CHEMICAL PROCESSING

°C

Improve
BATCH REACTOR
temperature control

Understand the likely causes and fixes for common problems in reaching set points

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REACTOR TEMPERATURE control typically is very important to product quality, production rate and operating costs. With continuous reactors, the usual objectives are to:
- hold temperature within a certain band around the set point, preferably without oscillation;
- minimize operator intervention; and
- minimize consumption of utilities.

Batch reactors generally demand some additional objectives such as:
- fast heatup or cooldown to a new set point without oscillation and with minimal overshoot; and
- stable response to load disturbances, e.g., an exothermic reaction.

Achieving these objectives requires paying attention to many details of the equipment and controller logic. Systematic testing and optimization of the feedback control loops also can speed the startup of a new plant.

Figure 1 shows a common control system for glass-lined batch reactors where the slave loop operates on the jacket inlet temperature to protect the lining. The heating/cooling supply can have various split-range (TY) configurations such as control valves to hot/cold headers (which we'll call Case 1), control valves to steam and chilled-water heat exchangers (Case 2) and control valve on the chilled fluid and variable electrical heating (Case 3). Here, we'll look at some challenges and opportunities based on real data from three such reactors as seen
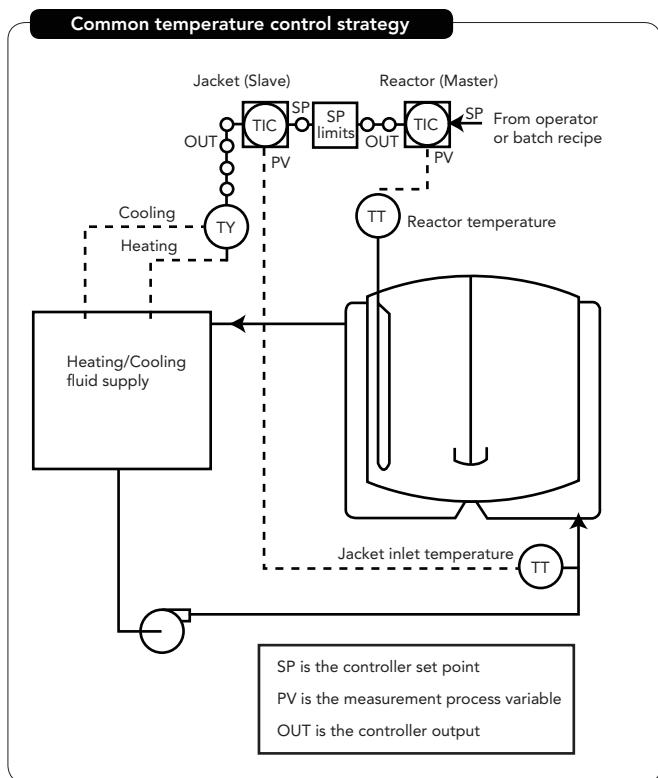
Common temperature control strategy

Jacket (Slave)   Reactor (Master)

SP

From operator
or batch recipe

OUT   TIC   SP   SP   TIC   OUT

limits

PV   PV

Cooling

TY

Heating

TT   Reactor temperature

Heating/Cooling
fluid supply

Jacket inlet temperature   TT

SP is the controller set point

PV is the measurement process variable

OUT is the controller output

Figure 1. Various split-
range (TY) configura-
tions can be used to
regulate jacketed glass-
lined batch reactors.

from the operators' trend charts.
We'll show symptoms of common
problems and examples of benefits
achieved.

CASE 1
A plant was starting up a new building with all
new reactors, instruments and Distributed Control
System (DCS). A consultant applied Lambda tun-
ing (which we'll discuss later) to give smooth fast
set-point and load responses without oscillation.
However, as shown in Figure 2, the default Pro-
portional + Integral + Derivative (PID) algorithm
produced temperature overshoot that exceeded the
recipe specifications on set-point steps. The over-
shoot is due to the presence of integral action in
both the controller and the process. Dominance of
integration (slow ramping) in the reactor tempera-
ture *process* may confuse the engineer, technician or
auto-tuner responsible for finding the best control-
ler tuning parameters. Integral action is needed in
the *controller* to correct for load disturbances. In a
modern control system it's easy to choose alterna-
tive algorithms (Figure 2) to prevent or reduce this
overshoot.

If we waited longer for the set-point responses
to settle, we'd see a slow *limit cycle* of ±0.5°C on

the reactor temperature and ±5°C on the jacket
temperature. The root causes are nonlinearity in
the jacket loop from selecting inappropriate control
valves and excessive dead zones in the split range
strategy. No tuning of the feedback controller will
eliminate limit cycles.

CASE 2
At another plant, temperatures of eight reactors
were oscillating. Figure 3 shows a set-point response
and a load response for one reactor temperature
loop. With the reactor set point initially at 30°C,
the slow oscillation caused the jacket to continu-
ously and alternately consume significant quantities
of steam and chilled water. Later, after the exother-
mic reaction, the jacket controller output began
swinging almost full scale up and down. Average
energy consumption was much greater than that
theoretically required to maintain the reactor tem-
perature. There also was a smaller faster oscillation
of the jacket loop.

The main problems identified by the consultant
and corrected were:
- oscillatory tuning of the reactor temperature
  controller;
- oscillatory tuning of the jacket temperature
  controller;
- excessive dead zone in the jacket split range
  logic; and
- control valve setup problems.

The plant personnel hadn't been trained in
modern loop-tuning methods such as Lambda
tuning, which gives nonoscillatory response at the
speed required by the production objectives. The
tests required for systematic tuning also revealed
the nonlinearities in the split range logic and
control valves. After applying corrections to three
reactors, energy savings on steam alone paid for the
consulting project in less than three months.

CASE 3
The as-found auto response was too slow, taking
more than two hours to reach the new set point (Fig-
ure 4). Note for the reactor (master) loop the units
of the SP, PV and output all are °C. For integrating
processes, fast closed-loop response requires driving
the output beyond the PV for some period of time.
Due to the slow tuning, the operators preferred to
make frequent manual adjustments to the jacket
set point until the correct reactor temperature was
achieved. This interfered with the operators' primary
duties such as sampling for quality control.

Due to nonlinearities in the control logic, it wasn't possible to find the best controller tuning parameters by hand calculation. Instead the consultant built a computer simulation using test data acquired from manual step responses. This led to much better tuning of the controller and allowed the operators to keep the reactor loop in auto mode — as designed.

The tests also identified several limitations in the jacket response (Figure 5). The response was much faster to cooling than to heating. The cooling response showed initial oscillation followed by a very slow attempt to recover to 40° C. The asymmetry in heating versus cooling indicates the need for a gain scheduling controller, which applies one set of tuning parameters for cooling and another for heating. Manual step testing of the jacket also showed that inappropriate derivative and filtering values had been installed for the jacket controller. Finally, ideal cooling response would require a different inherent flow characteristic in the cooling valve. Fixing all these problems in the jacket loop would further improve the reactor response.

METHODS FOR SUCCESS

In the typical chemical plant, there're several obstacles to achieving optimal control. Plant design and construction often emphasize chemistry, cost and safety instead of control. Academic control courses typically leave the plant engineer ill-prepared due to their emphasis on complex mathematics or sole focus on continuous processes. Early tuning methods, still taught in the industry, were designed to deliberately make the loop oscillate. The jacket and reactor temperature relationship includes integrating dynamics, making controller tuning less intuitive than for self-regulating (e.g., flow) loops.

Complex control systems have been developed to handle various reactor hardware, specific types of chemical reactions and production constraints [1]. For the fastest possible set-point response, you may want to consider a nonlinear control strategy as described in Ref. 2. However, for reactors controlled by simple cascade strategies (Figure 1),
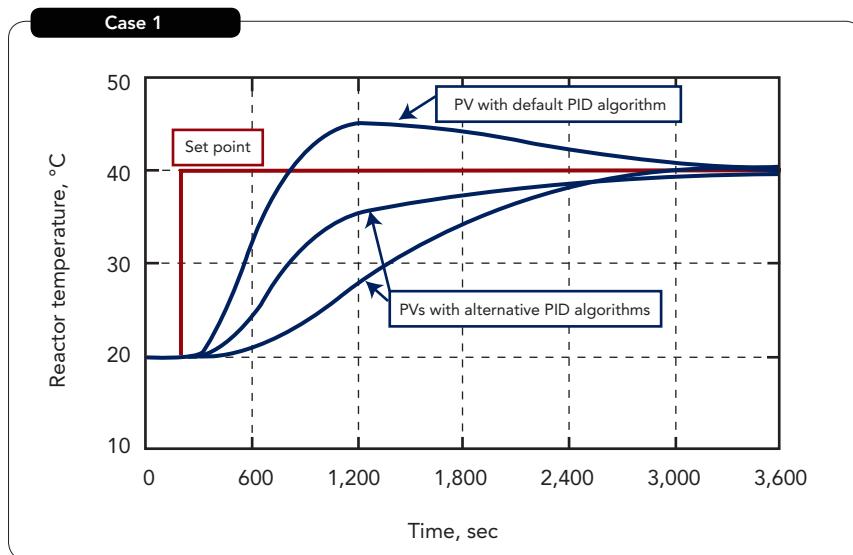

Figure 2. Overshoot afflicted set-point steps on an 800-L reactor with the reactor loop in auto and the jacket loop in cascade.

many problems can be prevented by applying the following five steps to each loop:

1. Make the process dynamics as linear as possible.
2. Minimize dead time.
3. Measure the process dynamics.
4. Choose the right controller algorithm to compensate for the process dynamics.
5. Tune for the speed required, without oscillation.

Linear means the process temperature PV responds consistently regardless of the size, direction or history of the controller output changes. In the jacket loop, achieving linearity requires selecting appropriate control valves and minimizing nonlinearities in the control strategy, e.g., dead zones in the split range logic. Figure 5 shows another example of nonlinearity: on the heating step, after the initial overshoot, recovery to 50° C was extremely slow due to the control-valve flow characteristic. Sometimes the limiting nonlinearity is in the utilities supplying the jacket, e.g., a steam-header pressure control loop. In the reactor loop, linearity means getting symmetrical set-point responses from the jacket. If the cooling and heating responses of the jacket are asymmetrical (as in Figure 5 or for steam versus cold water), consider a gain scheduling controller to compensate. This doesn't require any special coding because it can be easily configured by drag-drop-and-tune in modern control systems.

Dead time is the time measured from an output change before anything happens on the
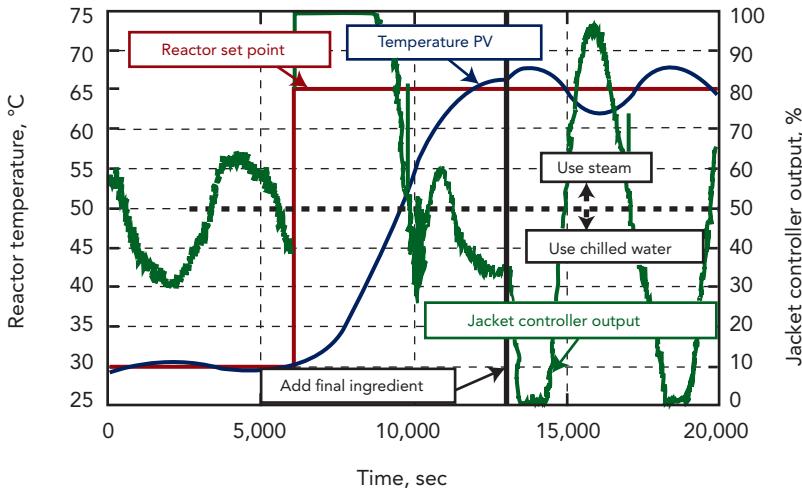
Figure 3. Oscillation occurred during set-point step on a 40,000-L reactor with the reactor loop in auto and the jacket loop in cascade; a load disturbance (exothermic reaction) also took place.

DCS. The two simplest types of process dynamics are:
- self-regulating processes (those that eventually settle at a new value during manual step tests); and
- integrating processes (those that ramp at various slopes during manual step tests).

The tests to measure these process dynamics also will reveal the nonlinearities in the process.

With a PID controller the type of process determines how to *compensate for the process dynamics*. For purely self-regulating processes we mainly use integral action in the controller. For purely integrating processes we mainly use proportional action. Derivative action normally isn't needed in the jacket controller but may be appropriate in the reactor controller.

The Lambda tuning method is one way of choosing the PID parameters to *tune for the speed required, without oscillation*. For process dynamics that are purely self-regulating or integrating, simple algebraic tuning rules developed for continuous processes [3] have proven applicable to batch processes. These rules can be taught to engineers, technicians and operators as a time domain method — without the need to use Bode plots or transfer functions.

We must observe the rule of cascade by tuning

PV. It's inherently destabilizing in a feedback control loop. In the jacket, one cause of dead time is transport delay or the time required for a new fluid mixture to pass from the control valve to the measuring element. Minimize this dead time by appropriate sen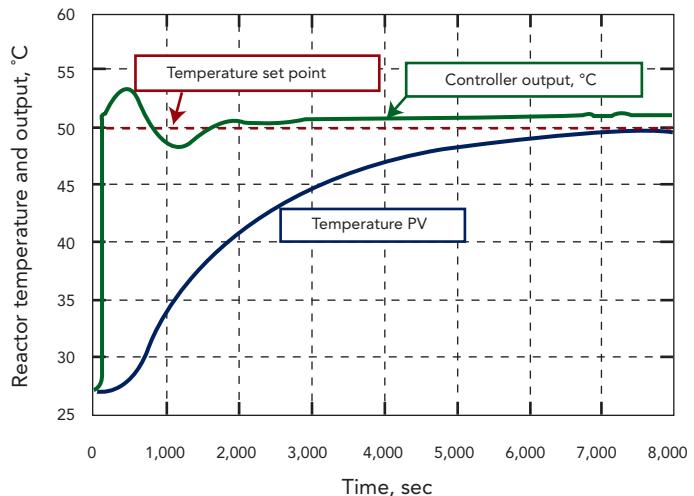sor location and by installing a circulating pump as shown in Figure 1. Also, the effect of filters added in the transmitter or the controller may look like dead time to the PID algorithm. In the reactor loop, we minimize dead time by getting the fastest linear response of the jacket loop, including allowing one overshoot on the jacket set-point response.

Process dynamics is a model of the shape and size of the PV response to output changes, which we need to optimally tune the controller. For most loops this can't be calculated before construction and is most conveniently determined from step tests with the controller in manual. The process dynamics can be manually calculated from trend charts or time series data acquired from an OPC server or, in some cases, automatically by software running in the

Figure 4. Response was far too slow for a set-point step on a 3,600-L reactor with the reactor loop in auto and the jacket loop in cascade.
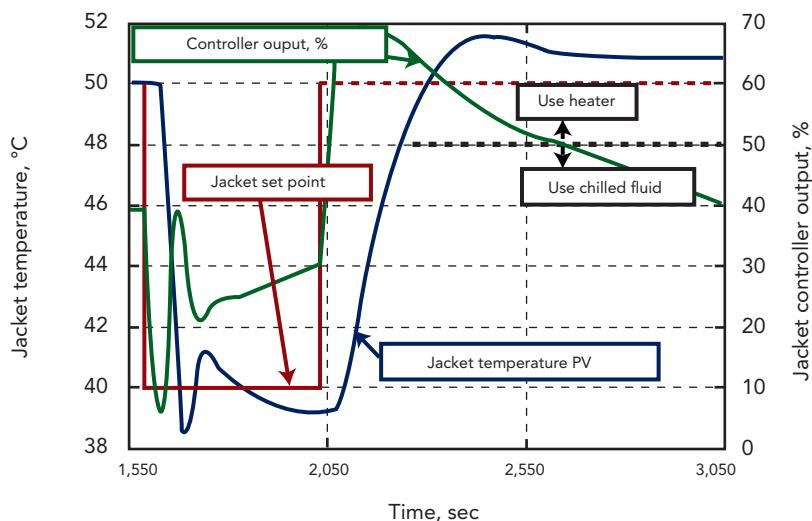
Figure 5. Jacket responded faster to cooling than heating as shown with reactor loop in manual and jacket loop in cascade mode.

heating of the reactor with no overshoot or oscillation. Again, the modern control system makes it easy to install this controller.

ACHIEVE BETTER CONTROL

Some plants have experienced oscillatory or sluggish response of batch reactor temperature. This can be caused by the integrating process response, limitations in the control system and lack of training. With a modern control system, a plant can set up the controllers to give fast set-point response without overshoot or oscillations. This offers the opportunity to maximize product quality, minimize batch cycle time and eliminate utilities waste — all positive impacts on your plant's profitability. ●

the jacket (slave) control loop first and faster than the reactor (master) control loop. The Lambda tuning method provides explicitly for tuning by the cascade rule because we can set the response time (λ) of each control loop as:

$$\lambda_{jacket} << \lambda_{reactor}$$

More-advanced tools are helpful for some situations. For instance, if the temperature process response has elements of both self-regulating and integrating dynamics, a different tuning rule is needed. When there's significant nonlinearities in the control logic (for example, the SP limiter block in Figure 1), a nonlinear computer simulation can accelerate finding the best controller parameters — today's control systems come with built-in simulation tools. In some cases a Fuzzy Logic Controller (FLC) can give control superior to PID. When there's no jacket but only electrical heating of the reactor, the FLC can provide the fastest possible

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REFERENCES
1. Process Control and Optimization, Volume VIII in "Instrument Engineers' Handbook," p. 1,664, 4th ed., B.G. Liptak, ed., CRC Press, Boca Raton, Fla. (2007).
2. Boudreau, M.A. and G.K. McMillan, "New Directions in Bioprocess Modeling and Control," p. 91, ISA, Research Triangle Park, N.C. (2007).
3. Bialkowski, W.L., in "The Control Handbook," p. 1,234, W. Levine, ed., CRC Press, Boca Raton, Fla. (1996).