Modeling and Control of a Fluidised Bed Dryer

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Abstract: In this paper, the modelling and control of the moisture content of the particles in a batch Fluidised bed dryer are studied. First, a lumped mechanistic model is developed to describe the heat and mass transfer between solid, gas and bubble phases and experimental validation shows that the model can be used to predict the particle moisture content and temperature profiles during the drying process in the bed dryer. Feedback control of material moisture content in a bed dryer is studied where the moisture content is obtained by measuring the humidity and temperature of the outlet gas. A controller is designed to achieve a desired drying rate for wet materials.

1. INTRODUCTION

Fluidised beds have been used for many years in the food, pharmaceutical and chemical industries for carrying out a wide range of chemical reactions and unit operations. One of the primary advantages of Fluidised bed systems arises from the fact that the high turbulence created in the bed provides high heat and mass transfer, as well as complete mixing of the solids and gases within the bed.

Much work has been done to model and analyse both continuous and batch Fluidised bed dryers Palancz [1983], Lai et al. [1986], Li and Duncan [2008], Syahrul et al. [2003], Wang et al. [2007b], Wang et al. [2007a] and several studies have attempted to control the moisture content in a continuous Fluidised bed dryer Abdel-Jabbar et al. [2005], Temple et al. [2000]. However, it seems that little work has been done to control batch Fluidised bed dryers. In fact, in many situations manual control procedures are used and it is also known that the majority of industrial dryers operate at low efficiency levels Dufour [2006]. It is clear that the use of control tools allow to improve quality product and to decrease energy consumption.

This paper presents a mathematical model to describe the heat and mass transfer between solids, gas and bubble phases, which is based on Palancz [1983] and Li and Duncan [2008]. This model can be used to improve the operating conditions in both open and closed loop control. A simple control scheme has been designed to control the material moisture content in the bed dryer. Because of the difficulty in online measurement of moisture content, compared with temperature measurement, it is usually necessary to estimate the moisture from other measurements (e.g. temperature) by means of an observer. To overcome this problem, it is proposed to measure the moisture content from the relative humidity and temperature of the outlet gas. This simplifies the control design process and as will be shown here, a simple (PI) control law can be designed that gives good performance under feedback control.

This paper is organised as follows. In Section 2, the mathematical model describing the bed dryer is presented, followed by the model validation in Section 3. The measurement and control of moisture in the bed dryer are described in Section 4. Finally, some conclusions are discussed in Section 5.

2. MODEL DESCRIPTION

In this section we briefly present the mathematical model used to describe the mass and heat transfer between solid, gas and bubble phases in a batch Fluidised bed dryer. This is based on a simple two-phase model Kunii and Levenspiel [1991] that includes a bubble phase and an emulsion phase, which in turn consists of an interstitial gas phase and a solid phase. The following are assumptions used to obtain the model:

1. In the bubble phase, gas moves upward as a plug flow.
2. In the bubble-gas phase, both the gas and the bubbles move upwards.
3. In the emulsion phase or dense phase, solids move downward.
4. All particles in the bed are uniform in size, shape and physical properties and have the same moisture

content and temperature at any instant during the drying process.

5. The interstitial gas is perfectly mixed with the solid particles. There is heat and mass transfer between the interstitial gas and the other two phases: bubble and solid phases.
6. The bubble phase contains no particles and the clouds surrounding the rising bubbles are sufficiently thin that the bubble phase exchanges heat and mass only with the interstitial gas phase. The bubble size is assumed to be uniform and does not depend on the location within the bed. The gas in each bubble is perfectly mixed so that the moisture content and temperature are the same in the bubble. The moisture content and temperature in a bubble depends only on its position in the dryer.

2.1 Mass and Energy Balance for Bubble Phase

It is assumed that as a bubble rises through the bed, its size and velocity remain constant with the bed height, while its moisture content and temperature change due to the exchange of mass and heat with the interstitial gas. This has been verified for the case $U_0 \geq 2U_{\rm mf}$ (Bukur et al. [1974]).

According to the simple two-phase model, the rising velocity of a single bubble relative to the emulsion phase and the absolute velocity of the bubble phase in the bed are given by

$$U_{br} = 0.711(gd_b)^{1/2} \quad U_b = U_0 - U_{mf} + U_{br}, \qquad (1)$$

where the minimum fluidization velocity can be found from (Kunii and Levenspiel [1991])

$$\frac{1.75}{\varepsilon_{mf}^3}\left(\frac{d_p\mu_{mf}\rho_g}{\mu_g}\right)^2 + \frac{150(1-\varepsilon_{mf})}{\varepsilon_{mf}^3\xi^2}\left(\frac{d_p\mu_{mf}\rho_g}{\mu_g}\right) = \frac{d_p^3\rho_g(\rho_w s - \rho_g)g}{\mu_g^2}. \qquad (2)$$

The fraction of the bubble volume in the bed δ_b is given by

$$\delta_b = \frac{U_0 - U_{mf}}{U_b} \qquad (3)$$

and the value of voidage of emulsion phase at the minimum fluidisation condition $\varepsilon_{\rm mf}$ can be calculated as

$$\varepsilon_{mf} = 0.586\xi^{-0.72}\left(\frac{\mu_g^2}{\rho_g(\rho_{ws}-\rho_g)gd_p^3}\right)^{0.029}\left(\frac{\rho_g}{\rho_{ws}}\right)^{0.021}. \qquad (4)$$

Mass Balance The mass balance for the bubble phase in the control volume can be written as

$$U_b\frac{dx_b}{dz}(z) = K_{be}(x_e - x_b) \quad \text{with } x_b = x_0 \text{ at } z = 0. \qquad (5)$$

The equation above can be integrated to find the analytical solution of the bubble moisture content (Li and Duncan [2008]), from which the average moisture content of bubbles along the vertical position of the Fluidised bed dryer can be found as

$$\tilde{x}_b = x_e + (x_e - x_0)\frac{U_b}{K_{be}H_f}\left(\exp\left(-\frac{K_{be}}{U_b}H_f\right) - 1\right). \qquad (6)$$

Energy Balance The steady state energy balance in the control volume leads to

$$\frac{dT_b}{dz}(z) = \left(\frac{H_{be}}{\rho_g U_b\left(c_g + c_{\rm wv}x_b\right)}\right)(T_e - T_b) \qquad (7)$$

with $T_b = T_0$ at $z = 0$. The interchange coefficient of mass transfer between the bubble and interstitial gas phases K_{be} and the interchange coefficient of heat transfer between the bubble and interstitial gas phases H_{be} are given in Kunii and Levenspiel [1991] and Li and Duncan [2008].

2.2 Mass and Energy Balance for the Interstitial Gas Phase

The interstitial gas exchanges mass with both the bubble phase and solid particles. It also exchanges heat with the dryer wall.

Mass Balance The mass balance can be simplified as (Palancz [1983], Li and Duncan [2008])

$$\rho_g\frac{U_{mf}}{H_f\delta_b}(x_e - x_0) = \rho_g K_{be}(\tilde{x}_b - x_e) + \frac{6\,(1-\varepsilon_{mf})(1-\delta_b)}{d_p\delta_b}\sigma\,(x_p^* - x_e) \qquad (8)$$

Energy Balance The energy balance can be simplified as (Palancz [1983], Li and Duncan [2008])

$$\frac{\rho_g U_{mf}}{H_f}(c_g + c_{\rm wv}x_0)(T_e - T_0) = \delta_b H_{be}(\tilde{T}_b - T_e) + \alpha_w h_w(T_w - T_e) + \frac{6\sigma}{d_p}(1-\varepsilon_{mf})(1-\delta_b)(T_p - T_e)\left(c_{\rm wv}\sigma\,(x_p^* - x_e) + h_p\right) \qquad (9)$$

where the specific wall-surface for heat transfer is $\alpha_{ex} = S_w/V_{tot}$ and the space-average bubble-phase temperature is obtained from (7) as

$$\tilde{T}_b = T_e + (T_e - T_0)\frac{\rho_g(c_g + x_b c_{\rm wv})U_b}{H_{be}H_f}\cdot\left(\exp\left(-\frac{H_{be}}{\rho_g(c_g + x_b c_{\rm wv})U_b}H_f\right) - 1\right) \qquad (10)$$

The coefficient of convective heat transfer between solids and gas is calculated by (Kunii and Levenspiel [1991])

$$\mathrm{Nu}_p = \frac{h_p d_p}{k_g} = 2 + 1.8\,\mathrm{Re}_p^{1/2}P_r^{1/3} \qquad (11)$$

with

$$\mathrm{Re}_p = \frac{d_p U_0 \rho_g}{\mu_g} \quad \text{and} \quad P_r = \frac{c_p\mu_g}{k_g}. \qquad (12)$$

The evaporation coefficient is given by $\sigma = (h_p\rho_g D_g)/k_g$. Several methods are available to predict the heat-transfer coefficient between the interstitial gas and the dryer wall. In Li and Finlayson [1977] the authors found that the best correlation for spherical packing is

$$h_w = 0.17\,\mathrm{Re}_p^{0.79}\frac{k_g}{d_p}. \qquad (13)$$

2.3 Mass and Energy Balance for Solid Phase

Mass Balance Under normal drying conditions the moisture content of a solid particle decreases by evaporation of its moisture into the interstitial gas. The rate at which the moisture content decreases is given by

$$-\frac{\rho_s}{1+\frac{\rho_s}{\rho_w}x_{pc}}\frac{d\tilde{x}_p}{dt}=\frac{6}{d_p}\sigma\left(x_p^*-x_e\right)\text{ with }\tilde{x}_p(0)=x_{p0}. \quad (14)$$

Energy Balance The energy balance for a particle can be simplified as (Palancz [1983], Li and Duncan [2008])

$$\rho_s(c_p+\tilde{x}_p c_w)\frac{dT_p}{dt}=\left(1+\frac{\rho_s}{\rho_w}x_{pc}\right)\frac{6}{d_p}\Big(h_p(T_e-T_p) - \sigma(x_p^*-x_e)(c_{\mathrm{wv}}T_e-c_wT_p+\gamma_0)\Big) \quad (15)$$

with the initial condition $T_p = T_{p0}$ at $t = 0$. In the equation above, γ_0 is the heat of vaporisation of water at a reference temperature $T_{\mathrm{ref}} = 0$. The value of the moisture content of the saturated drying medium at the surface of the solid particle depends on the temperature and the moisture content of the particle, i.e.,

$$x_p^*=\Psi_1(T_p)\,\Psi_2(\tilde{x}_p) \quad (16)$$

where $\Psi_1(T_p)$ can be obtained from Mollier charts, and $\Psi_2(\tilde{x}_p)$ is a correction function depending on the character of the solid-moisture system. $\Psi_1(T_p)$ can be approximated by (Palancz [1983])

$$\Psi_1(T_p)=0.622\,\frac{P_w}{760-P_w}\text{ with }P_w=10^{0.622+\frac{7.5\,T_p}{238+T_p}}, \quad (17)$$

when $0 < T_p < 100^oC$. A drying process consists of two phases: a constant rate drying and a falling rate drying. During the constant rate phase the correction function $\Psi_2(\tilde{x}_p)$ can be set as (Lai et al. [1986])

$$\Psi_2(\tilde{x}_p)=\begin{cases}1 & \text{for } x_p\geq x_{pc}\\ \dfrac{\tilde{x}_p^n(x_{pc}^n+K)}{x_{pc}^n(\tilde{x}_p^n+K)} & \text{for } x_p<x_{pc}\end{cases}. \quad (18)$$

3. MODEL VALIDATION

The process model has been validated using data obtained from a Sherwood M501 Fluidised bed dryer, where the wet product used is rice granules.

Equations (6), (8), (9), (10), (14) and (15), with appropriate boundary conditions, constitute the governing equations of the dynamic model of a batch Fluidised bed dryer. To determine the moisture content and temperature profiles of solid particles in the dryer during a drying process, the set of first-order differential equations (14) and (15) were solved using a 4th order Runge-Kutta algorithm. At each time step, the moisture content x_p^* of the drying gas on the surface of particles is firstly calculated according to the temperature and the averaged moisture content of the particle (see equations (16)-(18)). Then the algebraic equations (6) and (8) are solved to determine the moisture contents of bubble and interstitial gas phases $\tilde{x}_b$ and x_e. The interstitial gas and the bubble gas temperature, T_e and $\tilde{T}_b$, can be calculated using equations (9) and (10). Finally the moisture content and temperature of solid particles are updated based on the calculated results.

In order to predict the moisture and temperature profiles of the wet product in the dryer, the physical properties of the product and the geometrical parameters of the dryer have to be determined for use in the model. As some of the parameters are difficult to measure (e.g. the constants n and K in equation (18), the effective bubble diameter) or vary from one batch to another (e.g. particle size, critical moisture content) approximations are made so that the profiles of the temperature and moisture content are predicted accurately for a range of initial conditions. A constant wall temperature assumption is not valid in this case, because a significant temperature increase of the dryer wall was observed during the drying process. Therefore, the wall temperature was measured and included in the simulations. The parameter values are shown in Table 1.

Table 1. Parameters used in the simulation of the drying of rice

$g = 9.81$	$k_g = 2.93\times10^{-2}$	$D_g = 2.1\times10^{-5}$
$n = 1.1$	$c_w = 4.19\times10^3$	$H_f = 0.56$
$\rho_g = 1$	$\mu_g = 2.1\times10^{-5}$	$\rho_s = 760$
$D_c = 0.16$	$\gamma_0 = 2.5\times10^6$	$c_g = 1.06\times10^3$
$K = 0.45$	$c_{\mathrm{wv}} = 1.93\times10^3$	$c_p = 1.6919\times10^3$
$\rho_w = 1000$	$d_p = 2\times10^{-4}$	$d_b = 0.06$
$\xi = 1$	$x_{pc} = 16.5\%$	

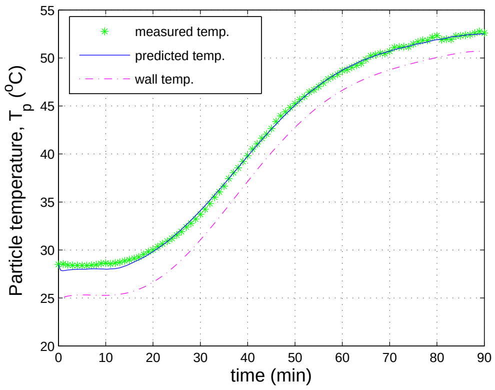

Fig. 1. Particle and wall temperature.

In the test, the inlet air velocity was kept constant at $2.63\,\mathrm{m\,s^{-1}}$ during the first 6 minutes after which it is reduced to $2.39\,\mathrm{m\,s^{-1}}$. The inlet air temperature was fixed at 65 °C. The initial moisture content (x_{p0}) was 25.81%, the initial particle temperature (T_{p0}) was 28.5 °C and the initial moisture content of the inlet air (x_0) was set to 1.1%. The predicted temperature and moisture with the measurements is shown in Figures 1 and 2 respectively. It is concluded that the model can predict well the temperature and moisture content profiles.

4. CONTROL OF MOISTURE CONTENT BY MEASURING OUTLET GAS PROPERTIES

Feedback control of material moisture content in a bed dryer is studied by measuring the outlet air temperature and relative humidity. It is explained how to obtain from these measurements the moisture content of the material in the bed. A controller is designed to achieve a desired drying rate for wet materials. Results show that it is possible to control the drying rate.

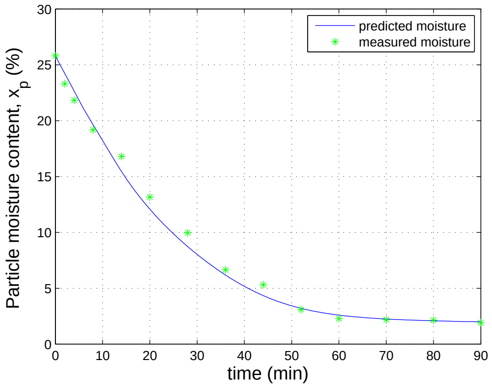

Fig. 2. Moisture content in the particles.

Table 2. Parameters used to calculate P_v.

$a_0 = 6.11176750$	$\tilde{a}_0 = 6.41525348$
$a_1 = 0.443986062$	$\tilde{a}_1 = 7.2647332$
$a_2 = 0.143053301E-01$	$\tilde{a}_2 = -2.9896001$
$a_3 = 0.265027242E-03$	$\tilde{a}_3 = 1.105979031$
$a_4 = 0.302246994E-05$	$\tilde{a}_4 = -0.317993273$
$a_5 = 0.203886313E-07$	$\tilde{a}_5 = 4.763777499E-2$
$a_6 = 0.638780966E-10$	

4.1 Moisture Measurement

It is possible to measure the moisture content in a Fluidised bed dryer by measuring the relative humidity and the temperature of the outlet gas. To do that we first need to find the saturation vapor pressure (P_v). This can be done using the approximation given in Flatau et al. [1992],

$$P_v = a_0 + a_1 T_{\text{out}} + a_2 T_{\text{out}}^2 + \cdots + a_6 T_{\text{out}}^6 \tag{19}$$

where P_v is the saturation vapor pressure in mbar, T_{out} is the temperature of the outlet gas in ^{o}C, and the coefficients a_i are shown in Table 2. Note that it can also be approximated by

$$P_v = \frac{1}{100} \exp\left(\tilde{a}_0 + \tilde{a}_1 \left(\frac{T_{\text{out}}}{100}\right) + \cdots + \tilde{a}_5 \left(\frac{T_{\text{out}}}{100}\right)^5\right),$$

where the coefficients $\tilde{a}_i$ are shown in Table 2. Once P_v is know it is possible to calculate the partial pressure of water vapor (P_w) as follows

$$P_w = \frac{H_r\, P_v}{100} \tag{20}$$

where H_r is the percentage of relative humidity of the gas. The humidity ratio at the inlet and outlet of the dryer can now be calculated as follows

$$M_{w,\text{in}} = 0.62198 \frac{P_{w,\text{in}}}{P_a - P_{w,\text{in}}}, \quad P_{w,\text{in}} = \frac{H_{r,\text{in}}\, P_v}{100} \tag{21}$$

and

$$M_{w,\text{out}} = 0.62198 \frac{P_{w,\text{out}}}{P_a - P_{w,\text{out}}}, \quad P_{w,\text{out}} = \frac{H_{r,\text{out}}\, P_v}{100}. \tag{22}$$

In the equations above $M_{w,\text{in}}$ and $M_{w,\text{out}}$ are the inlet and outlet humidity ratios, $H_{r,\text{in}}$ and $H_{r,\text{out}}$ are the relative humidity of the inlet and outlet gas, respectively, and P_a is the atmospheric pressure in mbar.

The inlet air flow rate M_f is given by

$$M_f = 0.006362 \cdot 0.9\, \rho_{\text{air}}\, U_0, \tag{23}$$

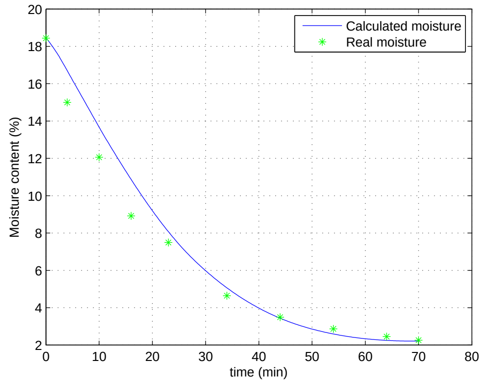

Fig. 3. Measured and calculated moisture content in a bed dryer.

where U_0 is the inlet air velocity in m^3/min and the density of the air, ρ_{air}, can be calculated as

$$\rho_{\text{air}} = d_0 + d_1 T_{\text{out}} + d_2 T_{\text{out}}^2, \tag{24}$$

with $d_0 = 1.24703$, $d_1 = -0.002787$, and $d_2 = -3.23518E-5$. Now it is possible to calculate the total water loss (W) from the solid phase

$$W = \int_0^t (M_{w,\text{out}} - M_{w,\text{in}}) M_f \, dt. \tag{25}$$

Finally, the particle moisture content can be found as follows

$$x_p = \frac{W_0\, x_{p,0} - W}{W_0 - W}, \tag{26}$$

where W_0 is the initial sample weight, $x_{p,0}$ is the initial particle moisture content, and W is given in (25). Figure 3 shows one example of the calculated moisture and the real one.

Sensitivity analysis In this subsection we study the sensitivity of the above approach to variations in the initial weight (W_0), initial moisture ($x_{p,0}$), and relative humidity of the inlet air ($H_{r,\text{in}}$). Figure 4 shows the effect of a variation of 5% in the initial weight (W_0). It can be seen that the relative error is increasing with time and the maximum relative error can reach up to 40%. The effect of the initial moisture $x_{p,0}$ is shown in Figure 5. Unlike Figure 4, the difference between the original and changed data changes less with time. However, the maximum relative error can reach up to 47%. Variations in $H_{r,\text{in}}$ affect much less the calculated moisture content as can be seen in Figure 6. The error changes less with time.

4.2 Control Of Fluidised Bed Dryer

In most industrial processes, accurate moisture control of wet particles is required to improve the quality and consistency of the product. Because of the difficulty in measuring the moisture content directly, it is necessary to include the design of an observer in the control loop in order to estimate the moisture content from the measured temperature of the wet product. Another alternative is to obtain the moisture content by measuring online the outlet gas properties as described in the previous section.

In the model parameter sensitivity analysis of batch Fluidised bed dryers Li and Duncan [2008], it has been shown

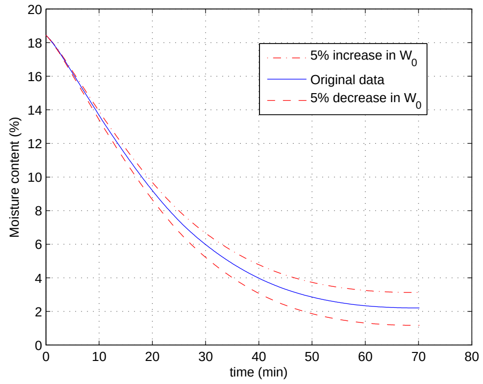

Fig. 4. Sensitivity with respect to W_0.

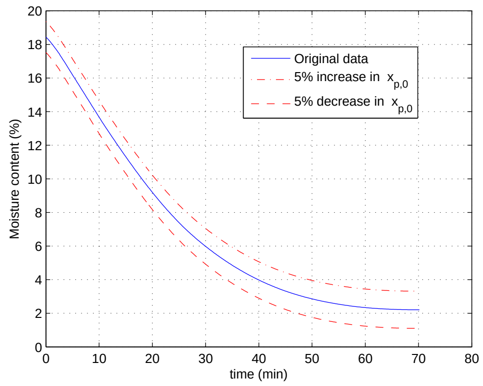

Fig. 5. Sensitivity with respect to $x_{p,0}$.

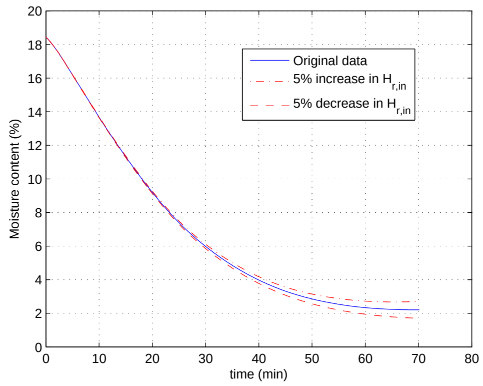

Fig. 6. Sensitivity with respect to $H_{r,\text{in}}$.

that the performance of a Fluidised bed dryer is dominated by the inlet gas velocity rather than the inlet gas temperature (T_0). This suggests that the inlet gas velocity (U_0) can be chosen as the only manipulated variable for control, while the inlet gas temperature can be kept constant, see Fig. 7. A PI (proportional plus integral) controller was designed to achieve a desired drying rate of wet materials. The manipulated inlet gas velocity is constrained to lie in the range $0.3\text{m}\,\text{s}^{-1} \leq U_0 \leq 3.5\text{m}\,\text{s}^{-1}$. Two different situations are considered in the experiments:

1. First, the desired drying rate is set to a constant value of 5×10^{-5} per second. In this case, the proportional

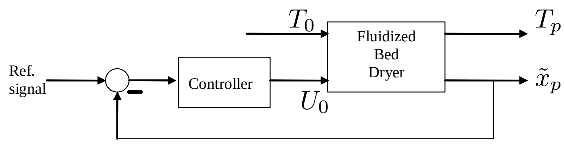

Fig. 7. Control Loop.

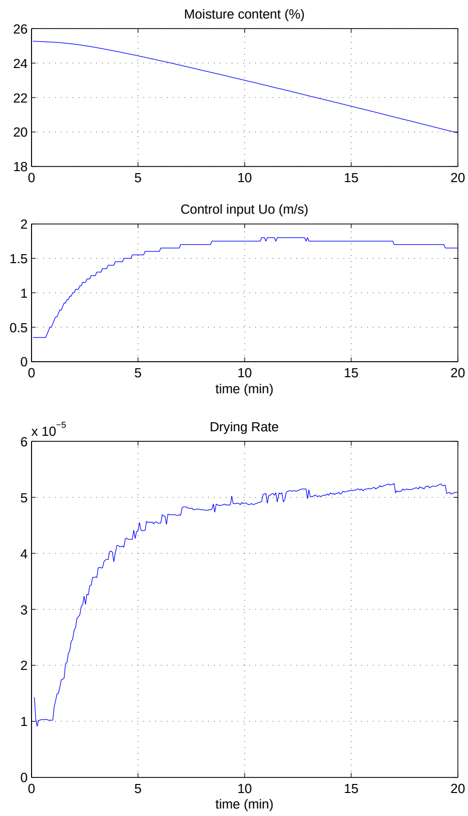

Fig. 8. Control input and moisture content using a PI controller (top), and drying rate (bottom).

gain K_p is set to 100 and the integral gain K_I is set to $0.01\,s^{-1}$. Fig. 8 shows the output of the closed-loop system. It can be seen that the particle moisture profile follows the desired drying curve with a drying rate of 5×10^{-5} per second, see 8.

2. In a second instance, the reference signal is set so that different desired drying rates are followed. In this case, the proportional gain K_p is set to 100 and the integral gain K_I is set to $0.08\,s^{-1}$. The output of the closed-loop system is shown in Fig. 9. Again, the output follows the desired drying curve with an average error less than 5%.

5. CONCLUSIONS

A dynamic model has been developed for a batch Fluidised bed dryer. The experimental validation shows that the proposed lumped dynamic model can be used to predict the particle moisture content and the temperature profiles during the drying process. Feedback control of material moisture content in a bed dryer has been studied by measuring the outlet air temperature and relative humidity. It is seen that including the measurement of the moisture content in the control loop simplifies the design process. A

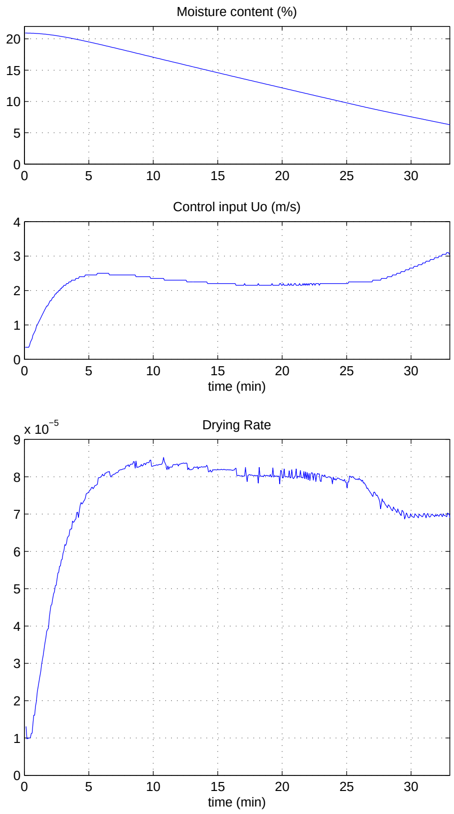

Fig. 9. Control input and moisture content using a PI controller and different drying rates (top), and drying rate (botton).

simple PI controller was designed and it is shown that it can be successfully used to control a batch Fluidised bed dryer.

NOMENCLATURE

- A Area of air distributor (m^2)
- c_g Heat of drying gas ($\mathrm{J\,kg^{-1}\,K}$)
- c_p Heat of particles ($\mathrm{J\,kg^{-1}\,K}$)
- c_w Heat of water ($\mathrm{J\,kg^{-1}\,K}$)
- c_{wv} Heat of water vapor ($\mathrm{J\,kg^{-1}\,K}$)
- d_b Effective bubble diameter (m)
- d_p Mean particle diameter (m)
- D_c Diameter of the bed column (m)
- D_g Diffusion coefficient of drying gas ($\mathrm{m^2\,s^{-1}}$)
- g Acceleration due to gravity ($\mathrm{m^2\,s^{-1}}$)
- H_f Height of bed (m)
- h_p Heat transfer coefficient between drying gas and solids ($\mathrm{J\,s^{-1}\,m^{-2}\,K^{-1}}$)
- h_w Heat transfer coefficient between drying gas and dryer wall ($\mathrm{J\,s^{-1}\,m^{-2}\,K^{-1}}$)
- i_b Enthalpy of gas bubbles ($\mathrm{J\,kg^{-1}}$)
- i_{we} Enthalpy of water vapor in emulsion gas ($\mathrm{J\,kg^{-1}}$)
- Nu Nusselt number
- k_g Thermal conductivity of drying gas ($\mathrm{J\,s^{-1}\,m^{-1}\,K^{-1}}$)
- Pr Prandtl number
- Re Reynolds number
- T Temperature
- U_0 Inlet gas superficial velocity ($\mathrm{m\,s^{-1}}$)
- U_b Gas superficial velocity in bubble phase ($\mathrm{m\,s^{-1}}$)
- U_{br} Linear velocity of a bubble ($\mathrm{m\,s^{-1}}$)
- U_{mf} Minimum fluidization velocity ($\mathrm{m\,s^{-1}}$)
- x Moisture content (kg/kg)
- $\tilde{x}$ Average moisture content (kg/kg)
- x_p^* Moisture content of drying gas on surface of a particle

Greek symbols

- ε Void fraction, ξ Sphericity of particles,
- δ_b Fraction of bubble, ρ Density ($\mathrm{kg}\,m^{-3}$),
- γ_0 Heat of vaporization ($\mathrm{J\,kg^{-1}}$),
- μ_g Viscosity of gas ($\mathrm{kg\,m^{-1}}$),
- σ Evaporation coefficient ($\mathrm{kg\,m^{-2}\,s^{-1}}$)

Subscripts

- g Gas phase, e Emulsion phase, b Bubble,
- p Particle, s Solids

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