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BASIC CONCEPTS OF PRILLING TOWER DESIGN

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ABSTRACT

This paper presents a noval design method of prilling tower which was integrate from sub-models dealing with the importance basic concepts of the prilling process. This design methodology allowes an approximation for certain sub -models while retining some level of detail for other sub-models depending on which sub-model needs to contract and which to expend .The overall model was supported by CFD Stimulation cod (Fluent 6.3) which was a promising tool in analyzing and designing of the tower. In relating to this methodology, a number of important criteria were suggested against which the adequacy of the design results was tested. The prilling of highly concentrated ammonium nitrate solution was considered as case study. Producing an auniform size of prills was acocomplished by using considered as a head spray system where creating a quiescent zone at the spray system had a significant effect of decreasing the second disintegration of the droplets. The measured size of produced prills was greater than the predicated due to the presence of an ammonium bubble at the center of the prills, therefore, spray ability and the physical- chemical properties of the material must be carefully considered before preceding the tower design.

Keywords

Prilling, design, CFD, spray, droplet, particle

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1. INTRODUCTION

Many solid products from chemical and other process industries, especially those produced in huge quantity, tend to be made into granules, which are more convenient for use, storage, and transportation because of their much smaller specific surface area and larger bulk density [1]. One of the major processes for granulation from melt is the prilling. This process is the production of a granular solid by allowing droplets of a salt melt or a highly concentrated solution, to fall through a gas cooling medium and solidify into particles. These granular particles are called prills. Practically most fertilizer materials (e.g., urea and ammonium nitrate) of low viscosity (<5 centipoises) and melting point and high surface tension can be prilled in this way [2].

Prilling have the advantage of being able to create ideal spherical particles with narrow size distribution and minimal external specific surface area in one single step, scaleable to basically any capacity range needed [3]. The simplest method of producing uniform droplets is by the discharge of the molten material through an orifice nozzle. There are two principal modes by which the liquid breaks up into droplets: liquid dripping and liquid column/jet break up mode. Various mechanisms have been proposed to account for these breakup modes, such as dripping mechanism, Rayleigh mechanism [4], Weber theory [5] and Ohnesorge criteria [6].

The first mode occurs at low flow rates. The individual drops are formed at the tips of nozzles. This have the advantage of giving a uniform drop size but the output per nozzle is low, leading to a complex and expensive spray system. At higher rates the second mode takes over, in which the breakdown of the liquid jet is caused by the growth of a disturbance in the jet [7].

Producing an uniform droplets by second mode can be accomplished by using a limited types of prilling devices, such as rotating bucket or shower type spray heads located at the top of the prilling tower. In general, the faster types of prilling devices "rotating bucket" operate in the turbulent range, have one or up to 40 high capacity openings that are far from filled with liquid. Their droplet size is primarily governed by the high exit speed of the liquid film, which shatters, into a wide droplet distribution. The slower types "Shower Heads" operate under laminar conditions have hundreds or thousands of low capacity openings that may become filled completely. They generate strings of liquid that break up in a better controlled way. The droplet size is closely linked to the actual size of the openings and the distributions become close to monodisperse. Therefore the stationary "Shower Heads" are primarily used for the big particle solidifying of fertilizers and inorganic materials [3].

Procedure for designing prilling tower are still very much up to the individual, being based on practical experience, together with laboratory- scale tests, and basic principles. By using data on melting point, viscosity, surface tension, etc., of the material, together with laboratory- scale spraying tests, it is possible to specify optimum temperature, pressure, and orifice size for the required prill size and quality [8]. Honti, in his book on nitrogen industry, uses the solidifying time as the key parameter in determining the height of prilling tower [9].

The objective of the present work is to develop a basis for prilling tower design by combining fundamental principles of fluid mechanism and transport phenomena with practical experience and the published studies in the literature. The major design parameters are identified as the physical properties, the droplet size, the type of prilling device and the flow pattern of cooling air inside the prilling tower. Using computational fluid dynamics (CFD), the air flow pattern as well as particle trajectories can be predicted.

2. Methodology of Design

In this section we break up the important components of the designing process. In order to submit an optimum procedure for designing the prilling tower, the theoretical basis and practical experience are used roughly to sizing the prilling tower, which can then be investigated more exactly with a computational fluid dynamic (CFD) method.

2.1 Droplet atomization

Atomization is defined as the disintegration of a liquid into small droplets. The type of atomization principle or atomizer used for a specific application depends on the operational parameters that have to be tackled. The material properties of the liquid that has to be atomized play an important role. The significant properties of liquid material are (in order of significance): viscosity, surface tension, and density [10]. In prilling process the normal ways of atomization by prilling devices ranged from very fast, highly turbulent and disordered conditions to slow, laminar and ordered. When passing a liquid of low viscosity through small hole, i.e., a plain- orifice, the liquid can be readily atomized [11].

Based on the pioneering works of Rayleigh and Weber [4,5], Producing a very uniform droplets can be generally limited by using a shower head spray type which operates under laminar conditions. For prediction the droplet size, it is important to consider the jet breakup. For steady injection of a liquid through a single nozzle with circular orifice into a quiescent gas (air), the mechanism of jet breakup are typically classified into four primary regimes according to the relative importance of inertial, surface tension, viscous, and aerodynamic forces. These regimes are Rayleigh, First wind induced, Second wind induced, and atomization regimes. A detail of these regimes can be found in references [10-14].

In addition to liquid Reynolds number, there are two important dimensionless numbers characterizing these regimes, namely the Weber number and the Ohnesorge number. The Weber number is a measure for the ratio between drag forces and surface tension.

$$We_g = \frac{\rho_g d \left(u_l - v_g\right)^2}{\sigma} \quad , \quad We_l = \frac{\rho_l d\, u_l^{\,2}}{\sigma}$$

The Ohnesorge number describes the ratio of viscous effects in the liquid and surface tension.

$$Oh = \frac{\mu_l}{\sqrt{\rho_l \cdot d \cdot \sigma}}$$

For very low velocities no jet is obtained. This is the dripping mode. If the velocity of the fluid is large enough, but still low, the break-up of the jet is governed by the Rayleigh mechanism, which is a competition of liquid inertia and surface tension. It leads to the formation of droplets which have a diameter approximately twice the jet diameter.

Monodisperse particles can be attainable by operating the showerhead in the Rayleigh jet breakup regime, so that the criteria for Rayleigh jet breakup would be [13]:-

$$We_l > 8 \quad \text{and} \quad We_g < 0.4 \ \text{or} \ 1.2 + 3.41 Oh^{0.9} \qquad \textbf{(1)}$$

The jet breakup regimes is largely influenced by the internal geometrical nozzle characteristics and the nature of nozzle internal flow where the state flow of the liquid jet at the exit of the atomizer depends on the flow field in the atomizer, therefore, it is important to shed more light on the internal flow detail by applying the laws of liquid flow through this shower head which considered as plain orifice nozzles, where the liquid is accelerated through the nozzle, form a liquid jet, and then form droplets.

The plain orifice may operate in three different regimes: single-phase, cavitating and flipped [15]. The transition between regimes is abrupt, producing dramatically different sprays. The internal regime determines the velocity at the orifice exit, as well as the initial droplet size. To consistent with operating the showerhead in the Rayleigh jet breakup regime, the plain orifice must operate in the single phase regime where liquid completely fills the orifice as shown in Figure 1 [16].

To accurately predict the spray characteristics, one must identify the correct state of the internal flow regime for the plane orifice atomizer by using several parameters. These parameters may be combined to form nondimensional groups ike the Reynolds number based on hydraulic head (Re_h) and the cavitation parameter (K).

$$\mathrm{Re}_h = \frac{d\rho_l}{\mu}\sqrt{\frac{2(p_1 - p_2)}{\rho_l}}$$
$$K = \frac{p_1 - p_V}{p_1 - p_2} \qquad \textbf{(2)}$$

The cavitation number is an essential parameter for predicting the inception of cavitation. To include the effects of inlet rounding and viscosity, an empirical relationship for inception of cavitation [16] is used:

$$K_{incep} = 1.9\left(1 - \frac{r}{d}\right)^2 - \frac{1000}{\mathrm{Re}_h} \qquad \textbf{(3)}$$

Similarly, a critical value of (K) where flip occurs is given by

$$K_{crit} = 1 + \frac{1}{\left(1 + \frac{L}{4d}\right)\left(1 + \frac{2000}{\mathrm{Re}_h}\right)e^{70r/d}} \qquad \textbf{(4)}$$

The cavitation number (K) is compared to the values of (K_{incep}) and (K_{crit}) to identify the nozzle state. Once the nozzle state is determined, the exit velocity is calculated. Another important parameter for describing the performance of nozzles is the coefficient of discharge (C_D). The coefficient of discharge is the ratio of the mass flow rate through the nozzle to the theoretical maximum mass flow rate.

For a single-phase nozzle $\left(K > K_{incep}, K \geq K_{crit}\right)$ **[17], the coefficient of discharge is:-**

$$C_D = \frac{1}{\frac{1}{C_{DU}} + 20\frac{(1 + 2.25L/d)}{\mathrm{Re}_h}} \qquad \textbf{(5)}$$

Where C_{DU} is the ultimate coefficient of discharge and is defined as

$$C_{DU} = 0.827 - 0.0085\frac{L}{d} \quad \textbf{(6)}$$

The effective mass flow rate of the nozzle is defined by

$$\dot{m}_{eff} = C_D A\sqrt{2\rho(p_1 - p_2)} \quad \textbf{(7)}$$

For a single-phase nozzle, the estimate of exit velocity comes from the conservation of mass and the assumption of a uniform exit velocity:

$$u_l = \frac{\dot{m}}{\rho_l A} \quad \textbf{(8)}$$

Finally, Rayleigh-Weber equation [11] is used to calculate the droplet diameter.
Where

$$\lambda_{opt} = 4.44d \qquad \text{non-viscous liquids}$$

$$\lambda_{opt} = \sqrt{2\pi}d\left(1 + \frac{3\mu_l}{\sqrt{\rho_l \sigma d}}\right)^{0.5} \text{viscous liquids} \quad \textbf{(9)}$$

$$D = \left(1.5\lambda_{opt} \cdot d^2\right)^{1/3} \quad \textbf{(10)}$$

Where λ_{opt} is the wavelength of liquid column at the optimum perturbation.

At this point, the mass flow rate, velocity, and droplet size have been determined and the initialization of the injections is complete.

2.2 Solidification of droplets

The molten droplets leave the plain orifice (shower heads) only slightly above their melting point T_m. The droplet of radius R is solidified at T_m and cooled to T_{p1} as they fall through a counter current stream of air at T_a. Both the heat of solidification and the sensible heat must be removed, and in many instances solid phase transition must be allowed for.
For the purpose of analysis, the thermal history of a flight droplet can be divided into three regions:-

2.2.1 Cooling in fully liquid state

for a spherical droplet, the change in internal heat content due to convective heat transfer can be expressed by:

$$c_{p,l}\frac{dT_p}{dt} = -\frac{6h}{\rho_p D_p}\left(T_p - T_a\right) \quad \textbf{(11)}$$

Where h is the heat transfer coefficient. The Ranz-Marshall correlation [18] has been frequently used to determine the heat transfer coefficient:

$$h = \frac{k_a}{D}\left(2 + 0.6\,\mathrm{Re}^{0.5}\,\mathrm{Pr}^{0.33}\right) \qquad \textbf{(12)}$$

By using this conventional correlation, it is assumed that air turbulences effects during heat transfer from droplets were neglected.

2.2.2 Solidification

This stage can be described by the time-dependent heat conduction equation in spherical coordinates:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho C_p}\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right) \qquad \textbf{(13)}$$

With boundary conditions

$$\frac{\partial T}{\partial r} = 0 \qquad r = 0 \qquad t > 0 \qquad \textbf{(14)}$$

$$-k\frac{dT}{dr} = h\left(T - T_a\right) \qquad r = R \qquad t > 0 \qquad \textbf{(15)}$$

$$T = T_m \qquad t = 0 \qquad 0 < r < R \qquad \textbf{(16)}$$

Since the droplets that is sprayed by shower heads is considered as very coarser, then the rate at which the centre of the droplet reaches a specified temperature will be controlled by internal conduction. The first boundary condition arises from symmetry considerations. The second boundary condition describes the case of a heat lost from the droplet to the surrounding air according to Newton's law of cooling, with a constant heat transfer coefficient (h), with the final condition prescribing an initially uniform temperature profile within the droplet.

Special consideration is required for handling this model because of the inner boundary condition moves relative to the centre of the droplet during the process of solidification.

$$T = T_m \qquad r = R_s \qquad t > 0 \qquad \textbf{(17)}$$

The analytical solution for this case was obtained by equating the heat liberation at $r = R_s(t)$ (the liquid-solid interface) resulting from the solidifying of the droplet to the heat flow across the spherical surface at $r = R$ (the solid-air interface).

$$-\left(\rho\Delta H_s\right)\left(4\pi R_s^{\,2}\right)\frac{dR_s}{dt} = \frac{h\cdot 4\pi R^2\left(T_m - T_a\right)}{1 - \left(hR/k\right) + \left(hR^2/kR_s\right)} \qquad \textbf{(18)}$$

$$t_s = \frac{\rho\Delta H_s R}{h\left(T_m - T_a\right)}\left[\frac{1}{3} + \frac{1}{6}\frac{hR}{k}\right] \qquad \textbf{(19)}$$

Where ΔH_s is the solidification heat.

2.2.3 Cooling in the fully solid state

After the droplet is completely solidified, it cools down further in the solid state. This process can be evaluated from:

$$c_{p,s}\frac{dT_p}{dt} = -\frac{6h}{\rho_p D_p}\left(T_p - T_a\right) \tag{20}$$

Within a typical spray forming application, comparison of the heat fluxes from convection and radiation obtains a heat transfer due to convection which is two orders of magnitude higher than the heat transfer due to radiations. Therefore the heat transfer due to radiation from the droplet has been totally neglected [12].

2.3 Sizing of the prilling tower

In industry the whole process of droplet solidification and cooling proceeds in dynamic condition: the droplets fall and are cooled by counter current air stream where the droplets start with a finite velocity and accelerate to their terminal velocities.

The motion of particles in the air flow field is described in a Lagrangian way by solving a set of ordinary differential equations along the trajectory in order to calculate the change of particle location and the components of the particle velocity. This requires the consideration of all relevant forces acting on the particle. Inter-particle forces, such as van der Waals forces, capillary forces, and electrostatic forces have been neglected since the particle sizes used in this case are large and inter-particle forces are insignificant.

The equation of motion can be derived from a substitution of the forces working on the particle in Newton’s second law of motion [19]:

$$m_p\frac{d\vec{u}}{dt} = \frac{C_D\rho_a A_p\left|\vec{v}-\vec{u}\right|\left(\vec{v}-\vec{u}\right)}{2} + \frac{\pi}{6}D^3\left(\rho_p-\rho_a\right)\vec{g} - \frac{\pi}{4}D^3\rho_a\Delta P \tag{21}$$

The first term denotes the drag force of the air on the particle. The second term is the buoyancy force, and because the density of the particle is much larger than the air, this term constitutes the gravitational force. The last term is the pressure gradient force and is negligible in the case of prilling. Therefore, the equation of motion for a droplet is given by:

$$m_p\frac{d\vec{u}}{dt} = \frac{C_D\rho_a A_p\left|\vec{v}-\vec{u}\right|\left(\vec{v}-\vec{u}\right)}{2} + m_p\vec{g} \tag{22}$$

The drag coefficient is given as a function of the particle Reynolds number:

$$\mathrm{Re}_p = \frac{\rho_a D_p\left(\vec{v}-\vec{u}\right)}{\mu_a} \tag{23}$$

From the dependence of the drag coefficient of a sphere (spherical particle) on the Reynolds number, one may identify several regimes which are associated with the flow characteristics around the sphere [20]:-

For small Reynolds numbers (i.e. $Re_p < 0.5$) viscous effects are dominating. Therefore, an analytical solution for the drag coefficient is possible as proposed by Stokes [21]:-

$$C_D = \frac{24}{Re_p} \quad \textbf{(24)}$$

This regime is often referred to as the Stokes-regime.

In the transition region (i.e. $0.5 < Re_p < 1000$) inertial effects become of increasing importance. A frequently used correlation is that proposed by Schiller & Naumann [22], which fits the data up to $Re_p = 1000$ reasonably well.

$$C_D = \frac{24}{Re_p}\left(1 + 0.15\,Re_p^{\,0.687}\right) \quad \textbf{(25)}$$

Above $Re_p \approx 1000$ the drag coefficient remains almost constant. This regime is referred to as Newton-regime with:

$$C_D \approx 0.44 \quad \textbf{(26)}$$

It is useful for estimating terminal falling velocity of particles, by assuming an unidimensional flow of both particles and air in the vertical direction in the prilling tower [8]. Terminal falling velocity conditions occur when the buoyancy force acting on the particle is counter balanced by the drag force of the air [23]:

$$\frac{\pi}{6} D^3 \left(\rho_p - \rho_a\right)\vec{g} = \frac{C_D \rho_a A_p \left|v - u_v\right|\left(v - u_v\right)}{2} \quad \textbf{(27)}$$

$$u_v - v = \sqrt{\frac{4D\left(\rho_p - \rho_a\right)g}{3C_D \rho_a}} \quad \textbf{(28)}$$

In the case of prilling, equation (25) can be used to replace C_D

In order to complete the analysis of particle's motion, the distance-time relationship can be obtained by rearrangement equation (21)

$$\frac{d(u_v - v)}{dt} = \frac{g\left(\rho_p - \rho_a\right)}{\rho_p} - \frac{C_D \rho_a A_p \left|u_v - v\right|\left(u_v - v\right)}{2m_p} \quad \textbf{(29)}$$

Where

$$m_p = \frac{1}{6}\pi D^3 \rho_p, \quad A_p = \frac{1}{4}\pi D^2$$

The above equation is identical to Lapple and Shepherd equation [24] in calculating particle trajectories from a nozzle atomizer in non-rotating air where the movement in the vertical direction is more substantial.

Therefore , in sizing the prilling tower ,the effective height of the tower is specified by equating it to the vertical distance of the droplet of average size(D_{50}) which is traveled from the shower head until hitting the base of the tower through the estimated time for solidifying and cooling the droplet.

The diameter of the prilling tower is determined primarily by the number of spray nozzles necessary for the desired production rate where the prilling tower must have sufficient dimensions to envelope the flight paths of the biggest droplets of the distribution (D_{99}) which must not hit the walls before it is safe. The biggest size of prills was estimated by using Kjaergaard's model [4] where

$$D_{99} = 1.5 D_{50} \quad \textbf{(30)}$$

The critical time of flight for the biggest droplet (D_{99}) is when the outer 1/3 of the mass of droplet has solidified. At this stage, contact with the walls can be allowed [4].

2.4 CFD Modelling

Computational fluid dynamics (CFD) simulation can be applied to examine prilling tower design. It predicts the air flow and calculates the trajectories of the prills, and then determines the hitting regions of the walls. By CFD, The air phase is modeled as continuum using the Euler approach and the droplet/ particle phase is modeled by the Discrete Phase model (Lagrange approach) [16]. In essence, CFD is the numerical solution of the equations governing fluid flow in the prilling tower; this involves generating a mesh that divides the flow region of interest into a large number of small control volumes. Simple algebraic equations can then be developed for each control volume to describe the conservation of mass, momentum, and energy. The collection of all equations over all control volume amounts to a large number of simple equations that can be solved by number-crunching techniques on a computer [25].

3. Case Study

Application of the above concepts to the design of an industrial prilling tower will now be described. The material to be prilled is highly concentrated (99.8%) ammonium nitrate solution [26]. It is desired to design of a prilling process for 20 ton/day of high density prills of ammonium nitrate. The concentrated (99.8%) ammonium nitrate solution is fed from the head tank at 180 ^{o}C to the prilling device (shower type spray head) located at the top of the prilling tower as shown in Figure 2. The liquid droplets fall from the shower head counter currently through air which enters the tower at ambient temperature (25 ^{o}C). Air is sucked into the base of the tower by exhaust fans mounted on top. The product is removed from the tower base to a conveyor belt using a conical hopper.

4. Results and discussions

For the purpose of illustration, the results of the design calculation carried out for the specific set of operating condition of the case described above were summarized in Table 1.

Eighty showerheads type fabricated in plant workshop were installed at the top of the tower for atomization highly concentrated ammonium nitrate solution. Each with forty holes distributed in concentric circles. The number in use is adjusted to fit the rate of operation. Figure 3 shows the arrangement of spray header at the top of the tower.

The diameter and effective height of the tower calculated according to the method above provide a flight time for the biggest droplets (D_{99}) of 4.5 second which is predicted by CFD simulation tool. This flight time was greater than the time needed to solidify 1/3 of the mass of the biggest droplet calculated according to equations (11, 19).

The produced particles collected at the bottom of the prilling tower had an uniform measured size of 2.3 mm and in the spherical or spheroidal form, and this is different from the predicted size by above model. The reason is refer to the way by which the generic morphology of the final prills is attained. In industry, all the stages of the operations during the manufacture of ammonium nitrate take place in excess of ammonia where the alkaline medium delays thermal decomposition and improve the quality of the product [26]. The presence of ammonia may allow to a bubbles at the centre of the prill to form during the solidification stage. As the outer layer of droplet cools, it solidfyifies forming a shell. As the thickness of the shell increases the forming solid liberates ammonia bubbles. The liberation ammonia accumulates in the interior of a sphere which is not quite solid. Finally the pressure in the inside of a prill becomes higher than the ambient air pressure which causes the expanding of the bubbles and inflation of the particle. This mechanism is confirmed by an experimental work [27]. And this interprets why the size of the produced prill in industry is different from the size of pure ammonium nitrate prill.

It was noted that the particles of sizes < 1 mm was less than 5% of the mass of product collected (prills) at the bottom of the prilling tower. This firstly indicates that the secondary atomization (disintegration) is rarely take place when using the showerheads for spraying in comparison with other types of atomization devices. Secondary, the selection of the spraying temperature was correct (180 ^{o}C) where the higher temperature causes the rapid liberation of ammonia which results in the efflorescence the particles, and this has a significant effect on the performance of prilling process, where this efflorescence reveals as an effluents in the form prill carry over which is sucked through air exhausts fans to atmosphere. In addition to loss of production capacity, this causes a contamination of air. Therefore, the contamination may be minimized, by careful design of the prilling devices, the selection of spraying temperature and optimization of the average velocity of air through the tower, where the higher the air velocity the larger the particles which can be carried out of the tower. Thus the weight of particles carried over increases very rapidly with air velocity. In this design, the average velocity of air through the tower was 1.0 m/s.

In operation of prilling process, it was suffered from blockage the orifices of the shower heads at discrete periods due to presence of impurities, which arises from oxidation of the pipes and equipments or containing in the liquid feeds. These suspended impurities made build up of solid material in the holes. Fortunately, there are a sufficient number of stand by showerheads that were installed to replace the blockage showerheads which were isolated and cleaned to reinstall again. To avoid this specific problem, it is suggested to install a vibrated system that it helps to avoid build up of solid material in the holes. An additional advantage of the vibrated system is that it leads to continuous breakup of the liquid jet into identical droplets.

In several applications, prills of almost identical size are needed, therefore in operating of the prilling process, it is necessary to obtain a substantially monodispersed droplets by operating the showerheads in the Rayleigh jet breakup regime where the predominant breakup mechanism is the surface tension force where the jet disintegrates into fairly identical droplet sizes. This regime is attainable at this criterion (Equation (1)). As example in operating the prilling process, the level of the ammonium nitrate solution in the head tank (Figure 2) must be kept at specific value to provide the appropriate hydrostatic head which introduce a desired velocity for disintegration of the jet in the Rayleigh jet breakup regime. In addition to the level in the head tank, the air velocity play an important role in the attaining to this regime, by creation of relative quiescent zone near the showerheads region, where in the absence of aerodynamic effects, the air friction decreases and the optimum wavelength increases and as a consequence, the droplet diameter increases. This quiescent zone was of 1.7 meter distance from the showerheads to the exhaust fans as shown in Figure 2. This zone is very clear in the predicted counter of air velocity (Figure 4) by the CFD simulation where the predicted air velocity in this zone is approximately 0.1 m/s.

5. Conclusions

In order to achieve a good prilling process, it is necessary to setting a convenient design regarding the following parameters:-

-the spraying characteristic and the spraying temperature

-the physical properties of the molten or concentrated solution.

-the flow of air

Mastering simultaneously all of these parameters is necessary to obtain good product equality such as monodispersing prills and smooth operation. These goals can be achieved by controlled through the sizing the prilling tower, selection an appropriate spraying device.

The presented sub models were properly integrated to a novel rigorous design method which was backed up by a CFD simulation. The presented CFD simulation code (Fluent **6.3)** was a promising tool in analyzing and designing of the prilling tower.

An important consideration in prilling tower design is the selection of suitable criteria against which the adequacy of the design results can be tested. A number of such criteria suggest themselves. The first criterion selected in the present design method requires that a prilling device obtains substantially monodispersed droplets under creation a relative quiescent zone near the showerheads. The second criterion selected uses the solidifying time as the key parameter in determining the size of prilling unit needed. The flight time of the particle in the prilling tower should be somewhat greater than the time needed to solidify 1/3 of the mass of the biggest droplets. The third criterion selected is reducing of effluents especially in the form prill carry over. In addition to loss of production capacity, this causes a contamination of air.

In regard to production of industrial ammonium nitrate, the particle size is larger than pure ammonium nitrate because of the inflation of particle due to ammonia bubbles located in the centre of the particle.

Nomenclature

u	velocity	m/s
v	air velocity	m/s
We	Weber number	-

A	cross section area	m^2
A_p	particle projected area	m^2
C_D	drag coefficient	-
C_{DU}	ultimate drag coefficient	-
c_p	specific heat	$kJ/kg \cdot K$
d	nozzle diameter	mm
D_p	particle diameter	mm
D_{50}	average particle size	mm
D_{99}	biggest particle size	mm
g	gravitational acceleration	m/s^2
h	heat transfer coefficient	$kW/m^2 K$
ΔH_s	solidification heat	kJ/kg
K	cavitation parameter	-
k	thermal conductivity	$kW/m \cdot K$
L	nozzle length	mm
m	droplet mass	kg
Oh	Ohnesorge number	-
P	pressure	pa
Pr	Prandtl number	-
R	radius	mm
r	radius of cuvature(nozzle)	mm
	radial coordinate	
T	temperature	K
t	time	s
Re	Reynolds number	-
Sc	Schmidt number	-
Sh	Sherwood number	-

subscript

a	air
$crit$	critical
d	droplet
eff	effective
g	gas
h	hydraulic head
$incep$	inception
l	liquid
m	melting
opt	optimum
p	droplet/particle
s	solid
V	vapour
v	vertical
1	upstream
2	downstream

Greek letters

λ	wavelength	mm
σ	surface tension	N/m
ρ	density	kg/m^3
μ	viscosity	$kg/m \cdot s$

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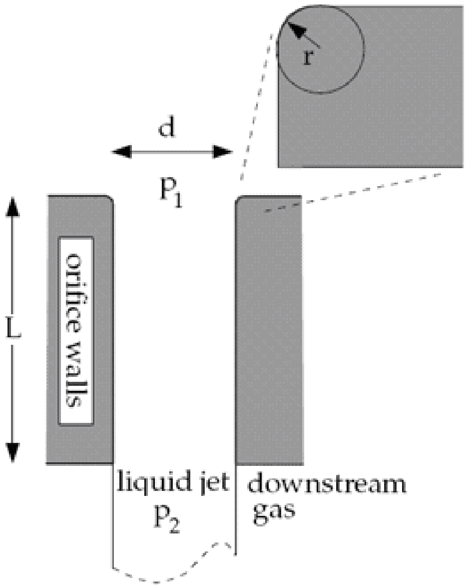

Figure 1: Single phase nozzle flow [16]

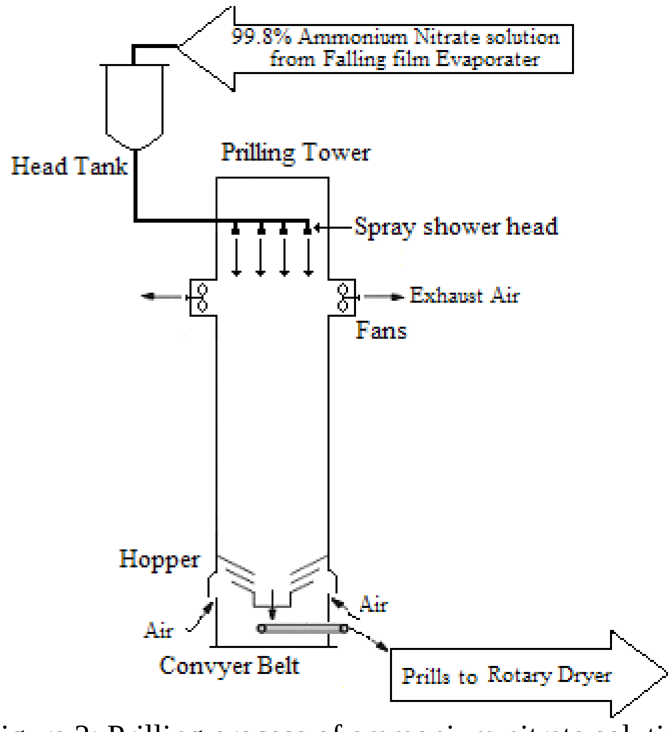

Figure 2: Prilling process of ammonium nitrate solution

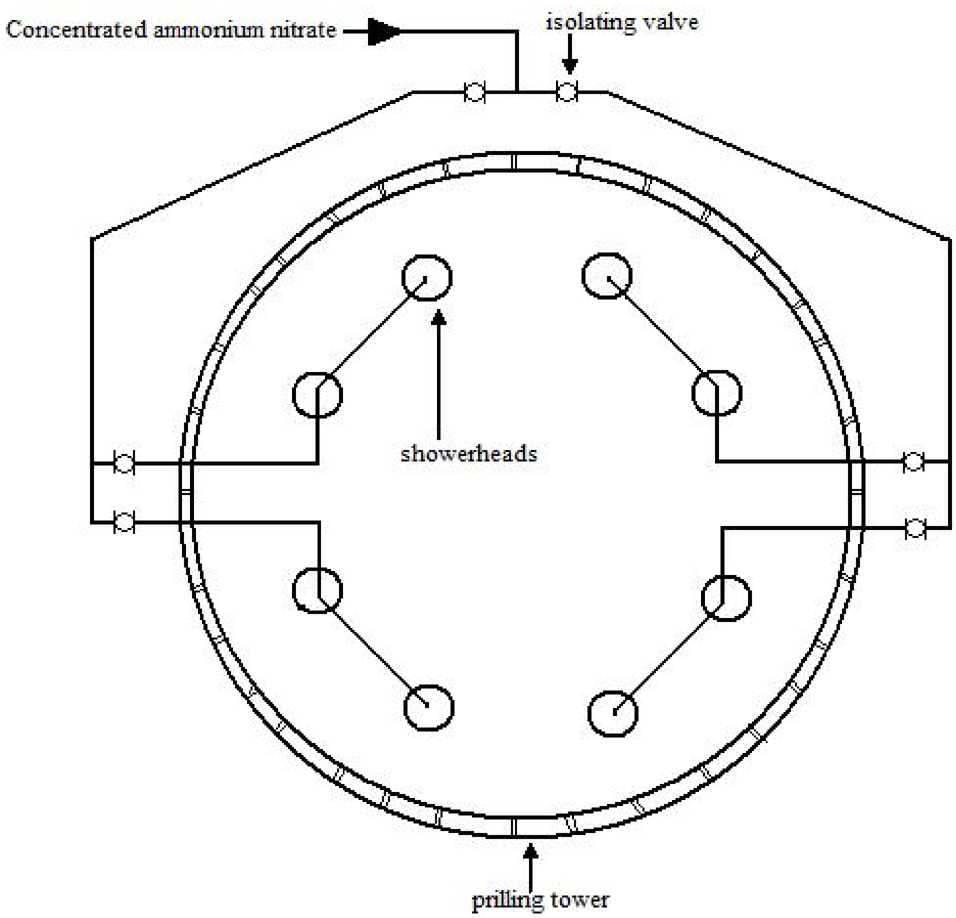

Figure 3: Arrangement of spray header at the top of prilling tower

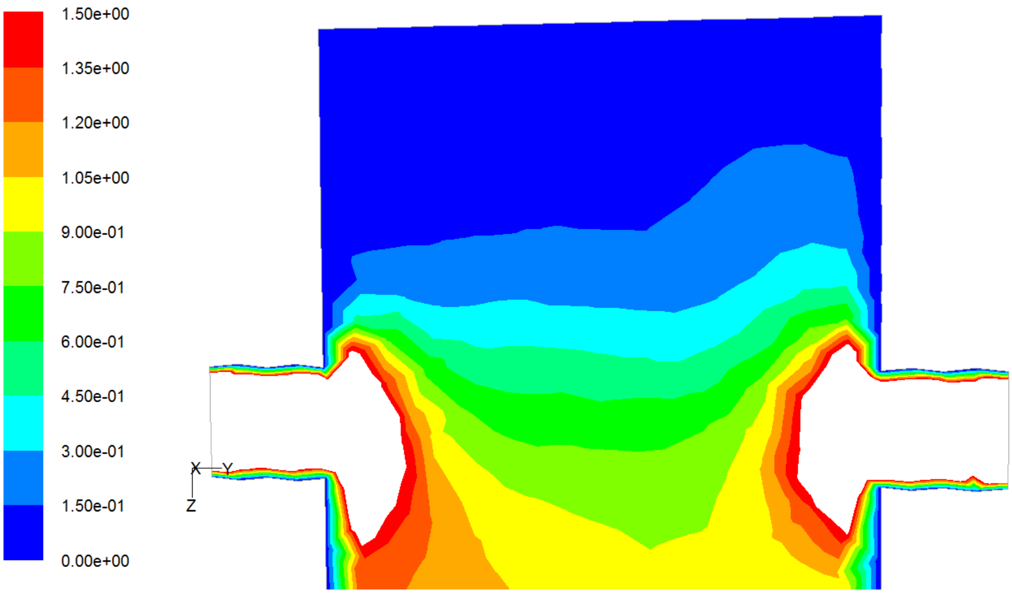

Figure 4: Counter of predicted air velocity (m/s) in the upper section of the prilling tower

Table 1: Results of design calculation

Effective height of tower	30 m
Diameter of tower	2.8 m
Nozzle diameter	1 mm
Nozzle length	5 mm
No. of exhaust fans	4
Average particle size D_{50}	1.92 mm
Biggest particle size D_{99}	2.9
Air flow rate	22000 m^3/hr
Air velocity	1m/s
No. of showerheads	8

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