooling air stream along the height of the tower occurs, and thus a solidification-cooling process takes place. The product, urea prills, goes from the tower base to a conveyor belt where it has collected and packed. The air stream exhaust from the tower through the exhausted stakes located at the top of the tower where it spreads in the surrounding environment.

As ambient air is used in the process of cooling and solidification of the prills inside the tower, thus both the dry bulb temperature and humidity of the ambient air highly affect the quality of the final product. In this study, a case study of a prilling process in Abu Qir Fertilizers Co, Alexandria, Egypt is considered. Based on the reported information from the company that is in some days in summer session, the prills are hot to the limit that cannot be packed directly. The delay in the packing process leads to a decrease in the yearly company production. In addition, in humid/ hot days, the lamp of prills forms at the bottom of the tower that also is not desired for the product quality.

Through the open literature, there are few studies discussed the modeling of the prilling process beginning from the work of Bakhtin [1]. The mathematical description of the model represents the Cauchy problem for a system of first-order differential equations resulting describing the dynamics and the internal energy of the particles. Bakhtin concluded that the optimum height of the tower is that at which the droplets becomes completely solidified.

Yuan et al [2] used a simple shrinking unsolidified core model for the tower-prilling to introduce a new design for the prilling tower. The model was based on a lumped method where the whole particle temperature is assumed constant. Alamdari et al [3] introduced a more enhanced model. In this study, the prilling process was simulated by a simultaneous solution of the continuity, hydrodynamics, mass and energy transfer equations. Hashemi and Nourai [4] determined the critical value of the particle size below which no particle can fall down the prilling tower, and consequently carried over to the top with the air stream and discharged to the atmosphere.

The aim of this study is to build a mathematical model for a prilling process at Abu Qir Fertilizers Co, with productivity of 500,000 tons/ year, located in Alexandria, Egypt with a schematic diagram shown in Fig. 1. A numerical technique is used to solve the mathematical model in order to calculate the following parameters within the prilling tower:

- Velocity components of particles with different sizes at different rotating speeds of the rotating drum.
- Temperature and moisture content along the particle radius.
- Variation of particle average temperature and moisture content at different operating conditions along the

Manuscript received August 5, 2012; revised September 25, 2012.

The first author is supported by a scholarship from the Mission Department, Ministry of Higher Education of the Government of Egypt which is gratefully acknowledged.

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DOI: 10.7763/IJCEA.2012.V3.216

height of the tower.

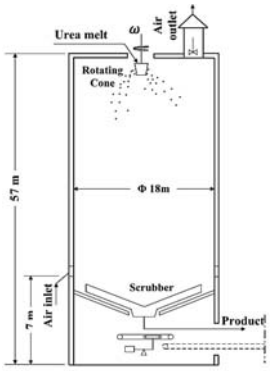

Fig. 1. A schematic diagram for the urea prilling tower

II. Mathematical Model of Urea Process

A. Model Assumptions

In the derivation of the model, the following assumptions are considered:

1) The droplet/ particle are spherical (from experimental measurements as shown in Fig. 2 for a shot of the particle surface under the electronic scanning microscope JSM-5200 LV).
2) Steady state for the urea melt fed to the rotary drum.
3) The pressure drop along the tower is neglected (about 0.01 Pa); therefore, constant pressure conditions can be applied.
4) Evaporation of urea in the whole process, as well as the conversion of urea to ammonia and carbon dioxide (around 0.4% as reported from the company) is neglected.
5) Radiation heat transfer between urea prills and the prilling tower walls is neglected (estimated about 0.6%).
6) An adiabatic process is considered due to the material (concrete low thermal conductivity =0.8-1.4 W/m. K) and large thickness of the tower wall (0.25 m)
7) The volumetric ratio of droplets/ particles in the prilling tower is normally very small (around 0.1% only) so that the effects of droplets/ particles on each other in both heat transfer and movement are neglected.
8) Average value of the air velocity in the axial direction is considered (0.63 m/s measured by the company).

B. Hydrodynamics

The prilling tower has a cylindrical shape. Thus, the prilling process hydrodynamics model is derived in the cylindrical coordinates (r,θ,z) with the unit vectors $(\hat{e}_r,\hat{e}_\theta,\hat{k})$ in the directions of r,θ and z, respectively. The datum of this coordinate system is taken at the air intake openings level of the tower. Whereas, for the particle heat and diffusion equations, spherical coordinates (r_p,θ_p,φ) are used.

Three forces affect on the particle during its fall through the tower. These forces are; the weight force $\vec{F}_W$ that acts downward, buoyancy force $\vec{F}_B$, and drag force $\vec{F}_D$ both of them acts upward as illustrated in Fig. 3. The equation of motion of the particle in the medium (cooling air) is given as follows

$$m_p \frac{d\vec{v}_p}{dt} = \vec{F}_B + \vec{F}_D - \vec{F}_W , \quad (1)$$

$$\vec{F}_W = m_p g\hat{k} = \rho(\frac{4}{3}\pi R_p^3) g\hat{k} , \quad (2)$$

$$\vec{F}_B = \rho_a V_P g\hat{k} = \rho_a(\frac{4}{3}\pi R_p^3) g\hat{k} , \quad (3)$$

$$\vec{F}_D = \frac{1}{2}\rho_a C_D A_p v_{rel}^2 \hat{v}_0 = \frac{1}{2}\rho_a C_D(\pi R_p^2) v_{rel}^2 \hat{v}_0 , \quad (4)$$

where $\vec{v}_p$ is the particle velocity, v_{rel} is the velocity of the particle relative to the air and $\hat{v}_0$ is the unit vector of the relative velocity. The drag coefficient C_D is determined by the formula of [4] for the range of the particle Reynolds number Re_p between $2 < Re_p < 500$

$$C_D = \frac{18.5}{Re_p^{0.5}} , \quad (5)$$

where $Re_p = \frac{\rho_a \bar{v}_{az} D_p}{\mu_a}$.

The average air velocity is $\bar{v}_{az}$ in z-direction and the particle diameter is D_p. The projection of the vector equation in the direction (r,θ,z) resulted in three differential equations that solved using 4th order Runge-Kutta method using appropriate initial condition for the particle velocity.

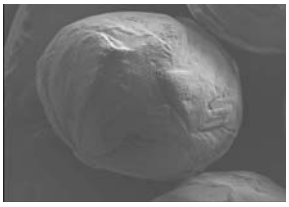

Fig. 2-a

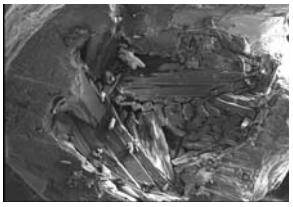

Fig. 2-b

Fig. 2. SEM images for the urea particles illustrates particle sphericity (a) and internal section (b)

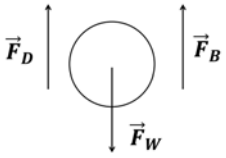

Fig. 3. Forces affect on the particle during its fall

C. Energy Balance

Heat transfer between the particles and the cooling air takes place along the height of the tower. Three zones of state have been assumed for each particle as it falls from the top to the bottom of the prilling tower. In the first zone, the liquid droplet loses its sensible heat to the cooling air until it reaches the crystallization temperature. In the second zone, a solid layer $\delta(z)$ begins to appear on the surface of the droplet, and hence two phases exist in each droplet liquid and solid. Heat from the core of the particle transfers to the ambient air by conduction through the liquid and solid phases of the prills. In this stage, the solid layer moves toward the center decreasing the liquid phase until the droplet becomes completely solid. In the last zone, the solid particle loses

sensible heat and further cooling takes place until the particle exits from the bottom of the tower at certain temperature. The three zones are shown in Fig. 4.

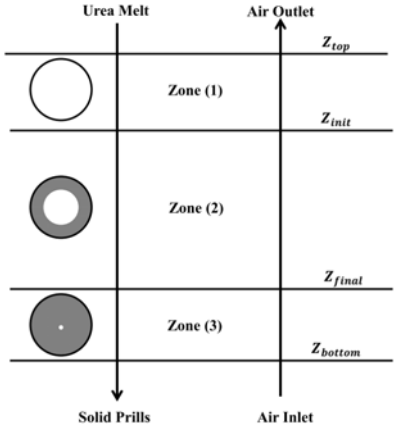

Fig. 4. Three zones of the prilling tower

For a spherical particle, the temperature variation only in the radial direction r_p and uniform initial temperature at the top of the tower T_{init} is considered. The governing equation for the heat transfer in liquid and solid phases during the three zones, assuming constant density ρ, specific heat C, and thermal conductivity K for the solid and liquid phases of the urea, is given as follows

$$Cv_z \frac{\partial T_l}{\partial z} = K \frac{\partial^2 T_l}{\partial r_p^2} + \tag{6}$$

For $0 < r_p < R_p$, $z_{top} < z < z_{init}$,
And $0 < r_p < \delta(z)$, $z_{init} < z < z_{final}$,

For $\delta(z) < r_p < R_p$, $z_{init} < z < z_{final}$,
And $0 < r_p < R_p$, $z_{final} < z < z_{bottom}$.

$$\rho C v_z \frac{\partial T_s}{\partial z} = K \frac{\partial^2 T_s}{\partial r_p^2} + \frac{2K}{r_p} \frac{\partial T_s}{\partial r_p} \tag{7}$$

The governing equations are subjected to the symmetry condition at the core of the particle and convection boundary condition at the outer surface of the particle.
where the heat transfer coefficient is obtained from the Ranz-Marshall's equation [3] as follows

$$-K \left. \frac{\partial T_{l,s}}{\partial r_p} \right|_{r_p = R_p} = h_v \left(T_{l,s}(R_p) - T_a(z) \right) \tag{8}$$

For $0 < Re_p < 200$, $0.71 < Pr < 380$,

$$Nu = 2 + 0.6\, Re_p^{1/2} Pr^{1/3} \tag{9}$$

where Nu and Pr are the dimensionless Nusselt and Prantdl numbers, respectively.

In the second zone, a solidification process takes place. This is the well-known two-phase Stefan Problem with the conditions at the interface $\delta(z)$.

$$T_l(\delta(z), z) = T_s(\delta(z), z) = T_m \tag{10}$$

Urea particle size distribution (sieve analysis) was determined by experimental measurements using analytical sieve shaker for a sample of 700 g taken from the bottom of the prilling tower. The Gaussian distribution of the sample results in an average particle diameter of 1.6 mm.

$$-K \left. \frac{\partial T_l}{\partial r_p} \right|_{r_p = \delta(z)} + K \left. \frac{\partial T_s}{\partial r_p} \right|_{r_p = \delta(z)} = \rho L v_z \frac{d\delta}{dz} \tag{11}$$

The air temperature variation along the tower is obtained from the following equation, Fig. 5.

$$\rho_a \bar{v}_{az} C_{pa} \frac{dT_a}{dz} = h_v \frac{6\varepsilon}{d_p} \left(T_{l,s}(R_p) - T_a(z) \right) \tag{12}$$

Considering d_p is the average diameter of the particles, and ε is the fraction of the tower volume occupied by the urea prills.

D. Mass Balance

The moisture is extracted from the prills during their fall downward the prilling tower by the humid cooling air. The transient variation of the moisture in the radial direction of the prills is given by with uniform initial moisture content of the particle M_{init}, symmetry boundary condition at the particle core and convection mass transfer at the outer surface

$$v_z \frac{\partial M}{\partial z} = D \frac{\partial^2 M}{\partial r_p^2} + \frac{2D}{r_p} \frac{\partial M}{\partial r_p} \tag{13}$$

$$-D \left. \frac{\partial M}{\partial r_p} \right|_{r_p = R_p} = h_{mass} \left(M_{r_p = R_p} - W(z) \right) \tag{14}$$

The mass transfer coefficient h_{mass} is determined also from the equation of Ranz-Marshall given as follows [5]

$$Sh = 2 + 0.6\, Re_p^{1/2} Sc^{1/3} \tag{15}$$

For $0 < Re_p < 200$, $0 \le Sc \le 250$,

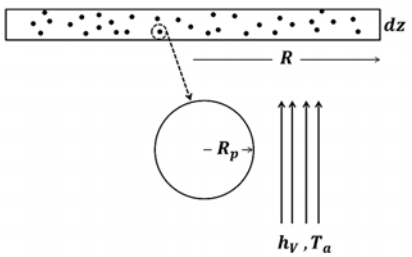

Fig. 5. Slab of the tower with height dz

$$\rho_a \bar{v}_{az} \frac{dW}{dz} = h_{mass} \frac{6\varepsilon}{d_p} \left(M(R_p) - W(z) \right) \tag{16}$$

where Sh and Sc are the dimensionless Sherwood and Schmidt numbers, respectively, and $W(z)$ is the absolute

humidity of the air at the slab level. The variation of the absolute humidity of the air is determined from the mass balance as follows

III. Solution Scheme

The enthalpy method is proposed for the solution of energy evaluation during the tower. The enthalpy method is a well-known method used for solving the moving boundary problems appear in the phase change phenomena [6]. In this method, an enthalpy function $E(T)$, which is the total heat content of the substance, is used to represent the equation. Accordingly, Eq. 6 and Eq. 7 can be written in one equation that will be as follows

$$v_z \frac{\partial E}{\partial z} = K \frac{\partial^2 T}{\partial r_p^2} + \frac{2K}{r_p} \frac{\partial T}{\partial r_p} \quad (17)$$

The governing equation is subjected to the same boundary conditions. The solution domain (r_p, z) is discretized into N, M intervals in r_p and z directions with step sizes dr_p and dz, respectively, Fig.6

TABLE I Operating Conditions from the Company

Variable	Value
Tower Height	57 [m]
Tower Diameter	18 [m]
Rotary drum conic angle	23 [deg.]
Rotating speed of the drum	255[rpm]
Temperature of inlet urea melt	140 [C]
Moisture content of inlet urea melt	0.5 [% weight]
Amount of urea melt	27487[Kmol/day]
Density of air	1.166 [Kg/ m3]
Viscosity of the air	1.870264x10-5 [Pa. s]
Specific heat of the air	1.005 [KJ/ Kg. K]
Total flow rate of the cooling air	520,000[Nm3/hr.]
Particle average size	1.6 [mm]

TABLE II Properties of Urea from [7]

Variable	Value
Density of urea melt	1220 [Kg/ m3]
Melting point of urea	132 [C]
Thermal conductivity of urea	2.651x10-5 [KW/ m. K]
Specific heat of urea	1.334 [KJ/ Kg. K]
Melting heat of urea	224 [KJ/ Kg]

The forward finite difference formula is applied for the derivative of the enthalpy. Whereas, the central difference formula is applied for the first and second derivatives of the temperature. An explicit scheme is obtained to get the temperature variation of the particle along its radius at different heights of the tower, considering the singularity of the heat equation at the core of the particle resulting from the symmetry condition. For the airside in the energy model, the forward divided difference scheme is used for the air temperature derivative. The same procedure is applied for the solution of the mass balance equations to obtain the variation of the particle moisture content. The explicit scheme is solved using a step size of 0.1 m (the tower height is 50 m) in z direction and 0.05 mm in r_p direction. The operating conditions used in the present results are produced in Table I as reported from Abu Qir Fertilizers Co., while the thermal and chemical properties of urea are obtained from [7] and illustrated in Table II.

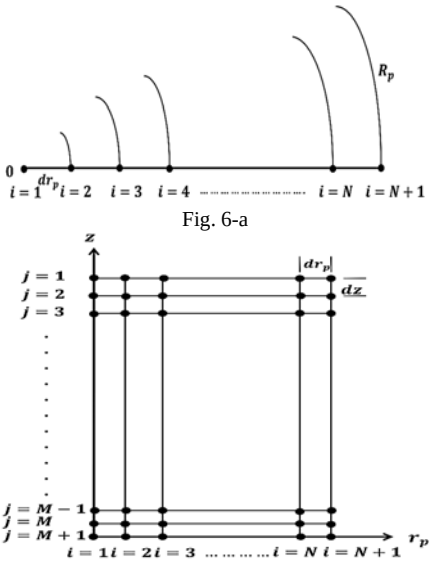

Fig. 6-a

Fig. 6. b

Fig. 6. Discretization of the particle radius (a) and the solution domain (r_p, z) (b)

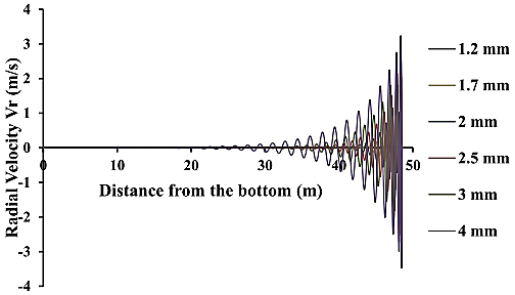

Fig. 7-a

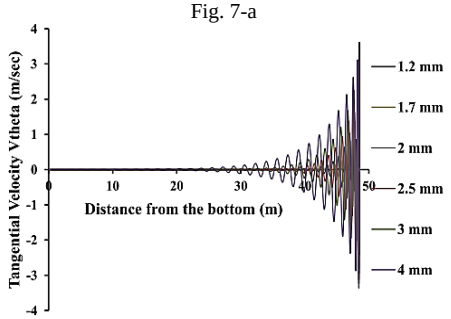

Fig. 7-b

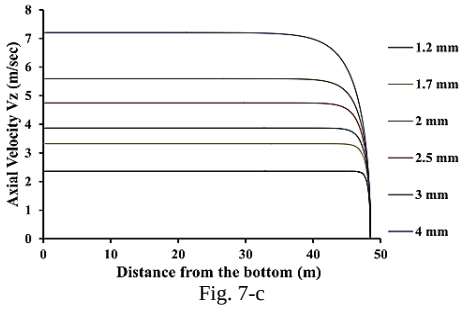

Fig. 7-c

Fig. 7. Radial, tangential, and axial velocity with different particle diameters

IV. Results and Discussion

The three components of the particle velocity, radial, tangential and axial, are calculated from the hydrodynamic analysis for different particle sizes as shown in Fig. 7-a, b, c, respectively. The results show that the larger the particle diameter, the higher the oscillation of both radial and tangential velocity before reaching the zero value. The coarse particles, diameter of 2 mm or larger, have higher axial velocity than the fine ones. As mentioned, the melt is fed to a rotating conical drum with variable radius along the height of the drum. Different droplets from different sections of the drum have distinct amplitude of oscillation of the radial and tangential velocity, whereas variable drum radius has slice effect on the axial velocity as seen in Fig. 8-a, b, c, respectively. A similar effect is obtained for changing the rotating speed of the drum as illustrated Fig. 9-a, b, c, respectively. Increasing the rotating speed of the rotatory drum leads to higher oscillation in radial and tangential velocities.

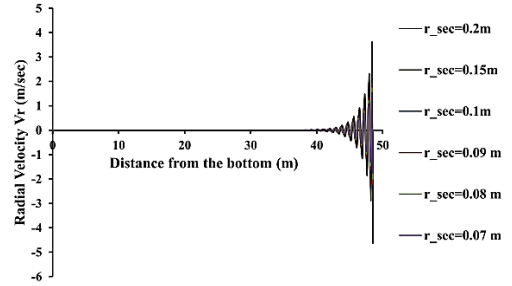

Fig. 8-a

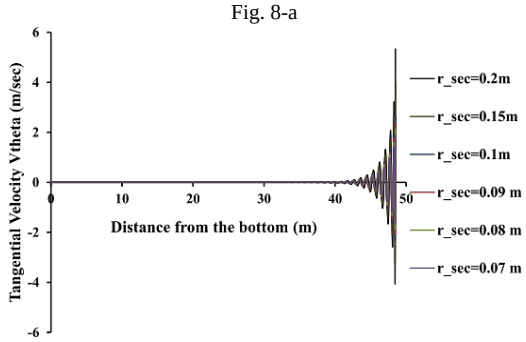

Fig. 8-b

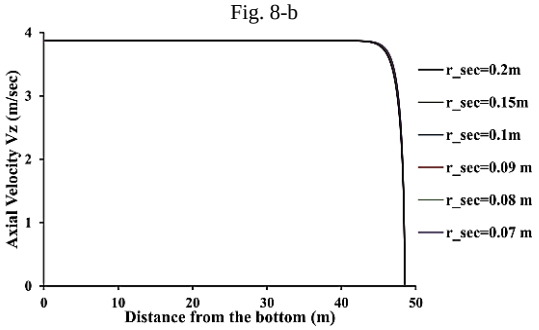

Fig. 8-c

Fig. 8. Radial, tangential, and axial velocity at different sections of the rotating drum

The temperature variation along the radius of the particle at different heights of the tower is shown in Fig. 10. The air temperature is needed at the outlet of the prilling tower. The particles exit the prilling tower (at z=0 m) with core temperature above the melting point of 132 C. In addition, cooling of the prills in the solid phase takes place faster than that in the liquid phase due to the release of the latent heat of crystallization at the interface of solid and melts layers within the particles. The temperature at the outer surface remains approximately constant along the height of the prilling tower. This is due to the slice variation of air temperature along the height of the tower. Fig. 11 shows the variation of the particle average temperature with the tower height. The results show that the lower the air temperature at the inlet, the lower the average temperature of the particles at the bottom of the tower.

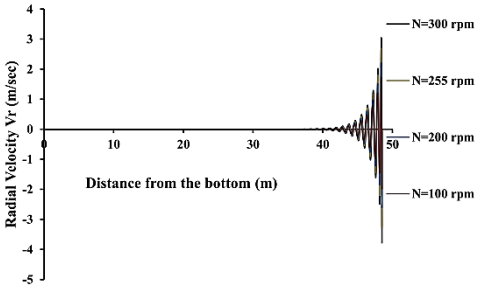

Fig. 9-a

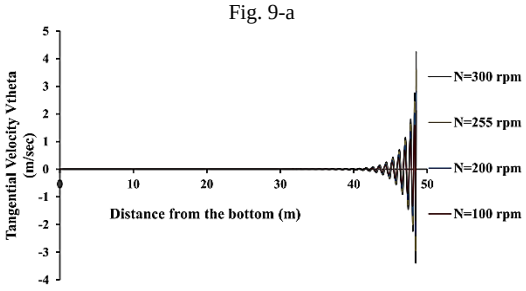

Fig. 9-b

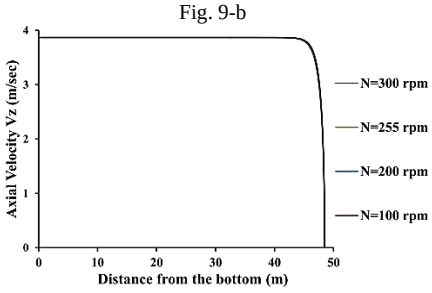

Fig. 9-c

Fig. 9. Radial, Tangential, and Axial Velocity at different rpms of the rotating drum

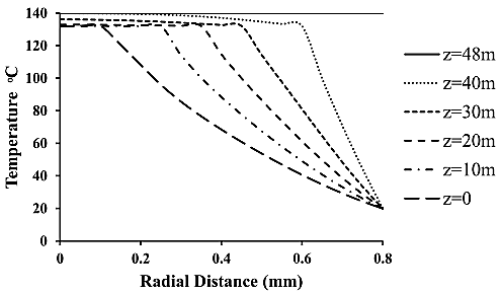

Fig. 10-a $T_a = 20°C$

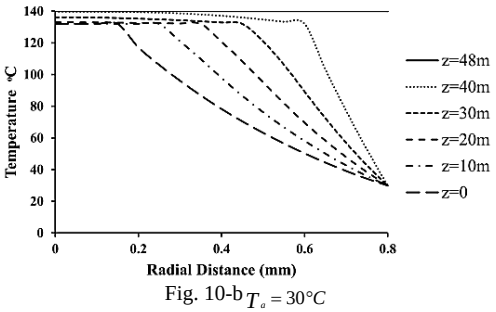

Fig. 10-b $T_a = 30°C$

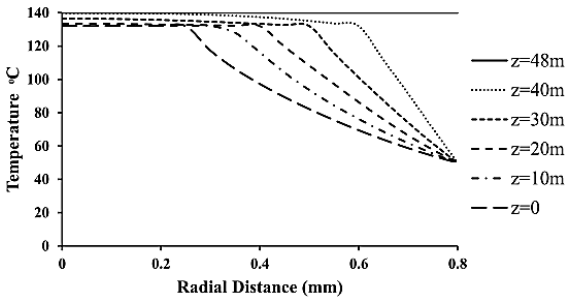

Fig. 10-c $T_a = 50°C$

Fig. 10. Temperature variation along the radius of the particle at different air temperature

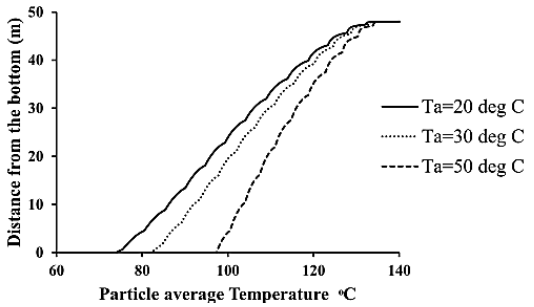

Fig. 11. Variation of average particle temperature with the tower height

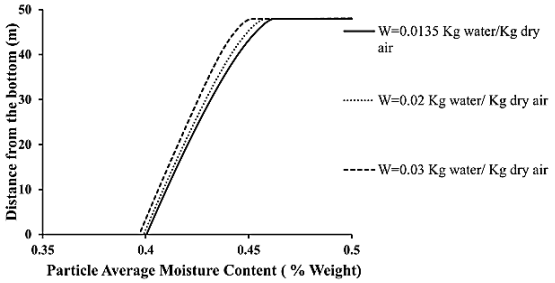

Fig. 12. Variation of average particle moisture content with the tower height

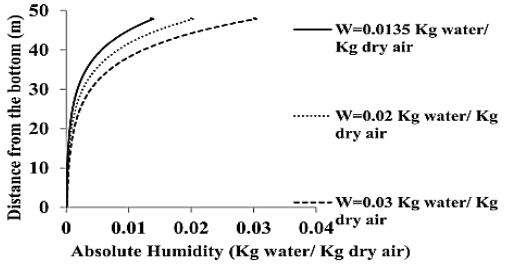

Fig. 13. Variation of air humidity with the tower height

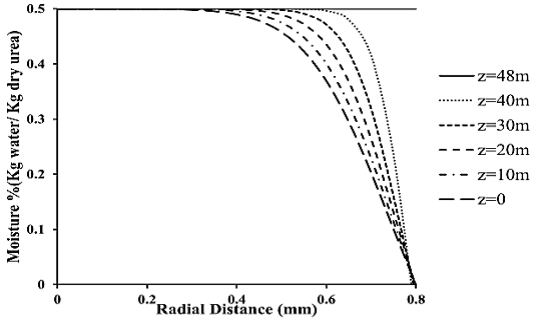

Fig. 14-a. $W = 0.0135$ (Kg water)/(Kg dry air)

The change in average moisture content of the particle along the height of the tower is shown in Fig. 12 at different air humidities. Fig.13 illustrates the variation of absolute air humidities along the tower height. From Fig. 12 and Fig. 13, it can be seen that the larger the air humidity at the outlet, the larger the amount of moisture that extracted from the prills. Hence, product of less moisture content is obtained. Fig. 14 illustrates the variation of the moisture content along the radius of the particle at different air humidities.

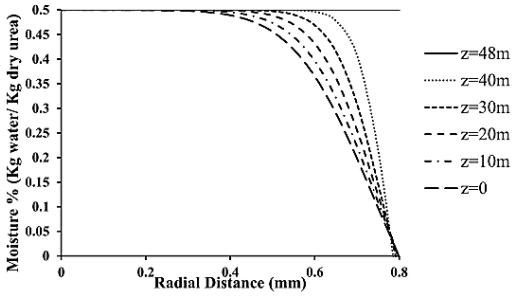

Fig. 14-b. $W = 0.02$ (Kg water)/(Kg dry air)

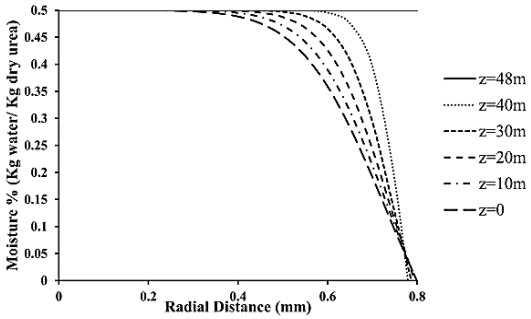

Fig. 14-c $W = 0.03$ (Kg water)/(Kg dry air)

Fig. 14. Variation of moisture content along the radius of the particle at different air humidity

V. Conclusion

Urea prills are produced in the prilling towers where a solidification-cooling process takes place. The ambient air is used as the cooling air stream for this process. In hot days, the temperature of the product at the bottom of the tower are hot that cannot be packed directly. In addition, in hot/ humid days, the prills form lamps and cakes with each other and on the scrubber. A mathematical model based on the hydrodynamics, heat, and mass transfer between the urea and the cooling air is developed. A numerical technique with an explicit scheme is used to solve the model. The study results are as follows:

- The results show that the velocity component values of the particles with different diameters at different operating conditions increase with increasing the rotating speed of the rotary drum. This leads to an enhanced penetration of the particles through the tower and hence product of better quality.
- The model results describe the variation of the temperature and moisture along the radius of the particle. Hence, the model results introduce an interpretation of the problem of caking and lamps formation appears because of the incomplete solidification of the prills at the bottom of the tower.
- The variation of average particle temperature and moisture content is produced along the tower height as well as for the airside. Thus, the model predicts the quality of the product under different operating

conditions of the ambient cooling air.

ACKNOWLEDGMENT

The first author is supported by a scholarship from the Mission Department, Ministry of Higher Education of the Government of Egypt which is gratefully acknowledged.

NOMENCLATURE

A_p	External area of the particle [m2]
C_D	Drag coefficient
D	Diffusion coefficient [m2/s]
D_p	Particle diameter [m]
d_p	Average particle diameter [m]
C	Specific heat capacity of the urea [KJ/ Kg. K]
C_{pa}	Specific heat capacity of the air [KJ/ Kg. K]
E	Local enthalpy of the particle [KJ/ Kg]
$\hat{e}_r$	Unit vector in r-direction
$\hat{e}_\theta$	Unit vector in θ-direction
$\vec{F}_B$	Buoyancy force [N]
$\vec{F}_D$	Drag force [N]
$\vec{F}_W$	Weight force [N]
g	Acceleration of gravity [m/ s2]
h_v	Heat transfer coefficient [KW/ m2. K]
h_{mass}	Mass transfer coefficient [m/ s]
$\hat{k}$	Unit vector in z-direction
K	Thermal conductivity of the urea
L	Latent heat of crystallization of urea [KJ/ Kg]
M	Local moisture content of the particle [% weight]
Nu	Nusselt number
Pr	Prantdl number
R_p	Radius of the particle [m]
Re_p	Particle Reynolds number
Sc	Schmidt number
Sh	Sherwood number
T_a	Temperature of cooling air [C]
$T_{l,s}$	Temperatures of liquid and solid urea [C]
$\bar{v}_{az}$	Average air velocity [m/ s]
v_p	Particle velocity [m/ s]
v_{rel}	Particle velocity relative to the air [m/ s]
$\hat{v}_0$	Unit vector of the relative velocity
W	Absolute humidity of the cooling air
ε	Fraction of tower volume occupied by the particles
ρ	Density of urea [Kg/ m3]
ρ_a	Density of air [Kg/ m3]
μ_a	Kinematic viscosity of the air [Pa. s]
δ	Interface position [m]

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