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Predictive control with multiobjective optimization: Application to a sludge drying operation

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ABSTRACT

The main objective of this study is to develop an offline tuning of the operating input parameters for a sludge drying operation, by using multiobjective optimization techniques combined with a predictive control method. The manipulated variables concerned are the temperature and the relative humidity of the drying air (T_{air}, RH_{air}). The optimal time for the reversal operation of the product is also investigated. The optimization procedure is coupled to a one-dimensional numerical model that allows the simulation of moisture content and temperature field evolutions in the product during the drying step. A genetic algorithm is used to identify the two manipulated variables, at each step time, by minimizing simultaneously three objective functions over a finite horizon. These objective functions are linked to penalties concerning the heating and dehumidifying of the outside air used for the drying stage and to a global moisture content gap relative to a drying target. First, the heat and mass transfer model is validated for the drying step of a plate sample of sludge, with a reversal operation. Afterwards, the optimization procedure is carried out, and the results are discussed in terms of an energetic analysis.

1. Introduction

For processes already in operation or for studies focused only on products, the energetic efficiency of the drying stage is often directly linked to the control procedure of the operating input parameters (Banga et al., 2001; Zorrilla et al., 2003; Dufour, 2007). As far as drying processes are concerned, many authors use the response surface method, obtained by design of experiments, in order to realize afterwards a tuning of the optimal parameters through the use of a desirability function (Karimi et al., 2012; Silva et al., 2013; Erbay et al., 2014; Patil et al., 2014). The response surface method leads to linking the outputs (observables) of a process to the inputs (manipulated variables) with the help of a first or a second order polynomial function. However, the difficulties of using this method appear when strong nonlinearities are present. Furthermore, no discontinuities in the evolution of the observables should occur within the field of the study concerned. Process input parameters could also be determined with the use of determinist or heuristic optimization methods. Barttfeld et al. (2006) have proposed an optimization of a drying process of a liquid film on a substrate. The manipulated variables (temperature and air velocity) are identified according to four scenarios. The goal of the first two scenarios is to obtain a film with a certain final solvent content by minimizing the total heat consumption with a fixed production rate or by maximizing the production rate. The other two scenarios concern minimizing the final solvent mass in the film or maximizing the total flow of evaporated solvent. Each scenario, represented by an objective function, is examined separately (mono-objective optimization). Nevertheless, the parameter estimation procedure requires, most of the time, the optimization of simultaneously possibly conflicting multiple objectives. There are different ways to approach a multiobjective optimization problem. The most common one is to transform a multiobjective into a mono-objective optimization problem by making a single composite objective function as the weighted sum of the objectives. However, authors mention the difficulties of this transition, notably to obtain optimal points from non-convex objective functions (Marler and Arora, 2004). The general approach is to determine an entire Pareto optimal solution set. Multiobjective optimizations are often conducted with the help of a Genetic Algorithm (GA), which provides a Pareto surface from a manipulated population. This metaheuristic algorithm considers some elementary operations (selection, crossover, mutation) that are widely described in the literature (Konak et al., 2006). Several studies have used a GA as a multiobjective optimization solver in order to identify the operating input parameters of thermal or chemical processes (Yuzgec et al., 2006; Arbiza et al., 2008; Sendín et al., 2010; Liu and Sun, 2013).

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In addition, model predictive control (MPC) is a relatively recent technique for the optimal control of processes; by its simplicity, it has created a real interest in the industrial field (Morari and Leeb, 1999; Qin and Badgwellb, 2003). This control method belongs to the class of model-based control strategies. The principle of this method is to control the operating input parameters of a process in order to follow a reference trajectory closely, while taking into account the future behavior of the system. The tuning of the operating input parameters is based on the resolution of an optimization problem, and the future behavior of the system is obtained with the help of a numerical prediction model. In the context of drying processes, researchers have shown an interest for tuning the optimal operating input parameters by using a predictive control method. Thus, Dufour et al. (2003) used this method for drying a coat of paint with an infrared source. In their study, the issue is of Single Input Single Output (SISO) type. The main objective is to follow an imposed temperature kinetic for the paint through determining the optimal command policy of the infrared emitter. Temmerman et al. (2009) have proposed an optimization for a pasta drying process by using a predictive control strategy. The optimization is conducted with a single objective function related to the pursuit of a drying kinetic target. The resolution of the underlying optimization problem is carried out with a deterministic algorithm (Levenberg-Marquard). The manipulated variables for the process optimization are the temperature and the relative humidity of the drying air. Laabidi et al. (2008) have worked on the development of a predictive control strategy with multicriteria optimization for a nonlinear multimodel system, in order to realize a set point tracking. A GA is used for the resolution of the multicriteria optimization problem. The procedure provided an optimal control law of the system. The authors emphasize that the predictive control method associated with a multiobjective optimization problem enabled them to take into consideration some perturbations due to noise or load variations of the system more efficiently.

Thus, in the context of drying operations, few studies deal with the development of a predictive control procedure based on a multicriteria optimization problem coupled with a nonlinear multiphysics model. The operating input parameters tuning procedure proposed in the present study is based on a predictive control strategy with receding horizon combined with a nonlinear multiphysics model and a genetic algorithm for solving the multiobjective optimization problem. The optimization procedure proposed is applied to a field that arouses interest among researchers: sludge drying (Vaxelaire and Cézac, 2004; Bennamoun et al., 2013).

In addition, modeling the reversal operation during the drying step is also rarely investigated in the literature. The optimization procedure proposed in this study can also determine the ideal moment for the reversal operation of the product. In this context, an effort is focused on the development of a numerical model that allows taking into account the reversal operation on the one hand, and enables an accurate prediction of the water content evolution of the product according to the control signal matched (T_{air}, RH_{air}), on the other hand.

First, the experimental setup and the heat and mass transfer model used are presented. The second part of the paper presents the optimization procedure and the objective functions characterizing the multiobjective aspect of the optimization problem concerned. A model validation with a reversal operation is carried out preliminary to the optimization phase, in order to prove its suitability. Then, two optimization cases are presented: one with a basic multiobjective optimization solved with a genetic algorithm, and another one whereby the predictive control method is added to this optimization procedure.

2. Formulation of the drying problem

The dynamic optimization procedure is applied to the thermal drying, at low temperature, of an agricultural sludge. A plane flat configuration is used for the sample, with convection and conduction exchanges on each face (Fig. 1). The laboratory dryer used allows adjusting the thermo-aeraulic conditions of the drying air applied on the upper face of the sample. A temperature can be imposed at the bottom of the sample (T_b) by using a contact-heating device. A mass loss measurement is used to obtain the evolution of the average moisture content in dry base X. This apparatus has been presented in a previous study (Louarn et al., 2014). The goal of our study is to determine several pairs of variable optimal operating input parameters (air temperature and relative humidity) during the drying cycle. In order to accelerate the drying step, the ideal moment for the reversal operation is also looked for. The reversal operation involves manually extracting the product from the crucible and turning it over (by inversion of the upper and lower face) before reintroducing it into the crucible in order to continue

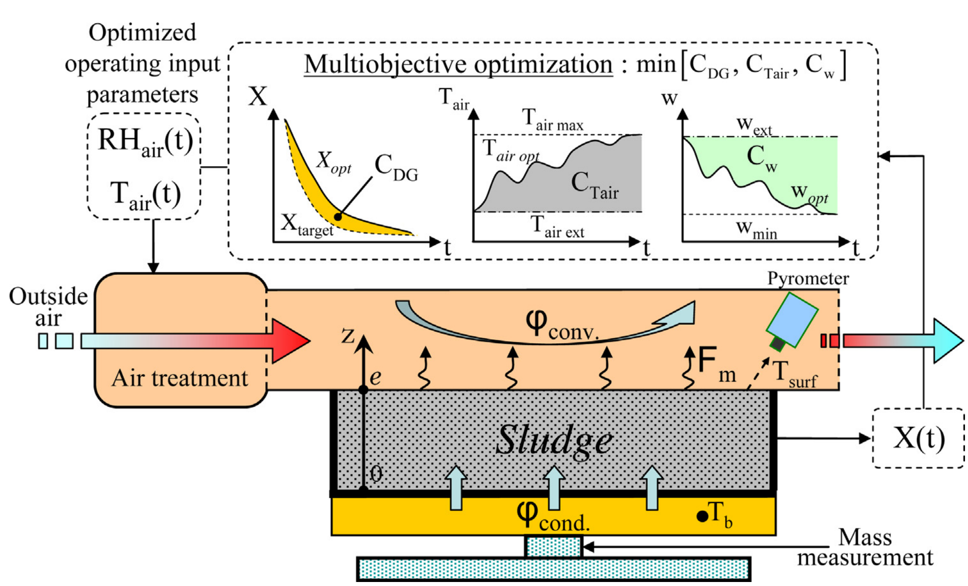

Fig. 1. Summary of the proposed procedure.