Mathematical modeling for prilling processes in ammonium nitrate production

Ahmet Ozan Gezerman

Department of Chemical Engineering, Yildiz Technical University, Istanbul, Turkey

Correspondence
Ahmet Ozan Gezerman, Toros Agri-Industry, Research and Development Centre, Mersin, Turkey.
Email: ozan.gezerman@toros.com.tr

Abstract
In ammonium nitrate (AN) production, determining the standard particle size for the granulation process is a fundamental problem. Therefore, a system model is proposed for this final stage of the manufacturing process. In the proposed model, prilling is simulated by analyzing data from the continuity, hydrodynamics, and mass and energy transfers. The direction of the movement of AN particles, the temperature, and humidity distribution of the cooling air with variation in particle size, and the height of the prilling tower are calculated. The air temperature profile determined by the model is compared with that of an actual AN plant. The comparison shows that the results obtained by the model are consistent with the plant data. In addition, it is shown that an increase in the cooling rate of particles has the potential to enhance the properties of AN particles. Moreover, a detailed analysis of the granulation process is conducted to estimate the impact of the parameters of the proposed model such as the prilling tower height, particle size, and temperature. Thus, this model could be used to obtain more accurate results at an industrial plant.

KEYWORDS
ammonium nitrate, mathematical modeling, prilling, simulation, spray crystallization

1 | INTRODUCTION

The motion trajectory of droplets of various liquids produced during the prilling method, in addition to the granulation model, has been the subject of previous research. The pretreatment of a molten solution involves solidifying the solution by spraying it into a filling medium in small droplets. The purpose of this process is to solidify the liquid solution. In this process, drops falling from a given member form a spherical shape due to the surface tension. During the fall, the outermost part of the liquid droplet cools first and begins to solidify. This study focused on the prilling of ammonium nitrate (AN), which encounters problems during the granulation process. During the AN granulation process, the effect of cooling air on the sprayed droplet starts the solidification process from the outermost surface. Solidification occurs from the surface of the droplet toward the center. This is the same process as the granulation of urea. This process is also known as spray crystallization. After spraying from a prilling bucket, molten AN solution is solidified with cool air. When cooling occurs, a transformation process begins. However, the effects of moisture transfer and particle size distribution have not been considered. For the mathematical modeling, while analyzing humidity and temperature...
within the tower, the vertical change was taken as reference instead of the horizontal change. Particles of equal height can be ignored because the moisture and temperature changes are similar. For different heights of the prilling tower, particle size differs significantly, and some parameters vary, that is, specified humidity. Therefore, the assumptions are made for vertical heights, not horizontal heights. It is to be noted that several methods have been developed in which particle size and moisture content are considered to be variables. In addition, regarding cooling air, no studies have been conducted to investigate the change in particle size during droplet solidification. Various methods are available for prilling. When working with a vibrating prilling bucket in the Rayleigh regime, it was found that the vibration frequency had a significant effect on the size of the prill particles. In the other study related to prilling, the system particles fed back into the system after the prilling process were brought into production using a granulation model, and then particle size distribution was analyzed within the proposed model. Another way to model the dropwise solidification process from a mixture in the liquid phase was proposed for carrageenan gelation. Using this model, satisfactory results were obtained for industrial scale granulation processes. Another modeling approach for the prilling process was proposed using the Oldroyd-B equation. In the related study, the solidification performance of liquid droplets solidified during the prilling process was investigated, and their applicability to industrial processes was assessed and reported. Another way to model the granulation process was established for nanofiber production. In the proposed model, Frenet's equations were used, and characterization was performed using the Weber number. Moreover, an example of mathematical modeling of the granulation process on an industrial scale was considered in the pharmaceutical industry. A spraying granulation model was introduced for the purposes of the pharmaceutical industry. A drug liquid composition of mystic, stearic, and behenic acids was obtained and then granulated through spraying. The spraying method was modeled considering the temperature as a main parameter. The stabilization of this drug mixture was observed at a temperature of 25°C, however, it was not possible to maintain the stabilized structure for a period longer than 6 months. Mathematical modeling for the prilling process was conducted also for the fertilizer containing nitrogen and phosphor (NP fertilizer). Due to the unstable nature of NP fertilizer, the important task was to define the model for the transformation phase under conditions of cooling. In this study, mathematical modeling was performed by developing a solid-liquid binary phase diagram for the urea-monoammonium phosphate mixture. Consequently, the best results were obtained by employing the Wilson parameter. This allowed observing the conformance between the results of the mathematical experiment and the factory data observed actually. The physicochemical nature of the chemicals used in the spray granulation process may differ for some substances due to limitations in the process such as moisture absorption and phase conversion. In this study, a mathematical modeling method has been developed specifically to account for the high moisture absorption potential of AN and the need to complete the phase transformation in the cooling process. Therefore, a model has been proposed to simulate different sizes of AN particles considering the changes in humidity, temperature, and movement direction of the cooling air. In this study, this transformation process has been analyzed and modeled.

2 DEVELOPMENT OF THE MODEL FOR THE SOLIDIFICATION PROCESS OF AN DROPLETS

Various physical equations such as momentum and mass energy transfer can be used to analyze such a process. Throughout the prilling process, the temperature, humidity, and droplet velocity distribution within the tower can be calculated for all heights within the tower.

One feature of the mathematical model studied here is that it has been studied for all particle sizes between 3.35 and 0.5 mm obtained by spraying in the tower at an industrial scale. The particle size distribution can be evaluated by taking samples from particles that solidify on the prilling tower floor. The particle size selected as standard in the production of AN on an industrial scale is within this range. The range of the particle size is determined by the European Fertilizer Manufacturers Association. The particle size was accepted in this range since the study was carried out under industrial conditions.

For such a process, the steady-state conditions of the AN droplets during solidification are evaluated according to the moisture content of the AN droplets at the end of the process (from 0.3% to 0.5%). Since the prill tower diameter is usually very large (18 m), the air velocity profile in the downstream direction is considered constant. At the industrial scale in which this work takes place, the gas-phase separation in the AN droplets moving vertically in the tower (ie,
the removal of gaseous ammonium from AN) is negligible. Furthermore, it is accepted that no mass and heat transfer between the air environment outside the tower and the environment inside the tower can be realized due to the thick walls of the prilling tower.

2.1 AN SOLIDIFICATION PROCESS DURING THE PRILLING PROCESS

Three types of forces act on the AN droplets within the tower during the prilling process. Gravity exerts a downward force on the droplets in response to the movement of the droplets during spraying. Since the density of AN droplets is greater than the density of the air, the upward resistance force exerted by the air on the droplet surface can be omitted. Newton’s law of motion can be applied along the tower height (z).

\[
m_p \frac{dv_z}{dt} = m_p g - \frac{1}{2} C_D \rho_A A_p \vec{v}_{rel} \cdot \vec{v}_z.
\]  

(1)

In this equation, \(m_p\) can be expressed as the mass of the droplet, \(v_z\) is the velocity of the droplet in the vertical direction, \(\rho_A\) is the density of air, \(A_p\) is the predicted area of the droplet, \(\vec{v}_{rel}\) is the velocity of the AN droplet sprayed relative to the air movement in the prilling tower, and \(C_D\) is the drag coefficient. A similar motion equation can be written for any radius point specified within the AN droplet in motion. Numerical methods\(^1\) have been developed for the numerical solution this equation.

2.2 MOISTURE ANALYSIS OF AN PARTICLES PRODUCED BY SPRAYING IN THE TOWER

Moisture is continuously transferred from the droplets of AN formed by spraying from the prilling tower to the surrounding air until the droplet velocity at the tower bottom ceases. The moisture transfer continues until the equilibrium between the droplets and air is achieved. To find the moisture distribution in the AN droplets where moisture transfer occurs, a moisture concentration gradient can be written as follows.

\[
\frac{\partial M}{\partial t} = D \frac{\partial^2 M}{\partial r^2} + \frac{2D}{r} \frac{\partial M}{\partial r},
\]  

(2)

Here, \(M\) is the local moisture content in the particle. The moisture content, \(M(r, 0)\), is the initial moisture content \((M_{\text{initial}})\) in the droplet centre (the moisture centre in which the moisture moves), and any radius \(r\) in the particle is determined as a boundary condition. The equilibrium moisture equation for the particle radius \(R\) can be expressed as \(M(R, t) = M_{\text{equilibrium}}\). \(M_{\text{equilibrium}}\) was measured under experimental conditions, where \(D\) is the diffusion of moisture in the AN particle, and the change in the moisture content of the surface is shown as \(\frac{\partial M}{\partial r}\).

2.3 MOISTURE ANALYSIS OF THE CIRCULATED AIR IN THE PRILLING TOWER

The change in the moisture content of the air in the prilling tower is equal to the amount of water removed from the AN droplets during the solidification process from the molten state. From the AN droplets, a concentration gradient may be formed as follows for the amount of moisture transferred to the surrounding air.

\[
\frac{dW}{dz} = \sum \frac{G_p f(D_p)}{G_a} \frac{d\bar{M}(D_p)}{dz},
\]  

(3)

where \(W\) is the moisture content of the air surrounding the particle surface, \(\bar{M}\) is the average amount of moisture contained in each droplet, \(G_p\) is the mass flow rate of the AN droplets falling down the prilling tower, \(f(D_p)\) is the mass fraction for the average particle diameter \((D_p = 2\text{ mm})\), and \(G_a\) refers to the mass flow rate of air circulating in the prilling tower.
2.4 THERMAL ANALYSIS

During prilling, a temperature difference ($q_1$) occurs in the AN beads, which are made into liquid droplets by means of the prilling bucket, due to the solution temperature before granulation and the temperature of the cooling air in the tower. The direction of the heat transfer resulting from the temperature difference is from the center of the AN particle to its surface. This temperature difference results in a moisture transfer from the center of the particle to the particles surface. In this way, the thermal energy in the particle is transferred from the particle surface to the air environment in the prill tower. The heat transfer from the center of the particle to the particle surface can be expressed as follows.

$$\sum q_1 = G_a h_f \pi R^2 \frac{dW}{dz} dz + \sum q_2.$$  (4)

In this equation, $h_f$ is the evaporation energy of the water evaporated as a result of the heat transfer in the particle, and $R$ is the radius of the prilling tower. The term $q_2$ is the amount of energy transferred from the particle into the prill tower, which is equal to the enthalpy change ($q_3$) of the air moving through the prilling tower as a result of the heat transfer.

$$q_3 = (\rho_a v_a c_p a + \rho_a v_a c_p W) \frac{dT_\infty}{dz} \pi R^2 dz.$$  (5)

Here, $\rho_a$, $v_a$, $c_p$, $T_\infty$, $c_p$ are the density, linear velocity, specific heat, and temperature values, respectively, of the air exposed to the heat transfer in the prilling tower. $c_p$ is the enthalpy of evaporation of the air in contact with the particle surface as a result of the heat transfer from the center of the particle to its surface. The amount of heat transmitted through the cooling air can be expressed as follows.

$$\sum q_2 = h(D_p)a(D_p)(T_p - T_\infty)\pi R^2 dz.$$  (6)

In this equation, $h(D_p)$ and $a(D_p)$ are the heat transfer coefficient and the total surface area of the AN particles remaining within the selected unit area, respectively. $T_p$ is the surface temperature of each AN particle in the selected unit air volume. The heat transfer coefficient, $h$, can be obtained using the following equation for each AN particle.

$$Nu = 2.0 + 0.6(Re)^0.5(Pr)^{1/3}, (Nu = hD/k, Pr = uC_p/k, Re = GD/u).$$  (7)

In Equation (7), the Nusselt, Reynolds, and Prandtl dimensionless numbers are used to determine the heat transfer coefficient ($h$) occurring in AN particles with the effect of cooling air at different heights in the tower. In addition, this equation indicates the relations between these numbers.

For this mathematical model, the entire prilling tower can be divided into three zones from the base to the highest point. The first zone is “where the particles’ temperature falls” at which the solution is sprayed to the temperature at which the criterion is first observed. The second zone is the point at which the whole particle solidifies from the outermost layer where crystallization begins. In this region, the outermost layer of the droplet begins to crystallize, and the heat of the crystallization is transferred to the cooling air. At this point, the prilled particles are sent to the third zone to cool down to a lower temperature. The heat transfer mechanism inside the particle in the first zone is expressed as follows. The temperature is between 180°C and 150°C.

$$k_1 \frac{\partial^2 T_1}{\partial r^2} + \frac{2k_1}{r} \frac{\partial T_1}{\partial r} = \rho_1 c_p v_p \frac{\partial T_1}{\partial z}.$$  (8)

Here, $\rho_1$, $c_p$, $k_1$, $T_1$, and $v_p$ are the density, specific heat, thermal conductivity, temperature, and linear velocity of the AN particle at the respective height, and $r$ is the tower radius within which the particle moves in the prill tower. This equation is numerically solved with appropriate initial conditions (for 50 m prilling height at 180°C: 0.73 g/cm³, 5 kJ/kmol, 163 w/m K, m, Cp: 1507 kJ/kg°C at 180°C, 0.125 m-s⁻¹ and 1 m) and boundary conditions (for 6 m prilling height at 100°C: 0.94 g/cm³, 6.7 kJ/kmol, 157 w/m-K, m, 1.740 kJ/kJ°C at 100°C, 0 m/s and 9 m).

In the second zone, the crystallization of the particles begins at $r = R_p$ (starting at the entire tower diameter) and the heat released during the crystallization is transferred from the center of the particle to the outer surface of the particle. This heat transfer occurs from the center of the melt (droplet) to the solidified surface and then to the air moving in the
FIGURE 1  Behavior of the particle in relation to the cooling rate of three different thermal zones (Zone I, Zone II, Zone III) in the prilling tower.

tower, since the solidification begins at the outermost surface of the particle. Because of the heat transfer effect, the solid interface \( S(z) \) moves to the center of the droplet, since the solidified layer continues to grow.

Equation (8) can be applied to the energy transfer occurring from the molten part 0 of the particle to the outer surface \( S(z) \) during the solidification process. Using solid AN properties, this equation can be applied to different limits \( S(z) < r < R_p \). The boundary conditions for the solid-melt interface can be expressed as shown below.\(^{10}\)

\[
T_s(r, z) = T_1(r, z) = T_m r = S(z),
\]

\[
k_s T_s \frac{\partial T_s}{\partial r} - k_l T_1 \frac{\partial T_1}{\partial r} = \rho_s \lambda v_p \frac{\partial S(z)}{\partial z} \quad r = S(z).
\]

In these equations, \( T_m \) is the temperature at which solidification starts, \( \lambda \) is latent heat of the melt during crystallization, \( T_s, k_s, \) and \( \rho_s \) are respectively, the temperature of AN during solidification (154°C), the thermal conductivity (165 W/m-K) and the density (average 0.80 g/cm\(^3\)). Equation (10) is derived for the ultrathin layer formed during the phase transition to the crystalline state from which melt solidification begins. The energy transferred during the transition from the molten state to this film is the same as the amount of energy generated during the conversion from this film to the solid phase.

The unit volume, expressed as the third zone in the prilling tower, is the same as the equations used for energy transfer in the first zone, which calculates the amount of energy transferred for phase transformations. However, the \( \rho_s \) (density), heat transfer coefficient \( (k_s) \) and \( c_p \) values used should be those for solid AN at 100°C.

The heat transfer and thermal behavior within the particle in Zone I, Zone II, and Zone III are shown in Figure 1.
### 2.5 CALCULATION METHODS

Thermal differential equations for the first and third zones can be solved using the Crank-Nicolson method. The thermal differential equations in the second zone can be solved by stipulating specific limit values. Various enthalpy methods have been developed by Crowley, Voller, Cross, and Tacke for energy calculations during solid-liquid phase transformations due to heat transfer within the tower. In these methods, the \( H(T) \) function was used to express the enthalpy.

Different researchers conducted studies that demonstrate the use of these methods for energy transfer calculations in solid-liquid phase transformations in the prilling tower. Assuming that the particle size does not vary across the entire tower and that no moisture transfer occurs within the particle, these energy calculations can be compared in-house. Obtaining the same results for the limits determined in all models shows that the assumptions are correct. The assumptions during modeling are as follows: particles blown off from the prilling bucket will not agglomerate due to the vertical effect of cooling air, and moisture transfer in the particle will not change. However, moisture change in AN production occurs to a large extent prior to the granulation process. This is because, in the production of AN, the moisture content of the molten substance and the moisture content of the final product, which is granulated, do not differ greatly from each other.

The schematic representation of the particle size and temperature change depending on the height in the prilling tower is shown in Figure 2.

### 3 RESULTS AND DISCUSSION

The temperature of the air moving along the height of the prilling tower was physically monitored and calculated using Equation (7). The mathematical model of the system characterized that the temperature change in the AN particle which is cooled in free fall is neglected. For this characterization process, it was assumed that there was no temperature change
in the whole AN particle. Figure 3 shows the change in air temperature inside the prilling tower while making this assumption. In this study, it is observed that the data obtained on industrial scale are not compatible with the values obtained with the method proposed for AN granulation (the Crank-Nicolson method).\textsuperscript{2} This inconsistency shows that the temperature change in the free fall particle in the prilling tower cannot be neglected in the study conducted on an industrial scale.

However, for the initial and boundary conditions, it is very important that the values accepted by the province are compatible so that the equivalents are consistent with the industrial scale values. Plant production data were obtained by measuring the air temperature over the entire height (40 m) used for the AN prilling process, at 2.5 m from the prill tower wall, using a platinum temperature measuring instrument. When the phase transformations of AN at related temperatures are analyzed, the results obtained in the determined model and factory data show little difference. The model's assumptions can be considered correct, since there are no significant changes in the phase change points of AN in the same temperature zones (Zone I, II, III).

Figure 4 shows the temperature distribution along the AN particle diameter in the mathematical model proposed in this study. The values of all parameters expressed in this model are given in Table 1. AN particle size distribution was monitored by using sieve analysis. During the prilling process, the physical properties of ANAN were examined for particles with diameter of 0.5 and 3.35 mm. The temperature changes obtained by the mathematical model for particle sizes 0.5 and 3.35 mm at different heights within the prilling tower are shown in Figures 5 and 6. Figure 7 shows the
**TABLE 1** Operation conditions used in ammonium nitrate plant

| Variables                              | Values       |
|----------------------------------------|--------------|
| Prilling tower height (m)              | 40           |
| Prilling tower diameter (m)            | 18           |
| Bucket angle with vertical line (deg)  | 10           |
| Rotation speed (rpm)                   | 300          |
| Ambient pressure (atm)                 | 0.86         |
| Volume flow rate of air (m³/h)         | 540000       |
| Inlet air temperature (°C)             | 30.0         |
| Relative humidity of Inlet air (m³/h)  | 45           |
| Capacity of plant (Metric ton per Day) | 1800         |
| Temperature of ammonium nitrate feed (°C) | 170         |
| Moisture of ammonium nitrate feed (% by wt.) | 0.5       |
| Average prill diameter (mm)            | 2.0          |
| SD (mm)                                | 0.49         |

**FIGURE 5** Temperature changes at different heights of the prilling tower for fine particles of 0.5 mm in diameter

**FIGURE 6** Temperature changes at different tower heights for large particles of 3.35 mm in diameter
temperature changes in the free-falling AN particles of 0.5 mm in size, at a tower height of 40 m. According to the data obtained, it is very useful to determine the temperature changes in fine particles such as 0.5 mm at a height of 20 m in the prilling tower. Figure 8 shows that large AN particles such as 3.35 mm in the prilling tower do not reach thermal equilibrium with the cooling air. Figures 5 and 6 show the temperature point at which the crystallization of the AN melt occurs as 132°C, that is, the solidification of the outermost layer of the AN droplet begins. These figures show the elevations due to temperatures in the prill tower (first, second, and third zones). As the diameter of molten AN particles is reduced, the rate of crystallization increases, but they can leave the last (third) zone of the tower before the AN droplets become solidified.

A similar comparison study that examined the production of urea fertilizer produced by the prilling method concluded that the relevant modeling was compatible with the factory data because the process conditions were similar. For example, the variation of the particle diameter in the prilling tower in relation to tower height and the distance from the center of the tower shows a similar pattern in the modeling of the urea process. Urea showing similar physicochemical properties to AN is an indication that modeling has been successful.

As seen in Figures 5 and 6, the crystallization starts at a temperature of about 140°C in the AN particles exposed to the cooling air to form a thin crystallization layer and continues until the free fall to the bottom of the tower is complete. In the industrial scale study, the temperature of the AN particles leaving the prilling tower is approximately 100°C. Droplets of AN from 169.9°C to −17°C undergo five different phase transformations. The crystal structure resulting from each
Phase transformation can be expressed as 169.6°C (liquid), 125.2°C (cubic), 84.2°C ($\alpha$-rhombic), 32.3°C (tetragonal), and 16.8°C ($\beta$-rhombic). Since the AN temperature that leaves the tower during the prilling does not fall below 100°C, it is possible that only two of these phase transformations (cubic and $\alpha$-rhombic) occur within the tower. In today’s industrial AN production, the minimum temperature that can be reached during prilling is 100°C. Temperatures below 100°C can only be achieved by using fluidized bed coolers after the AN leaves the prilling tower.17 The lowest tower temperature in the production of AN is 100°C in this case. For AN, the third phase transition temperature of 84.2°C does not occur in the tower. Only changes to the cubic lattice structure occur in the tower within the liquid phase between 170°C and 125°C. Thus, the volume variation of these phase transformations is normally limited between −2.1% and 1.3%.

Figure 7 shows the moisture content of particles of maximum and minimum diameters of 3.35 and 0.5 mm, respectively, in the prilling tower depending on the height of the tower. As the particle diameter decreases, the removal of moisture from these particles is faster and easier. This rate of moisture diffusion from the center of the particle to the particle surface is usually achieved when the AN droplet is in the liquid phase before the AN droplet is solid.

As the temperature of the air increases continuously due to the heat transfer from the molten AN solution, the air velocity in the prilling tower increases as a result of the decrease in the air density. Figure 8 shows the Reynolds number variation for AN droplet particles of different diameters. As seen in Figure 8, as the height of the prilling tower increases, the particles are more exposed to the effect of cooling air. In this case, the increase in particle size increases its Reynolds number. This is because cooling air accelerates the solidification process of the particles. Thus, AN phase conversions occur faster.

Figure 9 shows the mechanism of action of the small AN particles which tend to move close to the walls of the prilling tower and to the center of the tower. According to Figure 9, it is apparent that the particles moving downward within the prilling tower tend to move closer to the tower center as the size increases. Therefore, the increase in particle size and the particle movement in the tower are related to each other. Accordingly, it can be stated that as the particle size increases, the distance from the tower center decreases.

Figure 10 shows the variations of the heat transfer coefficients in different AN particles. Accordingly, based on the data in Figure 10, AN particles falling from the tower show different thermal properties with the increase in tower height. As the particles fall from the tower, they are exposed to the effect of continuous cooling air. Under these conditions, solidification begins on the surface of the particle. It can be stated that AN, which begins to solidify from the surface inward, decreases heat transfer due to the increase in particle diameter.

As the particle diameter increases, the Reynolds number increases as the particle velocity in the tower increases (Figure 8). Consequently, Nu is increased, as calculated by Equation (7), but the change in the particle diameter (Dp) is greater than the Nu change, relative to the relationship between the prilling tower height and the particle diameter change (h: [Nu.k/Dp]). Therefore, the relationship between particle diameter and prilling tower height (h) is more clearly seen in this equation. The increase in the particle diameter of the AN droplets in Figure 6 shows that the heat transfer from the center of the particle to the cooling air surrounding the particle is reduced and as a result, the heat transfer coefficient in the particle which tends to solidify decreases.
Figure 11 shows the moisture content of the cooling air due to the heat absorbed from the AN melt along the prilling tower. The humidity of the air increases with the transfer of heat and moisture from the AN melt as it falls along the tower height. The change rate of moisture at the top of the tower is higher than at the bottom of the tower. This is because the AN droplets are in the liquid phase, so that most of the moisture is removed from the particle in the tray of the tower. This is also due to the fact that, as shown in Figure 12, the humidity of the air is lower in the tower tray than at the lower point of the tower, and the moisture content of the particles in the tower tray is mostly absorbed by the air.

4 | CONCLUSION

In this industrial-scale mathematical modeling study, the correlation of theoretical equations with the data obtained for the AN prilling process is discussed. The importance of the study is to establish a temperature gradient across the radius of the AN droplets. The humidity and temperature of the cooling air along the prilling tower were compared with the
industrial scale data and the data obtained as a result of the equations. In the comparison, it is demonstrated that the data obtained as a result of the theoretical energy equations are compatible with the real-time industrial-scale data.

With the data obtained from the energy equations and the temperature and humidity gradients, the effect of process variables such as moisture content, temperature and flow rates of the air and the AN droplets in the prilling tower on AN product quality could be evaluated. With these results, it is clear that important data can be obtained for any subsequent prilling process design.

In this study, it was not possible to remove the heat required to completely solidify large AN droplets (3.35 mm) under factory operating conditions. Thus, for the height of this prilling tower (40 m), it was also impossible to achieve thermal equilibrium. However, achieving the thermal equilibrium for the height of any prilling tower will lead to the solution of many quality problems such as caking in AN production processes.

CONFLICT OF INTEREST
The author declares that there is no conflict of interest regarding the publication of this article.

MODEL FORMULATION PARAMETERS
- $A_p$: projected area of particle (m$^2$)
- $a(D_p)$: total surface area of particles in unit volume of tower (m$^2$/m$^3$)
- $c_{pa}$: specific heat of air at constant pressure (J/kg$^\circ$C)
- $c_{pl}$: specific heat of melt ammonium nitrate at constant pressure (J/kg$^\circ$C)
- $c_{pv}$: specific heat of water vapor at constant pressure (J/kg$^\circ$C)
- $C_D$: drag coefficient (dimensionless)
- $D_p$: particle diameter (m)
- $D$: diffusion coefficient of moisture through ammonium nitrate melt or solid within
- $f(D_p)$: weight fraction of particles with average size $D_p$ within the size range
- $G_p$: mass flux of particles (kg/m$^2$s)
- $G_a$: mass flux of air (kg/m$^2$s)
- $g$: mass flux of air (kg/m$^2$s)
- $h(D_p)$: convective heat-transfer coefficient between air and particles of diameter $D_p$ (w/m$^2$C)
- $h_{lg}$: latent heat of vaporization of water at the particle surface temperature (J/kg)
- $k_l$: thermal conductivity of melt ammonium nitrate (W/m°C)
- $k_s$: thermal conductivity of solid ammonium nitrate (W/m°C)
- $M$: local moisture content of particle at radius $r$ (kg H$_2$O/kg dry ammonium nitrate)
- $ar{M}$: average moisture content of particle (kg H$_2$O/kg dry ammonium nitrate)
mass of a particle (kg)
Nusselt number (dimensionless)
Prandtl number (dimensionless)
rate of heat transfer (W)
radius of the tower (m)
Reynolds number (dimensionless)
particle radius (m)
radial distance from particle center (m)
temperature in liquid phase (°C)
crystallization temperature of ammonium nitrate melt which equals to 132.7°C
temperature at particle surface (°C)
temperature in solid phase (°C)
temperature of air in the bulk (°C)
time it takes a particle falls the distance z from the top (s)
velocity of air (m/s)
velocity of particle (m/s)
vertical velocity of particle (m/s)
relative velocity of particle to air (m/s)
humidity of air, dry basis (kg H₂O/kg dry air)
distance from top of the tower (m)
Mass flow (kg/m²s)
viscosity (m²/s)

density of air (kg/m³)
density of particle (kg/m³)
density of solid particle (kg/m³)
l latent heat of crystallization (J/kg)

Greek Symbols

Peer Review Information

Engineering Reports thanks the anonymous reviewers for their contribution to the peer review of this work.

ORCID

Ahmet Ozan Gezerman https://orcid.org/0000-0002-0039-4615

References

1. Wallwork IM, Decent SP, King AC, Schukes RMSM. The trajectory and stability of a spiralling liquid jet Part 1: inviscid theory. J Fluid Mech. 2002;459(2002):43-65. https://doi.org/10.1017/S0022112002008108.
2. Alamdari A, Jahanmiri A, Rahmaniyan N. Mathematical modelling of urea Prilling process. Chem Eng Commun. 2000;178(1):185-198. https://doi.org/10.1080/00986440008912182.
3. Rahmanian N, Homayoonfard M, Alamdari A. Simulation of urea prilling process: an industrial case study. Chem Eng Commun. 2013;200(6):764-782. https://doi.org/10.1080/00986445.2012.722147.
4. Gurney CJ, Simmons MJH, Hawkins VL, Decent SP. The impact of multi-frequency and forced disturbances upon drop size distributions in prilling. Chem Eng Sci. 2010;65(11):3474-3484. https://doi.org/10.1016/j.ces.2010.02.030.
5. Abbasfard H, Rafsanjani HH, Ghader S, Ghanbargi M. Mathematical modelling and simulation of an industrial rotary dryer: a case study of ammonium nitrate plant. Powder Technol. 2013;239:499-505. https://doi.org/10.1016/j.powtec.2013.02.037.
6. Mehrez A, Ali AH, Zahra WK, Ookawara S, Suzuki M. Study on heat and mass transfer during urea Prilling process. Int J Chem Eng Appl. 2012;3(5):347.
7. Saleh SN, Ahmed SM, Al-mosuli D, Barghi S. Basic design methodology for a prilling tower. Can J Chem Eng. 2015;93(8):1403-1409. https://doi.org/10.1002/cjce.22230.
8. Mehrez A, Ookawara S, Ali AH, Suzuki M. A numerical study on cooling-solidification process of urea particles in prilling tower. J Chem Eng Japan. 2014;47(8):628-634. https://doi.org/10.1252/jcej.13we019.
9. Rahmanian N, Naderi S, Supuk E, Abbas R, Hassanpour A. Urea finishing process: prilling versus granulation. Proc Eng. 2015;102:174-181. https://doi.org/10.1016/j.proeng.2015.01.122.
10. Saleh SN, Barghi S. Reduction of fine particle emission from a prilling tower using CFD simulation. Chem Eng Res Design. 2016;109:171-179. https://doi.org/10.1016/j.cherd.2016.01.017.

11. Sharma SP, Garg H. Behavioural analysis of urea decomposition system in a fertiliser plant. Int J Ind Syst Eng. 2011;8(3):271-297.

12. Hassanien S, El Safty M. Mathematical modelling for drying towers. Trans Egyptian Soc Chem Eng. 1985;11(1):61-71.

13. Garg H, Sharma SP. Behavior analysis of synthesis unit in fertilizer plant. Int J Quality Reliab Manag. 2012;29(2):217-232. https://doi.org/10.1108/02656711121199928.

14. Rahmanian N, Homayoonfard M. A comparison of co-current and counter-current modes of operation in urea prilling tower. Adv Mater Res. 2014;917:199-208.

15. Skydanenko M, Sklabinsky V, Saleh S, Barghi S. Reduction of dust emission by monodisperse system technology for ammonium nitrate manufacturing. Processes. 2017;5(3):37. https://doi.org/10.3390/pr5030037.

16. Taran YA, Morozov RV, Taran AL. Calculation of process of finish-granulation by fattening technology with random granule-wise distribution of finish-granulating flow. Chem Petroleum Eng. 2017;53(5–6):355-363. https://doi.org/10.1007/s10556-017-0347-1.

17. Bidoret A, Guihard L, Cauret L, Poncelet D. Production of κ-carrageenan beads by prilling process. Can J Chem Eng. 2017;95(4):799-805. https://doi.org/10.1002/cjce.22739.

18. Alsharif AM, Uddin J. Instability of viscoelastic curved liquid jets with surfactants. J Non-Newtonian Fluid Mech. 2015;216:1-12. https://doi.org/10.1016/j.jnnfm.2014.12.001.

19. Shikhmurzaev YD, Sisoev GM. Spiralling liquid jets: verifiable mathematical framework, trajectories and peristaltic waves. J Fluid Mech. 2017;819:352-400. https://doi.org/10.1017/jfm.2017.169.

20. Vervaeck A, Monteyne T, Siepmann F, et al. Fatty acids for controlled release applications: a comparison between prilling and solid lipid extrusion as manufacturing techniques. Eur J Pharm Biopharm. 2015;97:173-184. https://doi.org/10.1016/j.ejpb.2015.09.011.

21. Fachlevie F, Hidayat M, Sediawan WB. Determination of solid-liquid binary phase equilibrium of urea-mono ammonium phosphate (MAP). AIP Conf Proc. 2019;2085(1):020042. https://doi.org/10.1063/1.5095020.

22. Gezerman AO, Çorbacıoğlu BD. Effects of sodium silicate, calcium carbonate, and silicic acid on ammonium nitrate degradation, and analytical investigations of the degradation process on an industrial scale. Chem Ind Chem Eng Quart. 2015;21(2):359-367. https://doi.org/10.2298/CICEQ140705038G.

23. Crowley AB. Numerical solution of Stefan problems. Int J Heat Mass Transf. 1978;21(2):215-219. https://doi.org/10.1016/0017-9310(78)90225-9.

24. Voller V, Cross M. Accurate solutions of moving boundary problems using the enthalpy method. Int J Heat Mass Transf. 1981;24(3):545-556. https://doi.org/10.1016/0017-9310(81)90062-4.

25. Tacke KH. Discretization of the explicit enthalpy method for planar phase change. Int J Numer Methods Eng. 1985;21(3):543-554. https://doi.org/10.1002/nme.1620210312.

26. Xu ZX, Fu QX, Wang Q. Phase stability of ammonium nitrate with organic potassium salts. Central European J Energ Mater. 2016;13(3):736-754. https://doi.org/10.22211/cejem/65013.

27. Kiiski H. Properties of Ammonium Nitrate Based Fertilizers. Helsinki, Finland: Helsinki University Printing House; 2009.

How to cite this article: Gezerman AO. Mathematical modeling for prilling processes in ammonium nitrate production. Engineering Reports. 2020;2:e12173. https://doi.org/10.1002/eng2.12173