Part 1

Gas Handling: Process Control for Compressible Flow

Controlling flow in gas-handling applications can present challenges because of the fluids' compressibility. This article presents an overview of how compressible gases behave in response to interacting variables

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IN BRIEF

- COMPRESSIBLE FLOW
- PRESSURE AS DRIVING FORCE
- FLOW MEASUREMENT AND CONTROL
- PRESSURE CONTROL
- CONTROLLING THE DRIVING FORCE

Gas handling operations are common in almost every part of the chemical process industries (CPI). Some examples are obvious, and others not as much so. Process plants may have heating, ventilation and air conditioning (HVAC) systems for recirculating air, auxiliary steam systems for heating unit operations, or even compressed air for pneumatic valve and tool operation, among others.

FIGURE 1. Since gases are compressible, variable densities alter volumetric flowrate and velocity. This compressible flow presents unique challenges to facilities in the chemical process industries

While controlling parameters such as flow and pressure in a gas-handling process may be an intuitive goal, the methods of achieving it may not be. There are certainly physiochemical reasons to control flow and pressure, but there are regulatory reasons as well. For example, controlling pressure drop to keep the sound levels from getting too high in a process plant is a major topic in the Occupational Safety and Health Administration's (Washington, D.C.; www.osha.gov) OSHA Technical Manual.

Compressible flow

Process control involving gases has many different aspects, but this article presents a high-level discussion of process control from the fluid system perspective. Chemical engineers need to understand how process fluids behave in response to changing variables. However, the details of process control become especially cloudy when working with process gases because of their compressibility (Figure 1).

Compressible flow presents unique challenges and requires special considerations because density is a function of temperature and pressure. This relationship is represented by equations of state, which are often not considered with liquid systems. With gases, this changing density changes volumetric flowrate and velocity. In a theoretical adiabatic (no heat transfer to or from surroundings) pipe of constant cross-sectional area, the fluid velocity increases along with dropping pressure down the line — even though the mass flowrate is steady. In compressor systems, the heat of compression must be considered. This changes the volumetric flowrate – although the mass flow is constant.

Because gas handling operations typically involve compressible flow, they are complicated by sets of coupled variables, among which are flow and pressure. Gas handling processes flow require precise control of flow and pressure. To understand the process control for these parameters, you need to understand the relationship between the two.

Pressure as driving force for flow

The discipline of chemical engineering has a unique focus on transport phenomena. Chemical engineers understand the unifying cornerstone that any transfer of mass, energy and momentum materializes from a driving force. In the case of industrial gas handling, pressure is that driving force for momentum transfer. It helps to remember that pressure is dimensionally consistent with momentum flux. A pressure differential causes a process fluid to spontaneously move from high to low pressure, in accordance with the second law of thermodynamics.

In simpler terms, flow occurs when a difference in pressure is present. When talking about flow and pressure control as separate controlled variables, we might ask "are we really controlling one or the other?" The answer is that the two parameters are not independent of one another; we really control and affect both. It is just a matter of what the objective is, and the reference point.

In operations involving gas handling, there is often a desire to control one parameter over the other: either the goal is a certain flowrate, or a certain pressure. However, there is commonly a secondary goal to keep the counterpart in check – for example, to control the flowrate while ensuring that the pressure does not exceed the maximum allowable operating point. In these situations, it becomes important to remember pressure and flow are not independent of one another.

Flow measurement and control

First, let's discuss cases where flow measurement and control are the primary objectives.

It is common to specify flowrates as mass flowrates when discussing compressible flow. The conservation of mass is a fundamental principle, while the conservation of volume is not. However, it is quite common for engineers to measure and handle volumetric flow because of the ease of direct measurement at a single point. In gas-handling systems with changing fluid densities, engineers need to pay careful attention to the type of measurement taken.

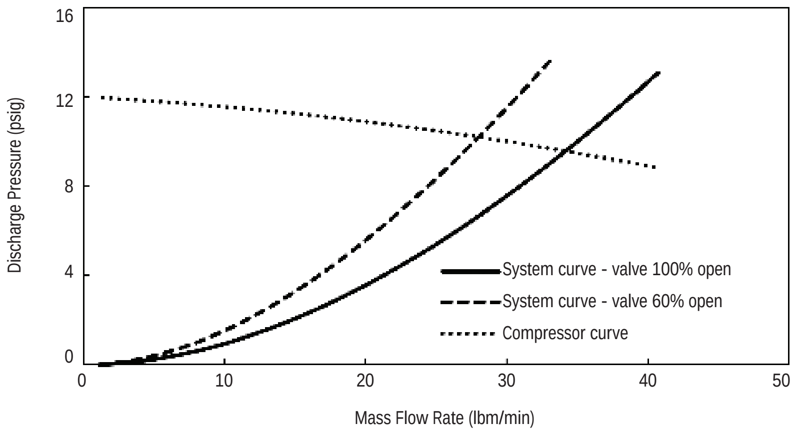

FIGURE 2. Compressors supply energy in the form of flow (kinetic energy) or pressure (potential energy). This concept can be shown with a compressor curve versus system curve with manual valves

Flow readings may come from measuring the pressure drop across an orifice plate, the displacement of a ball flowmeter, or by measuring the velocity with a pitot tube. However, the volumetric flowrate at this single measurement point is not constant down the rest of the pipe. Pressure and temperature data are required to convert the volumetric measurement into a mass flowrate. Controlling volumetric flowrate may be the end goal, but to do a system analysis, you will need to know the mass flowrate for fundamental continuity analysis.

While measuring volumetric flow is a more direct process, there are also measurement tools that yield mass flowrates, such as a thermal mass flowmeter that determines a mass flowrate based on heat transfer. However, these tools are a less direct way of measuring flowrate and require more careful calibration. Both types of flow specifications provide useful information as long as the implications of each are understood, especially when designing process control schemes.

To remain consistent with the fundamentals, the rest of this discussion will focus on mass flow rate.

Process controls all usually have a similar, high-level pattern. A measuring device reads a certain parameter, and a signal is sent to compare the actual reading with a desired setpoint. The difference between the two causes an actuator to trigger a change in the process. In flow controls specifically, there is communication to an actuator valve that will open and close to affect the fluid flow.

While this is a common operation, the reason for why this works is not always obvious. If a compressor runs at a constant speed, you might expect the flowrate to also be constant. According to the law of conservation of mass, a constant flowrate will remain no matter what other changes are made to the system. By closing a valve, the area through which the fluid flows is made smaller, and thus, an increase in velocity is observed to keep that same flow.

But it is important to understand that centrifugal compressors can generate different steady-state flowrates with one motor speed. They operate on a curve, similar to a pump. By closing the valve, you have increased the frictional losses in the system, and thus the compressor will need to supply more pressure to overcome those losses. This increase in pressure is coupled with a decrease in flowrate. That is why compressor curves are downwardsloping. A compressor supplies energy in the form of flow (kinetic energy) or in the form of pressure (potential energy). Increasing one decreases the other (Figure 3).

It is easiest to show this concept with a compressor versus a system curve for a simple system (Figure 2). The system curve represents the pressure demanded by the system at a range of flowrates. The intersection of the compressor and system curve is the operating point. Increasing the frictional losses in a system will move the system curve leftward (System curve – Valve 60% open) to a new operating point. There is more pressure demanded by the system to ensure that flow occurs because now there are more losses. This example is presented as the control of a manual throttling valve, to help simplify the system behavior and understand the role of component losses and flowrate. (A control valve similarly controls flow based on its pressure-loss information, but the generation of a system curve to visually represent flow control becomes difficult because the valve changes its loss information across the varying flowrates to meet its setpoint.)

Of course, centrifugal compressors are not the only way to move gases. Reciprocating compressors are also common, and they operate at a single flowrate on a near-vertical compressor curve. In the case of reciprocating compressors, the flowrate is not controlled via typical means. Rather, you will only change the operating pressure by the changing losses through the system. If you want to change the flowrate, you will have to modify the compressor directly.

It is also common for steam systems to not have a compressor at all, where the flow travels from a boiler to a lower temperature and pressure trapping. In this case, while there is no compressor to operate on a curve, the flowrate is still determined by the frictional losses in the system. It can be helpful to define these losses as "resistance," with an indirect relationship with flow. The more resistance in a system, the less flow will be generated.

Now that the bases of flow control have been discussed, let's get into a compressible-flow-specific topic: sonic choking. Most process engineers do not instigate choked flow on purpose, but it is a form of controlled flow, nonetheless. Sonic choking occurs when the velocity of the fluid is the same as the local speed of sound (that is, having a Mach number of 1). This tends to occur at restrictions in the pipe, such as control valves. Aside from flowing through a special converging-diverging nozzle, this is the limit of flow. No matter how low you drop the downstream pressure, you will not drive any more flow. It is very important for engineers to keep an eye on gas velocities through control valves because they may be approaching that choke point.

Pressure control

It was previously mentioned that a pressure differential is the driving force for flow. In any case other than choked flow, engineers can control flow by controlling the pressure in the system. Although the goal may be to control flow, keep in mind that an operator actually controls the driving force behind it, not the end-controlled variable directly.

Perhaps an engineer is more interested in controlling pressure than controlling flow. That is, pressure becomes the controlled variable. When dealing with a steam system, you may want your pressure to remain low enough to avoid condensation and slug flow in your lines. Maybe you are interested in keeping a high-enough pressure downstream to avoid high velocities and their accompanying noise levels.

Valves are a source of pressure loss in the system. This gives engineers a solid foundation to design, and they can use that to their advantage to throttle flow. In most processes, there are two main categories of pressure control valves: pressure-reducing and pressure-sustaining. Relief valves are a common component in gas handling, but they are meant more for safety precautions than for controlling pressure. Pressure-reducing valves control the pressure downstream, while pressure-sustaining valves control pressure upstream.

There is a unique aspect to this type of control. Many control valves operate on a pneumatic or hydraulic pressure signal from the controller for actuation. In this special case, pressure is both the controlled variable and the actuating signal, allowing design for a self-actuated pressure control valve. These do not go through a typical control loop with an outside signal to a controller. In industry, self-actuated pressure control valves and pressure regulators are used synonymously. Not all pressure-control valves are self-actuating, but it is helpful to understand the

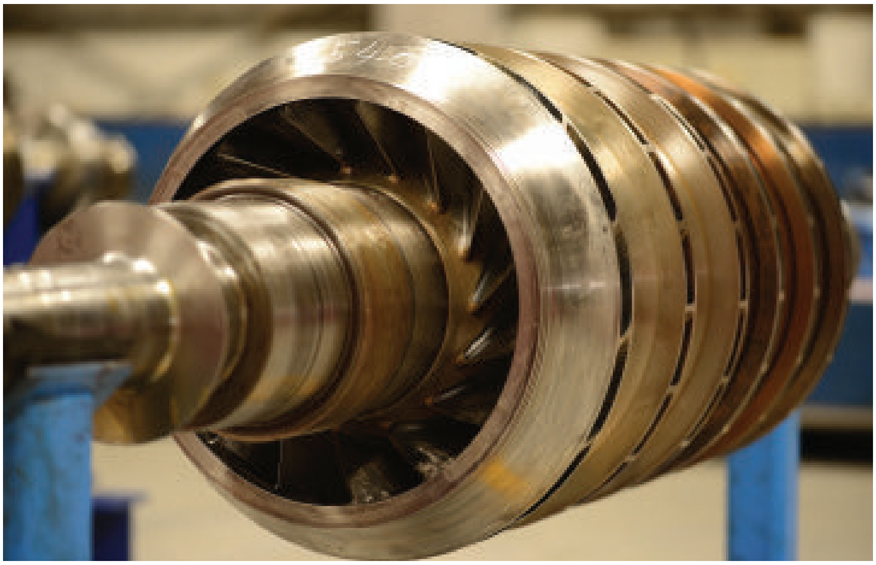

FIGURE 3. Centrifugal compressors can generate different steady-state flowrates with a single motor speed

potential for process simplification.

Pressure-reducing valves exercise control by closing to create more frictional loss and pressure drop, or by opening to do the opposite. A pressure-sustaining valve will operate similarly (by opening and closing), but for controlling the upstream pressure. Many people understand pressure-reducing valves because valves are said to cause pressure drop. But the flipside to that pressure drop is that a higher pressure is sustained upstream. The same opening and closing can achieve both goals.

This is an easier concept to grasp when looking at an example of flow going from a 100-psig tank to am 80-psig tank, with a valve directly in the middle of a 500-ft line. Figure 4 shows the pressure profile of two cases. When a valve is in a more closed position, there is more pressure drop across the valve; there is less pressure drop with an open valve. However, the flow from tank to tank will always have a profile going from 100 to 80 psig, no matter what losses are present in the line.

By closing a valve, you both decrease the downstream pressure and increase the upstream pressure. It is up to the engineer to decide what is the controlled variable of interest. Don't forget that there will be less flow in the scenario with a more closed valve; there is more resistance in that line. When you see a pressure profile such as this in a gas-handling process, also keep in mind that density, velocity, volumetric flowrate and temperature are also changing down the line, even though mass flowrate is constant.

The other common type of pressure valve is a relief valve. This type of valve does not typically operate as part of a control loop. However, it is not unheard of for relief valves to be actuated by an outside controller communicating with a separate part of the process. Most often, pressure-relief valves are mechanically operated valves that crack open when the upstream pressure is past a set threshold. This valve relieves an upstream pressure, but it is not meant to control the pressure to a certain setpoint.

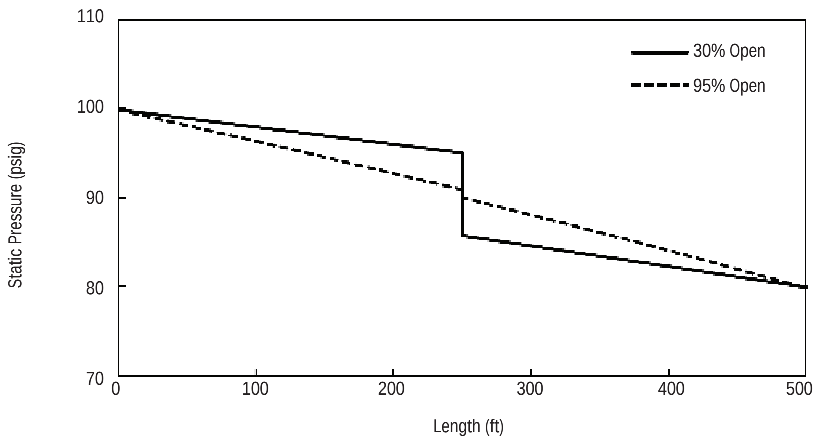

FIGURE 4. The graph shows the pressure profiles for two cases, one in which a valve is more open (dashed line) and one with the valve more closed (solid line). The pressure drop is higher with the more closed valve, but the starting and ending pressures are the same

Relief valves are used more as safety devices in gas handling processes. With the multi-faceted coupling of parameters in compressible flow, pressure can change for many different reasons. This extra complication makes controlling pressure a more difficult task, and thus the common remedy to pop open valves when pressure gets too high.

The traditional relief valve operates on a pressure differential across the valve. If the difference is greater than the setpoint, the valve will crack to relieve upstream pressure. A balanced relief valve is the kind that operates only on the upstream pressure, not a differential. It has means of cushioning the effects of back-pressure on valve operation. This type of valve can be very useful when a process requires precise pressure relief upstream of the valve.

A loud whistling sound is almost always experienced with a relief valve cracking. Of course, it depends on what pressure magnitudes are being relieved. With non-hazardous process gases, relief valves often vent to atmosphere. That can result in quite large drop in pressure from the process line. This extremely low pressure produces a large driving force for flow. And that flow moves out of the valve with a very high velocity. When venting to such an open space, there is a major drop in the potential and kinetic energy of the fluid. As a result, the gas cools, slows down and drops pressure.

Since energy cannot just disappear, the question becomes "where does it go?" Some of the energy goes into the volume expansion, and some goes into producing sound. A common safety concern with valves is sound levels. In fact, this is not just the case with relief valves, but with any type of valve. By dropping the pressure and increasing the velocity, you will hear an accompanying sound. Some of the pressure loss gets converted into sound, which is just the propagation of a pressure wave. The level of that sounds depends on the velocity, flow area, pressure differential, and the mitigation efforts in place. This aerodynamic noise has been the cause for OSHA safety guidelines (Section III: Chapter 5) to protect the hearing of those in the field.

Controlling the driving force

There are many factors to keep in mind when designing for flow or pressure control in gas handling processes. Pressure is the driving force of the system, even when you are designing for flow control. By changing the frictional losses in the system, you change the operating mass flow rate. Mass conservation is a fundamental law, but volume conservation is not. Volumetric flow, velocity, density, and temperature will all change according to the fluid's equation of state even though mass flow may be constant. Down the length of an adiabatic and constant cross-sectional area pipe, you will see pressure and density decrease, volumetric flow rate and velocity increase, and most often will see temperature drop.

When pressure is your controlled variable, you affect both the upstream and downstream pressure (and flow) with the same valve operation. Closing a valve will create larger pressure losses, which implies a greater upstream pressure, a lower downstream pressure, and a lower mass flow rate. A pressure reducing valve controls the downstream pressure, while a pressure sustaining valve controls upstream.

Depending on the process application, engineers design a wide range of flow and pressure control methods, but it all boils down to changing the pressure to change the momentum transfer. That is the beautiful consistency of chemical engineering: there is always a driving force behind transport phenomena. Controlling that driving force is how you ultimately control your process variables. ■

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