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Robust feedback control of convective drying of particulate solids

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ABSTRACT

This work considers robust control of continuous convective drying of particulate solids where the major process uncertainty lies in the kinetics of the second (falling-rate) drying period. Using the concept of normalised drying curve, for arbitrary shape of the curve, the steady state particle moisture content is derived. Applying appropriate uncertainty models, a robust feedback controller is designed to guarantee desired product moisture. Advantages of this approach are discussed in comparison to convential PI and LQ-optimal control. The approach is exemplified for the case of fluidised bed drying of baker's yeast particles. Results show very good performance with respect to parametric uncertainty and disturbance rejection even at non-nominal steady-states.

1. Introduction

Drying, the removal of liquid from a solid material, is one of the major unit operations in solids processing, e.g. chemicals, pharmaceuticals, food and paper [1,2]. The liquid can be removed mechanically, e.g. draining, wringing, filtering, or thermally by induction of a phase change, e.g. by evaporation or sublimation of the liquid. Thermal drying is extensively used and is one of the most energy-intensive processes, taking up approximately 10–25% of a nation's energy output [1].

The basic steps in thermal drying are: (1) heat supply to the moist solid; (2) phase change of the liquid into vapour; (3) removal of the vapour. Dryers can be classified by the method of heat supply, e.g. convective dryers use a flowing gas stream to supply the energy to the moist solid and to remove the vapour; in contact dryers the heat is supplied by contact of the solid with heated surfaces, e.g. the apparatus walls or immersed heating tubes.

Considering convective drying of particulate solids, characteristic evaporation rates as a function of moisture content X, i.e. the mass of liquid per mass of dry solid, are shown in Fig. 1(a): For moisture contents $X > X_{cr}$, where X_{cr} is the material-specific critical moisture content, a constant evaporation rate is observed; for moisture contents $X_{hyg} < X < X_{cr}$ a material-dependent falling rate is observed. If the moisture content reaches X_{hyg}, thermodynamic (adsorption) equilibrium is attained and the evaporation rate vanishes.

The first (constant) drying period refers to the surface-wet particle, i.e. direct heat and mass transfer between liquid and gas. In this period, the heat and mass transfer is gas-side controlled, i.e. the gas conditions, e.g. temperature and mass flow rate, directly determine the evaporation rate. In the second drying period, the falling rate period, moisture is mostly located in the (porous) interior – heat and gas now have to penetrate the solid by conduction and diffusion first in order to evaporate the liquid; also the vapour has to be transported to the particle surface, e.g. by vapour diffusion or capillary pumping, before it can be taken up by the main gas flow. The farther inside the moisture is located, the longer diffusion and conduction processes take and thereby reduce the evaporation rate in the second drying period.

From this phenomenological description, two different aspects can be identified that influence the drying process: (1) gas-side conditions and (2) material properties. A variation of gas-side conditions only will yield different evaporation rates; the material-specific part, however, remains the same, i.e. the evaporation rates are qualitatively but not quantitatively similar.

Moisture transport in the second drying period depends on different effects, for example vapour or liquid diffusion or pumping of liquid from the interior to the surface due to capillary forces. Modelling of these effects is difficult; often an effective diffusivity of moisture is assumed, leading to a partial differential equation for

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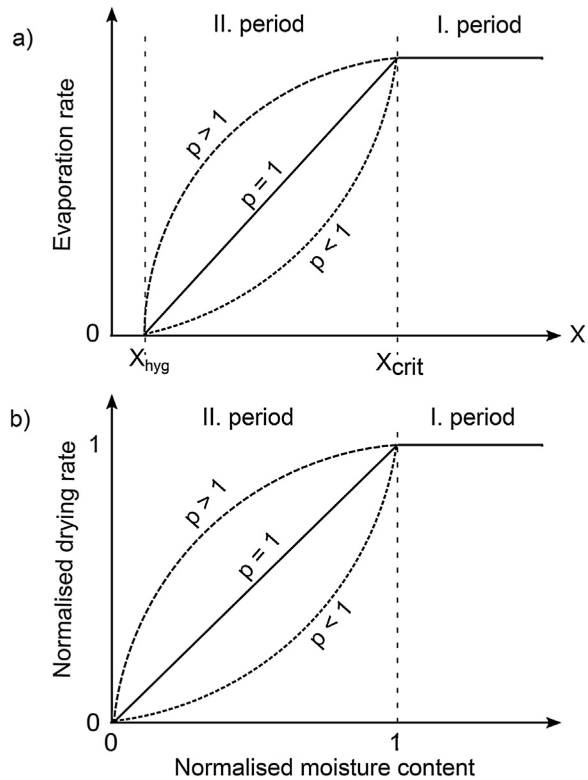

Fig. 1. Schematic overview of (a) experimentally observed evaporation rates in drying of particulate solids and (b) principal shapes of the normalised drying curve (NDC).

the strongly coupled moisture and temperature fields in the particle [3]. Main obstacle in the application of these models is the determination of a large number of spatially and property distributed parameters, for instance effective diffusivity, as functions of process conditions. Furthermore, in many industrial applications the moisture distribution is not of prime interest but the average product moisture. In these cases, the modelling and computational effort of the diffusion/conduction model is considered too high.

One approach to ease the effort is the REA approach (reaction engineering approach) by X.D. Chen and co-workers [4,5]. Here, the evaporation rate is formulated in an Arrhenius-type expression, linking the sorptive equilibrium and material parameters by fitting of a (ficticious) activation energy.

An alternative approach is given by the concept of *normalised drying curve* $\dot{\nu}$ (NDC), originally developed by van Meel [6]. Here, the second drying period rate is expressed in terms of the (known and constant) gas-side controlled first drying period rate. Main advantage of the NDC is that it can be obtained directly from considerably simpler measurements than effective diffusivity [7]; main drawback is that it only allows describing the evolution of the average moisture content, X. However, as this value is of primary concern in many practical applications, the concept of normalised drying curve has found wide-spread use for dryer design, optimisation and troubleshooting.

The normalised drying curve is defined as:

$$\dot{\nu}(\eta) = \frac{\dot{m}_{evap,II}}{\dot{m}_{evap,I}}, \quad \eta = \frac{X - X_{hyg}}{X_{cr} - X_{hyg}}, \tag{1}$$

where η denotes the normalised moisture content, with values $0 \leq \eta \leq 1$ denoting the second drying period. Given experimental data, the normalised drying curve can be fitted and used for process modelling and feedback controller design as will be shown in the following. It has to be mentioned that the applicability of this approach is limited; some limits are given for instance in Suherman et al. [8].

Control (either open-loop or by feedback) of convective drying of particulate solids has been considered before due to its industrial importance. In fluidised bed drying, for instance, the works [9–12] have to be mentioned: Therein, different routes to control the moisture content and/or product temperature are taken, for instance applying SISO and MIMO PI-control, adaptive fuzzy logic control and an infinite-dimensional distributed controller to control moisture profiles in the dryer and product. However, none of the studies explicitly consider uncertainties in the kinetics of the second drying period.

In conveyor-belt drying, e.g. [13–15], and spray-drying, e.g. [16–21], the situation is similar, although applied methods range from response surface methodology over artificial neural networks, PI control to model predictive control [21]. Again, robustness of the controller is only provided by the feedback structure, no bounds on parameter uncertainties are provided or taken into account.

In this work, we present a general approach to robust feedback control of continuously operated convective dryers. We do not limit the presentation to a specific dryer design, the only requirement is that the drying process can be described by the normalised drying curve approach. In the following section, we present the dynamic drying model equations, introducing a case study on drying of baker's yeast pellets in a fluidised bed, followed by a short discussion of the open-loop dynamics. Afterwards, the robust controller is designed and its main features are discussed. In the Results section, the performance of the controller, designed for a nominal operating point, is presented with respect to model uncertainties and different operating points. A comparison of the performance with a standard PI-controller and a linear-quadratic optimal controller (LQR) giving identical nominal behaviour is performed and the advantages of the robust controller are highlighted, especially at non-nominal operating points and under parameter uncertainty. The work closes with Conclusions and Outlook on future work.

2. Process modelling and dynamics

2.1. Derivation of process equations

For the purpose of this work, we pose the following assumptions: (i) The particulate phase in the apparatus can be (at least theoretically be considered) as well-mixed. (ii) The gas-phase is also considered as well-mixed, i.e. spatial gradients in gas or particle properties are not considered. (iii) The particulate phase is either mono-disperse or represented by a constant Sauter mean diameter (d_{32}), i.e. a particle size distribution is not considered. Each particle dries as if it was a single particle, i.e. interaction with other moist particles is not considered. (iv) Drying is kinetically-controlled, i.e. drying gas is not close to saturation. (v) Drying takes place under approximately adiabatic conditions, i.e. sufficient insulation of apparatus provided to avoid significant heat loss to the environment. (vi) Particles enter the apparatus with an average moisture content X_{in} at a dry mass flow rate $\dot{m}_{dry,in}$. (vii) Evaporation takes place from the total surface area of all particles. (viii) The average residence time of particles in the continuously operated dryer is τ, which can be regulated, e.g. by speed of conveyor, or hold-up mass control.

Then, starting from a mass balance of the wet solid $m_{wet} = X m_{dry}$, the following mass balances for the dry solid (hold-up) and the average moisture content can be derived:

$$\frac{\mathrm{d}X}{\mathrm{d}t} = \left(\dot{m}_{dry,in} X_{in} - \frac{m_{dry}}{\tau} X - \dot{m}_{evap} - X \frac{\mathrm{d}m_{dry}}{\mathrm{d}t} \right) / m_{dry}, \tag{2}$$