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Practice Article

Comparison of model-based and conventional controllers on a pilot-scale heat exchanger

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ABSTRACT

This pilot-scale heat exchanger demonstration compares two relatively simple nonlinear model-based control strategies to conventional proportional-integral (PI) control. The two nonlinear controllers, generic model control (GMC) and process-model based control (PMBC), use a first-principles model thereby providing characterization of the nonlinear process throughout the operating range. There are two approaches to GMC, one uses a dynamic model, the other a steady-state model. This work uses the steady-state model; accordingly, will use the term GMC-SS, which can be classified as output characterization for a PI controller, making it relatively simple to implement. PMBC uses a dynamic model and adapts to represent the process. These two nonlinear controllers were selected for this application evaluation because of their simplicity (they can be implemented in-house within many commercial control systems), diversity (steady-state and dynamic models), and demonstrated utility for control of nonlinear single-input–single-output processes. The application and results are presented and discussed.

Summarizing the results: Within a small temperature operating range PI provides good control, but over the full operating range, the nonlinear and variable delay of the process lead to poor control with PI. GMC can handle the nonlinear issues, but using the convenient steady-state model; it also, provides poor control because of the variable delay associated with flow rate. PMBC was able to provide good control throughout the entire operating range. PMBC has a further advantage of only having one tuning coefficient, while PI and GMC-SS have two.

1. Introduction

Demand for efficiency, quality, compliance, and safety in chemical process plants motivates the use of more advanced and reliable control methods. Often nonlinearity and delay make controlling chemical processes difficult for conventional control methods. These issues provide motivation for two simple nonlinear controllers, generic model control (GMC) with a steady-state model (GMC-SS) and process model based control (PMBC), and this exploration of their potential in controlling nonlinear processes

Even though PID controllers are popular and simple in structure, their linear basis is not appropriate for controlling process with nonlinear behavior or variable dead time. The inherent nonlinearity of chemical processes has been a challenge for automatic control [1]. Several nonlinear control strategies have been developed to handle nonlinear behavior of processes, such as nonlinear internal model control (NLIMC) [4], nonlinear model predictive control (NLMPC) [18], nonlinear inferential control (NLIC) [16], generic model control (GMC) [11], and process model based control (PMBC) [22]. Traditional internal model control (IMC) [7] is based on a linear model of the process while NLIMC uses inverse of a nonlinear model to determine the desired controller action.

Generic model control (GMC) uses either a steady-state or a transient model developed from first-principles, and integrates these with a closed loop control algorithm. The models may also contain some empirical features or they may be completely empirical. Reported applications of GMC include grain drying, distillation, batch reactors, pH, crystallization, and a blast furnace [2,3,5,9,10,15,19,25–27].

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PMBC is also based on a nonlinear process model, based on fundamental laws of mass, momentum, and energy conservation. Although this model is a first-principles, elementary mechanistic model and is not a comprehensive full-featured, rigorous model, it is grounded in the engineer's understanding of the process. It is not an empirical model from step testing. Mahuli et al. [12,13], and Natarajan and Rhinehart [14] applied PMBC for pH control. Paruchurri and Rhinehart [17] demonstrated the use of steady-state models within PMBC for temperature control of a heat exchanger and dynamic models within PMBC for fluid flow rate control. Subawalla and Rhinehart [23] used both steady-state and dynamic models within PMBC for control of pressure in plasma reactor. Skach et al. [24] implemented PMBC for pressure drop control on a packed absorption tower.

Heat exchangers are frequently used as a demonstration of control [2,6,8,17,20]. They are relatively easy to use experimentally, and they express nonlinear and non-stationary properties that represent general process control difficulties.

Although both GMC and PMBC share strengths such as capability of handling nonlinearity of processes, and ease of on-line tuning with the same heuristic procedures that are practiced for conventional PI control; GMC is not efficient in controlling processes with variable dead time. This is because, similar to PI control, it uses the integral of the actuating error as the feedback correction. In this study, the PMBC, GMC-SS and conventional PI control strategies are applied on the nonlinear process (a heat exchanger) to control the output temperature. Setpoint changes, disturbances, and constraints are implemented to compare the efficiency of the respective controllers.

Here, the PMBC method uses a nonlinear steady-state model of the process and assumes the process responds with second-order dynamics as it moves toward the steady-state value. This is a Hammerstein-type model. This work explores two PMBC versions; one asks the process intermediate variable to follow a first-order reference trajectory toward the setpoint, and the other asks the process output to follow a second-order reference trajectory to the setpoint. Though the first-order dynamics is simple, it is not appropriate to ask high order processes to follow first-order response. Hence, second-order response is also considered in model development.

For many processes, such models are close to being true to the process, except for one feature. Such features might be friction losses, tray efficiency, catalyst activity, or heat transfer coefficient, which change in time, and have relatively uncertain values. Such model parameter values can be adjusted on-line to match the model output to the process output, as is implemented here. This keeps the model locally and temporally true to the process, and is useful for process analysis, constraint identification, supervisory optimization, etc. The PMBC controller objective is to determine values of manipulated variables that force the model to follow a reference trajectory. Simultaneously, the model is adjusted by including the estimated steam temperature inside heat exchanger shell.

This application article describes the heat exchanger process, explains the GMC-SS, and first and second-order PMBC along with the controller structure and equations. The experimental procedure and results are discussed for the four control strategies and the results of PMBC are compared with PI and GMC-SS methods.

2. Process description

The process of this work is a steam condenser within a heat exchanger network in the unit operations instructional laboratory. The heat exchanger is a four-pass shell-and-tube type with water on the tube side and steam on the shell side. The function of the heat exchanger is to raise the tube side water temperature, which is the controlled variable (CV), by condensing steam. The exit water temperature can be controlled by adjusting either the water or the steam flow rate. For this study, water flow rate was chosen as the manipulated variable (MV) while the steam flow rate was used as a disturbance. Although this CV–MV choice may be unusual, it was chosen to exacerbate the nonlinearity and variable dead time aspects of the process. Fig. 1 illustrates the control scheme for the process.

The nominal pipe diameter is 1 in. with reducer expanders for 3/4 in. control valves. The control valve time-constants are about one second. Water flow rate could be varied over a range from about $1.1 \times 10^{-4}\,m^3/s$ (1.7 gpm) to $8 \times 10^{-4}\,m^3/s$ (12.7 gpm) corresponding to the practical minimum (15%) and maximum (100%) controller output. At an MV value of 15% the valve is effectively closed. A supply of steam was available at about 310 kPa (45 psig). The inlet water temperature was about 293 K (68°F).

Since the inlet water came from the building supply, within an experimental trial there was an approximate variation of plus/minus 10 K in its temperature. Further, the nominal building water supply pressure of 70 psig fluctuates plus/minus 10 psig within 5 min intervals. Both create unmeasured and uncompensated disturbances to the experimental trials.

Figs. 2 and 3 show the layout of the heat exchanger network showing the location of the control valves and exit water temperature measurement.

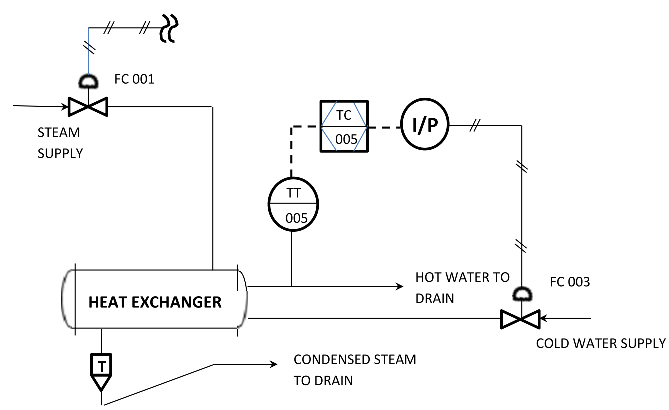

Fig. 1. Heat exchanger P & ID.

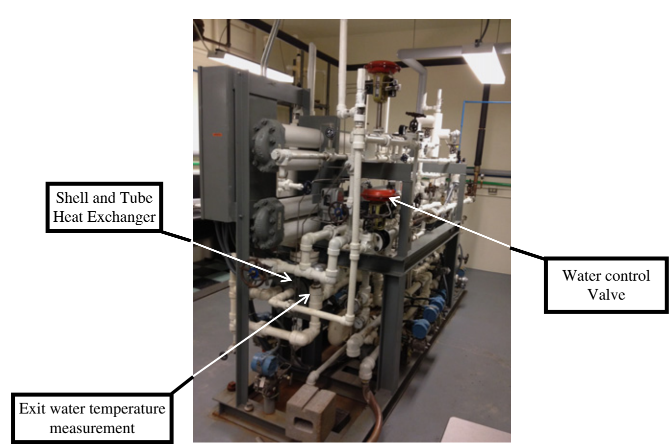

Fig. 2. View of heat exchanger network (view from Northwest).