INTRODUCTION
Compressor systems are used extensively in the upstream, midstream, and downstream oil and gas industry. Typical installations include gas reinjection systems, gas pipeline booster stations, gas processing plants, LNG facilities, gas storage facilities, ethylene, ammonia, and air plants, to name a few. Operation and output of these different installations vary, as often there are cases of plant operation that fall outside of the minimum flow capability of the compressors used. In these cases, the anti-surge control system is used to load balance the facility in order to maintain production. Equipment that was intended for only start-up and protection must now be used in continuous duty operation. Anti-surge control valves, anti-surge control systems, and the DCS need to be integrated in order to provide safe operation of equipment and to prevent damage to the compressors, control valves, and the plant.

OBJECTIVES
Plant Operations and Flow Range Variations
In upstream installations, there are wide variations in operating conditions as a production field transitions from initial start-up, to full production, to end of life. Initial start-up of the field may include start-up with a reduced number of wells that reduces system flow rates well below flow ranges when all wells are online. Late life in the field may see reduced production rates, once again with reduced flow through compressors. Compressors selected for gas reinjection need to be able to handle the highest amount of flow, and may be marginally suitable for the lower amount of flow seen during the initial and end of life conditions. Time constants on start-up, normal operation, and end of life in the oil patch, is on a different time scale than other industries, often taking months or years as compared to a process industry, where start up may be measured in hours.

In midstream installations, the variation in flow is related to the application. Pipeline booster stations typically are not high rangeability systems, and tend to have very slow transients on operating conditions due to the large pipeline volumes. LNG facilities can see more load variations on their refrigeration systems. Air finned cooler systems can see significant variations in load from day to night, or during a rain event. BOG (Boil Off Gas) systems can see a significant difference in load from normal production which handles relatively small amounts of boil off gas to tanker loading when the gas boil off rate is high. Gas storage systems operate on a seasonal cycle where gas compression of pipeline gas for injection and storage occurred. However, with the growing number of gas fired power plants, injection and withdrawal from storage may occur much more frequently from cyclic gas demands. This demand fluctuation can put more load variation on injection compressors.

In downstream installations, compressor flow variations tend to be less frequent. Ethylene plants may have as much compression capacity as an LNG plant, but load on the ethylene plant is controlled mainly with the furnace, thus reducing variations in compressor load. Ammonia plants, air separation plants, refineries, etc. also have less variation in loads or can control fluctuations more effectively by other means (e.g. steam turbine speed). This reduces the need for low flow and continuous compressor recycle operation to short term unit outages. Nevertheless, due to large sizes of machines employed, the savings in energy when operating at low flow conditions may be quite dramatic.

Compressor Loops and Anti-Surge Control
A compressor system consists of a number of components, and systems can have a significant variation. As shown in Figure 1, typical major components consist of a suction drum, a compressor, a driver, an intercooler, anti-surge control valves, and an anti-surge control system.

The anti-surge control valve has a number of different operational modes. The anti-surge valve is normally used in flow control during the start-up and shutdown of the compressor, load transfer to the process, surge control during transients in operation, and surge control during a power interruption of the driver to the compressor. To avoid inefficiencies, it is desired to keep the anti-surge valve closed during normal operation. However, conflicts in process operating range and compressor rangeability can necessitate using the anti-surge valve in a continuous throttling mode. The amount of flow bypassed during this throttling mode is a function of the compressor flow range, the anti-surge valve design, and the anti-surge control system dynamics (e.g. loop delay times).

In Figure 2, the operating range of a variable speed compressor operation is outlined. Minimum flow through a compressor is determined by the SLL (Surge Limit Line), where operation of compressor below the minimum flow will result in damage to the compressor. Maximum flow is determined by the stonewall or overspeed points where flow over the compressor blades becomes unstable. Minimum and maximum RPM curves are a function of the driver to the compressor. Additional restrictions for system pressure limits or driver power limits can also occur. Operating limits are different for each set of suction pressure, temperature, and gas density. Once operating limits are generated, a safety margin is added to each of these boundaries, defining the system operating range of flow rates.

The minimum flow safety margin line is normally identified as the SCL (Surge Control Line). As the compressor operating point approaches the SCL and the process causes the flow to continually decrease, the anti-surge valve will need to open to increase the available flow to the machine. The distance between the SCL and SLL is mainly a function of the control system response time, valve characteristics, and the control algorithm used. A faster and better designed system will require a smaller distance between the SCL and SLL. Ultimately the shorter distance improves operating rangeability and increases system efficiency.

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An industry requirement of anti-surge control valves is that they need to be sized with overcapacity so that:

- In start-up operation, there is additional capacity to bypass additional flow.
- Trapped gases in the upstream and downstream piping sections can be handled.
- There is capacity necessary for compressor protection during a power interruption event.

These requirements for overcapacity can vary by individual compressor systems and plant designs. Common requirements are:

- To size the anti-surge valve for 1.8 to 2.2 times the Cv required for conditions at the surge control line.
- Size with a linear characteristic.
- Ensure that noise and vibration checks are done at the surge control line, and that project noise requirements are met at the surge control line as extended operation at this point can occur.
- Overcapacity for safety margin can tolerate higher noise levels, as the overcapacity is normally a short duration event which infrequently occurs.

These overcapacity requirements and the Cv vs. travel characteristic for anti-surge valves will inherently limit the rangeability of the anti-surge valve and the ability of the valve to throttle at lower capacities.

Low Flow/Lift Operation Impact on Control Valves

Control valves are designed with a given maximum, and an inherent minimum, Cv. For most high performance anti-surge control valves, the valve of choice include: reciprocating, cage guided, pressure balanced designs. These valves need to dissipate the energy generated by the compressor in a manner where noise, excessive vibration, leakage, and erosion do not occur.

Rangeability of the control valve is defined by the ratio of the maximum Cv divided by the minimum Cv. Most manufacturers will provide Cv vs. stroke curves, showing the valve Cv as a function of lift, with the plot showing a zero Cv at the zero percent lift and a smooth transition as the valve opens. With cage guided valves, a step function in Cv occurs as the plug moves away from the valve seat. As soon as the valve lift exceeds the clearance between the plug and the seat, the clearance flow becomes the minimum flow that occurs on the valve. This step function occurs at very low valve lift, below ½% travel. All cage guided valves will have this step function.

There are other limitations for operation of anti-surge control valves at low lift. Most anti-surge valves are designed with low noise trim, which consists of multiple stage trim comprised of various multiple cage, labyrinth turn, or other trim designs. If anti-surge valves are throttled at very low lift, the valve operates in a region where the multiple stage pressure drop is not effective, and the potential for mechanical vibration and mechanical stresses are greater. Some designs use soft seats, and throttling in near proximity can cause the soft seat to extrude. Many designs will see a force change that occurs as the valve comes off the seat due to change in hydraulic areas, which can cause an oscillation issue.

While most control valves can transition through the low lift zone without an issue, continuous operation at very low lift can be detrimental to the life of the control valve.

Tight Shut-Off in the Anti-Surge Control System

There is a conflict between operating the anti-surge valve at minimum possible flow for efficient compressor operation and operating the anti-surge valve where mechanical damage is less likely to occur. For example, an anti-surge controller might only need to open the recycle valve 2% for machinery protection, but 10% is necessary to reduce valve wear. The 2% valve stroke is obviously more energy efficient, but such a position is not healthy for the valve.

If the anti-surge control valve is expected to operate for extended periods of time at low flow rates, then the anti-surge control system should utilize algorithms that ensure valve life as well as maintain machine efficiency. Tight Shut-Off operates by enforcing a controller output low clamp when the compressor is near surge and by removing the clamp when the compressor moves away from surge. The low clamp ensures that valve wear is minimized while the low clamp removal ensures maximum machine efficiency.

An example scenario for Tight Shut-Off (TSO) is illustrated below in Figure 7. The starting location of the compressor’s operating point is shown at point 1. At this point, the valve is completely closed and will remain closed even after moving to the left of the TSO as illustrated at point 2. The valve will then open when the operating point is on (or crosses) the Surge Control Line at point 3. At this point, the controller output will jump to the minimum clamp and the operating point will move to the right at point 4. Once the controller output is at the minimum clamp, the output will not return to zero until the operating point moves to the right of the TSO line at point 5. Once the system reaches point 5, the anti-surge valve will close, moving the system to point 6. This will be away from the SCL and the valve will remain closed. Eventually, the operating point returns to the vicinity of point 1 where the compressor normally operates with the anti-surge valve completely closed.

Two parameters need to be calculated in order for the algorithm to function properly: the minimum output clamp and the Tight Shut-Off distance. The minimum clamp is configured so that the valve, when commanded open, is at a minimum travel that does not produce significant component stress. The TSO distance must be set far enough away from the SCL (Surge Control Line) so that the step opening to minimum clamp does not immediately move the operating point to the right of the TSO line causing continuing oscillations. However, the TSO distance cannot be so great that the operating point never crosses to the right of the TSO line.
Anti-surge Valve Trim Characteristic
Most compressor sections protected by an anti-surge control valve operate at a high enough pressure ratio where the anti-surge valve is operating at critical drop. As a general rule, control valves on critical drop or constant high pressure drop systems are selected with linear characteristic. For anti-surge valves, linear characteristic trim is also often selected. The linear characteristic provides a uniform flow gain for programming of the anti-surge controller, and provides a good compromise between an equal percentage characteristic and quick open characteristic.

In systems where the anti-surge valve will be used in extended load balance operation, it may be advisable to provide a modified linear (see Figure 9) which is partially characterized to increase the stroke for low Cv’s. This trim characterization will provide a higher valve lift for a given flow. The trim characterization allows the TSO (tight shut off) line to be programmed nearer the SCL (surge control limit) line. Programming the TSO line as close as possible to the SCL line will reduce the amount of recycle flow around the compressor resulting in greater efficiency. The modified linear characteristic also provides a higher anti-surge valve lift, reducing potential stresses on the anti-surge control valve.

Figure 8

In plants where the anti-surge system is used in a continuous throttling mode, modifications for equipment may be needed. Equipment that was intended for only start-up and protection operation must now be used in continuous duty operation. Operation of load balancing where the anti-surge valve is used for continuous throttling needs to be stated in the equipment specification. Anti-surge control valves, anti-surge control systems, and the DCS need to be integrated to provide safe operation of equipment and to prevent damage to the compressors, control valves, and plant. The main engineering contractor, valve manufacturer, anti-surge control system supplier, and the end user need to review this modified operation so that the entire system can properly function. Not only is protection of the rotating equipment important, but safe and automatic operation of the controls and actuators is crucial as well. Communication between all suppliers is necessary to ensure proper and safe system integration.

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Joe Steinke is Principal Engineer at Control Components Incorporated and has 35 years valve business. While with CCI and Masoneilan, Joe has been involved with the application, sales, design, manufacture, and servicing of Severe Service Control Valves. Joe was awarded the 2008 ISA Doug Annin Award for his contributions to the control industry, holds 6 patents, and has published a number of technical papers on Severe Service Control Valves. Joe has extensive background Oil and Gas and Power Industries. Joe has a BSME from California State University at Fullerton.

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