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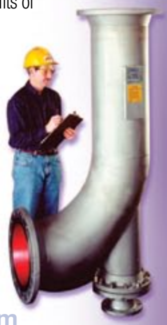

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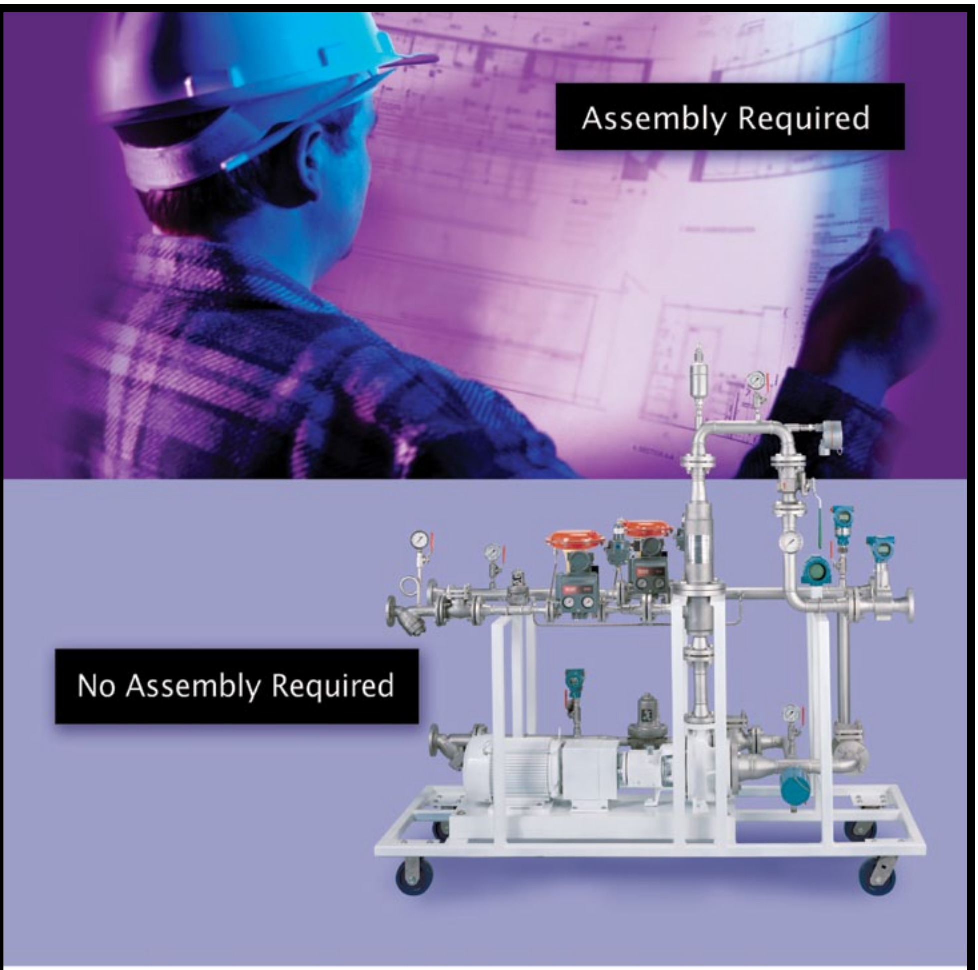

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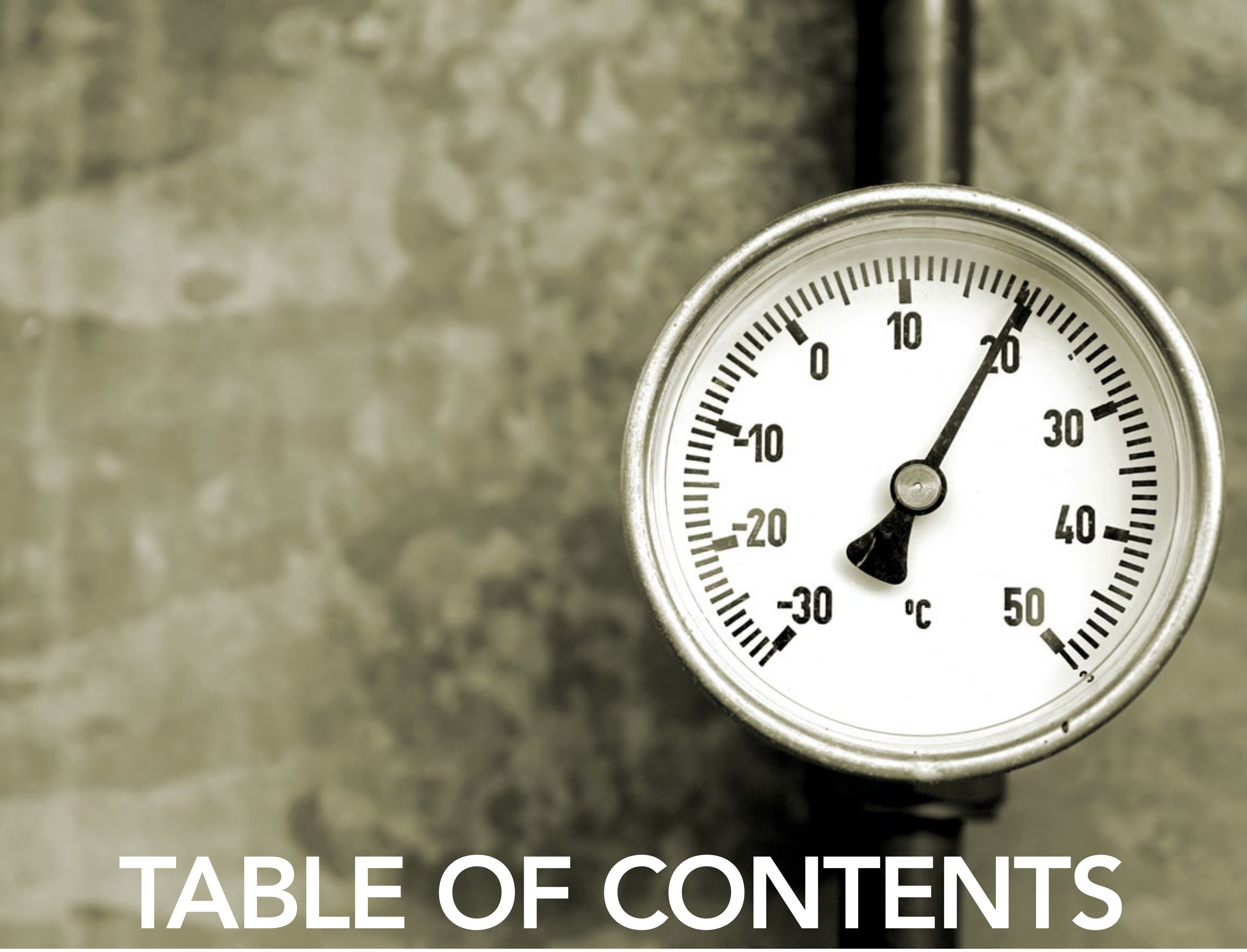


TABLE OF CONTENTS

NEXT PAGE ▶

Improve Batch Reactor Temperature Control

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

By Mark Coughran

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.

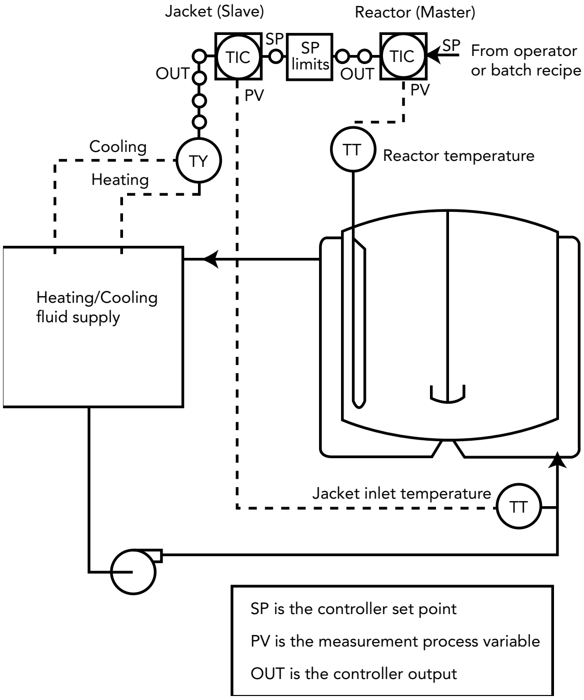
Batch reactors generally demand some additional objectives such as:

- 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

COMMON TEMPERATURE CONTROL STRATEGY



SP is the controller set point

PV is the measurement process variable

OUT is the controller output

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

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 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 tuning (which we'll discuss later) to give smooth fast set-point and load responses without oscillation. However, as shown in Figure 2, the default Proportional + Integral + Derivative (PID) algorithm produced temperature overshoot that exceeded the recipe specifications on set-point steps. The overshoot is due to the presence of integral action in both the controller and the process. Dominance of integration (slow ramping) in the reactor temperature *process* may confuse the engineer, technician or auto-tuner responsible for finding the best controller tuning parameters. Integral action is needed in the *controller* to correct for load disturbances. In a modern control system it's easy to choose alternative 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

CASE 1

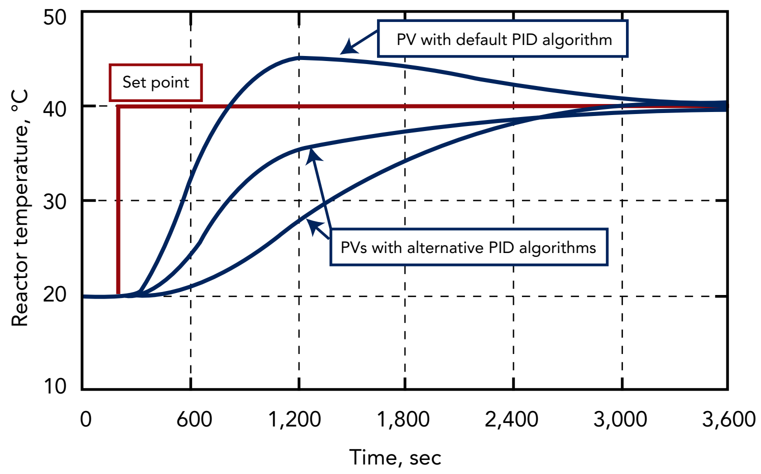


Figure 2. Overshoot afflicted set-point steps on an 800-L reactor with the reactor loop in auto and the jacket loop in cascade.

CASE 2

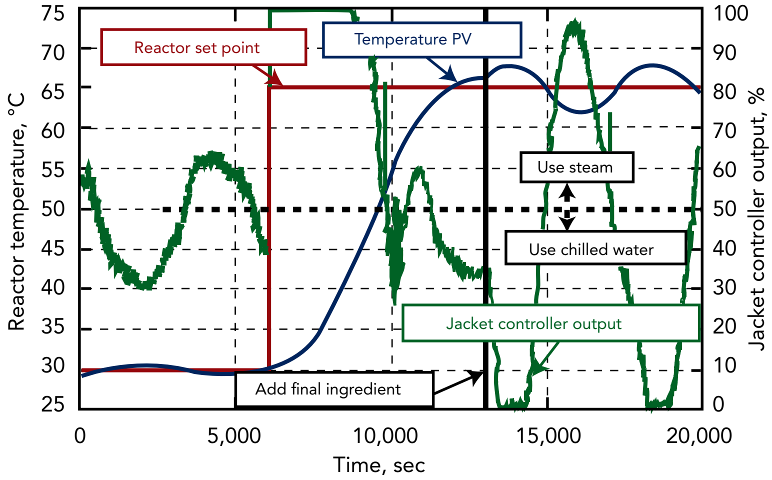


Figure 3. Oscillation occurred during set-point step on a 40,000-L reactor with the reactor loop in auto and the jacket loop in cascade; a load disturbance (exothermic reaction) also took place.

CASE 3

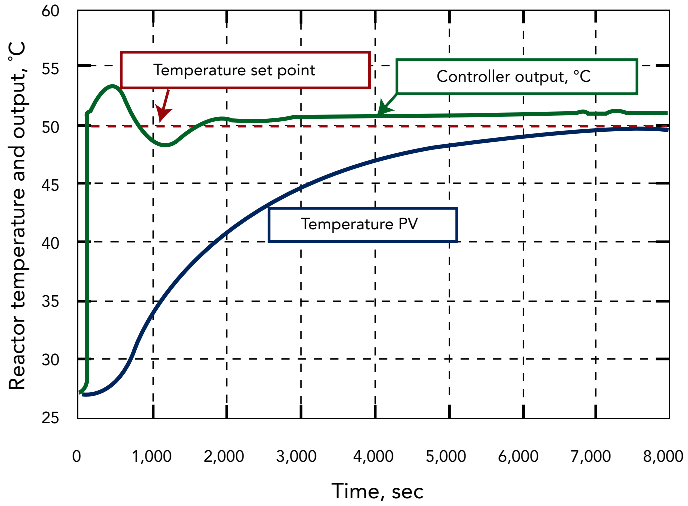


Figure 4. Response was far too slow for a set-point step on a 3,600-L reactor with the reactor loop in auto and the jacket loop in cascade.

ASYMMETRICAL RESPONSE

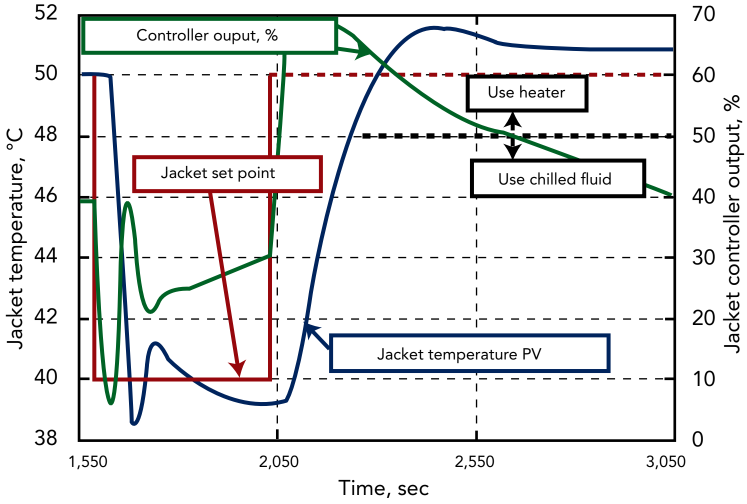


Figure 5. Jacket responded faster to cooling than heating as shown with reactor loop in manual and jacket loop in cascade mode.

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 continuously and alternately consume significant quantities of steam and chilled water. Later, after the exothermic 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 temperature. 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 (Figure 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), 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 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 sensor 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

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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 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 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're 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 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. ●

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Rethink Reactor Temperature Control

Cascade strategy offers simplicity and fast response

By Andrew Sloley

EVEN MINOR differences between control schemes can dramatically affect unit performance, as a recent project to improve control of a batch reactor illustrates.

Reactant A is preloaded into the vessel and then Reactant B is slowly added. A mixer provides good contacting for the first-order reaction to create the desired high-value specialty polymer product.

One reason for adding small amounts of Reactant B to a large quantity of Reactant A (or product) is that both Reactant A and product are much better heat sinks than Reactant B. For typical first-order kinetics, back mixing reduces the concentration and slows down temperature rise. The commonly used rule-of-thumb for most first-order reactions is that reaction rate doubles with an approximately 18°F (10°C) temperature rise.

Tight temperature control is critical to getting the right polymer properties. The process objective is to keep the reaction at as close to a constant temperature as possible. Cooling water in the reactor jacket carries away the reaction heat. The heat sink, back mixing and mixer in the vessel all aid smooth temperature control.

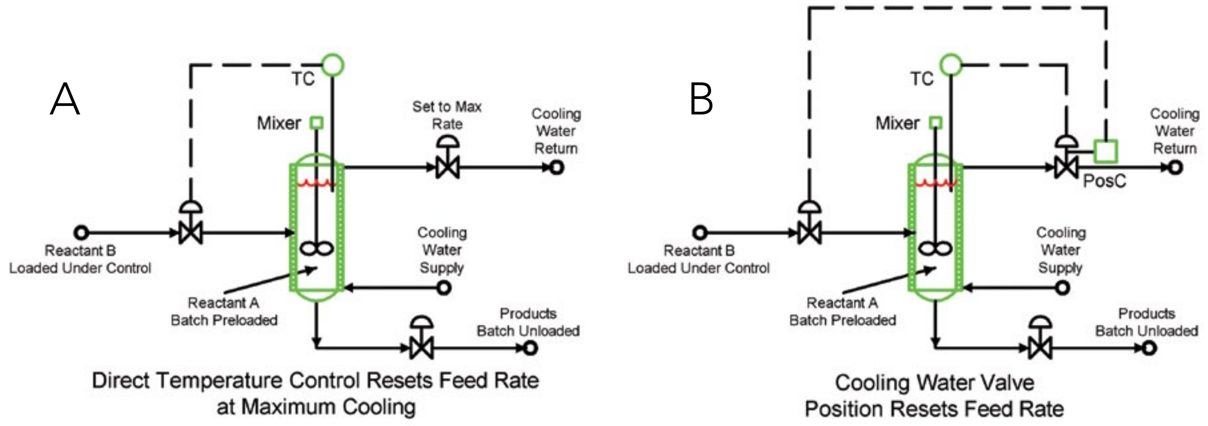
The obvious control strategy for greatest throughput is to operate the reactor at maximum cooling levels at all times (Figure 1a). Cooling water supply is set to its highest rate. The temperature controller varies Reactant B to meet the target temperature. This control scheme is simple to understand and straightforward. Simple and easy-to-understand methods tend to have high reliability and get left alone to work correctly.

However, this approach poses a problem that may not be apparent. It combines two dominant lags in series, making the system respond relatively slowly to disturbances. The first large lag is that changes in Reactant B must change the composition before reaction changes occur. The second lag is that the composition change then has to change the reaction rate before heat generation changes take place. Both of these have relatively long time constants in the system. Reactant B feed rate is small compared to the volume in the reactor. Second, the desired product forms at a relatively low temperature — hence at a relatively low reaction rate. Excursions take the control system too long to correct.

One proposal was to use an advanced predictive controller to simultaneously change cooling-water and reactor rates. This would require extra instrumentation on the cooling-water-supply pressure and temperature and a much more complicated control system. My experience is that most advanced control applications get turned off and abandoned sooner rather than later.

We needed a simpler alternative and came up with

REACTOR TEMPERATURE CONTROL



Direct Temperature Control Resets Feed Rate at Maximum Cooling

Cooling Water Valve Position Resets Feed Rate

Figure 1. Cascade SISO logic, diagram b, provides much faster response than more obvious option.

a solution that uses cascade single-input single-output (SISO) logic (Figure 1b). Reactor temperature controls cooling water supply. Cooling water valve position then cascades to Reactant B feed rate control. This provides much more rapid response. Position changes in the cooling water valve occur instantaneously with water flow rate. The cascade approach acts as fast as any advanced control system that attempts to simultaneously move both the Reactant-B and water-supply control valves. And, unlike advanced control methods, the logic is clear and maintenance requirements are minimal.

Choosing a reasonably high cooling-water-valve-position setting (90%) gives a cooling water rate close to the maximum possible. Reactor temperature control is stable; reactant and utility changes are quickly dampened.

Development of really good valve positioner technology has created many opportunities to improve plant control with straightforward SISO logic. The solution here is still simple, just different from the obvious. ●

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Keep Cool When Designing Batch Reactors

In designing such a unit, focus on effective temperature control to achieve optimum performance

By John Edwards

THE STIRRED batch reactor is a workhorse at many fine and specialty chemical plants, frequently serving multiple purposes. It can handle not just reaction but solvent extraction, crystallization and distillation. The successful installation of such a reactor depends to a great degree upon the proper design of its temperature-control system.

The most critical factor is the design operating temperature range. This, coupled with a site's practices and the initial fill cost, drives the selection of a heat transfer fluid (HTF).

An HTF must not be used at temperatures above the manufacturer's recommended maximum. It is considered good practice to select a fluid with temperature capabilities at least 20°C (36°F) higher than the required process maximum to safeguard against fluid breakdown. Table 1 summarizes the temperature capability of some common HTFs.

Note that the food industry prefers propylene glycol, due to its low oral toxicity, to ethylene glycol. Glycol water-based systems require inhibitors to keep dissolved oxygen from forming organic acids, which can cause corrosion and fouling.

Wherever possible, avoid pressurized systems by selecting a fluid with acceptable vapor pressure at the maximum operating temperature. This will simplify system design and operation. Then, evaluate the suitability of other crucial physical properties over the operating temperature range. The specific heat of water-based and organic HTFs can vary significantly. As Figure 1 shows, water has a higher heat-removal capability.

The liquid viscosity throughout the operating temperature range is a key parameter. At low temperatures, viscosity effects can become limiting, resulting in low jacket/coil-side heat-transfer coefficients and high pressure drops (Figure 2). Selection of an HTF with reasonable viscosity characteristics and an acceptable freeze point will allow operations down to -90°C (-130°F) [1].

FLUID TRADEOFFS

Organic HTFs offer a number of advantages:

- liquid state throughout the operating temperature range, which simplifies the control system, equipment configuration and operation;
- stable fluid properties over a wide temperature range;
- less corrosion and erosion of heat-transfer surfaces than water;
- controllable temperature differences, which minimize thermal shock effects; and
- flexibility to handle a variety of services.

However, they also pose disadvantages:

- lower thermal efficiency than water-based systems;
- higher initial equipment and installation costs;
- significantly greater cost for initial fluid charge;
- propensity to leak;

LIQUID SPECIFIC HEATS

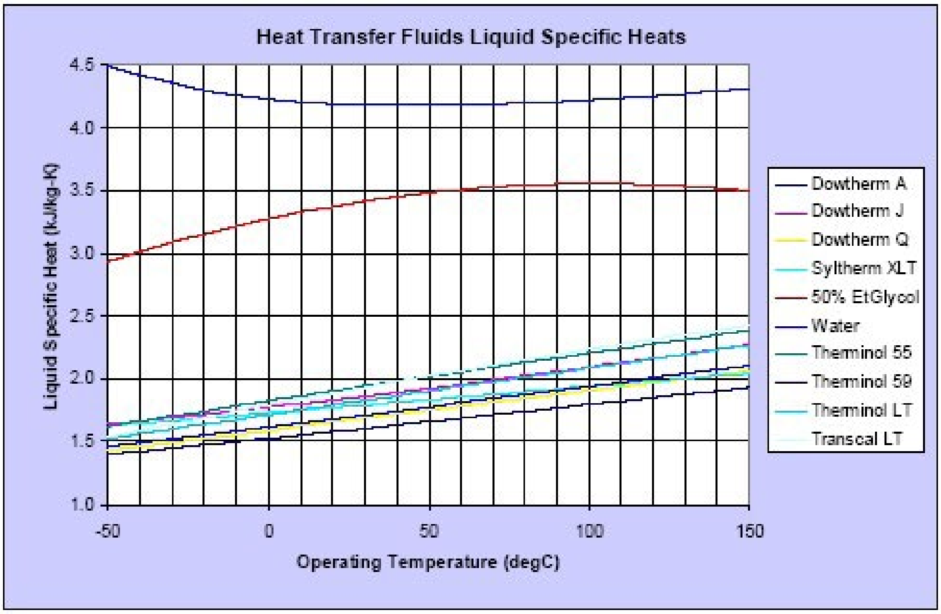


Figure 1. As this graph shows, water has a higher heat-removal capability.

LIQUID VISCOSITIES

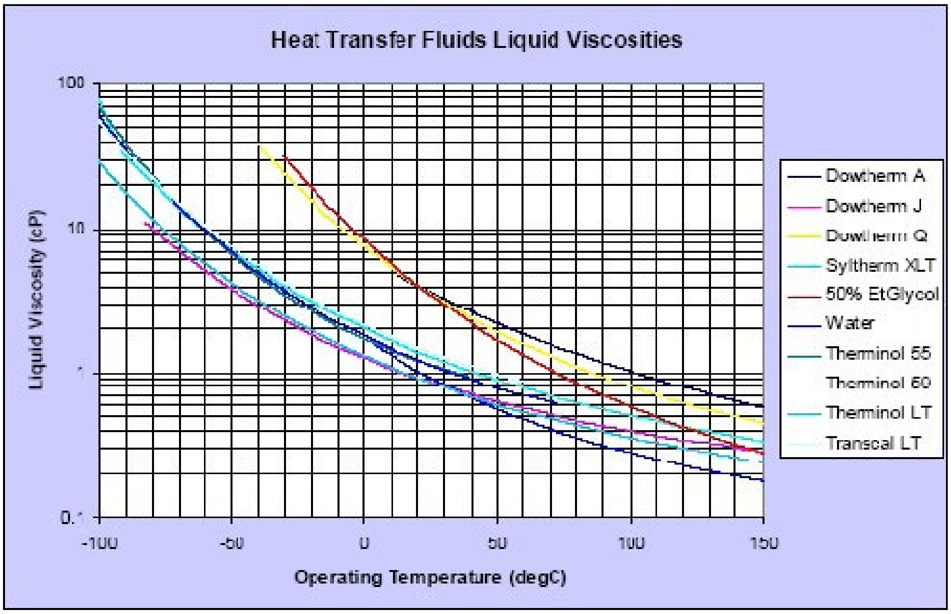


Figure 2. At low temperatures, viscosity effects can become limiting, resulting in low jacket/coil-side heat-transfer coefficients and high pressure drops.

- special commissioning, operational and maintenance procedures;
- longer downtime on equipment failure; and
- flammability, toxicity, odor and good manufacturing practice (GMP) concerns.

These HTFs will aggressively search for any leak paths and this must be considered when selecting equipment and specifying piping. Use sealless pumps for fluid circulation. To achieve the flow required to prevent bearing damage, install a restriction orifice in a spillback line. The piping design should specify ANSI 300 flanges, as a minimum, to allow for high bolting torques. The gaskets should consist of an asbestos-free filler reinforced with a stainless steel spiral.

These systems have to be thoroughly dried out by heating during commissioning to prevent operational problems and equipment damage. This can take days on large installations and needs to be done slowly to avoid equipment damage due to steam hammering. Manufacturers do not recommend water for pressure testing, preferring a suitable dry alternative. However, this is not usually feasible during the construction phase.

Water breakthrough, due to contamination or equipment failure, can result in considerable downtime to identify and rectify the problem. At low temperatures, water breakthrough will result in freezing, leading to loss of circulation and possible equipment damage.

REACTOR PARAMETERS

The heat-transfer-area/reactor-volume ratio increases as the reactor size decreases (Figure 3). This needs to

REACTOR VOLUME VERSUS HEAT-TRANSFER GAS

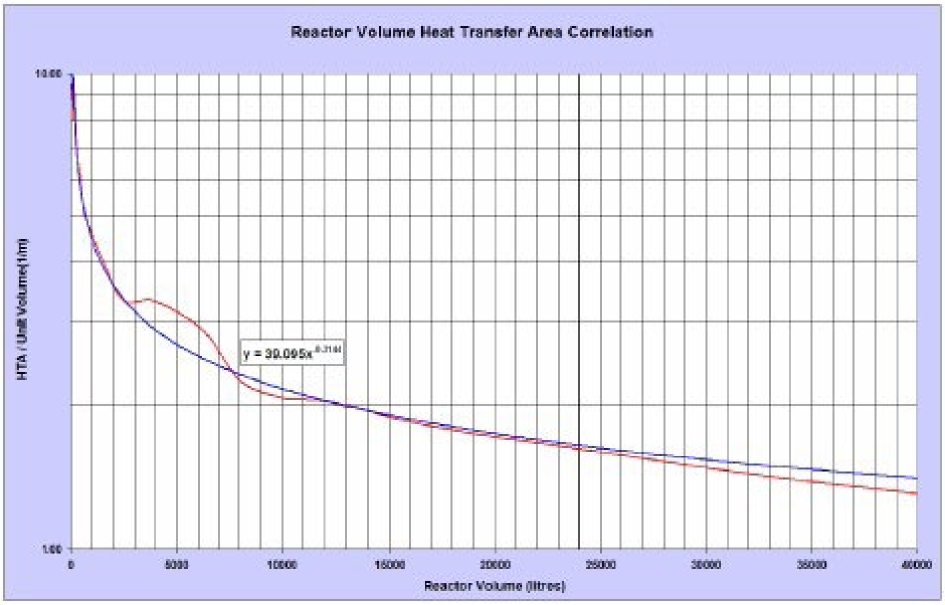


Figure 3. The heat-transfer-area/reactor-volume ratio increases as the reactor size decreases.

be considered carefully during scaleup and underscores the importance of correctly matching reactor size to batch size. Partially filled reactors not only reduce the heat-transfer area but can cause mixing problems and exothermic reaction instability.

The thermal conductivity of materials of construction significantly impacts reactor wall temperatures and, thus, can limit cycle times. Extreme temperature differences can result in product quality problems on certain processes. (The density and specific heat differences among materials aren't a critical factor in heat transfer.)

As vessel size increases, so too does the cross-sectional area for fluid flow, which is determined by the annulus width for jackets and the pipe diameter for coils. Unbaffled jackets result in laminar flow, which gives poor thermal performance. Baffling in the jacket annulus, dimple jackets, half coils and inlet agitating nozzles can provide higher velocity. Mechanical design, construction and cost constraints can limit options [2, 3].

Stirred batch reactors, with coils or external jackets, have inherent thermal lags due to the heat capacities of the masses associated with the reactor, reaction mix, jacket contents and jacket services [4]. To minimize these lags, reduce, wherever possible, jacket service volumes and thermal masses associated with external equipment and also install good thermal insulation.

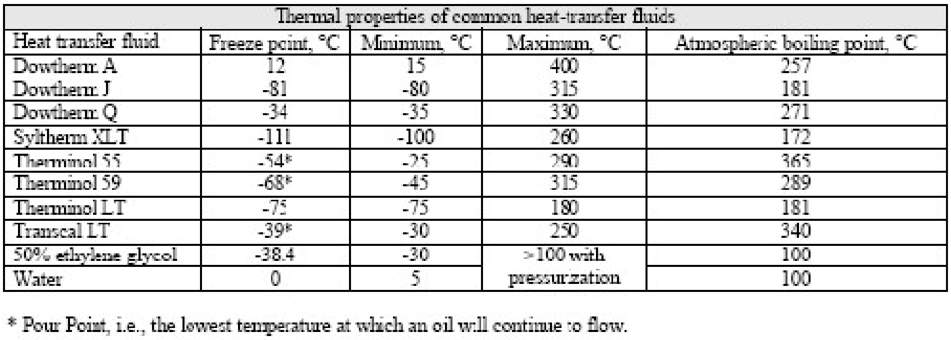
A study of the heatup and cooldown curves or responses to setpoint step changes can provide an estimate of time constant. For instance, the typical overall value for heating 1,000 kg of toluene in a 1,600-L Hastelloy C reactor with Dowtherm J fluid is 21.1 minutes; breaking down this estimate into the contributions for the different interfaces gives the inside contributing 15.4 minutes, the wall 3.1 minutes and the outside 2.6 minutes.

Endothermic reactions exhibit a marked degree of self-regulation in regard to thermal stability and do not need further consideration.

Exothermic reactions, however, require a detailed understanding of kinetics to obtain rate and heat of reaction. The heat removal capability is a function of the resistances to heat transfer, the temperature difference and the heat-transfer area. Reaction temperature increases lead to a higher rate of reaction and pose a risk of thermal runaway if heat cannot be removed fast enough; any reduction in heat-transfer area due to a decrease in reactor contents adds to the problem. Design cannot always provide stability where not enough heat-transfer area is available for the temperature difference. However, removing heat by boiling one or more of the components can ensure stability because this tends to create an isothermal system.

When reactions are carried out with all the reactants charged, carefully consider the implications of cooling failure, taking into account common mode failures. It is preferable

THERMAL PROPERTIES OF COMMON HEAT-TRANSFER FLUIDS



Thermal properties of common heat-transfer fluids				
Heat transfer fluid	Freeze point, °C	Minimum, °C	Maximum, °C	Atmospheric boiling point, °C
Dowtherm A	12	15	400	257
Dowtherm J	-81	-80	315	181
Dowtherm Q	-34	-35	330	271
Syltherm XLT	-111	-100	260	172
Therminol 55	-54*	-25	290	365
Therminol 59	-68*	-45	315	289
Therminol LT	-75	-75	180	181
Transcal LT	-39*	-30	250	340
50% ethylene glycol	-38.4	-30	>100 with pressurization	100
Water	0	5		100

* Pour Point, i.e., the lowest temperature at which an oil will continue to flow.

Table 1. This table shows the temperature capability of some common HTFs.

to limit the reaction rate by adding the reactant continuously at a controlled rate to ensure that the heat generated does not exceed the system's heat-removal capability.

Tempered reactions, i.e., those operating at the boiling point, remove heat using the latent heat of vaporization. This procedure is self-regulating, provided the sizing of the overhead condenser ensures material is not removed from the reaction (which would decrease the heat-transfer area). In this case, the reactor cooling system only needs to remove any excess heat from the reaction.

Gassy systems generate a permanent gas and require the total heat evolved to be absorbed by the jacket/coil cooling system.

It has been empirically established that a velocity of 1 m/s across the service-side heat-transfer surface will provide optimal economic heat transfer. Achieving this necessitates the use of circulating pumps and jacket-inlet circulating nozzles, which induce a rotational movement similar to spiral baffles and significantly reduce the circulation flow required for efficient heat transfer. The combined reactor and nozzle pressure drop determines the number and size of mixing nozzles. Vendors provide curves to establish the optimal circulation rate and pressure drop [5].

When using HTFs that might have high viscosities within the operating temperature range, circulating nozzle pressure drops might become limiting and half pipe coil constructions might be required.

Minimize the heat load on the refrigeration system by first using a higher-temperature cooling service and then switching to a lower temperature medium only when necessary. Excessive evaporator temperature in the refrigeration loop can result in compressor shutdown and, ultimately, failure. Any water present in the system will accumulate and freeze at the compressor suction.

Boilup and wall temperature might be excessive with direct steam and might require pressure control. Boilup can be limiting with indirect HTF systems and only can be boosted by raising the jacket temperature, which is subject to maximum operating-temperature constraints.

EXTERNAL HEAT EXCHANGERS

Batch operation can involve rapid temperature cycling that leads to severe thermal stresses. Therefore, use a fully welded shell-and-plate heat exchanger rather than a less expensive brazed unit, which might experience stress failure. The thermal fluid is usually on the plate side and the service fluid on the shell side. For cryogenic applications, opt for a coiled-tube heat exchanger with liquid nitrogen on the tube side [6].

Base the heat duty for exchanger sizing on the reactor heat-transfer area available at maximum operating level.

Inlet and outlet temperature differences are determined from the services' supply and return temperatures and by selecting reasonable HTF inlet and exit temperatures at the approach to the services' inlet temperatures.

For heating with steam, the inlet and outlet temperature differences are unlikely to be critical at the approach to maximum HTF temperature.

For cooling, the inlet and outlet temperature differences can be critical at the approach to minimum HTF temperature, particularly for low-temperature applications. Select a design temperature difference that gives an economic design while providing a heat-transfer capability that exceeds the reactor's by a reasonable margin.

The liquid service flow is established by setting an acceptable temperature difference across the heat exchanger, typically 10°C (18°F). The type of cooling system and its

FIGURE 4. INDIRECT HEATING AND COOLING

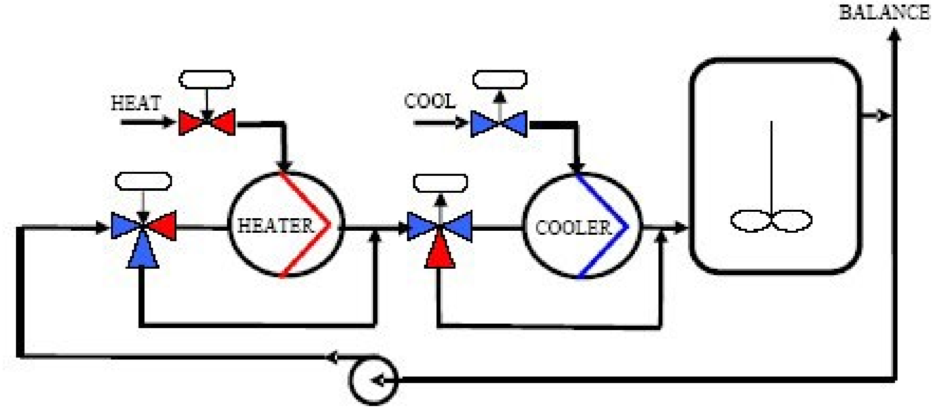


Figure 4. A three-way valve at the steam heat exchanger provides fast-response bypass control by eliminating the thermal lag associated with the heat exchangers.

operation determine the allowable return temperature.

A characteristic of plate heat exchangers is that the cross-sectional area for flow is small and the pressure drop, particularly at low temperatures, usually sets the number of plates and their geometric arrangement.

The heat-transfer area is estimated thermally, and the configuration then is adjusted to give an acceptable pressure drop. The plate area determined by pressure drop, usually on the circulating heat-transfer-fluid side, normally results in an increased design margin for heat-transfer area.

CONTROL STRATEGY

As reactor size increases, the thermal lag from reactor contents to reactor wall increases and the heat-transfer area per reactor volume decreases. Temperature control is characterized by sustained errors between setpoint and measurement during heatup and cooldown and by varying thermal responses.

A typical control system has the reactor contents' temperature primary controller output being cascaded to the jacket/coil temperature secondary controller setpoint.

The primary control modes normally are proportional (P) plus integral (I) plus derivative (D), with P typically set in the range 35% to 50%, the I mode set slower than the overall time constant and the D mode set at I/4. The I mode should only be activated when the measurement is within the proportional band; it should be set conservatively, ensuring that energy is not driven into the process at a rate faster than the process can accept it, to prevent oscillation.

The secondary control mode normally is a P-only controller, with P set <less than equal to>< 25%, as the I mode slows down the response.

Distillation boilup is determined by the temperature difference between jacket/coil and reactor contents. Boilup is controlled by the jacket/coil inlet temperature; the secondary controller will require I mode to be activated to eliminate offset.

For high-accuracy temperature measurements, use a resistance sensor with a Smart transmitter to provide flexibility when setting ranges. The thermal lag associated with the sensor is minimal. However, there can be a significant thermal lag associated with the thermowell if it is incorrectly designed or installed, and this can lead to an uncontrollable system. Fast response designs are available and should be used.

Satisfactory performance depends upon the selecting a control valve with the appropriate operating characteristics. A valve has an inherent characteristic (relationship between flow and stroke at constant ΔP) and an operational characteristic where the inherent characteristic is modified by the process pressure conditions. An equal-percentage operating characteristic tends toward a linear characteristic as ΔPmax/ΔPmin increases. A linear operating characteristic tends toward a quick opening characteristic as ΔPmax/ΔPmin increases.

An equal-percentage valve characteristic normally is used for temperature control, although situations might arise where a linear characteristic provides better control. The operational characteristic of a valve can be modified by controller output-signal characterization.

Use pneumatic control-valve actuators with positioners. The calibration for split-range operation of the valves should be achieved at the positioners, not with scaled multiple con-

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troller outputs, to ensure loop integrity is maintained under all failure modes.

HEATING/COOLING CONFIGURATIONS

Three options are available:

Direct heat/direct cool. The appropriate supply and return services are connected directly to the reactor jacket/coils. Temperature ranges from -20°C to +180°C (-4°F to 356°F) with water, steam or ethylene glycol/water are possible with pressurized systems. Arrangements vary from totally manual to fully automatic and include forced circulation with steam/water mixing facilities. Combined heating/cooling facilities require automatic valve sequencing and jacket/coil blowdown routines when changing services. This configuration exhibits good thermal response. Potential operational problems include cross-contamination of services, jacket fouling, corrosion, thermal shock of glass-lined equipment and product degradation from high wall temperatures.

Indirect jacket heat/direct cool. This uses a single HTF, with the coolant being injected into the reactor circulating loop. Heating is provided by a heat exchanger with steam on the service side. Changeover between heating and cooling mode is seamless using control valves in split range. However, in a multiple-reactor facility, this system does not provide complete segregation of the reactor service system from the other reactors. This could result in an extended shutdown of the total facility in the event of water breakthrough due to a single heat exchanger failure.

Indirect jacket heat/indirect cool. This is probably the most common arrangement. As shown in Figure 4, a three-way valve at the steam heat exchanger provides fast-response bypass control by eliminating the thermal lag associated with the heat exchangers [4]. Steam can be applied continuously to the heat exchanger shell at full pressure, eliminating problems associated with condensate lift and return, preventing freezing when operating below 0°C (32°F) and providing excellent linear control characteristics. Thermal response on cool is slower than direct injection due to the added thermal lag of the cooling heat exchanger. This exchanger allows for a less expensive fluid for the cooling service, which might provide cost benefits over a centralized refrigeration facility involving the use of significant volumes of an HTF. In such a system, take care to allow for thermal expansion throughout the loop.

This system also allows for segregation of the reactor service system from other reactors, which enables rapid identification of water breakthrough problems at a facility with several reactors. ●

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Consider Hot Water for Jacketed Heating

Hot water offers significant advantages over traditional steam-heated systems

By Philip Sutter, Pick Heaters, Inc.

MANY PROCESS plants currently use steam or hot water to heat jacketed devices such as tanks, kettles, dryers, reactors, glass lined vessels, or similar adaptations such as coiled tubing placed inside or outside tanks or vessels.

In this article, we will take an in-depth look at the advantages and disadvantages of steam and hot water for jacketed heating, and compare indirect and direct steam injection systems for making hot water.

In heating applications where processes require operating temperature up to 350°F (177°C) steam is often the first heating medium considered because it is readily available. However, hot water should be given equal consideration.

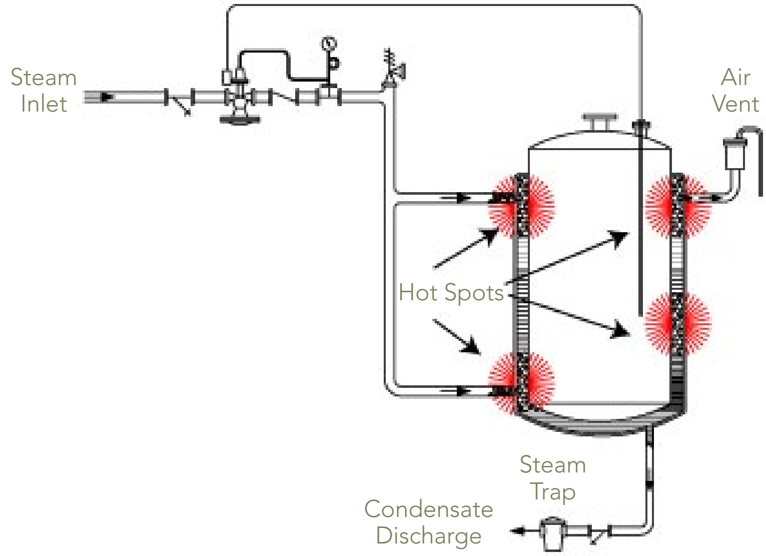


Figure 1. In a typical steam heated jacketed vessel, internal hot spots can cause uneven product heating.

ADVANTAGES AND DISADVANTAGES OF STEAM

Figure 1 illustrates a typical jacketed heating system using steam. Because it is readily available and easy to apply, steam is often used for jacketed vessel heating. Steam provides quick heat-up and it is predictable e.g. 100 PSIG (7 BARG) saturated steam is always 338°F (170°C) with 1,189 BTU/lb total heat content.

Despite its advantages, steam has several shortcomings. It does not offer precise temperature control, and energy transfer is not uniform. Due to uneven distribution,

higher temperature steam typically collects in the upper portion of the jacket, with cooler condensate collecting near the bottom.

Internal hot spots also develop around hot steam inlet nozzles, adding to the problem of uneven product heating. This increases the likelihood for product burn-on and local overheating.

Furthermore, a steam trap is a necessary component of a steam-heated jacketed vessel. It allows condensed steam to exit the jacket, making room for more steam. If improperly sized or poorly maintained, energy will be wasted and temperature control will be compromised, which frequently results in damaged product or lower product yields.

Reactions requiring both heating and cooling are cumbersome for the steam-heated system because of the dramatic temperature difference between the steam and the cooling water. At the conclusion of the heating cycle all steam and condensate must first be driven out of the jacket prior to introducing cooling water. This is a time-consuming process that is often not done completely. The problem is most severe with glass-lined reactors, which may be damaged by thermal shock and steam hammer if cooling water contacts residual steam in the jacket.

Currently, an increasing number of process engineers are switching from steam to hot water for jacketed heating. There are several basic reasons for this trend:

- The temperature in the jacket can be controlled much more accurately with hot water than with steam. This higher degree of control protects against damage to or loss of product through overheating.
- Hot water distributes heat more evenly than steam. This eliminates hot spots which often cause product to bake onto the walls of the vessel, and at worst, ruin the entire batch.
- Hot water ensures a better quality end product. This is particularly important in processes requiring very precise product temperature control.
- In critical processes utilizing glass-lined reactors, steam can shock and damage the lining. Hot water allows smooth transitions from heating to cooling with no thermal shock.

In addition, many are switching to direct steam injection (DSI) systems to create the hot water for several basic reasons:

- With an advanced-design steam injection heating system, the temperature of the process can be adjusted at any predetermined rate on any desired time cycle.
- A steam injection hot water system can be programmed to heat then cool a process by stopping the heating cycle and introducing cooling or tempered water into the jacket at any desired rate and temperature.
- In this system the condensate (from the steam that was injected) leaves the circulating loop through a back pressure relief valve at the lowest temperature after all the possible heat has been extracted. In a steam system, on the other hand, condensate at a much higher temperature must be returned to the boiler in a condensate return line with its inherent heat losses.

ADVANTAGES AND DISADVANTAGES OF HOT WATER

The use of hot water to heat reactor vessels solves many of the problems associated with steam. The jacket temperature can be controlled more accurately with hot water because hot water distributes heat more evenly over the wetted surface of the vessel. This eliminates hot spots, which can cause the product to burn onto the walls of the vessel and potentially ruin the entire batch. By eliminating burn-on, product quality is protected and product filtering and costly clean up time are minimized.

Hot water offers a wide range of operating temperatures because when pressurized, water will remain in the liquid state and not flash into steam. For example 72 PSIG (5 BARG) water can be heated in a pressurized circulating loop to 310°F (154°C) without boiling. The process can be gradually ramped up or down to desired temperatures, eliminating the potential of thermal shock.

For processes requiring both heating and cooling, hot water can be adjusted at a predetermined rate on a desired time cycle through the use of cascade or heat/cool temperature control loops, or an in-plant PLC or DCS. A hot water system can be programmed to heat, hold, then cool a process by introducing cooling or tempered water into the jacket at a controlled rate and temperature without having to stop the process as when using steam.

In addition to offering precise temperature control, water is readily available, easy to handle, non-flammable, safe to the environment, and inexpensive as compared to heat transfer fluids.

What is the downside of using hot water in jacketed vessels? The product heat-up time using hot water will not be as

rapid as it is with steam. However, once up to temperature the steam heated system may be difficult to keep from overheating.

Another limitation is that the jacket water temperature cannot equal or exceed the saturated temperature of the steam supplied to the system. For example, when operating the system with 150 PSIG (10.3 BARG) steam, the jacket water temperature cannot exceed 352°F (177°C) at 130 PSIG (9 BARG), because of the 20 PSIG (1.4 BARG) pressure differential requirement for DSI, and above that temperature the water will flash back into steam.

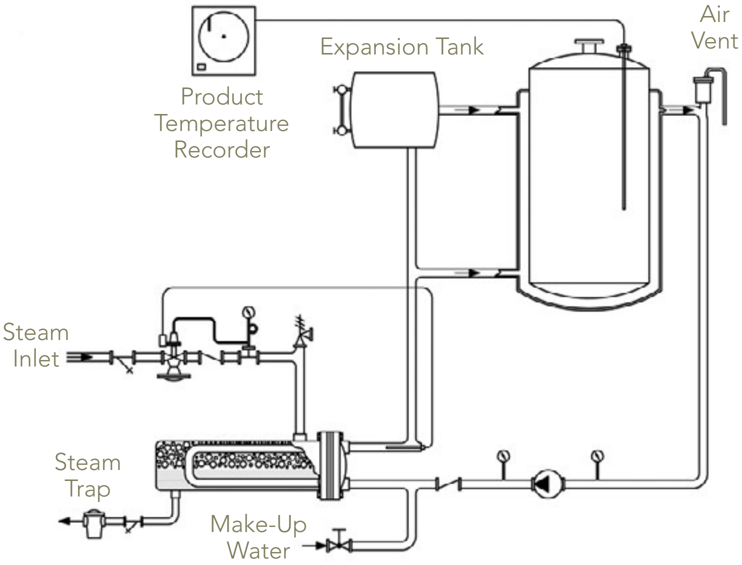


Figure 2: Where steam is available, indirect heat exchangers are commonly used to heat water for jacketed vessels.

MAKING HOT WATER WITH INDIRECT HEAT EXCHANGERS

Where steam is available, indirect heat exchangers are commonly used to heat water for jacketed vessels (see Figure 2). In these systems, steam does not come in direct contact with the water which is being heated. Heat energy is transferred across a membrane such as a tube bundle or series of plates. As energy is transferred, steam condenses and is discharged through a steam trap and routed back to the boiler.

Indirect heat exchangers are designed to use only the latent heat from the steam or approximately 83% of the total heat energy, while the sensible heat (or approximately 17% of the total BTU's) is discharged from the exchanger in the form of condensate.

Much of the remaining BTU's are lost en route back to the boiler making the indirect heat exchanger an inefficient method of heating a reactor vessel.

Another problem inherent in indirect exchangers is poor temperature control due to the lag time between the adjustment of control equipment and the time it takes to transfer heat energy from the steam through the tube bundle or plate surface. System start up times will be longer as all the metal mass in the heat exchanger must be heated up, and additional components such as an expansion tank is required to balance the system pressure.

Finally, a steam trap is still required in an indirect system with all of its inherent costs, maintenance, energy loss, and reduced productivity problems.

ENERGY COMPARISON - DIRECT VS. INDIRECT HEATING OF WATER

Direct steam injection (DSI) heaters inject steam directly into the circulating water loop.

For processes which return the jacket water below 212°F (100°C), they achieve 100% heat transfer by using both the sensible and the latent heat of the steam. Above this temperature there is a minimal drop in efficiency.

Let us compare the efficiency of an indirect (shell and tube type) heat exchanger to a DSI heater. The application chosen demonstrates the annual energy consumption for heating a jacketed blender which mixes powders with liquids and then dries the mixture. Assume the process operating conditions are as follows:

Product volume:	**10,000 lb of a water-like product**
Blender operating heat load:	**4,816,340 BTU/hr**
Jacket water temperature:	**250°F**
ΔT across jacket:	***55°F (250° - 195°F)**
Water circulating flow rate:	**175 GPM**
Water loop pressure:	**50 PSIG**
Steam pressure:	**150 PSIG Saturated**
Hours of operation:	**16 hr/day; 4000 hr/year**
Boiler fuel type and cost:	**Nat. Gas at 0.85 /Therm**
Boiler efficiency:	**82%**

* This is the required ΔT to be made up by the heater.

Based on these conditions, the steam requirement for heating with an indirect heat exchanger would be 5,620 lb/hr, while the steam requirement using a DSI heater would be 4,662 lb/hr. Factoring in the energy required by the boiler to preheat the feed water and to generate steam at 82% boiler efficiency, the indirect heat exchanger will require 7,182,634 BTU/hr while the DSI heater will require only 6,612,080 BTU/hr or 7.9% less energy than the heat exchanger! This energy savings of 570,554 BTU/hr will result in an hourly fuel savings of 5.71 therms of natural gas (a fuel heating value of 100,000 BTU/therm). At 85¢/therm this translates into a fuel cost savings of $4.85/hr, or an annual fuel savings of over $19,000. Results may vary depending upon fuel costs and operating conditions. This example demonstrates the dramatic energy savings to be realized by the DSI heater and is based upon the very conservative assumptions that:

1. The heat exchanger steam trap does not leak steam.
2. There is no volumetric loss due to condensate flashing at the receiver tank.
3. 195°F water discharged from the system using the DSI heater is not returned to the boiler. Instead, 65°F boiler make-up water is used.

PLEASE NOTE:
The 195°F water discharged from the closed loop as a result of DSI may be returned as boiler make-up water which would increase the fuel savings even further, up to 17% more efficient than the heat exchanger.

There are several objections to the use of DSI which need to be addressed when considering this approach. Most of these relate to the fact that the steam must be thoroughly absorbed into the water at the point of contact or it may result in "steam hammer". If the steam is not thoroughly absorbed, it will expand and then collapse downstream in the piping or the jacket. This creates an implosion due to the dramatic change in volume between steam and water which results in noise and vibration known as steam hammer. This is especially a problem with simple steam-to-water static mixers, spargers, and venturi/eductor type heaters. In order to assure thorough absorption of steam into water, the steam pressure should be at least 10-20 PSI greater than the water pressure at the point of injection.

Furthermore, cold make-up water must be heated at the boiler, because condensate might not be returned to the boiler. This could result in additional costs for chemical treatment. However, the energy savings from DSI will more than offset these costs.

MAKING HOT WATER WITH A DIRECT STEAM INJECTION (DSI) SYSTEM

When using an advanced design Pick™ DSI System, steam flow is modulated at two points: the steam control valve, and also at the point of injection within the heater. This dual modulation results in superior temperature control over a wide range of hot water demands or when a sequence of varying temperatures or pressures are needed to meet process requirements.

In a Pick™ DSI Heater, steam enters the cold water at low to moderate velocities through hundreds of small orifices in

an injection tube (see Figure 3). By breaking up the steam into multiple small streams and also maintaining a positive pressure differential, all the steam is quietly injected and instantly mixed into the flow of water within the heater body.

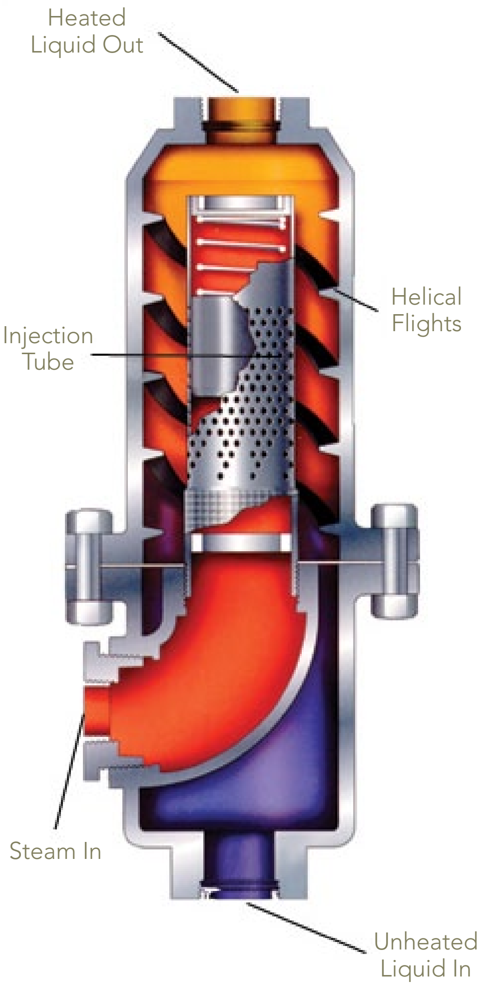


Figure 3: Direct steam injection (DSI) heaters inject steam directly into the circulating water loop.

During operation, steam pressure works against a spring-loaded piston inside the injection tube assembly. As the steam flow varies, it forces the piston to rise or fall exposing more or fewer orifices (see Figure 4).

By applying water pressure and spring force against the incoming steam, the spring-loaded piston constantly maintains steam pressure in excess of incoming water pressure. This prevents steam hammer which occurs when steam and water pressures are at or near equilibrium.

Another important design feature of the Pick™ DSI Heater is the helical flights within the mixing chamber. These create controlled turbulence to assure thorough and immediate mixing of the steam and liquid within the heater rather than in downstream piping. As a result, these heaters are much quieter to operate than (high velocity) venturi or static mixer type heaters.

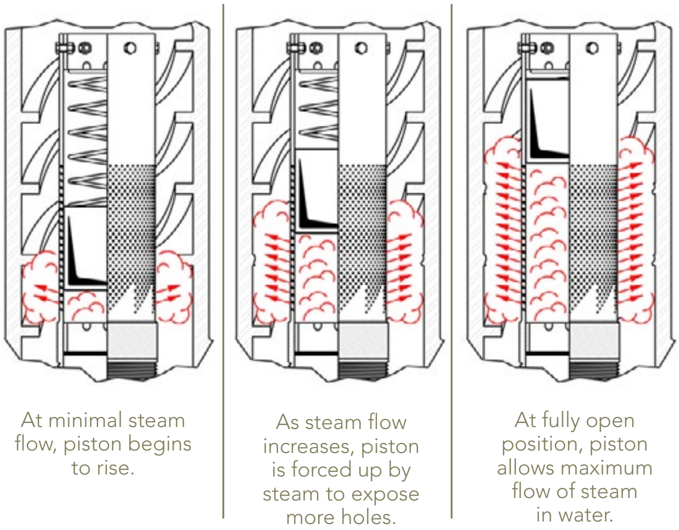


Figure 4: As steam flow varies, it forces the piston to rise or fall exposing more or fewer orifices.

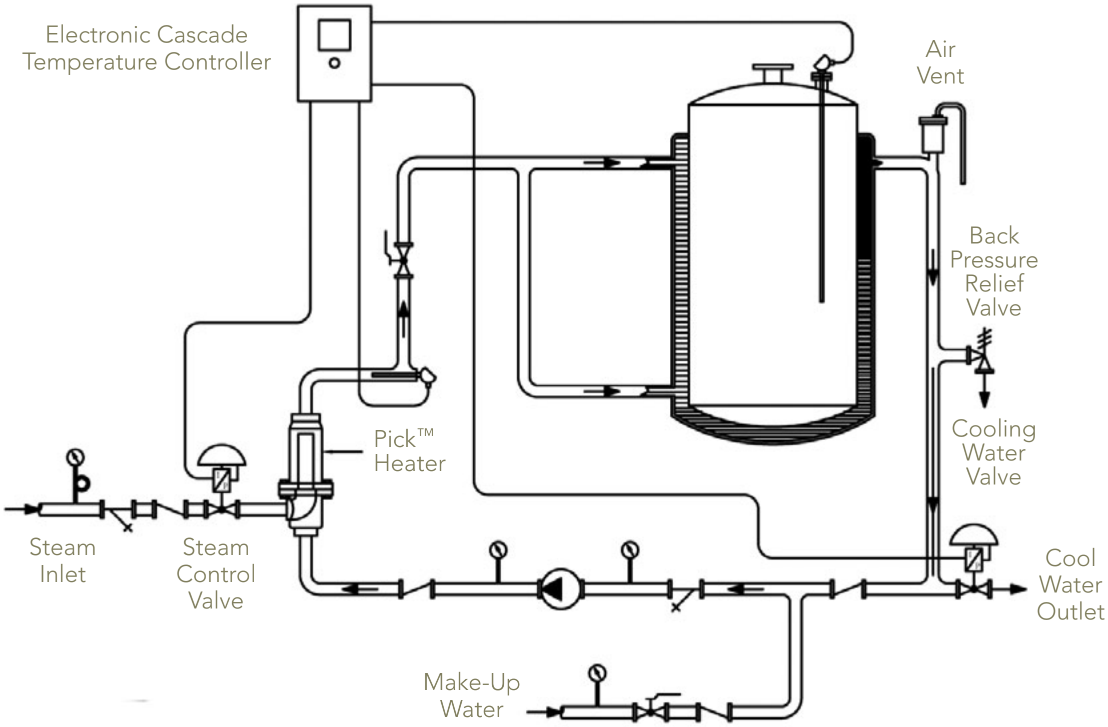


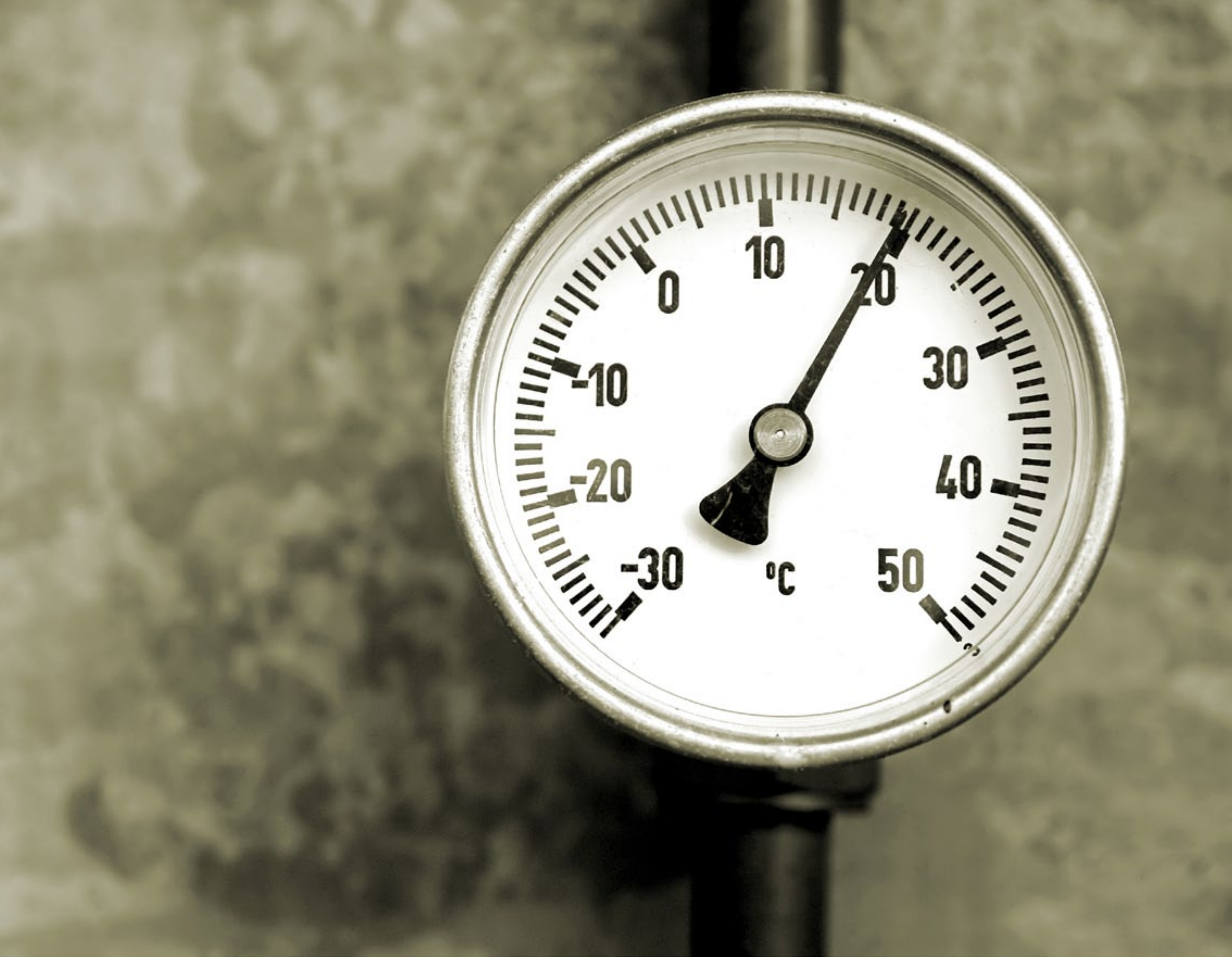
Figure 5: The external steam control valve on the Pick™ DSI is actuated by a temperature controller.

The heater creates very little internal restriction to liquid flow. Velocities are not excessive and very little pressure drop (less than 2 PSI) is generated across the heater, minimizing friction losses and pump horsepower requirements. The hot water discharge temperature can be sensed immediately downstream of the mixing chamber and requires very minimal piping (less than 5 pipe diameters) before entering the jacket.

The external steam control valve is actuated by a temperature controller, which is responding to water discharge temperature. This may be manually set to any desired outlet water temperature as Figure 5 illustrates. Water temperature setting may also be regulated remotely by a pneumatic or electronic temperature controller (PLC, DCS), and by sensing the product temperature (commonly referred to as cascade temperature control). With this arrangement, system operation is fully automatic. The operator simply inputs the desired product set point temperature. At the beginning of the cycle water temperature is driven to a predetermined maximum level. Then, as the product approaches set point, water temperature is gradually decreased to prevent overshoot.

Control is automatic – regardless of outflow demand. System loop pressure is maintained by an adjustable back pressure relief valve (BPRV) which eliminates the need for an expansion tank. As steam enters the system, an equal volume of condensate is pushed out of the BPRV. System pressurization at this valve permits water loop temperatures above 212°F (100°C).

A single steam control valve provides better than a



10:1 turndown capability. Turndown capabilities up to 100:1 can be obtained with the use of dual steam control valves. This capability is particularly important in heating jacketed vessels because the hot water demand at reactor start-up is significantly greater than it is as the product approaches set point.

IN CONCLUSION:

Water is superior to steam for heating jacketed reactors because it:

- eliminates hot spots and uneven heating – unlike steam, where temperature control is difficult to maintain and easily overheats.
- allows smooth transitions from heating to cooling with no thermal shock – unlike steam which requires complete purging of steam prior to the addition of cooling water.
- is environmentally safe and non-flammable – unlike heat transfer fluids which require special handling and constant monitoring.

Direct steam injection (DSI) is superior to indirect exchangers for heating water because of:

- rapid response to changing process conditions – ensures precise temperature control within a fraction of a degree.
- demonstrated costs savings – 100% energy efficiency saves as much as 17% in fuel costs.
- compact design and ease of maintenance – saves space and system down time.

In particular, Pick™ DSI heaters with dual modulating steam injection control provide:

- thorough mixing of steam and water within the heater body – eliminates the need for excessive downstream piping.
- the ability to handle the widest range of steam flow turndown of any DSI heater.
- lowest water pressure drop and lowest noise level of any DSI heater.

PHILIP SUTTER is a Vice President with Pick Heaters, Inc., West Bend, WI (262-338-1191; Fax 262-338-8489). He has over 30 years of experience designing, engineering, and selling liquid process heating systems for the food, chemical and pharmaceutical industries.

NEXT PAGE ▶

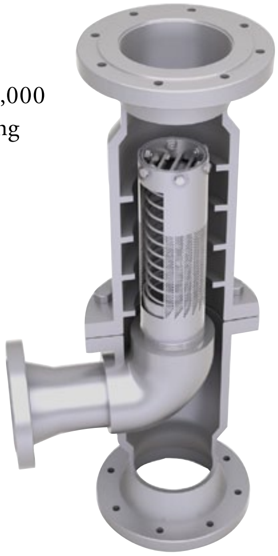
Innovation in Direct Steam Injection Heaters Since 1945

In 1945, Pick Heaters developed and patented a unique concept of Direct Steam Injection Heating. The original approach has remained unaltered...keep it simple and self-stabilizing, minimize moving parts and make it completely reliable regardless of operating environment. It is this design philosophy that has Pick at the heart of heating for over 60 years in industries ranging from food to chemical and pharmaceutical processing, pulp and paper to power plants.

Out of this philosophy has come a continuous flow of refinements and innovations.

- Pick is the only DSI company to offer a true **VARIABLE FLOW** design for multiple use points and on/off applications.

- Pick's **BX** heater is truly innovative. It's open design allows slurry flow without obstruction, at negligible pressure drop. For industrial starch cooking and slurry heating.



- Pick's **FABRICATED HEATERS** allow for flow rates and pressures far above the norm - up to 25,000 gpm or 1,400 PSIG. They also conform to existing piping from 1/2 to 32 inches and beyond, and in various materials of construction.

- Pick was the first direct steam injection (DSI) company to introduce a **3A CERTIFIED SANITARY HEATER** in 1984 and was also the first DSI company to offer a pilot scale version especially for R&D.

- Over 20 years ago Pick expanded its scope of supply to include **CUSTOM DESIGNED, PACKAGED SYSTEMS** including skid mounted pumps, instrumentation and other ancillary equipment to meet customers needs.

- Now, through **PCD (PICK CUSTOM DESIGN)** you can combine Pick's experience in heat transfer and packaging to meet all your process heating needs - direct or indirect heat transfer systems.

WHY CHOOSE PICK FOR DIRECT STEAM INJECTION?

Energy Efficient
100% heat transfer cuts fuel costs up to 28%

Precise Temperature Control
to within 1°C or less for many systems

Wide Operating Range
variable orifice injector provides unlimited turndown

Low Noise Level
normally below 85 dba

Low Liquid Pressure Drop
does not exceed 2PSI within normal flows

Complete Mixing in Heater Body
no need for pipe lengths after heater

Pick Heaters has a worldwide network of qualified engineers along with its highly qualified factory staff to work with you to design a process heating system to meet your specific requirements. Pick's international certifications include: CRN/Canada, CE/Europe, SA/Sweden, and TÜV/Germany.

PICK COMBINES THE RIGHT PRODUCTS WITH THE RIGHT PEOPLE - PICK THE BEST.

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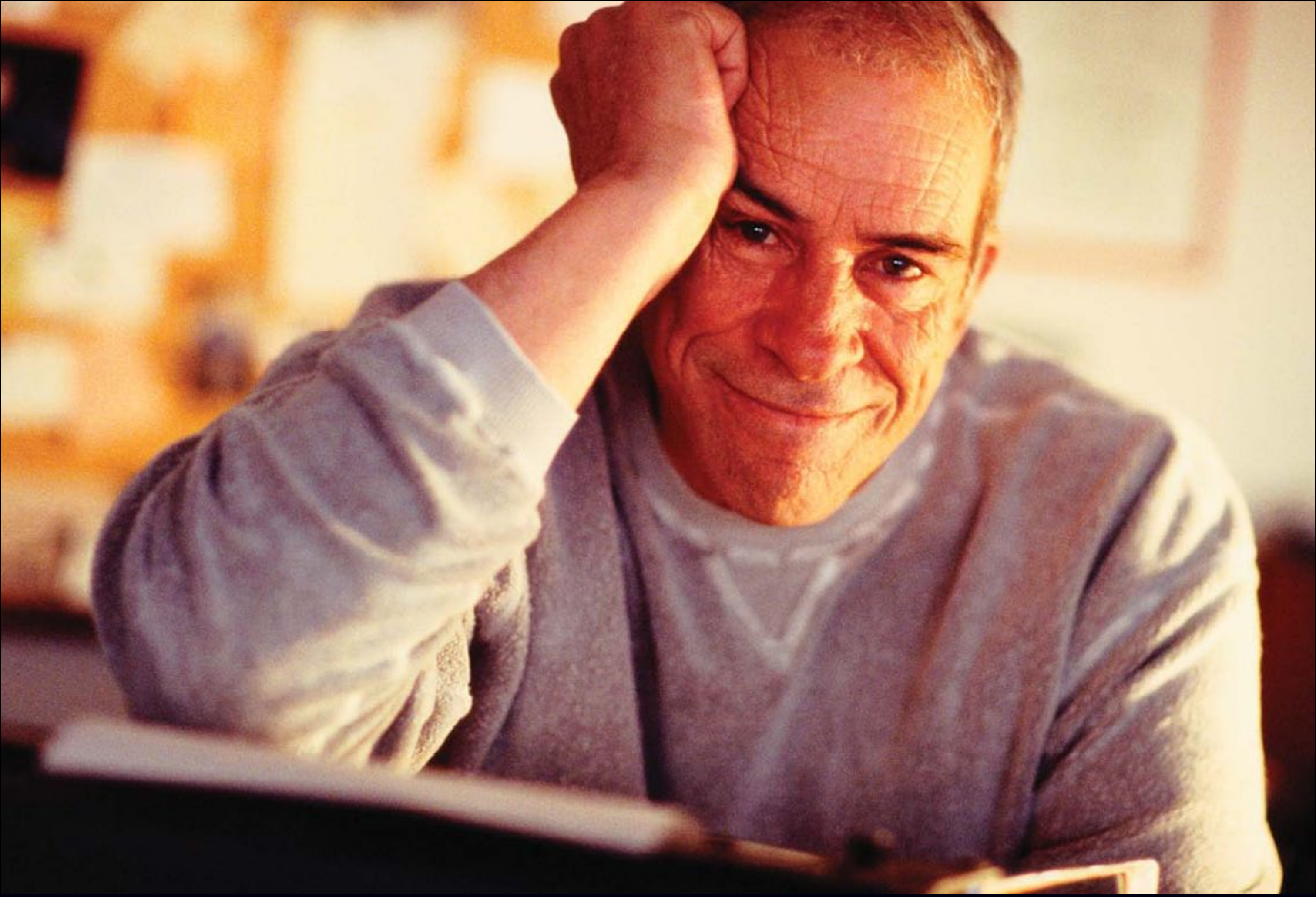

LARRY SCHUBERT FLAT LINED!
(And feels like a million bucks...)

Actually, the first thing he felt was relieved. Because Larry finally discovered absolute precision temperature control for all his chemical processing. Thanks to Pick Direct Steam Injection Heaters, now his process temperature graphs show one, long, beautiful, flat line. That's because Pick's exceptional temperature control automatically holds discharge temperatures to extremely close tolerances – within 1°C or less, while providing rapid response to changing process conditions.

Whether you require jacketed heating or other process liquid heating applications, Pick eliminates BTU losses for 100% energy efficiency. This alone could save Larry's company up to 17% in fuel costs. In addition, Pick's compact design, along with its ease of maintenance, saves valuable space and invaluable down time.

All this, combined with an unlimited supply of hot water, low water pressure drop, the lowest OSHA noise level, and the widest operating range of any direct steam injection heater is enough to make anyone's heart go pitter pat.

Which is precisely what flat lining can do to a guy.

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