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Design of a Spray Tower for the Granulation of Melt

Kaiser Muslem Abd Ali
Babylon University - College of Engineering
Electrochemical Eng. Dept.
E-mail: alassade_67@yahoo.com

Abstract.

In this paper a simulation of cooling-solidification tower was presented, sprayed droplets is one of major methods for prilling of melt. Traditionally, this is carried out in an empty tower, and the equipment requirements for producing larger particles is very high, for analysis and simulation, mathematical model of tower, the effect of molten drop size on height of tower, heat and mass transfer coefficients are estimated according to empirical correlations. Estimations are considered based on concept of energy and mass transfer correlation equations. The results showed that the height of equipment is greatly affected by atomized particle size.

Nomenclatures

A area, m^2
C_p heat capacity at constant pressure, kJ/kg.K
D_p particle diameter, m
g acceleration of gravity, m/s^2
H height of cooling tower (m)
h heat transfer coefficient, $W/m^2.K$
k thermal conductivity, W/m.K
L length, m
m mass flow rate, kg/s
Mw molecular weight, kg/kmol
Nu Nusselt number
n molar flow rate, kmol/s
P pressure, Pa
Pr Prandtl number
$\dot{Q}$ heat transfer rate W
Re_P particle Reynolds number
t_c cooling time
t_s solidification time
Q volumetric flow rate, m^3/s

Subscript

a air
int interface
m metal
sys system

Greek

μ viscosity kg/ m.s
λ latent heat of fusion kJ/kg
ν kinematic viscosity (or momentum diffusivity), m^2/s
ρ density, kg/m^3

1. Introduction

The 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.

Up to date, cooling-solidification of sprayed droplets is one of the major processes for granulation from melt, in which melt is sprayed into droplets with requested sizes and then cooled and solidified to yield granular solid product. Traditionally, the process is carried out in an empty tower, i.e., melt is sprayed at the top of the tower; the droplets formed are cooled and solidified as they fall downwards, and solid particles are collected at the bottom. This process has been used successfully in industries for many years, e.g., for urea and ammonium nitrate, and production capacity of a single unit can be as large as 70 to 80 tons per hour at present. The major disadvantage of the process is the requirement of a very high tower, resulting in cost increase and difficulties in transporting melt, operation and maintenance. Also, it is almost impossible to obtain the products with size greater than 2 mm in this way because of unacceptable height of tower.

A typical tower for melt granulation is shown in Figure 1. The dimensions of the tower must be determined such that the largest melt particles solidify before striking the walls or the floor of the tower. Mathematical modeling of this tower can be accomplished by considering the unsteady-state macroscopic energy balances for the melt particles in conjunction with their settling velocities. This enables one to determine the cooling time and thus the dimensions of the tower. It should be remembered that mathematical modeling is a highly interactive process. It is customary to build the initial model as simple as possible by making assumptions

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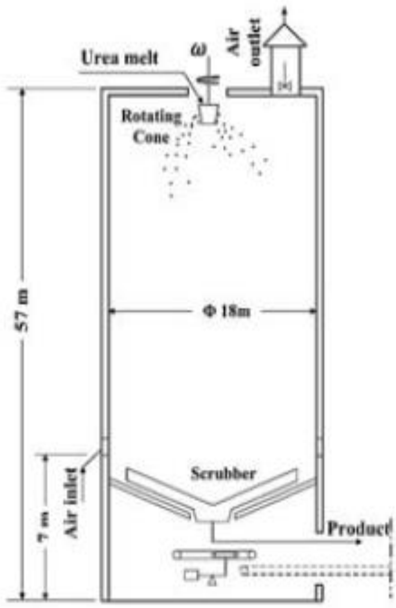

Figure (1): Schematic diagram for the Urea prilling tower. Ali Mehrez et.al (2012)

Experience gained in working through this simplified model gives a feeling for the problem and builds confidence. The process is repeated several times, each time relaxing one of the assumptions and thus making the model more realistic. In the design procedure presented below, the following assumptions are made:

- The particle falls at a constant terminal velocity.
- Energy losses from the tower are negligible.
- Particles do not shrink or expand during solidification, i.e., solid and melt densities are almost the same.
- The temperature of the melt particle is uniform at any instant, i.e., Bi << 1.
- The physical properties are independent of temperature.
- Solid particles at the bottom of the tower are at temperature Ts, the solidification temperature.

2. Analysis for tower prilling

2.1 General consideration

The key problems having to be solved in prilling of melt are: (1) The melt must be sprayed into droplets with uniform size as requested; and (2) The sprayed droplets must be fully solidified and cooled in order to avoid bonding of particles with each other and caking on the wall, and to ensure that the product collected at the bottom can be packed directly.

Industrially, the first problem has been solved successfully by employing rotary cup with perforated wall for spray, as widely used in urea and ammonium nitrate production, while the second raises the requirement for a high tower. As particle size increases, the settling velocity of particles and the resistance of surface solid shell to heat transfer increases exponentially and, at the same time, the specific interface area decreases significantly. So the height of the tower requested is a strong function of particle size.

2.2 Mathematical model

2.2.1 Shrinking unsolidified core model

The behaviors of melt or solution droplets during evaporation-solidification in a gas stream may vary from substance to substance. While in the experiments carried out by Wu *et* al. 1983, a solid film non-permeable to gas is found to form first on the surface of solution droplets of most substances tested, which contributes great resistance to heat and mass transfer, yielding the four-period drying mechanism. For generalization, it is considered that, after entering a cool gas stream, the surface of melt droplet solidifies first, and then the solid layer grows towards the center as the droplet falls down until completely solidified. The cooling-solidification process of droplet can be described with the shrinking unsolidified core model shown in Fig.2. If the difference between melt and solid densities is small, the solidified particle would be dense, while when the difference is large it may have a hollow central core. The volumetric ratio of droplets/particles to gas in prilling towers is normally very small (around 0.1% only) Wu *et.* al 2007.

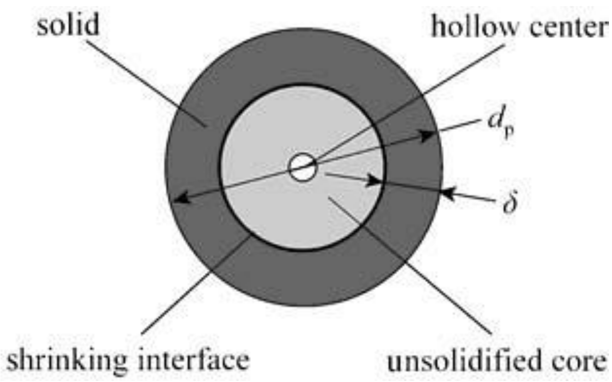

Figure (2): Shrinking unsolidified core model Wu *et.* al 2007.

So that, the effects of droplets/particles on each other in both heat transfer and movement can be neglected, and the behaviors of droplets/particles can be examined by analyzing a single droplet/particle with the average size, *d*p. For understanding the variations of the states of droplet/particle and gas stream along tower height, one-dimensional model is accurate enough. In addition, the following assumptions are made in the model establishment: (a) the droplet/particle is spherical. (b) The droplet/particle moves downward at its terminal velocity, u_t, throughout whole the process. In fact, in the case of using rotary cup with perforated wall for spray, the initial velocity of droplet in the vertical direction is near its terminal one and thus the time of unstable movement with varying velocity is negligible. (c) Since no mass transfer happens during the process of melt prilling and the shape of droplet is quickly fixed due to solid shell formed on the surface, the drop- let/particle is assumed to have a constant density.

2.2.2 Movement equation of droplet/particle

The relationships predicting terminal velocity, v_t, in various flow regimes are well known [Tosun and Aks¸ahin, 1993, Whitaker 1972]. For the actual velocity of droplet/particle moving in counter-current gas flow, the velocity of the latter, v_a, should be subtracted from

$$v_r = \frac{dH}{dt} = v_t - v_a \qquad \text{….. (1)}$$

2.2.3 Thermal behavior of droplet/particle

In the tower, the droplet/particle undergoes three periods of different natures: (a) Droplet cooling before solid at the surface appears; (b) After solidification starts at surface, the interface of melt core shrinks to- wards the center until completely solidified, during which the resistance of solid shell to heat transfer cannot be neglected; and (c) Further cooling after complete solidification. complete solidification. In period (a), the variation of droplet temperature, T_p, is determined by the heat balance:

3. Governing equations

The conservation statement for total energy under unsteady-state conditions is given by Tousn 2007

$$\left(\hat{H}\dot{m}\right)_{in} - (\hat{H}\dot{m})_{out} + \dot{Q}_{int} + V_{sys}\frac{dP_{sys}}{dt} + \dot{W}_s = \frac{d}{dt}\left(\hat{H}m\right)_{sys} \qquad \text{….. (2)}$$

The mass flow rate of air introduced to the tower is determined by heat balance around the tower:

$$\dot{m}_a\langle\hat{C}p_a\rangle[(T_a)_{out} - (T_a)_{in}] = \dot{m}_m\{\hat{c}p_m[(T_m)_{in} - T_s] + \hat{\lambda}\} \qquad \text{….. (3)}$$

The dimensions of tower can be determined using the following equation

$$D = \sqrt{\frac{4\dot{m}_a}{\pi\rho_a v_a}} \qquad \text{….. (4)}$$

Tower height, is determined from

$$H = v_t t \qquad \text{….. (5)}$$

The terminal velocity of the falling particle, due to stocks law

$$v_t = \frac{gD_p^2\Delta\rho}{18\mu}$$

The Turton-Clark 1987 correlation is an explicit relationship between the Archimedes and the Reynolds numbers as given by

$$\mathrm{Re}_p = \frac{Ar}{18}(1 + 0.0579Ar^{0.412})^{-1.214} \qquad \text{….. (6)}$$

Where $Ar = \frac{D_p^3 g\rho_a(\rho_m - \rho_a)}{{\mu_a}^2}$

When the particle diameter and the physical properties of the fluid are known, Archimedes number can be calculated directly, however, the definition of the Reynolds number involves the relative velocity, v_r , rather than the terminal velocity of the melt particle, i.e., Since the air and the melt particle flow in counter-current direction to each other Eq.1

3.1 Cooling time

The total cooling time consists of two parts: cooling period during which the melt temperature decreases from the temperature at the inlet to T_s, and solidification period during which the temperature of the melt remains at T_s. The cooling time, can be determined from the energy balance around the melt particle.

i) Cooling period:

Considering the melt particle as a system,

$$\dot{m}_{in} = \dot{m}_{out} = 0 \qquad \text{….. (7)}$$

$$\dot{W}_s = 0$$

$$\dot{Q}_{in} = -\pi D_P^2\langle h\rangle(T_m - \langle T_a\rangle) \qquad \text{….. (8)}$$

$$\frac{dp_{sys}}{dt} = 0$$

$$m_{sys} = \frac{\pi D_P^3}{6}\rho_m \qquad \text{….. (9)}$$

$$\hat{H}_{sys} = \hat{C}p_m\left(T_m - T_{ref}\right) \qquad \text{….. (10)}$$

So heat balance around the particle

$$-6\langle h\rangle(T_m - \langle T_a\rangle) = D_p\rho_m\hat{C}p_m\frac{dT_m}{dt} \qquad \text{….. (11)}$$

Integration of eq. 11 gives

$$t_c = \frac{D_p\rho_m\hat{C}p_m}{6\langle h\rangle} ln\left[\frac{(T_m)_{in} - \langle T_a\rangle}{(T_s - \langle T_a\rangle)}\right] \qquad \text{…. (12)}$$

ii) Solidification period:

During the solidification process, solid and liquid phases coexist and temperature remains constant at T_s . Considering the particle as a system, the terms appearing in Eq. (2) become

$$\dot{m}_{in} = \dot{m}_{out} \qquad \text{….. (13)}$$

$$\dot{W}_s = 0$$

$\dot{Q}_{in} = -\pi D_P^2 \langle h \rangle (T_s - \langle T_a \rangle)$ ….. (14)

$\frac{dp_{sys}}{dt} = 0$ ….. (15)

$m_{sys} = m_l + m_s$ ….. (16)

where m_l and m_s represent the liquid and solidified portions of the particle, respectively. Therefore, Eq. 2 reduces to

$$T_{ref} = T_s \Rightarrow \begin{cases} \hat{H}_l = 0 \\ \hat{H}_s = -\hat{\lambda} \end{cases} \Rightarrow (m\hat{H})_{sys} = m_l \hat{H}_l + m_s \hat{H}_s = -\hat{\lambda} m_s = - \quad \text{….. (17)}$$

$$\pi D_P^2 \langle h \rangle (T_s - \langle T_a \rangle) = \hat{\lambda} \frac{dm_s}{dt} \quad \text{….. (18)}$$

Integration of Eq. 18 gives the time required for solidification, t_s,

as $t_s = \frac{\hat{\lambda} \rho_m D_p}{6 \langle h \rangle (T_s - \langle T_a \rangle)}$ ….. (19)

Therefore, the total time, t, in Eq.(3) is

$$t = t_c + t_s$$

3.2 Heat and Mass transfer coefficients

The average heat transfer coefficient due to heat transfer process, is predicted by Whitaker correlation (Whitaker 1972)

$$Nu = 2 + (0.4 Re_P^{0.5} + 0.06 Re_P^{0.67}) Pr^{0.4} (\mu_\infty / \mu_w)^{0.25} \quad \text{….. (20)}$$

The correlation originally proposed by Steinberger and Treybal (1960) includes a correction term for natural convection. The lack of experimental data, however, makes this term very difficult to calculate in most cases. The effect of natural convection becomes negligible when the Reynolds number is high, and the Steinberger-Treybal correlation reduces to

$$Sh = (0.347 Re_P^{0.62} Sc^{0.33}) \quad \text{….. (21)}$$

Equation (21) is recommended for liquids when $2000 \leq Re_P \leq 16900$

4. Results and discussion.

Major results of simulation are made for urea prilling tower as a typical case. The operating conditions and properties data used are listed in Table 1, where the heat conductivity of chalk, $\lambda s = 2.651 \times 10^{-5}$ kW·m^{-1}·K^{-1}, was used to substitute approximately that of urea because the value for urea was not found. All the other data listed in the table are accurate, and most of them are taken from industrial operations.

The results run with Microsoft Excel 2010 are shown in Figs. 3, 4, 5, 6 and 7.

Table (1): Operating conditions and property data involved in urea prilling

Initial temperature of melt T_{p0}	110^{o}c
Temperature of product T_{pf}	≤70^{o}C
Temperature of cooling air T_{g0}	10^{o}c
Temperature of cooling air out T_{gf}	20℃
Air flow rate	*20.28 kg/s*
product flow rate	*0.83 kg/s*
Air velocity u_a	2 m/s
size range of product D_p	0.5-4.5 mm
Melting heat of urea	ΔH_m＝186 kJ·kg^{-1}
Melting point of Urea 404K Specific heat of melt cpm	1.46kJ·kg^{-1}·K^{-1}
Specific heat of solid urea cps	1.46kJ·kg^{-1}·K^{-1}
Density of urea particles ρ_p	1500kg·m^{-3}
Density of air ρ_g at 293K	1.2kg·m^{-3}
thermal conductivity of air k_g	2.56×10^{-5}kW·m^{-1}K^{-1}
thermal conductivity of solid k_s＝^{1}	2.651×10^{-5}kW·m^{-1}K^{-1}
Specific heat of air cp_g＝	1.004 kJ·kg^{-1}·K^{-1}
Viscosity of air μ_g	1.8×10^{-5}Pa·s
Diffusivity coefficient of air-Urea	1.5×10^{-15} m^2/ s

Fig. 3 shows that the Nesselt number increased slightly with increasing of solidification drop size this is due to increasing of heat transfer rate especial heat transfer coefficient

The effect of drop particle diameter on the spray cooling tower height as shown in Fig. 4. the height of column increased with increase of particle diameter small atomizer pole requires small tower and vice versa and the column becomes expensive for maintenance and construction of materials

Fig. 5 show that the heat transfer coefficient decreased slightly with increasing of solidification drop size this is due to increasing of heat transfer rate from air to the particle .

Fig. 6 show that the Sherwood number increased slightly with increasing of solidification drop size this is due to increasing of mass transfer rate especial mass transfer coefficient

The effect of spray cooling tower height on total time period as shown in Fig. 7 the total time period increased exponentially with height of column. The large particle should spend a long distance to reach the bottom of tower and become solid.

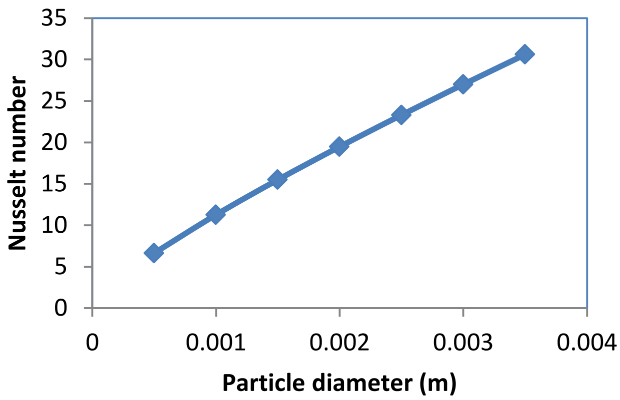

Figure (3): Effect of particle size on Nesselt number.

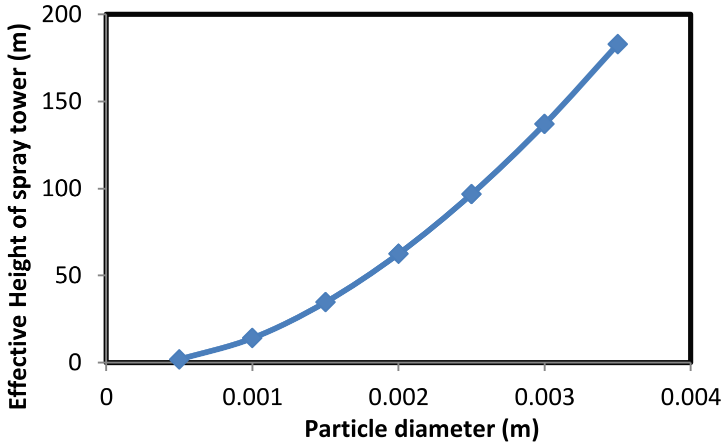

Figure (4): Effect of particle s size on height of spray tower**.**

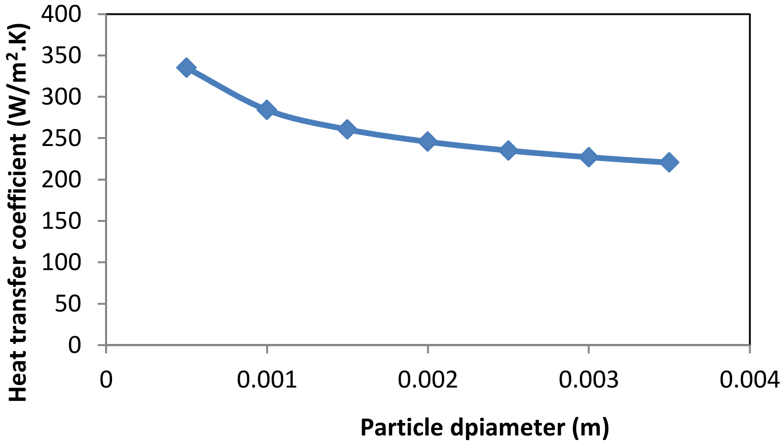

Figure (5): Effect of particle diameter on heat transfer coefficient**.**

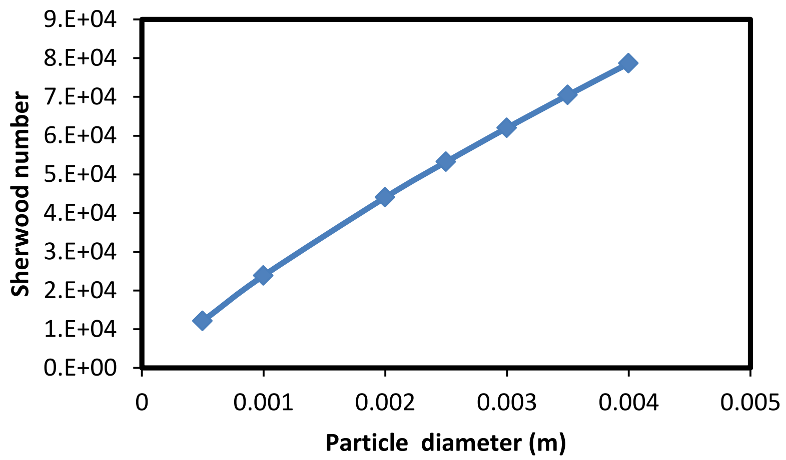

Figure (6) :variation of Sherwood number versius particle diameter**.**

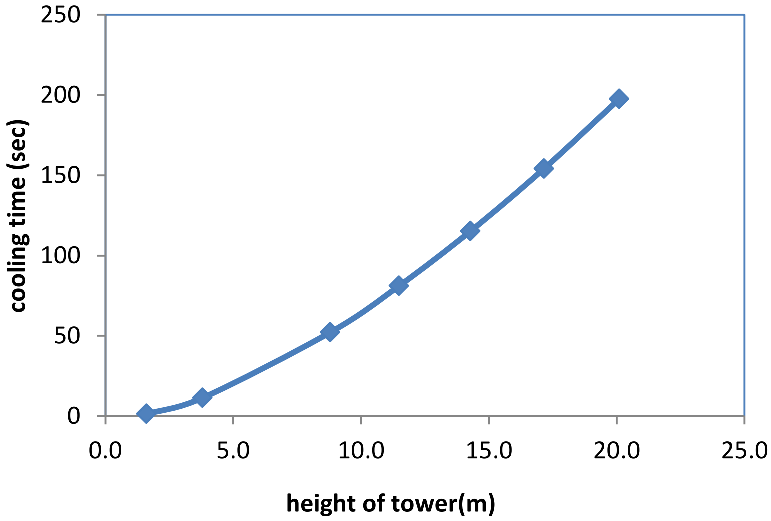

Figure (7): total time period against height of tower**.**

5. Conclusions

The results simulated for the traditional spray tower of granular melt show that significantly high tower is necessary to ensure sprayed droplets being completely solidified and fully cooled, and that to produce product of larger size less than or equal to 3 mm, is almost impossible because of unacceptable height of tower, the height of the tower requested is a strong function of particle size. The total time period increased with tower height.

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نمذجة برج الترذيذ لتكوير المنصهرات

د.قيصر مسلم عبد علي
جامعة بابل / كلية الهندسة / قسم الهندسة الكهروكيمياوية

الخلاصة

تضمن البحث المقدم دراسة نمذجة برج تبريد وتصلب قطرات اليوريا والذي يتم في برج فارغ ذو ارتفاع متزايد مع إنْتاج الجزيئاتِ ذات الحجم الأكبر، تم بناء النموذج الرياضي لبرج تبريد الحبيبات المنصهرة اعتمادا على معادلات اتزان الكتلة والطاقة، وذلك بأعتماد المعادلات التجريبية الخاصة بحساب معاملات انتقال الحرارة والكتلة ان تصميم الأجهزةِ لعمليةِ التبريد وتطبيقها يعتمد على تأثير حجم القطرة المنصهرة ومعاملاتَ انتقال الحرارةِ والكتلةِ. أظهرت النتائج ان أبعاد أجهزةِ التبريد تتأثر بشكل كبير بزيادة حجمِ القطرة المترذذة.