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Nonlinear model predictive control of a batch fluidized bed dryer for pharmaceutical particles

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ABSTRACT

The availability of reliable online moisture content measurements exploiting near-infrared (NIR) spectroscopy and chemometric tools allows the application of online control strategies to a wide range of drying processes in the pharmaceutical industry. In this paper, drying of particles with a pilot-scale batch fluidized bed dryer (FBD) is studied using a in-line NIR probe. A consolidated phenomenological state-space model of an FBD based on mass and energy balances is calibrated applying a nonlinear least-square identification to experimental data (grey-box modeling). Then, relying on the calibrated model, a nonlinear model predictive controller and a moving horizon state estimator are designed. The objective is to reach a specific particle moisture content setpoint at the end of the drying batch while decreasing cycle time and limiting particle temperature. A penalty term on the energy consumption can also be added to the usual tracking control cost function. Compared to a typical FBD operation in industry (mostly open-loop), it is shown that the drying time and the energy consumption can be efficiently managed on the pilot-scale process while limiting various operation problems like under drying, over drying, or particles overheating.

1. Introduction

Because of the difficulty to get some reliable in-line measurements and the regulatory environment in the pharmaceutical industry, manufacturing in this field is not deploying automatic and real-time optimization systems as fast as other sectors (US Food & Drug Administration, 2004; McKenzie, Kiang, Tom, Rubin, & Futran, 2006). The implementation of in-line process sensors would certainly contribute to a better understanding of the systems. Afterward, model predictive control and real-time optimization would surely improve quality control and performance of the manufacturing processes. The wet granulation process, which involves powder wetting and drying steps to create appropriate granules, is an interesting candidate for those improvements.

The fluidization of solid particles is widely used in the pharmaceutical industry for drying wet granules. Because of high thermal diffusivities and good mixing properties, the batch fluidized bed dryer (FBD) is an efficient option in terms of cycle time and drying uniformity (Kunii & Levenspiel, 1991). However, in most industrial applications, they are still operated without feedback using fixed batch times and inlet air conditions (Mujumdar, 2014). This can lead to multiple problems like under drying or over drying and particle overheating. During the batch, particle overheating can degrade products that are sensitive to high temperatures. Also, a hot product at the end forces operators to wait for a cooling period before manipulating the dried granules. Besides those problems, it may not be the fastest and the most energy-efficient solution. All those issues raised interests in FBD monitoring with in-line analytical instruments and advanced process control strategies (Briens & Bojorra, 2010).

Since most batch processes are highly nonlinear due to their usual lack of steady states and their common unidirectional behavior (Bonvin, Srinivasan, and & Hunkeler, 2006; Nagy & Braatz, 2003), nonlinear models and control strategies are more appropriate. More specifically for batch fluidized bed drying, the way the manipulated variables (inlet air flow rate and temperature) are varied influences the rate of drying but not the final particle moisture content, which is fixed by the inlet air humidity. Also, following positive or negative variations of the manipulated variables and from its initial value, the particle moisture content can only decrease until the final equilibrium point is reached. Finally, FBD exhibits two different drying dynamics through the batch defined as the constant rate and the falling rate periods (Li & Duncan, 2008a). The dynamics of the particle temperature are also very distinct during these two phases.

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Nomenclature

A_f	inlet blower speed, %
A_h	inlet heating power, %
a_w	specific heat-transfer surface of dryer wall, m^{-1}
c_g	specific heat of drying gas, J kg^{-1} K^{-1}
c_p	specific heat of dry particles, J kg^{-1} K^{-1}
c_w	specific heat of liquid water, J kg^{-1} K^{-1}
c_{wv}	specific heat of water vapor, J kg^{-1} K^{-1}
D_c	diameter of bed column, m
D_g	molecular diffusion coefficient of drying gas, m^2 s^{-1}
d_p	particle diameter, m
d_{b0}	bubble minimal diameter, m
d_{bm}	bubble maximal diameter, m
d_b	bubble diameter, m
D_{g0}	molecular diffusion coefficient at T_{ref}, m^2 s^{-1}
e_f	measured inlet airflow error, m^3/h
e_h	measured inlet temperature error, °C
g	gravitational acceleration, m s^{-2}
H_c	predictive controller control horizon in multiple of t_s, dimensionless
H_f	expanded bed height, m
H_p	predictive controller prediction horizon in multiple of t_s, dimensionless
h_s	heat transfer coefficient between drying gas and solids, J s^{-1} m^{-3} K^{-1}
h_w	heat transfer coefficient between drying gas and dryer wall, J s^{-1} m^{-3} K^{-1}
H_{bc}	volumetric heat-transfer coefficient between bubble and cloud-wake regions based on volume of bubbles, J s^{-1} m^{-3} K^{-1}
H_{be}	volumetric heat-transfer coefficient between bubbles and emulsion based on volume of bubbles, J s^{-1} m^{-3} K^{-1}
H_{ce}	volumetric heat-transfer coefficient between cloud-wake region and emulsion based on volume of bubbles, J s^{-1} m^{-3} K^{-1}
H_{mf}	bed height at minimum fluidizing condition, m
k	discrete time, dimensionless
K_{bc}	coefficient of gas interchange between bubble and cloud-wake regions based on volume of bubbles, s^{-1}
K_{be}	coefficient of gas interchange between bubbles and emulsion based on volume of bubbles, s^{-1}
K_{ce}	coefficient of gas interchange between cloud-wake region and emulsion based on volume of bubbles, s^{-1}
L_{or}	center-to-center spacing between adjacent holes on perforated plate distributor, m
N	observer window-size or horizon, dimensionless
N_{or}	number of orifices per unit area on perforated distributor, m^{-1}
N_u	Nusselt number, dimensionless
p_e	fluid bed dryer energy index weight in controller criterion, J^{-1}
P_w	pressure of saturated water vapor, mmHg
Pr	Prandtl number, dimensionless
R_{wv}	water vapor specific gas constant, J kg^{-1} K^{-1}
Re	Reynolds number for packed beds, dimensionless
s	Laplace variable, s^{-1}
T	temperature, K
t	time, s
t_s	control algorithm sampling time, s
T_w	dryer-wall temperature, K
T_{amb}	fluidized bed dryer room temperature, K
T_{ref}	reference temperature, K
W	fluid bed dryer energy consumption, J
x_i	χ_{pm} output disturbance state, %w.b.
z	elevation, m

Greek symbols

$\alpha_{\chi p}$	relative tolerance on particle moisture content setpoint for end-of-batch detection, dimensionless
χ	moisture content (dry basis), dimensionless
χ_p^*	moisture content of drying gas on surface of a particle (dry basis), dimensionless
χ_{pc}	particle critical moisture content (dry basis), dimensionless
δ_b	fraction of fluidized bed consisting of bubbles, dimensionless
γ	heat of vaporization at T_{ref}, J kg^{-1}
κ	offset constant in ψ_2 function
μ_g	dynamic viscosity of drying gas, kg m^{-1} s^{-1}
ν	exponent constant in ψ_2 function
ϕ	sphericity of particles, dimensionless
ψ_1	gas saturated humid curve
ψ_2	moisture film correction function based on the absorption characteristics of the particle
ρ_g	density of gas, kg m^{-3}
ρ_{ds}	dry bulk density of the bed, kg m^{-3}
ρ_s	dry particle density, kg m^{-3}
ρ_{ws}	wet bulk density of the bed, kg m^{-3}
ρ_w	water density, kg m^{-3}
σ	evaporation coefficient, kg m^{-2} s^{-1}
υ	gas superficial velocity based on the total cross-sectional area of bed, m s^{-1}
υ_{br}	linear velocity of a single bubble, m s^{-1}
υ_{mf}	gas superficial velocity at minimum fluidizing condition, m s^{-1}
ε_{mf}	void fraction at minimum fluidizing conditions, dimensionless
ε_0	inlet air relative humidity, %RH

Vectors and matrices

$\bar{\mathbf{x}}_0$	observer a priori state estimates (4 × 1)
$\hat{\mathbf{x}}$	observer estimated augmented states (4 × 1)
$\mathbf{d}$	measured disturbances (1 × 1)
$\mathbf{f}_A(\bullet)$	augmented model state update function (4 × 1)
$\mathbf{f}(\bullet)$	state-space model state update function (3 × 1)
$\mathbf{h}_A(\bullet)$	augmented model state output function (3 × 1)
$\mathbf{h}(\bullet)$	state-space model output function (3 × 1)
$\mathbf{M}$	setpoints tracking weights (3 × 3)
$\mathbf{N}$	manipulated input weights (2 × 2)
$\mathbf{P}$	horizon initial observation error estimated covariance (4 × 4)
$\mathbf{Q}$	process noise estimated covariance (4 × 4)
$\mathbf{R}$	observation noise estimated covariance (3 × 3)
$\mathbf{r}$	setpoints (3 × 1)
$\mathbf{u}$	manipulated inputs (2 × 1)
$\mathbf{x}_A$	augmented model states (4 × 1)
$\mathbf{x}$	phenomenological model states (3 × 1)
$\mathbf{y}_s$	phenomenological model outputs (3 × 1)
$\mathbf{y}$	process measured outputs (3 × 1)

Subscripts

0	inlet gas
b	bubble phase
e	emulsion phase: interstitial gas
m	measured
p	emulsion phase: solid particles