Cascade Control
A Develop Your Potential Article for CONTROL Magazine

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Introduction

There are a number of techniques that enhance PID, termed Advanced Regulatory Control (ARC). These were developed in the 30s and 40s and include reset feedback to prevent windup, override to prevent excessive or unsafe conditions, feedforward, and ratio to correct an anticipated upset (prior topics in this CONTROL series). Also, these include cascade (today's topic), and decouplers, gain scheduling, output characterization, and various forms of model-based adjustment. These ARC techniques remain very useful today.

These techniques were originally called Advanced Process Control, but today that term has migrated to mean Model Predictive Control. So, use the terms Classic Advanced Control or Advanced Regulatory Control.

Cascade Control Bottom Line

If you notice that either:

1. The process influence of a controller can also be affected by other influences, control that process input. For instance, if the controller adjusts the valve to change the flow rate, but line pressure might also affect the flow rate, control the flow rate to a set point.
2. Another process variable is an early indicator (a leading indicator) of what will eventually happen to the primary controlled variable (CV), then control that variable. For instance, tray temperature in a distillation column is a leading indicator of product purity. Instead of manipulating reflux to control the delayed and lagged purity measurement, manipulate reflux to control a tray temperature.

In cascade the output of the primary (supervisory) controller is the set point for a secondary (inner) controller.

The secondary loop needs to be faster than the primary loop for this to have an advantage. Some use the rule that $(\theta + 3\tau)_{inner} < \frac{1}{5}(\theta + 3\tau)_{outer}$.

Proportional-only control is often fully satisfactory for the inner loop. The integrator in the primary controller can compensate for moderate offset.

Tune the inner loop first, then tune the primary with the secondary in AUTO. To the primary controller, the inner loop is just part of the process.

You still need feedback from the primary controller because of calibration errors of secondary sensors and unmodeled and nonideal effects.

Reflux Example of Cascade

Figure 1 represents part of a distillation process. It is a reflux tank that receives the condensed vapor from a distillation column. The vapor has been purified by the sequential tray-to-tray "boiling" in the column. The distillate condensate enters the top of the tank. Some of the condensate is returned to the column as reflux, to control purity of the distilled product. The residual portion of the condensate is the distillate product. The tank needs to have the liquid level controlled – the Level Transmitter (LT) reports the level. The Analysis Transmitter (AT) is probably located in the vapor line exiting the column for faster response, but for convenience I show the AT on the tank. AT is commonly reporting the impurity in the distillate, not the purity.

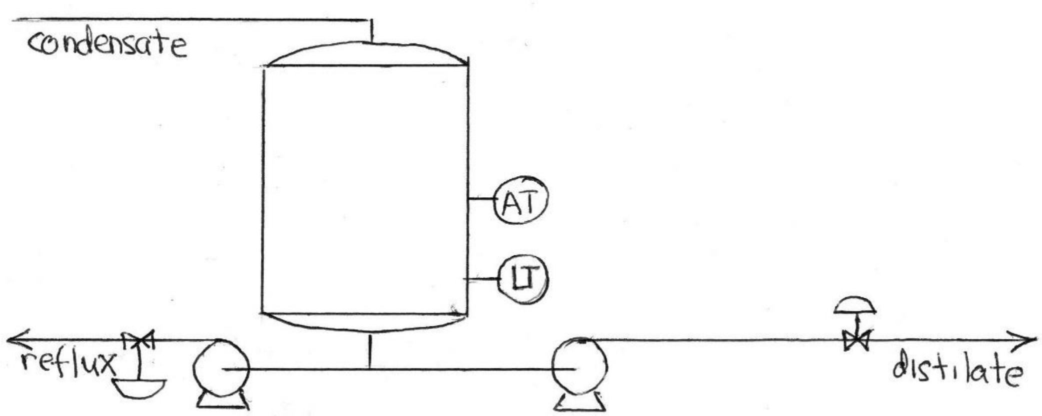

Figure 1 Condensate from a distillation process

Figure 2 illustrates a primitive control scheme. The ARC receives the AT information and sends a signal to the reflux valve. And the LIC listens to LT and sends a signal to the distillate product valve.

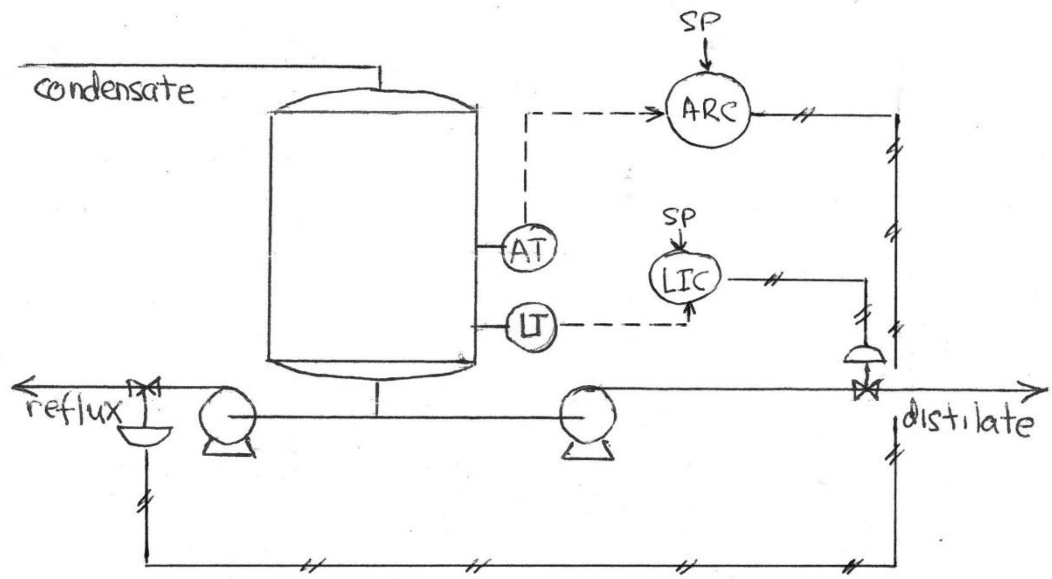

Figure 2 Primitive reflux control

Note: If the controllers were talking in English, they would be saying "Valve, go to xx% open."

Note: If both valves are air-to-open (ATO, alternately fail-closed FC) then LIC must be a direct acting controller. If the level goes up, the controller needs to open the valve, by increasing its output. And ARC must also be direct acting. If the impurity increases, ARC needs to increase its output to open the reflux valve to send more reflux back into the column to wash the impurity back toward the bottom.

An issue is that the AT provides delayed impurity information. Whether on the vapor exit or tank liquid, AT is might be a gas chromatograph with a 15-minute cycle time. A temperature measurement on a tray near the top of the column, however, provides an early indication of the impurity level. If the impurity rises, the tray temperature will rise. The temperature is easy to measure, responds relatively immediately, but is not an exclusive measure of impurity. The temperature is also dependent on the column pressure, and other components in the product.

This situation represents the second justification for a cascade strategy: If there is a leading indicator, control it.

Figure 3 illustrates a cascade strategy. The TIC looks at the column TT and adjusts the reflux valve to maintain the temperature at the set point. ARC has now been promoted to a supervisor, and sends the set point value to TIC. ARC has the primary responsibility, and TIC looks at a secondary variable. Hence, the nomenclature. But these are also termed outer and inner controllers.

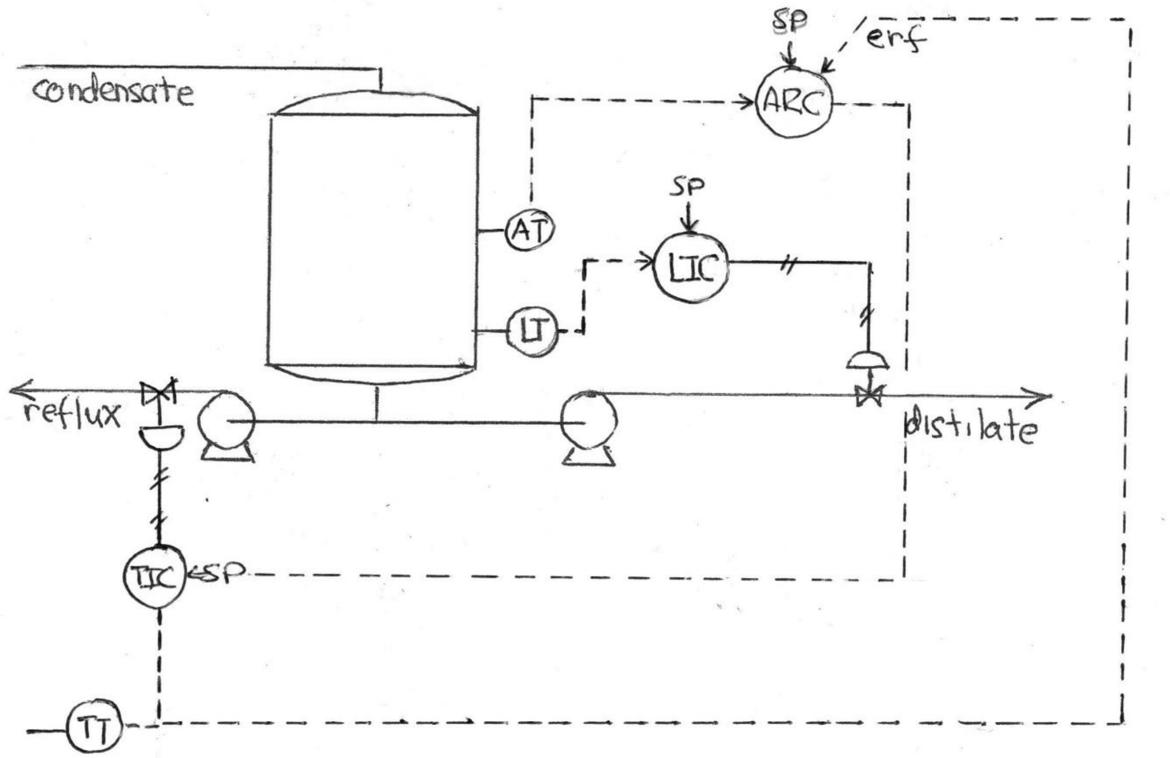

Figure 3 Reflux control with a cascade strategy

Note: ARC is now "talking" to TIC and is saying, "TIC your temperature set point is 87 ^oC." The ARC role has substantially changed.

Note: ARC is now reverse acting. If the impurity goes up, then the target temperature for the tray must go down. The ARC action needs to change from direct to reverse. In other cases the action might not change.

Note: The erf signal to ARC is the actual temperature. If ARC is in charge, then it will match the ARC output.

Note: The erf signal is not required. It may only infrequently provide benefit that matches its complication.

Heat Exchanger Example of Cascade and Ratio Combined

Figure 4 illustrates a steam-heated shell and tube heat exchanger. Cold process fluid enters on the left, flows through tubes, and exits on the right. Steam enters in the shell side, condenses on the tubes, and the condensate leaves at the bottom, with outflow controlled by a steam trap. Non-condensable gases in the steam will build up in the shell, prevent the steam from seeing a portion of the tubes, and need to be occasionally vented. I show this as a thermistor-type vent.

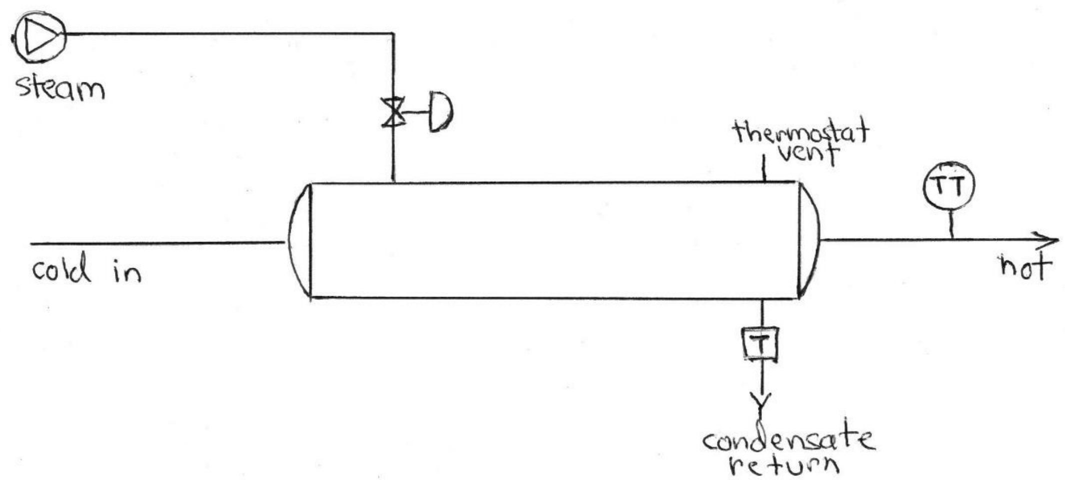

Figure 4 A heat exchanger process

The objective is to adjust the steam in-flow to control temperature. Inflow process flow rate and temperature, changes in ambient losses, and cycling of the non-condensable gas discharge all require continual steam valve adjustment.

Figure 5 illustrates the primitive control scheme. TIC is talking to the valve and saying, "Valve, go to 63% open." If the valve is ATO (FC), then TIC must be reverse acting. If something makes the temperature rise, TIC needs to reduce its output to move the valve toward a less open position.

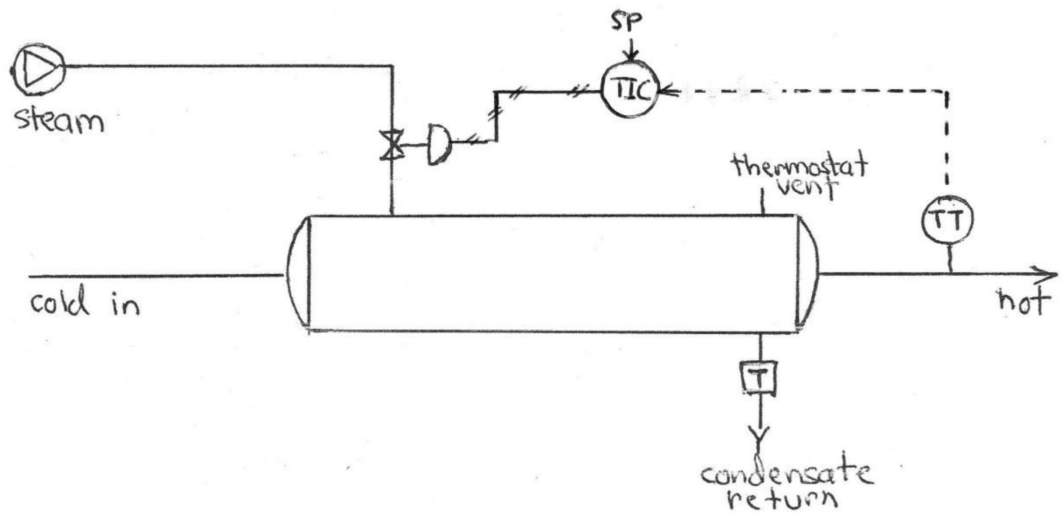

Figure 5 Primitive control of process fluid temperature

One issue is that the steam header pressure is frequently changing because of the varying demand of other users on the steam header. When pressure changes, the flow rate through the steam valve will change, and eventually TT will report the consequential deviation. Until this report happens TIC has no justification to change the valve. When it does see the need to change the valve position, the deviation is well developed.

From a process engineer's perspective, using material and energy balances, it is the steam flow rate that changes the product temperature, not the valve position. This situation represents the first of the two reasons to consider cascade. From a process view, the controller influence on the temperature is the steam flow rate. The controller changes steam flow rate through the valve. But some other influence can also affect the steam flow rate. So, control it.

Figure 6 illustrates a cascade arrangement. An FT has been added to the steam line, and an FIC to the control strategy. The TIC has been promoted to a supervisory position and is now "talking" to the TIC, not the valve. TIC remains reverse acting. Now, if the header pressure changes the steam flow rate into the exchanger the FT "immediately" reports it and, within the valve response time, the valve is moved to a position that returns the steam flow rate to the set point. Due to lags in the heat exchanger and temperature sensor, there will probably not be any detectable temperature deviation.

Again, erf is not a requirement, but if used must represent the TIC output value and meaning if TIC is in charge.

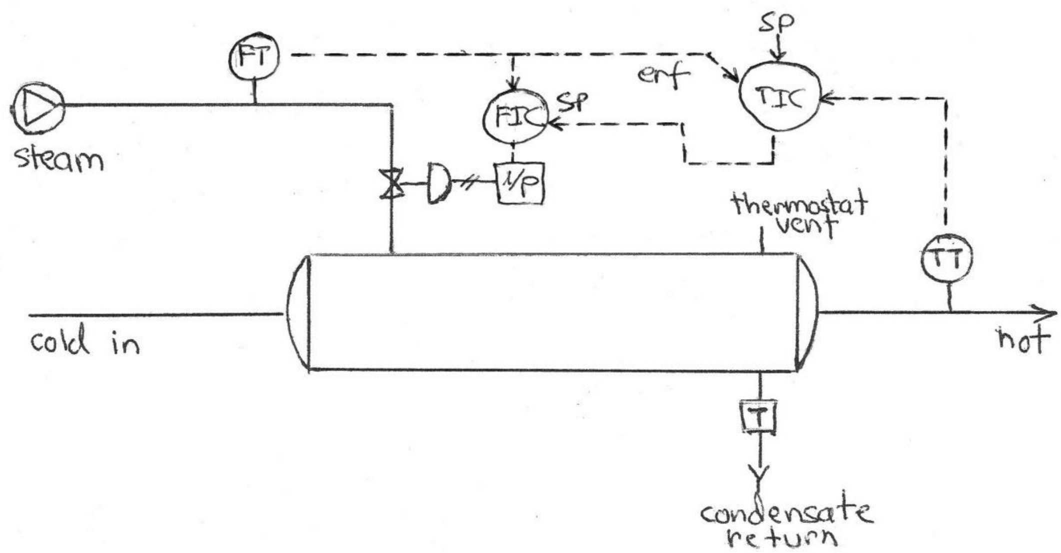

Figure 6 Cascade control of process fluid temperature

Figure 7 adds ratio to the cascade strategy. If the cold process fluid flow rate doubles, then the steam flow rate should also double. This proportionality view is the justification for a ratio strategy.

Now the output of TRC is a ratio value, representing the desired ratio of steam flow rate to process flow rate. As a process view the ratio might have the units of SCFM steam per gpm of process fluid. And talking to the x-block, we might imagine TRC saying "Hey, x-block, the desired ratio is 0.3 SCFM/gpm". But the controller output will be %. The x-block needs to perform the scaled signal calculation.

Now if the process inflow changes, before there is a temperature deviation, without TRC knowing about the event, the x-block will multiply the process inflow rate by the desired ratio to adjust the set point to the FIC.

If erf is used, the erf signal must represent what the TRC output would be – the same value and meaning. In this case the actual steam to process flow rate ratio. Since all signals are likely to be in % of full scale, again scaled signal calculations will be required.

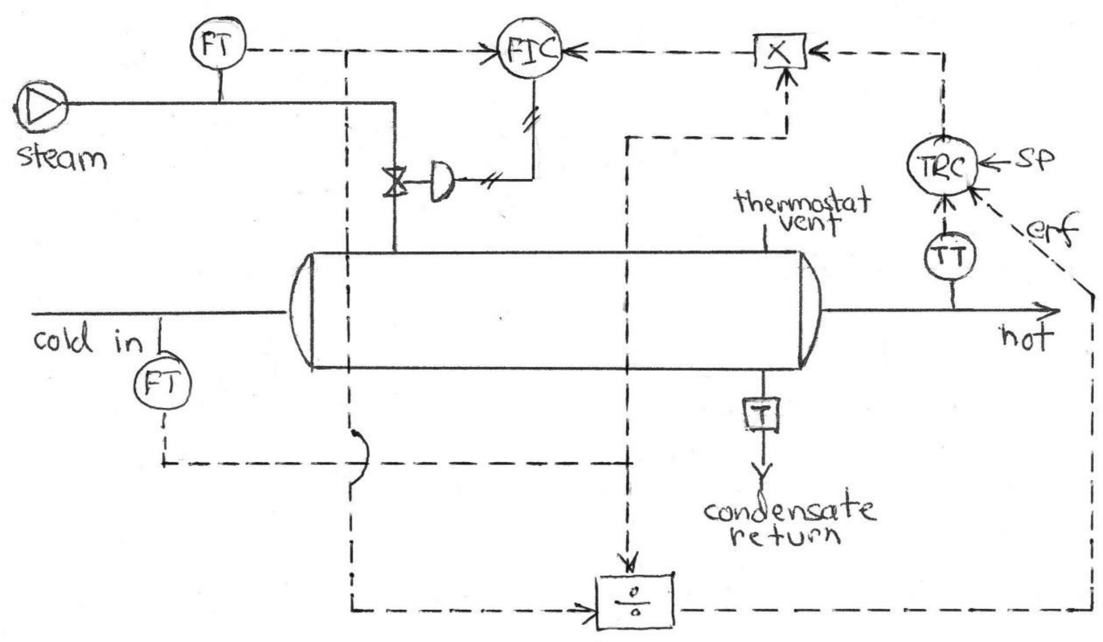

Figure 7 Combined cascade and ratio strategies for process temperature control

Notes about Cascade

Cascade is easy to understand from a process engineer's viewpoint, using values and units of the process variables. But it needs to be implemented in scaled signal calculations.

Relative to a primitive control strategy, cascade required a new flow transmitter and a new controller. The cost of installation and maintenance of these devices needs to be considered when the control benefit of adding cascade is being considered.

The inner loop needs to be about 5 times faster than the outer loop, for cascade to provide a substantial benefit.

ERF is not a requirement for cascade. It is a complication to implement, and it may only solve a brief issue after some infrequent situations. I like it. But, others may weigh the performance pros and implementation cons differently and choose not to implement erf.

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Russ Rhinehart started his career in the process industry. After 13 years and rising to engineering supervision, he transferred to a 31-year academic career. Now "retired", he enjoys coaching professionals through books, articles, short courses, and postings on his web site www.r3eda.com.