Increase System Efficiency with Cascade Control

Francisco Valentine, PE

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Introduction

During the glory days of pneumatic controls, air-handling units (Rooftop units, fan coil units, unit ventilator, etc.) were typically equipped with one or more pneumatic receiver controllers and pressure-independent terminal units were equipped with pneumatic VAV controllers. These controllers provided the pneumatic signals that actuated the pneumatic valve actuators (chilled and hot water) and control dampers. Air-handling units typically have damper assemblies which consisted of the outdoor, return, and relief (also called exhaust) dampers. Terminal units typically have a primary airflow control damper and may also have a hot water control valve to control the heat capacity. The valves and dampers were equipped with pneumatic actuators which received the control signal from their respective pneumatic controllers. This pneumatic controls system was truly "open" in that nearly anyone with pneumatics knowledge, supplies, and tools could work on and make adjustments. The Controls, Mechanical, and Testing, Adjusting, and Balancing (TAB) contractors worked in concert to get the building's Heating, Ventilation, and Air-Conditioning (HVAC) equipment working as designed and specified.

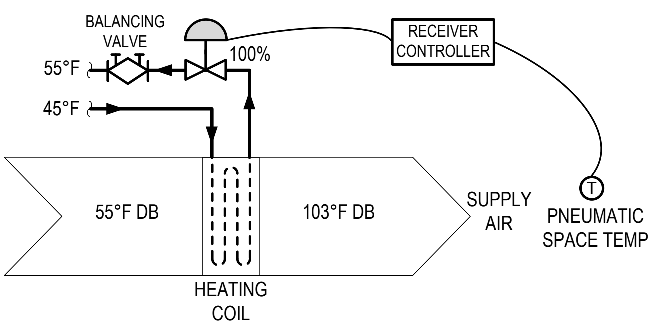

Figure 1 –Heating Coil with Pneumatic Controls

Direct Digital Controls

Today, we install Direct Digital Control (DDC) systems and utilize Proportional, Integral, and Derivative (PID) loops to control system parameters to setpoint. PID loops calculate the output signal required to minimize the error signal. The error signal is the difference between the process variable and its setpoint. As the name suggests, they are three components which govern how the output command is calculated. The proportional constant governs how the controller reacts to the instantaneous error signal. The Integral constant governs how the controller reacts to the length of time the signal error has existed or its integral. The Derivative constant controls how it reacts to the rate of change in the error signal. These variables are tuned to provide stable control and reasonable recovery from minor deviations from steady-state conditions.

$$Error_{Signal} = Process\,Variable - Setpoint$$

Equation 1 – Signal Error

Single PID Loop Control

Though we have progressed far beyond the capabilities of pneumatic controllers, we still control hydronic control valves in the same way we did 40-50 years ago – using a single control parameter (space temperature). Most mechanical designers and control contactors utilize a single PID loop whose primary control or process variable is space temperature. The PID loop monitors and compares it to the space temperature setpoint. The PID loop calculates the valve position required to minimize the difference between the process variable and setpoint (Appendix A). If discharge air temperature sensors are installed, they are often for monitoring and troubleshooting purposes only. During point-to-point checkout it provides a quick way to verify whether the discharge air temperature and space temperature sensors are correctly connected to the controller. A heat valve override will quickly verify connectivity of the temperature sensors.

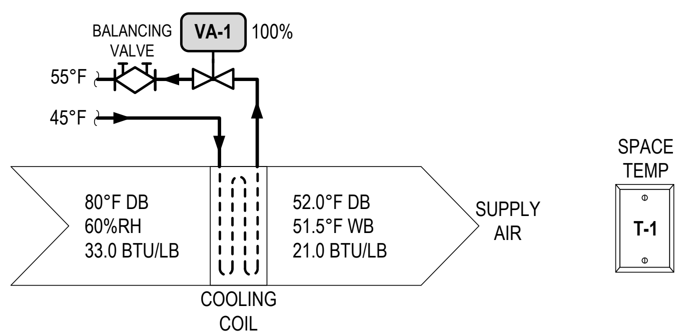

Figure 2 – Cooling Coil with DDC (Single PID)

When the process variable does not change rapidly (space temperature, return air temperature, humidity, carbon dioxide concentration, etc.), the PID loop is tuned for a slow acting process because the PID loop must allow time for a change in the process variable to occur before another output signal increment is generated. Discharge air temperature PID loops are tuned for a faster process as the discharge air temperature changes almost immediately with a small change in PID loop output signal.

On system startup or during abrupt changes in load, the PID loop needs additional time (several minutes) to settle out or recover from the upset in system equilibrium. The control valves typically end up wide open because the PID loops are tuned for small deviations from steady-state conditions (not large deviations). The PID loop continually calculates a larger and larger valve command as it tries to minimize the error signal. It eventually arrives at a 100% open command just as the pneumatic controllers did.

Cascade Control

Cascade control describes a control strategy where two control loops (PID loops) work in concert to control the primary process variable. The primary control loop provides the setpoint for the secondary or slave control loop. A higher degree of control accuracy and efficiency is provided because the secondary process variable can be monitored and maintained within an allowable range and it prevents the controlled device (valves and dampers) from assuming extreme positions (typically wide open).

Cascading control involves the use of an additional PID loop to control the space heating or cooling process. The original or primary PID loop that controlled the space temperature is modified to provide the discharge air temperature setpoint as its output instead of a valve command. The discharge air temperature setpoint modulates between maximum and minimum values to meet the room temperature setpoint. This range of discharge air temperature setpoints is defined in the PID loop parameters or linear logic block depending on the software program. The secondary PID loop receives the discharge air temperature setpoint from the primary PID and modulates the hydronic control valve to maintain the discharge air temperature at setpoint. The cascading control sequence is configured such that the slower space temperature control PID controls the setpoint of the faster discharge air temperature control PID (Appendix B). In addition, it provides the user, Owner, or programmer with an idea of exactly what the PID loops are trying to achieve.

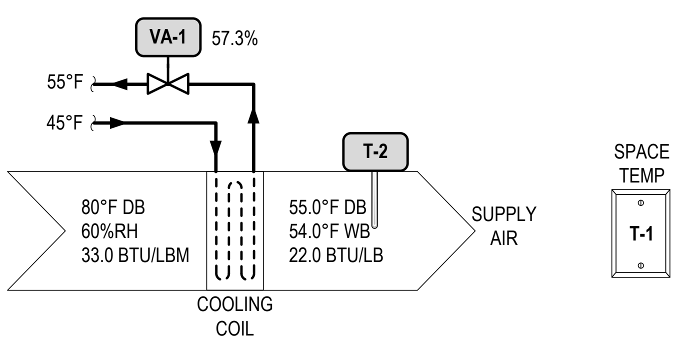

Figure – Cooling Coil with DDC (Cascade Control)

In the HVAC world, we are typically referring to hydronic heating and cooling coils when we discuss heat exchange between air and water streams. The law of conservation of energy indicates that energy is conserved. Therefore, when applied to a hydronic (chilled water and hot water) air coil, the amount of energy gained by the fluid water passing through a coil is equivalent to the energy that is lost by the air stream passing through the same coil and vice versa.

$$Q_{Air} = Q_{Water}$$

Equation 2

While operating under steady-state conditions, the hydronic control valve modulates to maintain the discharge air temperature at setpoint. The operating range of the discharge air temperature is limited to a pre-determined range depending on its service. Cooling coils are typically limited to a range of 55ºF to 75ºF. Heating coil discharge air temperatures are limited to a range of 70ºF to 95ºF. The main benefit of cascade control is evident on system startup or system upset. During these situations, the control valves typically go fully open making the hydronic system flows highly dependent on the quality of the balancing of the hydronic system. However, with cascade control the control valves remain in control preventing them from fully opening.

The cascading control strategy is nothing new. It is already commonly utilized in pressure-independent terminal units. The supply airflow rate for pressure-independent, Variable-Air-Volume (VAV) terminal units is defined by maximum and minimum supply airflow rates. They are commonly referred to as VAV boxes. The primary space temperature PID loop makes the comparison between space temperature and space temperature setpoint and calculates the required supply airflow setpoint. The secondary airflow control PID loop then compares the measured airflow rate to the airflow setpoint (provided by the primary PID loop) and produces the supply air control damper command required to maintain the supply airflow rate at setpoint. The space temperature PID loop is slow because the room temperature change process is slow while the airflow control PID is faster because the change in airflow rate due to damper movement is nearly instantaneous. The combination of the two PID loops allows airflow control to be maintained at all times.

With cascading control, we will no longer see very low cooling discharge air temperatures (<55ºF) or high heating discharge air temperatures (>95ºF) because the control valves will modulate to maintain control of the discharge air temperature. Discharge air temperatures beyond the design range while simulating maximum load conditions are an indicator of poor hydronic balancing. As long as hot water between 140ºF to 180ºF and chilled water at 42ºF to 48ºF is available to the hydronic coils, the hydronic control valves will modulate instead of fully opening. Cascading control utilizing both space temperature and discharge air temperature control allows us to break from the traditional single PID loop control strategy based only on space temperature control. If we incorporate the control of the discharge air temperature, the hydronic control valves modulate rather than go fully open on system startup or sudden change in the load.

Energy Efficiency

The discharge air temperature provides a real-time indication of the amount of heat exchange occurring on the air side which can be used to control the flow of chilled water through the cooling coil. The discharge air temperature is maintained at a minimum or maximum threshold to ensure that the control valve continues to modulate and does not fully open. Without cascading control, the cooling supply air temperature is free to drop below the design discharge air temperature setpoint (typically 55ºF) which can be extremely inefficient when there are downstream reheat coils. Additional heat will be required to maintain the space temperatures at setpoint if the supply air temperature is unnecessarily depressed. The same control strategy can be applied to heating coils in the hot water system. The only difference is that control sequence maintains the discharge air temperature below a maximum threshold (90ºF-95ºF) to maintain modulating control of hot water flow through the heating coils. Heating energy is unnecessarily wasted when the supply air is heated beyond the design discharge temperature. This overheated air is buoyant and typically remains at the top of the room where it does no conditioning of the occupied zone and contributes to vertical temperature stratification. In variable-air-volume pressure-independent terminal units (with reheat capacity), the supply air typically cannot reach the occupied zone while operating at minimum supply airflow rates also causing room temperature stratification. With the hydronic fluid flow under active control rather than the control valves fully opening, the hydronic circulating pumps (hot and chilled water) operate at lower speeds which produces electric energy savings and increases equipment service life.

Self-Regulating Hydronic Flow Control

If the chilled water control valves modulate to maintain a minimum discharge air temperature of 55ºF and the hot water control valves modulate to maintain a maximum discharge air temperature of 95ºF, these systems will in fact become self-balancing or self-regulating. The chilled water flow will be limited to that which will produce a 55ºF discharge air temperature. In the heating systems, the hot water flow will be limited to that which will limit the discharge air temperature to 90ºF to 95ºF discharge air temperature. System start-up and system upset are the only times when balancing valves are actually required. Cascade control allows the system to maintain hydronic flow control even during these periods. As long as active flow control is maintained, there is no need of balancing valves (in some systems).

Commissioning and Troubleshooting

Commissioning of the cascading control sequence is straightforward. In most cases, air-handling units already have discharge air temperature sensors. Most terminal units will also have a discharge air temperature sensor for system troubleshooting. Temperature sensors are very durable unless they are subject to physical damage or extreme temperature swings. In addition, they typically remain accurate over a long period of time. Calibration checks are recommended every two to four years to ensure maximum system accuracy and efficiency. The discharge air temperature and its setpoint provide additional data points that can be used to assess the quality and accuracy of control (space temperature and discharge air temperature). Alarms or warnings can be programmed if the discharge air temperature setpoints cannot be satisfied. If the target discharge air temperatures cannot be met, this may indicate insufficient hydronic flow, insufficient hydronic pressure differential, inadequate fluid temperature, sensor issue (temperature, air differential pressure transmitter, or hydronic differential pressure transmitter), or a mechanical/electrical issue with the damper or valve actuator. These potential issues are not apparent with just space temperature control.

Conclusion

Cascade control provides an easy way to improve system efficiency in existing and new hydronic systems because it facilitates active fluid flow control in coil assemblies. It permits active control of both the discharge air temperature as well as the space temperature. In chilled water systems, it ensures that the supply air temperatures are not unnecessarily depressed (<55ºF) which will require additional reheat energy to maintain space temperatures at setpoint. In heating systems (hot water and electric resistance), it ensures that the discharge air temperatures are not unnecessarily increased beyond 90ºF-95ºF threshold. Implementing cascade control means that the discharge air temperature will be maintained within a predefined range and the control valves will no longer race to the fully open position on system startup or system upset. They will maintain modulating control the flow of chilled water and hot water to ensure all coils receive their design flow. As long as hot water and chilled water are available at the design temperature range, this will prevent the control valves from fully opening as is typical of a single PID loop control. This solution requires no new software or controllers. It only required a discharge air temperature sensor if one is not already installed and some programming time. Cascade control can be applied to existing and new HVAC systems and units equipped with either two-way or three-way control valves.

Appendices

Appendix A – Conventional Space Temperature Control - Single PID Loop (Cooling)

Appendix B – Cascade Control - Space Temperature and Discharge Temperature Control PID Loops (Cooling)