Compressor Anti-surge with Volumetric Flow Control

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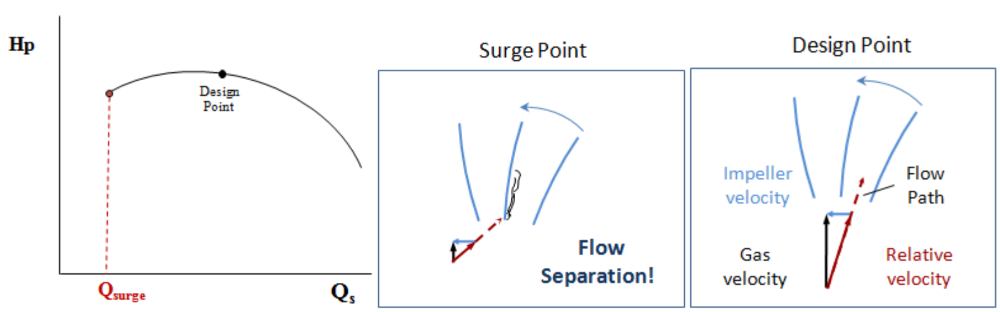
Volumetric Flow Control is a very simple and effective way to prevent compressor surge without excess false load.

Centrifugal compressor surge is caused by an insufficient inlet volumetric flow rate. Surge occurs when the "angle of attack" of the gas on the impeller is so steep that flow separation and instability occurs. It's the same thing that happens when an airplane wing stalls.

The images below illustrate what happens. At the design point, the gas path relative to the impeller results in minimum interference. As volumetric flow is reduced, or impeller speed increases the gas impinges on the face of the impeller. Eventually the impingement angle is so steep that flow separation occurs which destabilizes the flow pattern and triggers surge.



Surge is avoided by maintaining a minimum inlet volumetric flow rate. Regardless of the anti-surge controller algorithm used, if it avoids surge it does so by maintaining a minimum volumetric flow rate.

The Double Edged Sword

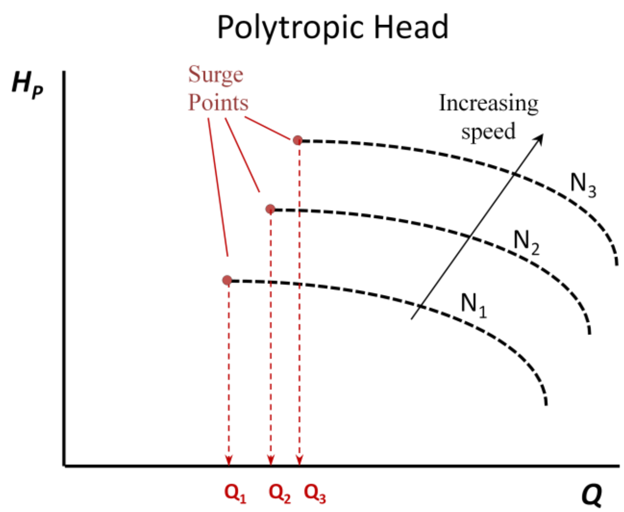
If maintaining minimum volumetric flow was the whole story then the solution to avoiding surge would be to simply fully open the throttle, vent, or false load valve in order to maximize volumetric flow rate. However, there is price paid for excess false load including lost capacity, unnecessary energy utilization, and stress on the compressor and drive train. This adds an important caveat to the objective of an anti-surge controller. A surge controller (or anti-surge controller) should maintain a minimum volumetric flow rate WITHOUT excessive false load. Worded differently, a surge controller should seek to minimize volumetric flow without allowing the flow to drop below the surge volumetric flow rate.

It always "boils down" to Inlet Volumetric Flow Rate

Regardless of the control variable used by your anti-surge controller, it is the inlet volumetric flow rate that matters. If your ASC avoids surge then it has succeeded in maintaining a minimum volumetric flow rate. If however, your surge control valve is frequently open, then it is very possible that your ASC is using excess false load and you're paying the price for that.

Compressor Performance Curves

The compressor manufacture provides performance curves for each stage of compression. The relationship between polytropic head and inlet volumetric flow is a function of impeller speed and geometry. The relationship is independent of gas conditions. This is illustrated by the fact that validation of performance provided by a compressor manufacturer is conducted with a gas other than the gas it will eventually be used to compress. At each speed there is a fixed volumetric flow rate that triggers surge. The volumetric flow rate below which surge occurs is independent of gas composition, inlet conditions, and discharge conditions.



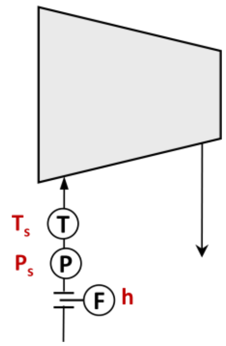
Volumetric Flow Control

It seems clear that volumetric flow control is a good method for avoiding surge. It is fundamental to the compressor design geometry , independent of gas conditions, and provides a direct method for maintaining minimum flow without excess.

Volumetric Flow Controller - Setpoint
By adding an acceptable safety margin, the volumetric flow controller setpoint comes from the compressor performance curve values for surge volumetric flow rates. It a simple matter of correlation Qsurge with Speed and then adding a safety margin. That simple calculation will provide a good setpoint that is valid at all speeds and all operating conditions.

Calculating Volumetric Flow Rate

In order to control volumetric flow rate, we need to be able to estimate its value. Volumetric Flow Rate can be estimated from gas composition and conventional instrumentation.



Flow Measurement Density Compensation

The inlet flow meter will be configured to indicate either volumetric flow rate or mass flow depending on how the meter constant was calculated.

$$Q_{indicated} = K^{Q}_{meter}\sqrt{h_o} \qquad M_{indicated} = K^{M}_{meter}\sqrt{h_o}$$

Where

$Q_{indicated}$	Volumetric flow rate indication
$M_{indicated}$	Mass flow rate indication
h_o	Head meter differential pressure
K^{Q}_{meter}	Volumetric flow meter constant value
K^{M}_{meter}	Mass flow meter constant value

In either case, density compensation is required to calculate the actual inlet volumetric flow rate.

$$Q = Q_{indicated}\frac{\sqrt{\rho_K}}{\sqrt{\rho}} \qquad Q = \frac{M_{indicated}}{\sqrt{\rho_K}\sqrt{\rho}}$$

Where

Q	Actual volumetric flow rate
ρ_K	Gas density value used to calculate the meter constant
ρ	Actual gas density

Actual Gas Density

Inlet gas density can be calculated using the ideal gas law and gas compressiblity.

$$\rho = \frac{1}{R}\frac{mw}{Z_S}\frac{P_S}{T_S}$$

Where

R	Ideal gas constant
mw	Gas molecular weight
Z_S	Gas compressibility at inlet (suction) conditions
P_S	Inlet Pressure (absolute)
T_S	Inlet Temperature (absolute)

Molecular Weight

If the gas composition is known, then you can calculate and use the number average molecular weight.

$$mw_n = f(Y)$$

Compressiblity

If gas composition is constant and variations in inlet temperature and pressure are small then it will be sufficient to calculate an average value off-line. If conditions change, then it is easy to include a Z-calculation in the control algorithm.

$$Z_S = f(Y, T, P)$$

Surge Test to find mw/Zs

Volumetric flow control can be implemented even when gas composition is unknown by using a surge test to find the value for mw/Zs. Only one test at any speed is needed to provide a value that will work at all speeds.

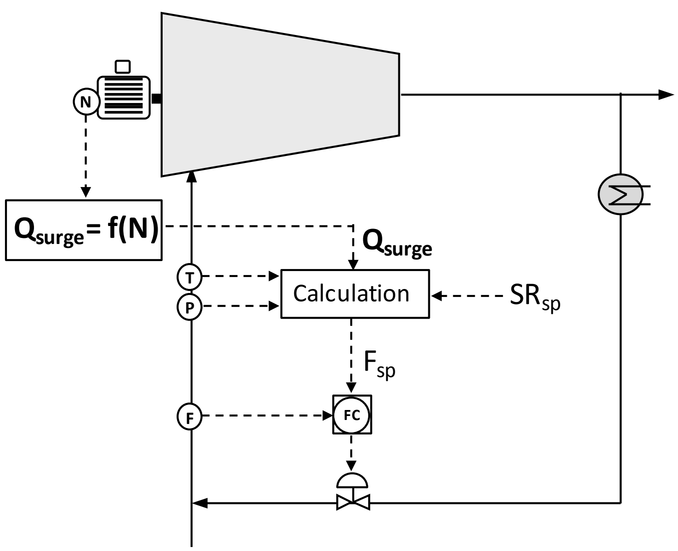
The surge test is conducted by putting the compressor in a light surge and recording the inlet conditions that existed when surge is initiated. These measurement values and the corresponding value of Qsurge provided by the performance curve are used to estimate mw/Zs

$$\frac{mw}{Z_S} = R\frac{T_S}{P_S}\left(\frac{Q_{indicated}}{Q_{surge}}\sqrt{\rho_K}\right)^2 \qquad \frac{mw}{Z_S} = R\frac{T_S}{P_S}\left(\frac{M_{indicated}}{Q_{surge}}\frac{1}{\sqrt{\rho_K}}\right)^2$$

Q_{Surge} = Surge Volumetric Flow Rate taken from the performance curve

Implementation

Here is one example of how volumetric flow control could be implemented. Consider a single stage variable speed compressor with conventional instrumentation and a inlet flow controller. "Calculation" represents the volumetric flow control algorithm that is executed frequently.



Example calculation algorithm

1. Calculate surge volumetric flow using a curve fit of performance curve surge volumetric flow rates.

$$Q_{surge} = f(N)$$

2. Calculate the volumetric flow setpoint. SRsp is the "surge ratio setpoint" and a value greater than 1.0

$$Q_{SP} = SR_{SP} * Q_{surge}$$

3. Calculate inlet gas density using best estimate of mw/Zs

$$mw_n = f(Y) \qquad Z_S = f(Y,T,P) \qquad \rho = \frac{1}{R}\frac{mw}{Z_S}\frac{P_S}{T_S}$$

4. Calculate the appropriate flow controller setpoint.

$$F_{SP}^{Q} = Q_{SP}\frac{\sqrt{\rho_K}}{\sqrt{\rho}} \qquad F_{SP}^{M} = Q_{SP}\sqrt{\rho_K}\sqrt{\rho}$$

<u>Calculation Frequency</u>
The fast reaction needed to prevent surge is provided by the local flow controller. The calculation frequency needs be only as fast as the inlet composition, temperature, and/or pressure can change.

Characteristics of Volumetric Flow Control

<u>Robust</u>
Since volumetric flow is the fundamental cause of surge it is valid and effective over the entire operating range of a compressor. Only changes in the impeller itself will affect the volumetric flow rate required to prevent surge. The volumetric flow rate that triggers surge is as fixed as the compressor itself.

Stable

Volumetric Flow control is very stable. The only variable that affects the value of the volumetric flow setpoint is speed. Changes in inlet or discharge conditions do not affect the setpoint.

If surge occurs the flow rate will drop and the controller action will be in the correct direction. There is no “falling off the cliff” when surge occurs characteristic of conventional anti-surge controllers.

Simple

Volumetric flow control is very simple to implement. There are no confusing parameters that only experts can set. There is no need for emergency action to prevent the incorrect response "cliff" characteristic of conventional anti-surge controllers.

Easy to Implement

As the description above should illustrate, implementation of volumetric flow control is easy.   Simply configure the flow controller and add the setpoint calculation. Remember that the flow controller takes care of any fast action and is the most critical component in the loop. All or part of the design can be implemented in a triple redundant PLC. My experience is that implementation on the standard DCS platform is sufficient.

Easy to Maintain

The simplicity of this approach makes it easy to maintain. There are no confusing parameters or values that require expertise to adjust.

Inexpensive

Given the ease of implementation and maintenance this approach will be significantly less expensive to implement and maintain. My experience over the last 35 years is that anti-surge control can be managed like any other critical loop in your process. Volumetric flow control can be implemented and supported by good, experience control engineers.

New Method For Volumetric Anti-Surge

Since posting this article a new method for volumetric control has been developed. The new method enables volumetric control with conventional instrumentation even in situation where gas composition is unknown and variable. That method will be described in a future article.

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