

Eulerian-Lagrangian Analysis of Multiphase Flow in Urea Prilling Process with Phase Changing

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The objective of this work is the mathematical formulation of a prilling tower taking into account the solidification of the urea droplets, calculated by a shrinking unsolidified core model. The multiphase gas-liquid flow was modelled using the Eulerian-Lagrangian approach, where the turbulence was treated with the Reynolds Averaged Navier-Stokes (RANS) equations. The turbulence was modelled with the standard $k-\epsilon$ model. The partial differential equations of the models were discretized using the finite volume method. A source code was written in C language programming and linked in the CFD software. The code consists of subroutines for solidification and the thermal coupling between the phases. A numeric simulation was conducted to analyse the physical consistency of the models and subroutines, whose results showed good agreements.

1. Introduction

Prilling process is widely used when it is conventional to obtain solid products that are easy to pack and convey. Urea prills have been produced in prilling towers based on the cooling-solidification phenomena. In this process, urea melt is pumped to the top of the tower, where the sprayed droplets falls downward inside the tower and exchange mass, heat and momentum with a cooling air stream which enters countercurrent at the bottom of the tower. This way, the air promotes the cooling and the solidification of the droplets. In a practical point of view, it is observed that the main problem in prilling towers is the formation of cake, due to the breakup of partially solidified droplets when they hit each other or hit the walls of the tower. During solidification, a solid thickness starts to grow and an internal conductive resistance inside the droplets appears. This internal resistance strongly affects the heat transfer between the air and the droplets, affecting also the solidification. This way, the heat transfer is one of the major aspects of investigation. Heat transfer investigation in prilling towers has been made by Hashemi and Nourai (2006), Yuan et al. (2007), and Mehrez et al. (2012). Thus, this work intends to simulate a hypothetical three-dimensional prilling tower to evaluate the heat transfer aspects involved and the solidification of the droplets and the physical consistency of the results.

2. Mathematical Formulation

The mathematical formulation of the problem can be described by the Eulerian-Lagrangian approach in which a continuum description is adopted to the gas phase (air) and the discrete phase (urea) is tracked by a Lagrangian trajectory analysis. A more detailed discussion about the Eulerian and Lagrangian approach can be found in Balachandar (2010), Cross et al. (2006), Hoef et al. (2008), Toschi (2009), Yeung (2002). The formulation takes into account some assumptions: the turbulence can be treated with the Reynolds Averaged Navier-Stokes (RANS) equations; the mass transfer is neglected; the interactions between the discrete and continuous phases considers a two-way coupling; constant temperature is assumed during solidification; the droplets has a spherical shape; and the heat transfer mechanisms considered are convection and conduction (during solidification). A shrinking unsolidified core model

described by Yuan (2007) is used to represent the solidification. In prilling process, the urea droplets have three distinct thermal periods: cooling in liquid state until the solidification temperature is reached; solidification at constant temperature in which a solid thickness starts to grow from the outer surface until it reaches the centre and an internal resistance to heat transfer starts to appear; cooling of the solid particles. Hereinafter, the subscripts g , p , l , s and eff represent the gas phase, the droplets or particles, liquid, solid, and effective.

2.1 Lagrangian equations

The first thermal period can be described by a heat balance on the droplets considering only the convective heat transfer:

$$\frac{dT_{pl}}{dt} = -\frac{6h(T_{pl} - T_g)}{\rho_l C_{p_l} d_p}, \quad (1)$$

where T is the temperature (K), ρ is the density (kg/m^3), C_p is the heat capacity (J/kgK), d is the diameter (m), and h is the convective heat transfer coefficient ($\text{W/m}^2\text{K}$). The Eq(1) is valid for $T_{p0} \leq T_p \leq T_f$. For the second thermal period, the latent heat of melting must be removed from the urea droplets by convection, so:

$$UA_p(T_{pf} - T_g) = \Delta H_f(\hat{r}_f)V_p, \quad (2)$$

where A_p is the surface area (m^2), ΔH_f is the latent heat of melting (J/kg), (\hat{r}_f) is the solidification rate (kg/sm^3), V_p is the volume (m^3), and U is the overall heat transfer coefficient ($\text{W/m}^2\text{K}$). Applying the shrinking unsolidified core mode, considering a solid thickness growing inside the liquid droplets, we have:

$$\frac{d\delta}{dt} = \frac{Ud_p^2(T_{pf} - T_g)}{\Delta H_f \rho_{ps}(d_p - 2\delta)^2}. \quad (3)$$

Eq(3) is used to calculate the solid thickness inside the droplets during solidification and it is valid for for $T_p = T_f$. The third period consists of a heat balance in the solid particle, so:

$$\frac{dT_{ps}}{dt} = -\frac{6U(T_{ps} - T_g)}{\rho_{ps} C_{p_{ps}} d_p}. \quad (4)$$

Eq(4) is valid for $T_{ps} < T_f$. The movement of the droplets can be described by a force balance on the droplets considering the weight force, the buoyant force, and the drag force. In this way:

$$\frac{d\mathbf{v}_p}{dt} = \frac{\mathbf{g}(\rho_g - \rho_p)}{\rho_p} + \mathbf{F}_D^{g-p}, \quad (5)$$

where \mathbf{g} is the gravitational acceleration (m/s^2) and \mathbf{F}_D^{g-p} is the drag force (m/s^2), responsible for the two-way coupling between the gas and the droplets. The specific heat (J/kgK) of liquid urea, predicted by Ruzicka-Domalski method, and the specific heat of solid urea, taken from Kozyro (1986), are considered as function of the temperature, where T is in K:

$$C_{p_L} = 8060.242 - 18.23T + 8.40917 \cdot 10^{-4}T^2, \quad (6)$$

$$C_{p_s} = 640.5 + 0.83T + 1.175 \cdot 10^{-2}T^2 - 1.435 \cdot 10^{-5}T^3. \quad (7)$$

2.2 Eulerian equations

Through the assumptions described, the energy conservation for the continuous phase (air) is:

$$\frac{\partial}{\partial t}(\rho_g C_{p_g} T_g) + \nabla \cdot (\rho_g \mathbf{v}_g C_{p_g} T_g) = \nabla \cdot (\lambda_{eff} \nabla T_g) + S_{Ek} + \sum_{i=1}^{n_p} Q^{g-p}, \quad (8)$$

where λ_{eff} is the effective thermal conductivity (W/mK) and Q^{g-p} is the thermal exchange between the phases (W/m^3). The sum term in the right side of Eq(8) is the thermal exchange between the gas and all droplets in the domain and it represents the two-way coupling. The momentum equation is described by:

$$\frac{\partial}{\partial t}(\rho_g \mathbf{v}_g) + \nabla \cdot (\rho_g \mathbf{v}_g \mathbf{v}_g) = -\nabla p_g - \nabla \cdot (\mathbf{T}_{eff}) + \rho_g \mathbf{g} + \sum_{i=1}^{n_p} \mathbf{F}_D^{g-p}. \quad (9)$$

The sum term in the right side of Eq(9) is the drag force from all droplets in the domain and it represents the two-way coupling; T_{eff} is the effective stress tensor (N/m²).

2.3 Closure equations for the model

It is clear that some terms present in the mathematical model presented need to be modelled by constitutive equations. The convective heat transfer coefficient in Eq(1) can be evaluated by the Ranz-Marshall's equation:

$$Nu = \frac{hd_p}{k_g} = 2.0 + 0.6Re^{1/2}Pr^{1/3}, \quad (10)$$

where the Reynolds and Prandtl numbers are, respectively:

$$Re = \frac{\rho_g d_p |\mathbf{v}_g - \mathbf{v}_p|}{\mu_g}, \quad Pr = \frac{\mu_g C_p}{k_g}, \quad (11)$$

where \mathbf{v} is the velocity (m/s) and μ is the absolute viscosity (Pa.s). The overall heat transfer coefficient from second period in Eq(3) is calculated based in two resistance: convective; and conductive. The conductive resistance during solidification is function of the solid thickness, so:

$$U = \frac{1}{1/h + \delta/k_s}, \quad (12)$$

where k_s is the urea thermal conductivity (W/mK). For the third period, in which the droplets are completely solid, Eq(12) becomes:

$$U = \frac{1}{1/h + d_p/2k_s}. \quad (13)$$

The drag force can be described by a constitutive equation defined as:

$$\mathbf{F}_D^{g-p} = \beta^{g-p}(\mathbf{v}_g - \mathbf{v}_p), \quad (14)$$

where the interface coefficient β^{g-p} in Eq(14) can be evaluated as:

$$\beta^{g-p} = \frac{18\mu_g C_D Re}{\rho_p d_p^2 24}, \quad (15)$$

and the drag coefficient C_D can be calculated by the relationships bellow:

$$\begin{cases} \text{For } Re \ll 1 \rightarrow C_D = \frac{24}{Re} \text{ (Viscous Region)} \\ \text{For } 0.1 < Re < 1000 \rightarrow C_D = \frac{24}{Re} (1 + 0.15Re^{0.687}) \text{ (Transition Region)} \\ \text{For } 1000 < Re < 1.0 - 2.0 \times 10^5 \rightarrow C_D = 0.44 \text{ (Inertial Region)} \end{cases} \quad (16)$$

The thermal exchange between the phases Q^{g-p} in Eq(8) is expressed by:

$$Q^{g-p} = UA_p(T_p - T_g). \quad (17)$$

The overall heat transfer coefficient in Eq(17) is evaluated by Eq(12) or Eq(13), depending on the thermal period of the droplets. The turbulence of the continuous phase was modelled with the k- ϵ model. Details about this model can be found on Wilcox (1994).

3. Numerical Study

The three-dimensional numerical simulations were carried out in the software FLUENT from ANSYS®. To perform those simulations, the mathematical equations that described the three thermal periods of urea needed to be implemented in the software because, in Lagrangian simulations, FLUENT does not compute the solidification of discrete droplets. However, the software allows the user to define its own source code and link it to the software. This is made by the User-Defined Functions (UDF), which has to be programed in C language. The code created basically introduces a scalar function that computes the solid thickness and the overall heat transfer coefficient. Into the code, a solidification law was created to inform the software how to compute the temperatures of urea based on the thermal periods. A switch criterion between the standard laws of fluent and solidification law was also created. A source term had to

be added to account the heat transfer from urea droplets to the gas phase. So, a numerical case was performed to analyse the behaviour of code created related to the solidification and also the behaviour of the prilling tower. The code was also tested to calculate the melting of the droplets, as described by Ricardo et al. (2012). A hypothetical cylindrical prilling tower of 2 meters in diameter and 60 m in height was simulated. Air enters at the bottom of the tower at a mean velocity of 1 m/s and at a temperature of 298 K. An injection of 20 liquid urea droplets was created in 55 meters from the bottom of the tower with a mass rate of 0.4 kg/s and a diameter of 1.2 mm. The velocity of injection was 10 m/s at a temperature of 413 K. A hollow cone type was used as injector. The problem was solved in steady state condition. The numerical grid has approximately 230,000 hexaedrics elements. The physical properties used were taken from FLUENT database, with the exception of the latent heat of melting, retired from Yuan (2007), and the specific heat of urea.

4. Results and Discussions

In Figure 1 and 2, the 0 in the horizontal axis represents the bottom and the 60 represents de top of the tower. It is possible to note in Figure 1 (a) that it takes almost 1 meter for the urea droplets to be cooled from its initial temperature (413 K) to the solidification temperature (405.85 K) is reached. This represents the first thermal period. After solidification starts, the droplets temperature becomes constant for approximately 25 meters; this is the second period (solidification). Then the solid particles are cooled until leave the tower at a temperature of 353 K (third period). This temperature profile is qualitatively consistent with the results obtained by Yuan (2007). In Figure 1 (b), the solid thickness remains constant at a value of 0 in the first thermal period, and then starts to increase from 0 until the maximum value of 0.0006. This means that in approximately 25 m the droplet is completely solidified. Then, during the cooling of the solid particle, the solid thickness remains constant.

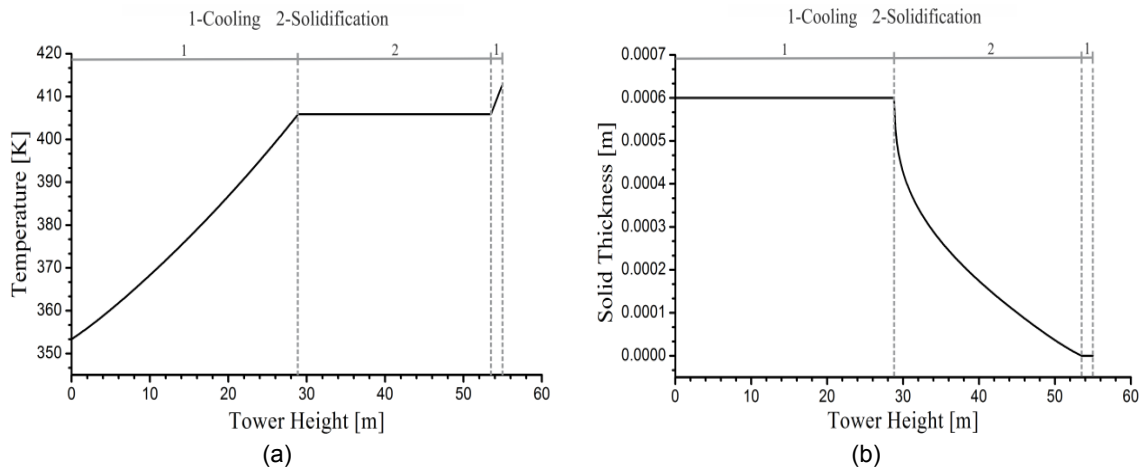


Figure 1: (a) Temperature profile of urea along the tower height; (b) Solid thickness behaviour of urea along the tower height.

The Figure 2 (a) shows the liquid phase diameter inside the urea droplets. Figure 2 (b) shows that in the first period (about 1 meter of fall) the overall heat transfer coefficient, affected only by the convective resistance, is reduced. This happens because when the droplet enters the gaseous medium its velocity is decreased, reducing the relative velocity between the droplet and the air. That reduces the Reynolds number and, thereby, decreases the coefficient value. During solidification, there is a great decrease of the coefficient due to the increase of the conductive resistance inside the droplet that, consequently, reduces the heat transfer between the urea and the air. That affects the complete solidification of the droplets. When the complete solidification is achieved, the coefficient becomes constant. That happens because of: (i) the thermal conductivity of urea was assumed constant and the solid thickness does not change anymore, so the conductive resistance became constant; (ii) the convective heat transfer coefficient is also constant, because the particles reached its terminal velocity, so the Reynolds number does no change and neither does the coefficient.

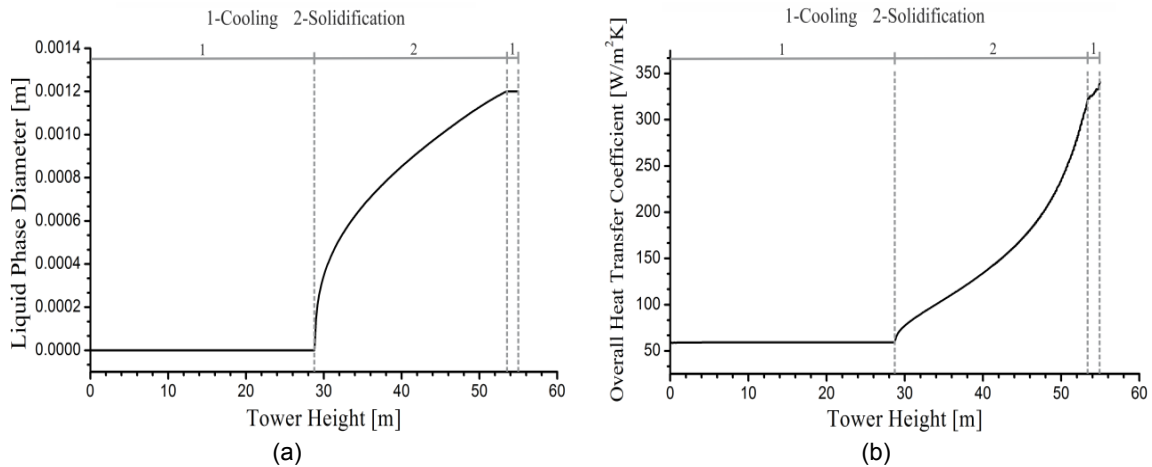


Figure 2: (a) Liquid phase diameter inside the urea droplet along the tower height; (b) Overall heat transfer coefficient along the tower height.

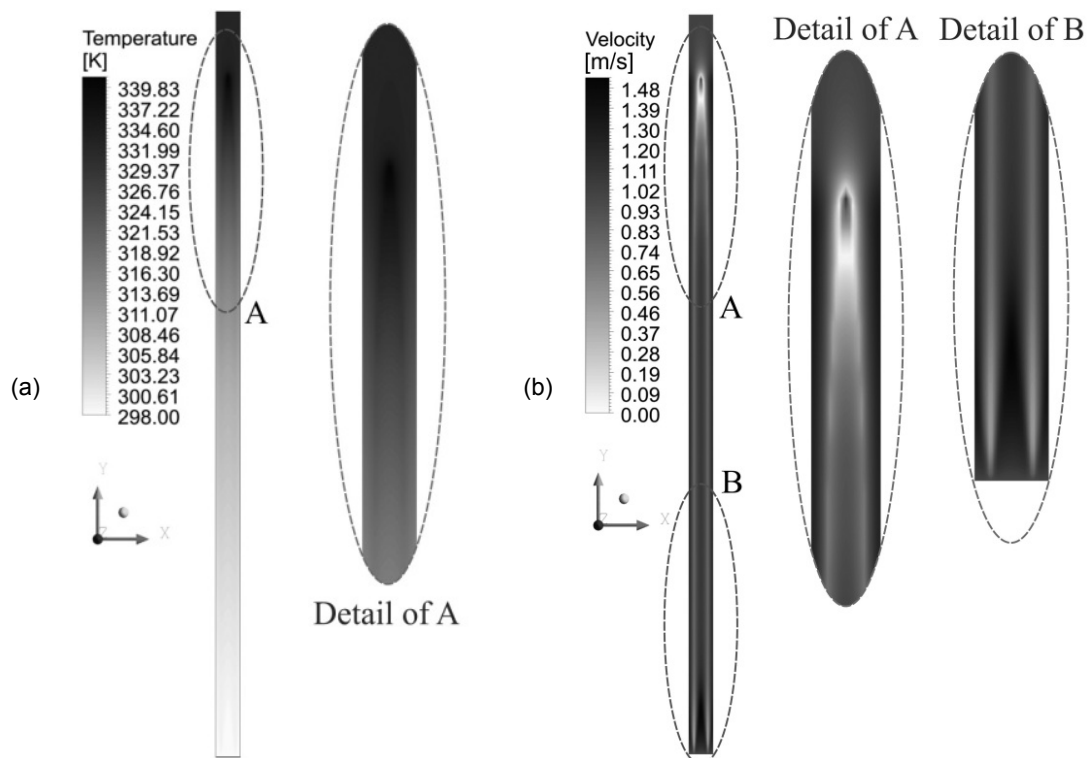


Figure 3: (a) Temperature field of air along the tower height; (b) Velocity field of air along the tower height.

Figure 3 (a) above shows that the air mean temperature at the exit of the tower is about 333 K, a little higher value than the one found by Yuan (2007). It is also noticed that, at the point of the urea injection, there is a sudden increase of the temperature due to the high concentration of droplets. In Figure 3 (b) the air speed is reduced to zero close to the walls. In the droplet injection point (top of the tower), it is observed that the presence of high concentrations of droplets causes a perturbation in the air flow, dramatically reducing its speed.

5. Conclusions

From the analysis of the results, some conclusions can be obtained: (i) the solidification phenomenon can be represented by the heat transfer between both phases; (ii) the results showed that the code developed

and its insertion in the software FLUENT have good agreement with the data presented by Yuan (2007) and that the subroutines are able to capture the solidification phenomenon; (iii) the temperature variation of the air and its temperature at the top of the tower seems acceptable; (iv) the solid thickness and the overall heat transfer coefficient have a direct influence on the heat transfer phenomenon. Thus, it is possible to evaluate important process variables, such as the solid thickness, the diameter of the liquid phase inside the droplets, the temperature profile of the discrete phase and the behaviour of the overall heat transfer coefficient. Also, it is observed that the results from the simulation have physical consistency.

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