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Performance analysis of a dynamic phenomenological controller for a pellet cooling process

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Abstract

The cooling zone of an induration furnace exhibits a nonlinear dynamic behavior in addition to a strong coupling between output pressure and temperature. Simulation studies show that linear controller performance is unacceptable from an industrial point of view. In order to obtain adequate performance on a wide operating range, a nonlinear predictive controller (NLMPC) based on a phenomenological process model is proposed. Since the furnace simulation model shows that the equipment behaves as a Hammerstein model, a variable change is performed and a linear model predictive controller (MPC) is developed for the cooling zone. Both controllers are tested for set-point changes and disturbance rejection and give relatively similar performances. It is concluded that for processes having structured nonlinearities, as the cooling zone considered here, linear MPC should be preferred to NLMPC since the computation time is far less demanding and the industrial implementation easier.

Keywords: Nonlinear model-based predictive control; Phenomenological model; Hammerstein model

1. Introduction

It is well recognized that one of the characteristics of chemical processes that presents a challenging control problem is the inherent nonlinearity of the process. In spite of this fact, chemical processes have been traditionally controlled by using linear system analysis and design tools. A major reason that the use of linear system theory has been so pervasive is that they offer analytical solutions and more rigorous stability and performance analysis tools. Also, the computational demands for linear system simulation and implementation are usually quite small when compared to nonlinear simulation [1]. The control problems encountered with metallurgical processes are similar to those of the chemical industry: nonlinearity, nonstationary nature, unmeasured disturbances, multivariable interactions, and time delays.

The linearization of nonlinear physical models by Taylor series expansion around a moving operating point is a common approach for linear control system design [2]. However, this approach is only adequate when the process nonlinearities are mild or when the plant operation is constrained to a narrow region [3]. Different control techniques for highly nonlinear processes have been reviewed by Bequette [1]. Recently, nonlinear model-based control (NLMBC) techniques, which may use either first principles or empirical models, have become more popular because they take advantage of the increased power and speed of computers. Nonlinear internal model control (NLIMC), process model-based control (PMBC), generic model control (GMC), nonlinear inferential control (NLIC), and nonlinear model predictive control (NLMPC) are NLMBC techniques.

NLIMC [4] uses the process inverse as the controller model with a nonlinear search method to determine the desired manipulated variable actions. PMBC [5] and GMC [6] are reference systems synthesis techniques that use models developed from the laws of conservation, and integrate these with a closed-loop control algorithm. The

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major advantage of these techniques is that they can be tuned on-line with the same heuristic procedures that are applied to conventional PID control. Parrish and Brosilow [7] developed NLIC techniques to estimate unmeasured disturbances and track a desired set-point trajectory. A direct extension of the linear model predictive control methods results when a nonlinear dynamic process model is used. The objective of NLMPC [8] is to select a set of future control moves (control horizon) in order to minimize a function based on a desired output trajectory over a prediction horizon. The constraints can be explicitly handled. According to Bequette [1], the NLMPC approach appears to handle much more common process characteristics (multivariable interactions between the manipulated and output variables, nonlinear dynamic behavior, constraints on the manipulated and states variables, ...) than the other nonlinear control techniques. Moreover, it is an intuitive approach that is easily understood by process operators. However, its major disadvantage is the computational time required to perform the prediction optimization.

The objective of this study is to explore the potential of NLMPC for an iron oxide pellet cooling process used in pyrometallurgical installations. The model included in the predictive controller is a phenomenological dynamic model based on heat transfer and fluid dynamics. The analysis is performed on a simulated process involving a process described by a set of algebraic and partial differential equations. The performance of the NLMPC is compared to the performance of a linear empirical model predictive controller (MPC) where a variable change is applied in order to linearize the process.

This study is part of a larger project related to the analysis of the behavior of an industrial pellet induration furnace. The project includes the development of a phenomenological process simulator, an observer, a fault detection algorithm, a real-time optimization strategy, and a control strategy that use the new tools developed. Since the behavior of this induration furnace is highly nonlinear, the objective of this study is to explore the potential of NLMPC for a process involving a distributed parameter heat transfer model. At the moment, the objective is not to implement the controllers on the real process, but simply to assess their feasibility and performance using a simulator that adequately represents typical nonlinearities encountered in pyrometallurgy. For the purpose of illustrating the control methods, only the cooling zone of the pellet induration furnace is simulated.

The paper first presents the process, the dynamic simulator, and its dynamic properties. Then, the structure and the tuning of the phenomenological and empirical MPC's are presented. Finally, the NLMPC and linear MPC control strategies are compared and evaluated for both set-point tracking and disturbance rejection. Industrial implementation considerations are discussed.

2. Process description

The preparation of iron ore concentrates for iron and steel making industries usually requires stages of ore concentration and agglomeration of iron oxide pellets. The agglomerated pellets are sintered in an induration furnace in order to give them the necessary mechanical properties for their handling and transportation to the reduction site. Induration furnaces can be separated in three zones where specific transformations occur: a first zone for drying the wet pellets, a second zone for high temperature sintering, and a last zone for pellet cooling in order to recycle the energy to the drying and cooking zones and to obtain pellets at a temperature suitable for subsequent handling. The induration furnace energy consumption greatly depends on the performance of the cooling zone, which, in turn, must be carefully controlled.

The process under study (Fig. 1) is the cooling zone of an induration furnace where there is a moving bed of solid pellets that has to be cooled for process operation requirements and energy recycling. Two fans are used to force the cooling air circulation. Since the air from the cooling zone is recovered to be used in the drying and cooking zones, a flowing resistance and an air-cooling zone are also added to simulate the downstream phenomena. The flowing resistance simulates the pressure drops in the drying and the cooking zones packed beds of pellets. Pressure drops in ducts are not simulated since they are relatively small in comparison to pressure drops in pellet beds. The air-cooling zone represents the air heat losses that occurred in the drying and the cooking zones.

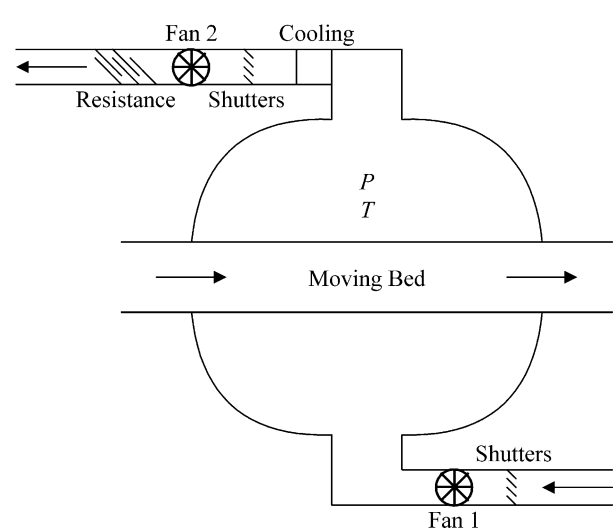

Fig. 1. Process under study.