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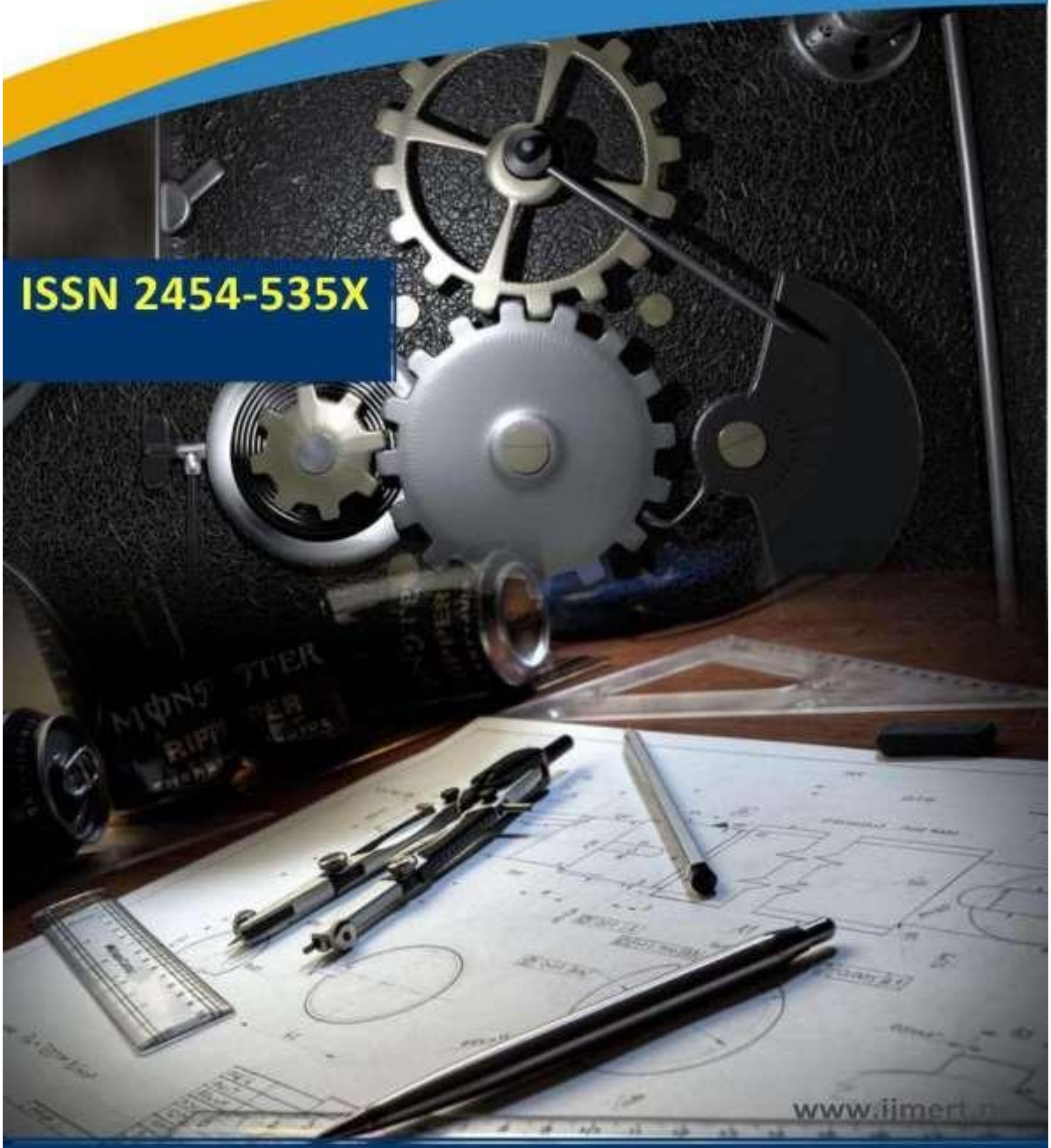

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Modeling of Superheated Steam Thi Thu Hang Tran Drying in Packed Bed

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ABSTRACT:

The continuum-scale model of packed bed superheated steam drying of ceramic particles is presented in this paper. The mass transfer between particles and agent is described in this model using the Reaction Engineering Approach (REA) model. The dehydration of porous particles is modeled in the REA as a process that requires activation energy to cross an energy barrier. After a successful validation, the continuous heat and mass conservation equations of the bed are integrated with the single particle drying model to simulate the drying process. The scaling-up technique suggested in this work can be used to characterize superheated steam dryers, according to the initiative results from the bed simulations.

KEYWORDS: continuum-scale model; Reaction Engineering Approach (REA); superheated steam dryers

INTRODUCTION

In the process of superheated steam drying (SSD), steam can be used as a drying agent at temperatures above the boiling point. Due to its low carbon dioxide emissions, great drying efficiency compared to hot air drying at temperatures above inversion temperature, and low energy consumption, SSD has been used to produce a wide variety of products, including sweet potatoes and coconut [1-3]. In both pilot scale and industrial scale, SSD has been tested in a variety of dryers, including flash dryers, fluidized bed dryers, spray dryers, packed bed dryers, etc. Modeling of heat and mass transmission in the dryer system is difficult [6], hence the solution to this problem lies in simulating the drying of single particles under steady-state circumstances. Single-particle SSD models first appeared in the literature under distributed

MATHEMATICAL MODEL

The packed bed is made of spherical porous particles (ceramic particles) and gaseous phase (superheated drying agent). The representative volume is shown in Figure 1. Model is built based on model in [6] with several assumptions as:

1. Bed porosity is uniform and gas flow is plug flow.
2. The viscos dissipation and compression are negligible.
3. Amount of vapor generated within the bed is relatively small compared to the steam flow supplied to the bed.135

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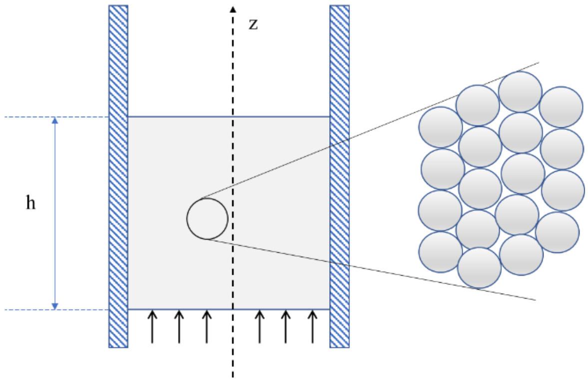

Figure 1. Schematic geometry of packed bed

Drying kinetic

As above mentioned, the drying kinetics is modelled like zero law of reaction kinetic, as called Reaction Engineering model (REA). The evaporation flux is written as:

$$\dot{m}_v = -\beta\left(\rho_{v,surf} - \rho_{v,b}\right) \tag{1}$$

Where β (m/s) is the mass transfer coefficient. $\rho\rho_{ssssssss}$, $\rho\rho_{vv,bb}$ (kg vapor/m3) are the density of the vapor at the particle surface and of the bulk steam flow.

Due to the appearance of solid, the vapor density on the particle surface is lower than that on the pure water droplet surface. This difference is modelled by:

$$\rho_{v,surf} = exp\left(\frac{-\Delta E_v}{RT_s\,[K]}\right)\rho_{v,sat}(T_s) \tag{3}$$

In which, ΔE_v is the activation energy represented for the energy barrier which evaporation need to overcome, T_s is particle temperature. When the heat and mass transfer between particle and drying agent cease, the particle temperature reaches the vapor bulk temperature and moisture particle equals to equilibrium moisture content. In this case, the activation energy is equilibrium activation energy, ΔE_{eq}.

$$\Delta E_{v,eq} = RT_{v,b}\, ln\frac{p_{v,b}}{p_{v,sat}(T_{v,b})} \tag{4}$$

The relationship between ΔE_v and ΔE_{eq} is determined in [13] as following:

$$\frac{\Delta E_v}{\Delta E_{v,eq}} = \frac{7.42\times10^{-3}}{\left(X - X_{eq}\right) + 7.63\times10^{-3}}, \tag{5}$$

with X and X_{eq} are the temporal moisture content and equilibrium moisture content of particles.

The heat transfer is calculated as [14] and mass transfer is calculated as [12]:

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$$Nu = 2 + 0.616\, Re^{0.52}\, Pr^{\frac{1}{3}}$$

$$Sh = 0.144 + 0.579\, Re^{0.5}\, Sc^{1/3} \quad (6)(7)$$

The above drying kinetic model was successful validated in [13], the typically validation of single ceramic particle drying in superheated steam is presented in Fig.2. In which, the experimental data is extracted from [14]. The drying conditions are as following: Particle diameter is 10 mm, initial water content is 0.15 kgw/kgs, initial bulk flow velocity is 4.8 m/s at temperature of 150C and pressure of 1 bar. There is good agreement between experimental and predictive data. Thus, in this work, the received model is applied to calculate evaporation flux from particle to bulk [15-18].

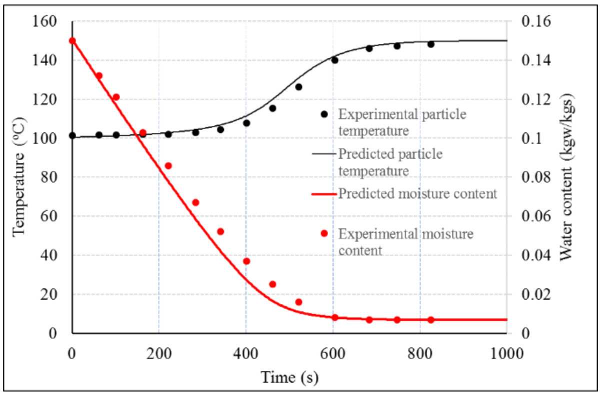

Figure 2. Evolution of particle temperature and moisture content over time of ceramic particle at $T_{v,b}$ = 150 °C and $v_{v,b}$ = 0.48 m/s

Heat and mass transfer equation

Energy conservation equation written for fluid phase as Eq.8. Inwhich, change of vapor temperature over time is due to the convective and conductive energy flow of the vapor phase, enthalpy flow from evaporated vapor and convective heat transfer flow between particle and vapor.

$$\psi c_{p,v} \rho_v \frac{\partial T_v}{\partial t} + c_{p,v} \rho_v v_v \frac{\partial T_v}{\partial z} = \frac{\partial}{\partial z}\left(\lambda_{v,eff} \frac{\partial T_v}{\partial z}\right) - m_v A_v c_{p,v} \left(T_v - T_s\right) - \alpha A_v \left(T_v - T_s\right) \quad (8)$$

Similarly, the change of solid phase temperature is the results of conductive thermal energy flow from solid, used evaporation heat flow and convective heat flow as:

$$(1-\psi)\left(c_{p,s,eff}\, \rho_{s,eff}\right) \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial z}\left(\lambda_{s,eff} \frac{\partial T_s}{\partial z}\right) - m_v A_v \Delta h_{evp} + \alpha A_v \left(T_v - T_s\right) \quad (9)$$

Mass conservation equation for solid phase

$$(1-\psi)\frac{\partial \rho_{s,eff}}{\partial t} = -m_v A_v \quad (10)$$

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In which, the evaporation flux is calculated by REA model. The effective solid density, heat capacity, effective thermal conductivity of solid and vapor are lculated as function 11-14. $c_{p,s,eff}\,\rho_{s,eff}\rho_{s,eff} = \rho_s\left(1+X\right) = \rho_s\left(c_{p,s}+Xc_{p,l}\right.$

1)12)$\lambda\left(1-\psi^{s}\right)_{,e}\quad {}_{s}\,V^{l}\;V$ (13)

$= \left(1-\psi\right)\left(\lambda_s\rho_s+\lambda_l\rho_l X\right)\lambda_{f,eff}=\psi\lambda_v(14)A_v$ m^2/m^3 is specific surface area of unit volume. It is calculated as the total of particle surface in the bed volume of 1 m^3. Initial conditions

Initial temperature and moisture contents are constant:

$T_v\left(0,z\right)=T_s\left(0,z\right)=T_i X\left(0,z\right)=X_i$(15)(16)

Thermal boundary conditions At the inlet, the temperature of vapor is assumed constant Particle temperature is determined by: $\partial T_v = 0\,\partial t$(17)

$$\left(1-\psi\right)c_{p,s,eff}\,\rho_{s,eff}\frac{\partial T_s}{\partial t}=\frac{\partial}{\partial z}\left(\lambda_{s,eff}\frac{\partial T_s}{\partial z}\right)\Bigg|_{z=0} - m_v A_v\Delta h_{evp}+\alpha A_v\left(T_v-T_s\right) \quad (18)$$

At the outlet, energy conservation for particles and vapor are calculated as:

$$\left(1-\psi\right)c_{p,s,eff}\,\rho_{s,eff}\frac{\partial T_s}{\partial t}=\frac{\partial}{\partial z}\left(\lambda_{s,eff}\frac{\partial T_s}{\partial z}\right)\Bigg|_{z=h} - m_v A_v\Delta h_{evp}+\alpha A_v\left(T_v-T_s\right) \quad (19)$$

$$\left(1-\psi\right)c_{p,s,eff}\,\rho_{s,eff}\frac{\partial T_s}{\partial t}=\frac{\partial}{\partial z}\left(\lambda_{s,eff}\frac{\partial T_s}{\partial z}\right)\Bigg|_{z=h} - m_v A_v\Delta h_{evp}+\alpha A_v\left(T_v-T_s\right) \quad (20)$$

The partial differential equation system developed in this work (Eqs. 8-10) is spatially discretized and the resulting ordinary differential equations are solved by *ode23s* function of MATLAB (version 2016) for packed bed drying of ceramic particles with a diameter of 10 mm, initial moisture content of 0.1 kgw/kgs and initial particle temperature is 40°C. The drying conditions are: initial vapor velocity is 0.5 m/s, initial vapor temperature is 175°C (pressure is 1 bar). In which packed bed height is 50 mm.

RESULTS

The mathematical model is applied to predict the heat and mass transfer between steam and superheated steam flow. The evolutions of particle water content, particle temperature and vapor temperature are reported as Fig.3 – Fig.5 at three positions in the packed bed, namely at inlet plane of vapor, at the middle height of bed and outlet plane of vapor.

Water content of particle

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Reduction of water content over time is the most important result because it effects on the drying time. Fig.3 shows the different evaporation velocity of three positions; in which, the drying at the bottom of bed is the fastest while the drying at the top of bed is the slowest. Particularly, while the bottom plane spent about 920 s to reach the equilibrium moisture content, the middle bed plane needs near 1250s to reach this state and the top bed plane takes about 1800s. This can be explained by the reduction of vapor temperature corresponding with the increase of height position as Fig.5 which will be discussed later.

In the first drying stage, the condensation of vapor on the drying particle can be observed clearly. This period occurs in around several second before particle temperature reaches the boiling point; however, the moisture content increases from 0.1 kgw/kgs at the beginning to 0.14 kgw/kgs. Thus, the drying model can be extrapolated to take the condensation period into account; of course, this needs to validate by experiment.

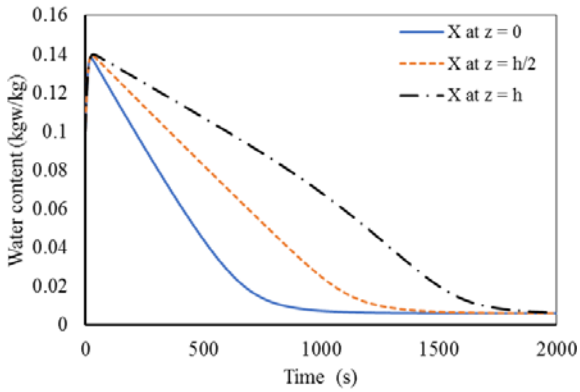

Figure 3. Evolution of particle water content over time at different positions.

Particle temperature

Changes of particle temperatures at different positions of bed are described in Fig. 4. Temperature particle increases from uniform temperature at the begining to the boiling point (near 100°C). This period corresponds with the condensation period as mentioned in Fig.3. Then the boiling temperature is remained for all positions for cetainly time period because the transferred heat is used for only evaporation. After that, the temperature at the bottom of the bed increases gradually, then followed by the middle bed and top of the bed. In this period, the thermal energy is used for both latent heat and sensible heat. The transition between the constant temperature period and increase temperature period is smooth. That is because the REA model does not separate the drying process into different periods. The bottom position reaches the vapor temperature after 1500s corresponsding with the equilibrium heat transfer of this position.

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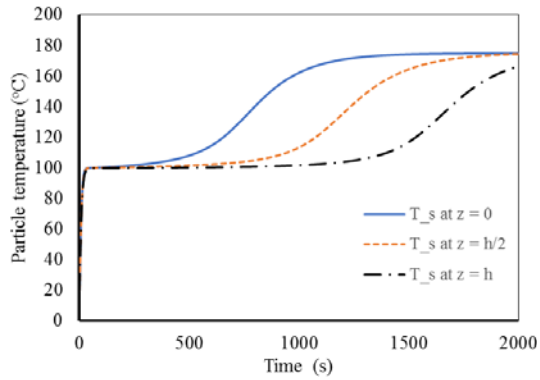

Figure 4. Particle temperature over time at different positions

Vapor bulk temperature

The vapor temperature field is shown in Fig.4. While temperature at the inlet of bed is remained constant as initial drying condition, the evolutions of temperature at other positions experience three periods. Firstly, temperature drop dramatically to near 123°C due to the highe evaporation speed. After that the temperatures are remained constant corresponding with the constant temperature of solid phase as Fig. 3. In other words, in this stage the heat and mass transfer in the bed are stable for both solid and vapor phases. Finally, the temperature of bed increases to the equilibrium tempeartue due to the reduction of evaporation speed in this period.

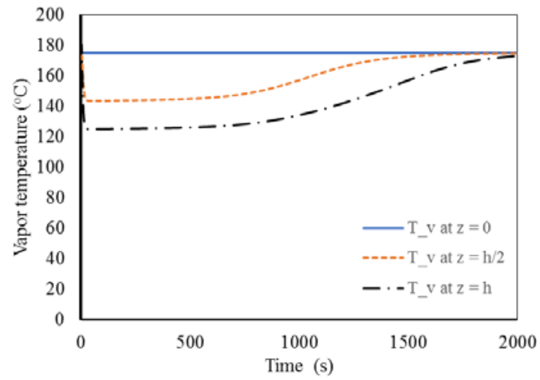

Figure 5. Vapor temperature over time at different positions.

CONCLUSIONS

In this work, a full model of superheated steam drying for ceramic particles in the packed bed dryer is presented. In which, the validated kinetic model is combined with the heat and mass balance equations for both vapor and solid phases. Changes of particle moisture content, vapor and particle temperatures are examined and verified. The heat and mass transfer occurred fastest at the bottom of the packed bed where the vapor temperature is the highest; the change of states can be earliest observed at this position. Although, the model still needs to validate by experiments, but the model can be promised to calculate the condensation period, in which, the particle temperature is still lower than boiling point. After that, the particle and vapor phases have the constant temperatures corresponding with the constant drying period. Finally, both the particle temperature and superheated steam temperature increase gradually to the equilibrium temperature (vapor temperature at the bottom bed). REA model expresses the good application ability to the packed bed drying model. This model can be certainly implemented in other dryer systems such as fluidized bed, spray dryer.

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