Journal of Process Control 57 (2017) 50–65

Contents lists available at ScienceDirect

Journal of Process Control

journal homepage: www.elsevier.com/locate/jprocont

An experimentally validated simulation model for a four-stage spray dryer

Lars Norbert Petersen[a,b], Niels Kjølstad Poulsen[a], Hans Henrik Niemann[c], Christer Utzen[b], John Bagterp Jørgensen[a,*]

[a] Department of Applied Mathematics and Computer Science, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark
[b] GEA Process Engineering A/S, DK-2860 Søborg, Denmark
[c] Department of Electrical Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark

ARTICLE INFO

Article history:
Received 10 May 2016
Received in revised form 27 March 2017
Accepted 6 May 2017
Available online 3 April 2017

Keywords:
Spray drying
Multi-stage dryer
Process simulation
Process modeling
Experimental data

ABSTRACT

In this paper, we develop a dynamic model of an industrial type medium size four-stage spray dryer. The purpose of the model is to enable simulations of the spray dryer at different operating points, such that the model facilitates development and comparison of control strategies. The dryer is divided into four consecutive stages: a primary spray drying stage, two heated fluid bed stages, and a cooling fluid bed stage. Each of these stages in the model is assumed ideally mixed and the dynamics are described by mass- and energy balances. These balance equations are coupled with constitutive equations such as a thermodynamic model, the water evaporation rate, the heat transfer rates, and an equation for the stickiness of the powder (glass transition temperature). Laboratory data is used to model the equilibrium moisture content and the glass transition temperature of the powder. The resulting mathematical model is an index-1 differential algebraic equation (DAE) model with 12 states, 9 inputs, 8 disturbances, and 30 parameters. The parameters in the model are identified from well-excited experimental data obtained from the industrial type spray dryer. The simulated outputs of the model are validated using independent well-excited experimental data from the same spray dryer. The simulated temperatures, humidities, and residual moistures in the spray dryer compare well to the validation data. The model also provides the profit of operation, the production rate, the energy consumption, and the energy efficiency. In addition, it computes stickiness of the powder in different stages of the spray dryer. These facilities make the model well suited as a simulation model for comparison of the process economics associated to different control strategies.

1. Introduction

Spray drying is a processing technique for drying of liquids or slurries. A spray dryer produces a free flowing powder. Spray drying is widely used in the food, chemical and pharmaceutical industries [1]. The main purpose of drying foodstuffs is to increase the shelf life as well as to reduce cost of transportation over long distances. Examples of spray dried foods are instant coffee, coffee whitener, eggs, milk, soups, baby foods, sweeteners, and cheese in powdered form [2]. Also, many powders occur in cooking. Chemicals are often dried to form non-dusty agglomerates that are easier to handle. These may be agrochemicals used in cultivation as well as optical brighteners used in households and many more. Pharmaceuticals are dried for the production of tablets. Aspirin, paracetamol and vitamins are typical examples.

In this paper, we consider a spray dryer with both an integrated and an external fluid bed. This is the preferred type of dryer for production of food powders. It provides product flexibility and the best energy efficiency compared to other spray dryers. It is a challenge and non-trivial to operate a spray dryer in an optimal way. One must maximize energy efficiency and production while minimizing down time [3]. These two goals are often conflicting, as increased production and efficiency may lead to an increase in the hours lost on process-related problems such as plugging, powder build-up, cleaning in place (CIP), etc. Constantly changing external disturbances, such as the ambient air humidity and feed composition, are the main reasons that the powder turns sticky and deposits start to build up on the dryer walls. The operator must perform

---

* Corresponding author.
E-mail addresses: lnpe@dtu.dk (L.N. Petersen), nkpo@dtu.dk (N.K. Poulsen), hhn@elektro.dtu.dk (H.H. Niemann), christer.utzen@gea.com (C. Utzen), jbjo@dtu.dk (J.B. Jørgensen).

http://dx.doi.org/10.1016/j.jprocont.2017.05.001
0959-1524/

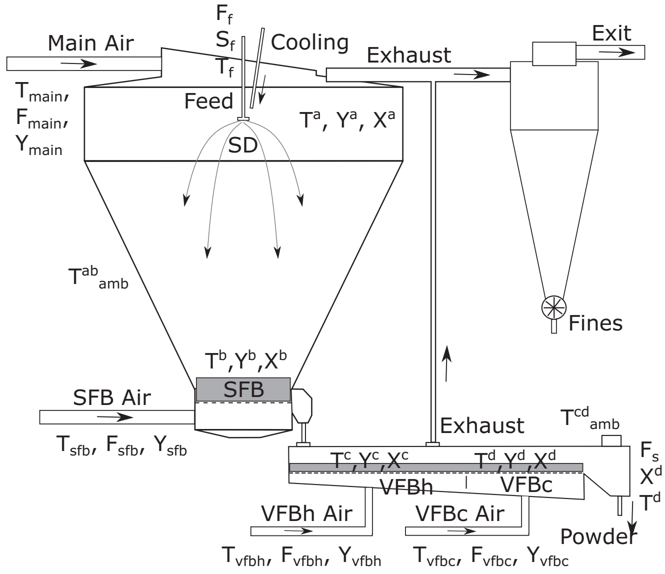

Fig. 1. Principle diagram of the four-stage spray dryer with both an integrated fluid bed and an external fluid bed.

frequent adjustments to the spray dryer to avoid depositions. These adjustments are hardly ever performed, as the operator have other important tasks to perform. Instead the spray dryer is operated in a conservative non-optimal way. Thus, automatic control systems to perform the adjustments are needed. To facilitate development of automatic control systems, a dynamic model is desirable to simulate the spray drying process and compare control algorithms in terms of economically related key performance indicators.

1.1. Process description

Fig. 1 illustrates a modern four-stage spray dryer with an integrated (static) fluid bed and an external (vibrating) fluid bed. The spray dryer consists of the primary spray drying stage (SD), the static fluid bed stage (SFB), the hot vibrating fluid bed stage (VFBh), and the cold vibrating fluid bed stage (VFBc). The main hot air is let into the upper section of the primary spray drying stage (SD) around the high pressure nozzles. The nozzles disperse the liquid feed into droplets. The heat is transferred from the hot air to the droplets. Due to this heat transfer, water evaporates from the droplets. In that process, the air temperature and the residual moisture of the droplets decrease. During drying, there is a transfer of evaporated water from the droplets to the air in the dryer. The rate of this transfer depends on the type and composition of the feed, the air temperature, the air humidity inside the dryer, and the air pressure. The dried product then enters the SFB and is dried further while being fluidized by hot air. After drying in the SFB, the powder is transported to the external vibrating fluid bed (VFB) for gentle drying and cooled to the temperature desired for handling and storage. The drying air from the chamber and VFB is passed through a cyclone, separating the powder contained in the air. The fine powder is returned to the chamber to form agglomerated powder particles. The air is also passed through a bag filter, not shown in Fig. 1, to remove any particles left before the air can be discharged.

1.2. Available mathematical models of spray dryers

Mathematical models of spray dryers exist as detailed computational fluid dynamics (CFD) models for static design oriented simulation [4–6], and as models for dynamic simulation. The models for dynamic simulation are linear models for control design that are also used for closed-loop simulation [7–9] and lumped first-principles engineering models [10–15]. The purpose of the dynamic simulation models is often to facilitate analysis and synthesis of advanced control schemes.

Clarke [7] designs a Generalized Predictive Controller (GPC) for a spray dryer and bases the controller on the CARIMA model, but does not provide a simulation model. Tan et al. [8,9] provide continuous transfer functions of first order with a delay that they use for controller design as well as closed loop simulation. They report models for spray drying of full cream milk [8] as well as spray drying of whole milk and orange juice [9].

A lumped first-principles model of a single stage spray dryer is developed in [10,11]. Mass and energy balances describe air temperature, the mean particle size, and the residual moisture content of the powder. A mathematical model based on mass, energy and momentum equations are formulated and solved in [12]. The model describes the moisture content and particle size of a single spray dried powder particle. In [13], a dynamic model of a single stage spray dryer is developed from first-principles and is validated experimentally to assist in control simulation studies. The model simulates the moisture content and particle size of the powder as well as the exhaust air temperature and humidity. Reference [14] extends the model in [13] by adding variable inlet droplet size and density of the milk powder particles. Reference [15] develops a single stage dynamic model for the simulation of the residual moisture control and air temperatures in an industrial detergent spray drying process. The above first-principles models simulate single stage spray dryers. Four-stage spray dryer models are available [16,17]. Reference [16] describes the air temperatures inside the dryer, the final residual moisture content, and the particle size of the produced powder. Powder residual moisture sensors are often not available. Therefore, the above models are based on irregularly sampled off-line laboratory measurements of the residual moisture. Reference [17] describes a lumped first-principles model for a four-stage spray dryer that is validated against in-line powder samples and describes the air temperature, air humidity, and residual moisture content of the powder.

1.3. Key contributions

The novelties of the model proposed in this paper are: (1) It is an experimentally validated dynamic model that enables simulation of the four-stage spray dryer at different operating points. The model is a first-principles engineering model and it is divided into an SD, an SFB, a VFBh, and a VFBc stage. Each stage describes the evolution of the temperatures, the air humidities, and the residual moistures of the powder. The model is validated against an experiment with in-line measurements of the residual moisture content of the powder; (2) It provides the key performance indicators such as the profit of operation, the production rate, the energy consumption rate, and the energy efficiency; (3) It offers stickiness constraints of the powder in each stage of the spray dryer.

To the authors knowledge, there does not exist such a dynamic model for simulation of the four-stage spray dryer that is experimentally validated, provides key economic performance indicators, and stickiness constraints. These facilities make the model well suited as a simulation model for comparison of the process economics associated to different control strategies.

1.4. Organization

The paper is organized as follows. Section 2 presents the model principles, while Appendix A presents the model details. Identification of the model parameters is described in Section 3. Section 4 validates the model using independent experimental data. Simulations with the model are performed in Section 5. Section 5 also