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MOLECULAR WEIGHT COMPENSATION CONSIDERATION IN COMPRESSOR SURGE CONTROL

Amit Saxena
Senior Control Systems Engineer
Dresser-Rand Company
Houston, TX, USA

Amit Saxena *is Senior Control Systems Engineer for rotating machinery at Dresser-Rand Company, Houston, Texas. He is responsible for design and development of compressor antisurge and performance control systems involving rotating machinery and realtime compressor performance monitoring systems. He has been with Dresser-Rand since 1996. Mr Saxena's areas of expertise are aerodynamics, compressor control, and related product development. He holds US and international patents in compressor control techniques. Mr. Saxena holds a M.S. degree in Mechanical Engineering from Texas A&M University.*

ABSTRACT

The effects of gas molecular weight variation on a centrifugal compressor's surge line and computation of the operating margin from surge for the purposes of antisurge control is discussed using different methods. This paper will review the accuracy of most commonly used coordinate system (reduced polytropic head vs reduced flow) for molecular weight compensation used by some OEMs and third party surge control vendors using test results from a FPSO application employing Main gas, Injection gas and Export gas compressors, and present an alternative highly accurate molecular weight compensation method that can be used by surge controllers to account for shifts in the surge point under varying molecular weight conditions. This alternate method has been field tested on several compressor control applications in FPSOs, refineries, LNG and petrochemical plants.

INTRODUCTION

Centrifugal compressors are the key drivers of many industrial processes, and as a result, surge damage to them can often result in costly maintenance expenditures, increased downtime and an overall drop-off in plant efficiency. Surging is one of the most common causes of compressor damage. Surging occurs when insufficient flow into the compressor and/or an increasing pressure rise across the compressor causes a condition in which forward flow is unable to be sustained. This results in a temporary reversal of flow within the impeller , causing a decrease in the discharge pressure and/or increase in suction pressure. This reduced pressure rise allows the compressor to reestablish forward flow. When forward flow resumes the resulting pressure rise again reaches a point where the compressor becomes unstable, flow is reversed, and this cycle is repeated. This continues until a change is made in the process and/or compressor conditions.

Surging can cause serious physical damage to pumps, fittings, valves, pipes and other ancillary pieces of equipment. Rotor shifting caused by the surge cycle can also destroy thrust bearings and in many cases, operating temperatures can exceed allowable limits and cause compressors to overheat. Because of this, it is always important to have effective anti-surge measures in place.

Surge can be prevented either by *blow-off* or *recirculation* of flow in order to keep the pressure differential across the compressor at a level in which reversal cannot occur. The moment at which either of these actions needs to take place is determined by a controller, which is designed to predict the point at which surging is imminent (i.e., the surge line) by measuring a function of pressure rise or polytropic head vs. flow. The challenge, however, is being able to accurately define the surge line over a wide range of operating conditions. At any given speed and suction pressure, variation in inlet gas temperature and in particular molecular weight causes significant shifts in the surge line. Given the difficulty in directly measuring the process gas molecular weight in real time, various indirect methods to compensate for this shift are in place and used by surge controllers today. Due to inherent inaccuracies in most of these indirect methods, control system designers and plant operating personnel generally have to err on the side of caution and operate compressors in a more conservative manner, resulting in decreased throughput and low operating efficiencies. This often translates into needless and excessive gas recirculation via the recycle loop and wasted energy.

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PROBLEMS WITH COMMONLY USED ANTISURGE TECHNOLOGY

The antisurge control technology that drives most antisurge applications today utilizes a model where surge prediction is based on the assumption that surge is defined under all operating conditions by a single surge limit line (SLL) on a coordinate system based on Polytropic head and volumetric suction flow squared (Figure 1). Furthermore as operating molecular weight and gas compressibility cannot be measured in realtime, these variables are simply removed from the calculation of polytropic head (Hp) and flow (Q) in the following way:

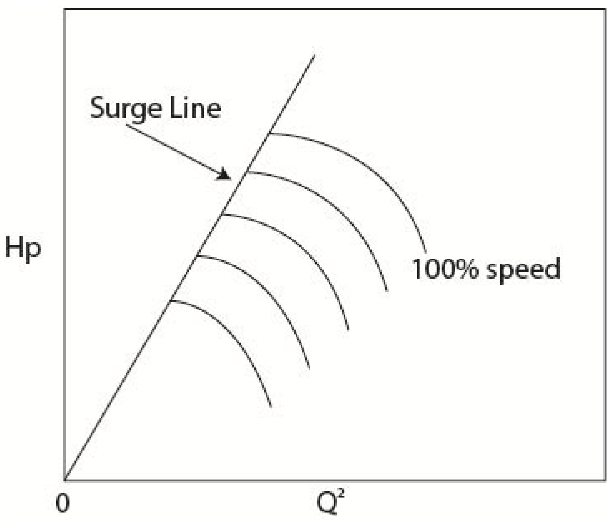

Figure 1. Co-ordinate system of Head vs Flow squared

By taking the ratio of polytropic head and volumetric flow squared as measured by the flowmeter equation, the molecular weight and compressibility terms cancel out.

$$\frac{Hp}{Q2} \propto \frac{\frac{Zs*Ts}{MW}*\frac{Rc^{\sigma}-1}{\sigma}}{\left(\frac{Zs*Ts}{MW}\right)*\frac{h}{Ps}} \qquad (1)$$

$$\frac{Hp}{Q2} \propto \frac{\frac{Rc^{\sigma}-1}{\sigma}}{\frac{h}{Ps}} \qquad (2)$$

The numerator in the above ratio is often referred to as “reduced head” and the denominator in the above ration is often referred to as “reduced flow” squared. By creating an antisurge control variable as a function of this ratio, the model contends that the value of the antisurge control variable at surge will not change at all gas molecular weights and compressibilities as these terms cancel out in the ratio calculation and a surge control setpoint can then be determined by incorporating a bias to the value of antisurge control variable at surge.

In a recent topside FPSO application antisurge controllers using this model were tested for accuracy with respect to molecular weight compensation of the surge lines during compressor operation at variable gas molecular weights. Results for three units are presented here for illustration purposes:

Main gas compressor:

Three compressors (one section, 6 impellers) operating in parallel on hydrocarbon gas. Molecular weight variation ranged from a low of 21.74 to a high of 34.75.

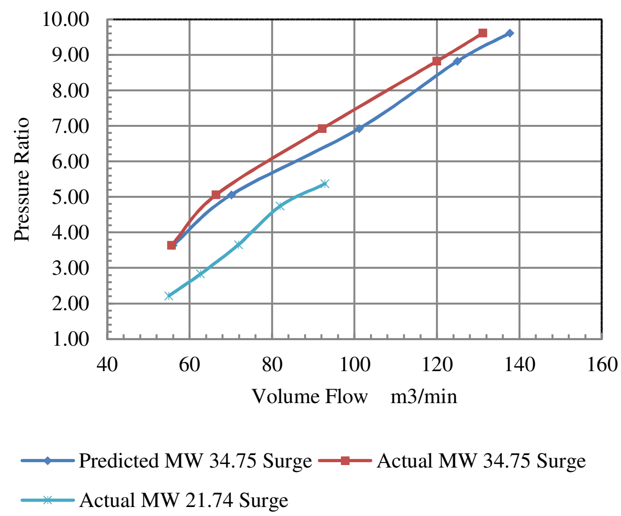

Figure 2. Actual vs Predicted Surge using reduced Head / Flow control variable for Main gas compressor.

Export gas compressor:

Three compressors (two sections, 7 impellers) operating in parallel on hydrocarbon gas – primarily a mixture of methane, ethane and CO_2. Molecular weight variation ranged from a low of 21.1 to a high of 34.8

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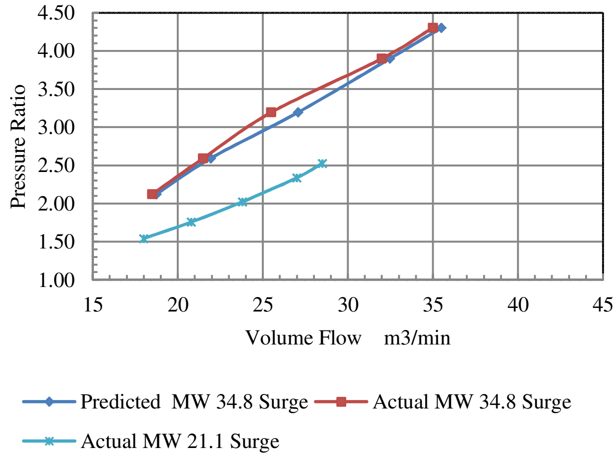

Figure 3. Actual vs Predicted Surge using reduced Head / Flow control variable for Export gas compressor.

Injection gas compressor:

Two compressors (one section, 6 impellers) operating in parallel on hydrocarbon gas - primarily a mixture of methane, ethane and CO_2. Molecular weight variation ranged from a low of 21.1 to a high of 39.4.

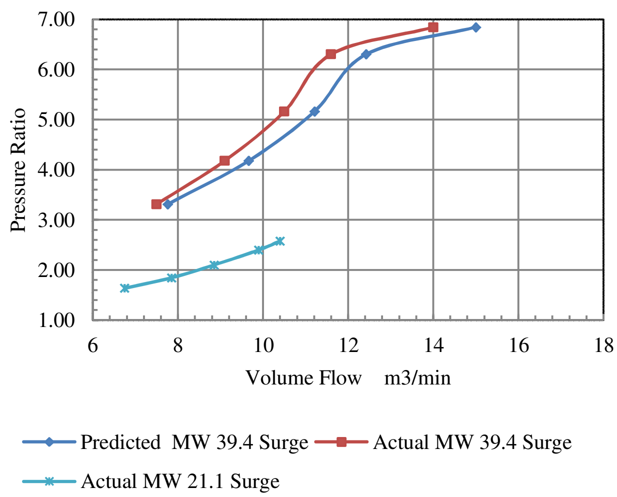

Figure 4. Actual vs Predicted Surge using using reduced Head / Flow control variable for Injection gas compressor

In the plots above utilizing this commonly used antisurge controller model, the predicted surge lines and the actual surge lines at higher molecular weights and higher heads do not always match the actual surge lines. Similar results were obtained by earlier tests (Gaston, 1992) using this model for molecular weight compensation in antisurge control. Molecular weight compensation errors by the antisurge controller when predicting the surge line range from 0 – 21 %. The compensation errors increase with increase in pressure ratios and increase in molecular weights. The inaccuracies of this compensation method can be attributed to the following factors:

- The antisurge controller model for molecular weight compensation is based on the theory that at any given rotational speed each compressor surge limit will correspond to fixed values of polytropic head and volumetric suction flow. This generally holds true for single stage compressors but many multistage compressors deviate from this theory when the molecular weight variations change the compressor stage bringing the onset of surge. In such cases the polytropic head at surge may not change but the volumetric flow at surge will change to correspond to the surge flow of the compressor stage that brings the onset of surge. When this happens the model gives large errors in the calculation of the surge flow.

- If the inlet molecular weight , temperature, specific heat ratio ‘k’ and compressibility were fixed, the surge limit line (SLL) would not move and eliminating these terms from the head / flow calculation would not affect the calculation of the surge control setpoint in normalized units. In variable molecular weight applications the surge line is not fixed but moves with changes in the inlet molecular weight, temperature, specific heat ratio ‘k’ and compressibility. These parameters affect the Mach number inside the impeller / diffuser and hence the point at which the compressor will surge at any given speed. The antisurge controller model does not take into account this aerodynamic shift in the surge limit line.

ALTERNATE METHOD FOR MOLECULAR WEIGHT COMPENSATION

In this method a base or a “reference” performance map of pressure ratio vs volumetric flow is selected as a reference performance map for the purposes of surge control. The molecular weight, temperature and compressibility applicable for this performance map constitute the reference conditions. When inlet gas conditions of molecular weight, temperature and compressibility deviate from the reference conditions during compressor operation, the actual volumetric flow is corrected to the reference conditions. This corrected flow is then plotted on the reference performance map for the purposes of computing the distance from surge for antisurge control. The following method is used to correct flow to compressor map reference conditions as recommended by the ASME (American Society of Mechanical Engineers) PTC-10 Performance Test code for compressors :

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$$Q_{corrected} = \frac{Q_{actual}}{\sqrt{\dfrac{RTZ_{actual}}{RTZ_{reference}}}}$$

Actual is Flow conditions at compressor site.

Reference conditions are from Compressor Performance Maps

As an example Figure 5 shows the compressor performance maps for two different gases – one at a molecular weight of 14 and another at a molecular weight of 24.

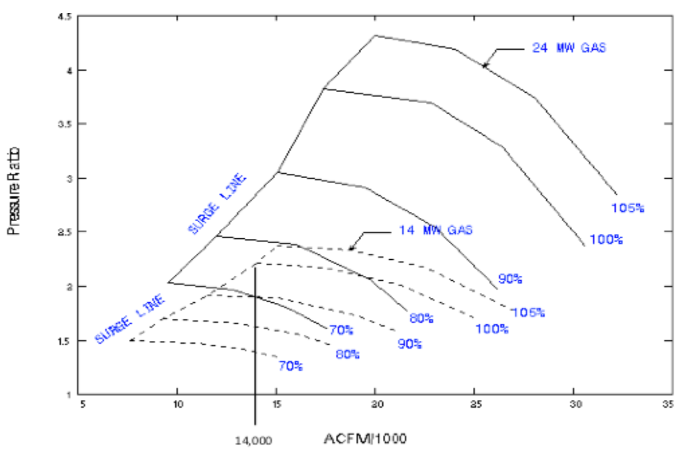

Figure 5: Performance maps shifts with MW variance

Figure 6 below shows that using the above formula for flow correction for the 14 MW gas, the performance map for the 14 MW gas shifts to the left and notably the surge lines for both molecular weights line up on top of each other allowing the use of a single surge line characterizer across the entire range of pressure ratios and molecular weight conditions, more specifically the entire range of inlet RTZ conditions.

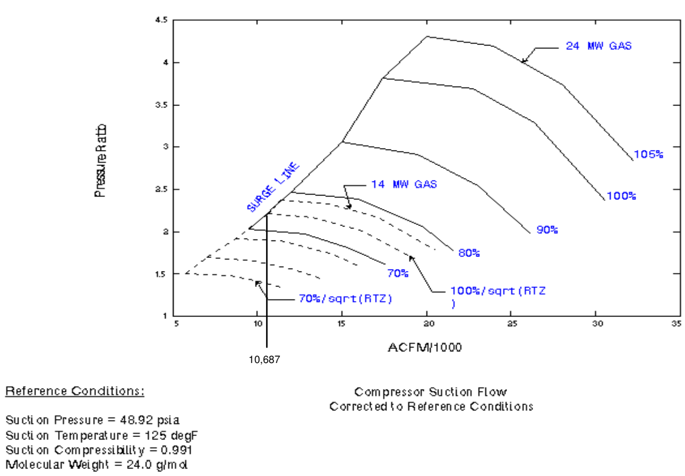

Figure 6: Performance map corrected to reference conditions

The equation for calculation of corrected flow now requires the values of RTZ at reference conditions that are known from the reference compressor performance map and values of flowing molecular weight and compressibility that are not easily measured by conventional instrumentation in realtime. In order to derive the corrected flow without directly measuring molecular weight and compressibility, the flowmeter equation for a differential head producing flowmeter is rewritten as follows:

$$\frac{Q_{act}}{\sqrt{R \cdot T \cdot Z_{act}}} = K_f \cdot \sqrt{\frac{h_f}{P_s}}$$

Multiplying both sides of the equation by $\sqrt{RTZ_{ref}}$

$$\frac{Q_{act}}{\dfrac{\sqrt{RTZ_{act}}}{\sqrt{RTZ_{ref}}}} = K_f\sqrt{RTZ_{ref}}\sqrt{\frac{h_f}{P_s}} \qquad (3)$$

Left side of the above equation is the expression for corrected flow to performance map reference conditions.

$$Q_{corrected} = K_f\sqrt{RTZ_{ref}}\sqrt{\frac{h_f}{P_s}} \qquad (4)$$

In the above equation, the only field measurements required to compute corrected flow are the suction pressure and the flowmeter differential pressure. Figure 7 shows the instrumentation setup for field measurements. By further measuring the discharge pressure we can calculate the pressure ratio and set up the reference performance map for antisurge control as shown in Figure 8. The corrected volumetric flow is calculated from equation (4) and plotted on the reference performance map for the operating pressure ratio. A surge control line characterizer is set up parallel to the surge line. The volumetric flow setpoint is interpolated from the surge control line characterizer for the operating pressure ratio. When the corrected volumetric flow drops below the volumetric flow setpoint on the reference performance map, the antisurge controller begins to open the antisurge valve.

The system described here provides accurate compensation for changes in inlet gas composition, temperature, pressure, compressibility and rotor speed across a wide range of molecular weights and operating pressures and temperatures.

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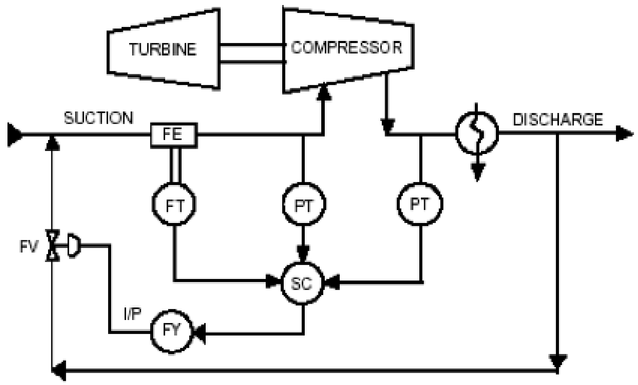

Figure 7: Field measurement setup for antisurge control

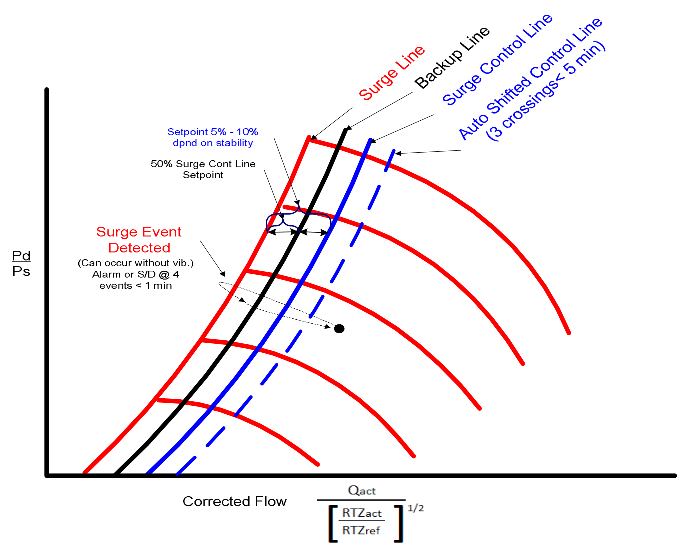

Figure 8: Setup of the Reference performance map for antisurge control.

The specific heat ratio 'k' can affect the accuracy of volumetric flow correction if there is a large difference in the 'k' value between the operating gas and the reference gas. However, the resultant error in volumetric flow correction has been found to be in the range of 1% or less. The surge control margin is generally in the neighborhood of 10%, so the marginal error in volumetric flow correction due to variation in 'k' becomes a non issue.

The equations for flow correction developed so far assume that the flow measuring element is located on the suction side of the compressor. In many compressor antisurge applications the flow measuring element is located on the discharge side of the compressor. In other antisurge applications like refrigeration compressors, flow measuring elements are often located in compressor sidestreams where the compressor section flow is the mixture of sidestream flow and previous stage flow. The flow correction equations for molecular weight compensation in such cases are different and are presented below.

Multistage compressors with sidestreams or with flow measuring element located at the discharge side.

Figure 9 shows a 3 stage refrigeration compressor. The first stage flow is measured by a suction flow measuring element, the 2nd stage sidestream flow is measured by the sidestream flow element and the 3rd stage flow is measured by a flow measuring element located at the final discharge side of the compressor. For the purposes of surge control, we need to calculate the corrected volumetric flow at the inlet of each stage.

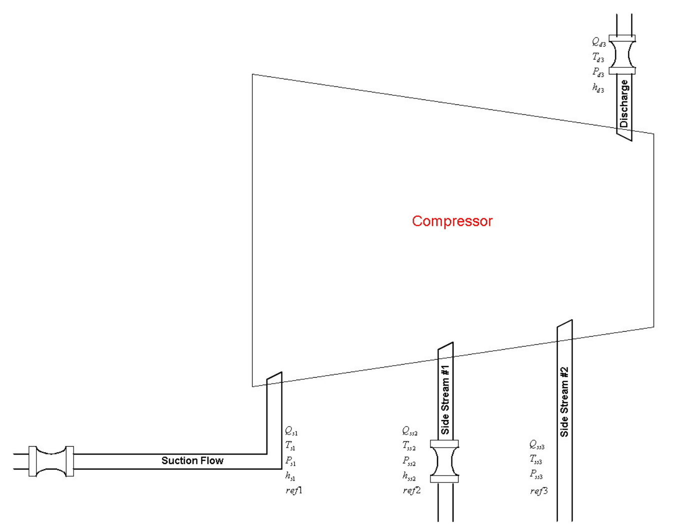

Figure 9. Flow element locations in a refrigeration compressor

1st Stage Corrected suction flow and pressure ratio calculation

The first stage corrected suction flow can be calculated by using equation (4), which in this case can be stated as follows:

$$Q_{s1\_corr} = K_{s1} \cdot \sqrt{R \cdot T \cdot Z_{ref1}} \cdot \sqrt{\frac{h_{s1}}{P_{s1}}} \qquad (5)$$

The only field measurement required at this stage is the suction flow measuring element differential pressure and the pressure of the suction stream to satisfy the above equation. All other parameters in the above equation can be calculated from the reference performance data for the compressor and flowmeter datasheets. The 1st stage discharge pressure used to calculate

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the 1st stage pressure ratio is given by

$$P_{d1} = P_{ss2}$$

The 1st stage pressure ratio is then given by $\frac{P_{ss2}}{P_{s1}}$.

2nd Stage Corrected suction flow and pressure ratio calculation with addition of sidestream

The 2nd stage suction flow is a combination of the incoming 1st stage flow and the side stream flow entering this stage. The only field measurement required at this stage is the sidestream flow element differential pressure and the gas pressure of the side stream.

The flow element equation for the 2nd stage side stream can be stated as follows:

$$\frac{Q_{ss2}}{\sqrt{R \cdot T \cdot Z_{ss2}}} = K_{ss2} \cdot \sqrt{\frac{h_{ss2}}{P_{ss2}}}$$

Dividing by RTZ at 2nd stage reference conditions

$$\frac{Q_{ss2}}{\sqrt{\frac{R \cdot T \cdot Z_{ss2}}{R \cdot T \cdot Z_{ref2}}}} = K_{ss2} \cdot \sqrt{R \cdot T \cdot Z_{ref2}} \cdot \sqrt{\frac{h_{ss2}}{P_{ss2}}}$$

$$Q_{ss2\_corr} = K_{ss2} \cdot \sqrt{R \cdot T \cdot Z_{ref2}} \cdot \sqrt{\frac{h_{ss2}}{P_{ss2}}} \qquad (6)$$

The suction flow for Stage 1 is given by the following flow element equation:

$$\frac{Q_{s1}}{\sqrt{R \cdot T \cdot Z_{s1}}} = K_{s1} \cdot \sqrt{\frac{h_{s1}}{P_{s1}}}$$

The discharge flow calculated from the polytropic law $PV^n = Const$ is given by

$$Q_{d1} = K_{s1} \cdot \sqrt{R \cdot T \cdot Z_{s1}} \cdot \sqrt{\frac{h_{s1}}{P_{s1}}} \cdot \left(\frac{P_{s1}}{P_{d1}}\right)^{\frac{1}{n_1}}$$

The 1st stage discharge flow corrected to 2nd stage reference conditions is given by

$$Q_{d1\_corr} = K_{s1} \cdot \sqrt{R \cdot T \cdot Z_{ref2}} \cdot \sqrt{\frac{R \cdot T \cdot Z_{s1}}{R \cdot T \cdot Z_{d1}}} \cdot \sqrt{\frac{h_{s1}}{P_{s1}}} \cdot \left(\frac{P_{s1}}{P_{d1}}\right)^{\frac{1}{n_1}}$$

Using the equation of state PV = MRTZ to substitute for RTZ terms

$$Q_{d1\_corr} = K_{s1} \cdot \sqrt{R \cdot T \cdot Z_{ref2}} \cdot \sqrt{\frac{P_{s1} \cdot Q_{s1}}{P_{d1} \cdot Q_{d1}}} \cdot \sqrt{\frac{h_{s1}}{P_{s1}}} \cdot \left(\frac{P_{s1}}{P_{d1}}\right)^{\frac{1}{n_1}}$$

Applying the the polytropic law $PV^n = const$ and substituting for $\frac{Q_{s1}}{Q_{d1}}$ we obtain the following equation.

$$Q_{d1\_corr} = K_{s1} \cdot \sqrt{R \cdot T \cdot Z_{ref2}} \cdot \sqrt{\frac{h_{s1}}{P_{s1}}} \cdot \left(\frac{P_{s1}}{P_{d1}}\right)^{\frac{n_1+1}{2 \cdot n_1}} \qquad (7)$$

The corrected 2nd stage suction flow is given by the following equation:

$$Q_{s2\_corr} = Q_{d1\_corr} + Q_{ss2\_corr}$$

Substituting from equations (6) and (7) and assuming that the polytropic exponent $n_1 = n_{ref1}$ for 1st stage and equating P_{d1} to P_{ss2} we get the final equation for calculating the corrected flow used in surge control for the 2nd stage as follows:

$$Q_{s2\_corr} = K_{s1} \cdot \sqrt{R \cdot T \cdot Z_{ref2}} \cdot \sqrt{\frac{h_{s1}}{P_{s1}}} \cdot \left(\frac{P_{s1}}{P_{ss2}}\right)^{\frac{n_{ref1}+1}{2 \cdot n_{ref1}}} + K_{ss2} \cdot \sqrt{R \cdot T \cdot Z_{ref2}} \cdot \sqrt{\frac{h_{ss2}}{P_{ss2}}}$$

All parameters in the above equation can be calculated from the reference performance data for the compressor, flowmeter datasheets and field measurements. The 2nd stage pressure ratio is then given by $\frac{P_{ss3}}{P_{ss2}}$.

3rd Stage Corrected suction flow and pressure ratio calculation – Flow element at the discharge side

The 3rd stage equations for calculating corrected suction flow and pressure ratio would be similar to the previous stage if the suction flow and suction pressure of the 3rd stage side stream is

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being measured. However, as is the case in this example if the 3rd stage is the final stage of the compressor and the discharge flow and pressure are being measured, the resulting equations can be derived as follows:

The flow element equation for the 3rd stage discharge flow can be stated as

$$\frac{Q_{d3}}{\sqrt{R \cdot T \cdot Z_{d3}}} = K_{d3} \cdot \sqrt{\frac{h_{d3}}{P_{d3}}}$$

The suction flow calculated from the polytropic law $PV^n = Const$ is given by

$$Q_{s3} = K_{d3} \cdot \sqrt{R \cdot T \cdot Z_{d3}} \cdot \sqrt{\frac{h_{d3}}{P_{d3}}} \cdot \left(\frac{P_{d3}}{P_{s3}}\right)^{\frac{1}{n_3}}$$

The suction flow corrected to 3rd stage reference conditions is given by

$$Q_{s3\_corr} = K_{d3} \cdot \sqrt{R \cdot T \cdot Z_{ref3}} \cdot \sqrt{\frac{R \cdot T \cdot Z_{d3}}{R \cdot T \cdot Z_{s3}}} \cdot \sqrt{\frac{h_{d3}}{P_{d3}}} \cdot \left(\frac{P_{d3}}{P_{s3}}\right)^{\frac{1}{n_3}}$$

Using equation of state PV = MRTZ to substitute for RTZ terms above

$$Q_{s3\_corr} = K_{d3} \cdot \sqrt{R \cdot T \cdot Z_{ref3}} \cdot \sqrt{\frac{P_{d3} \cdot Q_{d3}}{P_{s3} \cdot Q_{s3}}} \cdot \sqrt{\frac{h_{d3}}{P_{d3}}} \cdot \left(\frac{P_{d3}}{P_{s3}}\right)^{\frac{1}{n_3}}$$

Applying the polytropic law $PV^n = const$ and substituting for $\frac{Q_{d3}}{Q_{s3}}$ we obtain the following equation after simplification:

$$Q_{s3\_corr} = K_{d3} \cdot \sqrt{R \cdot T \cdot Z_{ref3}} \cdot \sqrt{\frac{h_{d3}}{P_{d3}}} \cdot \left(\frac{P_{d3}}{P_{s3}}\right)^{\frac{n_3 + 1}{2 \cdot n_3}}$$

Assuming that the polytropic exponent $n_3 = n_{ref3}$ for 3rd stage and equating P_{s3} to P_{ss3} we get the final equation for calculating the corrected suction flow used in surge control for the 3rd stage as follows:

$$Q_{s3\_corr} = K_{d3} \cdot \sqrt{R \cdot T \cdot Z_{ref3}} \cdot \sqrt{\frac{h_{d3}}{P_{d3}}} \cdot \left(\frac{P_{d3}}{P_{ss3}}\right)^{\frac{n_{ref3} + 1}{2 \cdot n_{ref3}}} \quad (8)$$

All parameters in the above equation can be calculated from the reference performance data for the compressor, flowmeter datasheets and field measurements. The 3rd stage pressure ratio is then given by $\frac{P_{d3}}{P_{ss3}}$.

ANTISURGE CONTROLLER OPERATION USING THE ALTERNATE METHOD

The operating point of the compressor or the process variable (PV) for an antisurge controller now becomes the corrected suction volumetric flow as computed by the equations derived above. The controller setpoint (SP) is the volumetric flow determined from the surge control line as shown in Figure 8, which is biased from the surge line in the reference compressor performance map. The amount of control line bias is often a function of the flatness of the performance curve at different molecular weights. At lower molecular weights the performance curves tend to get flatter close to surge and consequently the control line bias needs to be greater. The reverse is true for higher molecular weights. By positioning the surge control line in this manner, we ensure enough pressure rise to surge to allow for operating point movement around the surge control line and maintain process control stability.

Under Normal operating conditions

Under normal operating conditions, PI (Proportional & Integral) control is used to operate the compressor. The PI control loop is used to compare the control set point (SP) to the operating point of the compressor (PV) and provides an output to the antisurge valve to prevent flow from decreasing below the surge control line, which can be seen on the reference performance map in Figure 8. Under these conditions, surge control action is initiated at the control line by opening the antisurge valve. This prevents a further shift of the operating point to left towards the surge line

Under Abnormal operating conditions

In the case of rapid reductions in flow, such as process upsets, or large downward shifts in the molecular weight of the gas that can result in quick drops in the value of the corrected suction volumetric flow, three additional controls are implemented to prevent surge from occurring. The first control is a backup line, which is located between the control line and the surge line on the reference performance map. In the event that the operating point reaches this backup line, the antisurge

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controller's open loop step logic quickly forces the surge valve open to increase forward flow through the compressor.

The second control takes effect if the operating point of the compressor reaches the backup line a certain number of times within a specified period of time. When this occurs, the control setpoint is shifted to the right via the antisurge controller's set point shift logic. The corrected flow setpoint continues to be shifted until the cause of instability can be corrected. This action establishes a larger margin of safety from the surge line.

The third control is a variable proportional gain action that takes effect when normal PI control response is unable to prevent the corrected flow from dropping below the control line during rapid system upsets. To prevent surge under these circumstances, the antisurge controller preemptively opens the antisurge valve partially before the operating point reaches the surge control line. When the upset has been stabilized, normal PI control is resumed.

CONCLUSIONS

The key to maximizing compressor operating efficiency is to determine the surge line with a high degree of accuracy under varying molecular weight and process conditions in realtime operation. In doing so, the workable limits of the compressor can be clearly defined and unnecessary recirculation of flow and the resulting wasted energy can be kept to an absolute minimum. While the commonly used method of antisurge control using reduced head and reduced flow achieves this objective at lower pressure ratios, the errors of RTZ compensation in this method are quite significant at higher pressure ratios and result in unnecessary gas recirculation. The alternate method of antisurge control using corrected flow as the surge control variable has provided accurate RTZ compensation at all pressure ratios and gas molecular weight ranges.

NOMENCLATURE

h = Pressure differential across flow measuring device (typically orifice or venturi)
H_P = Polytropic head (feet, or meter)
k = Ratio of specific heats Cp and Cv of the gas
K = Flowmeter constant
MW = Molecular weight of the gas
n = Polytropic exponent
P = Pressure, (absolute)
Ru = Universal gas constant, 1545.3 ft lbf/(lbmol.*^{o}R) for English units, or 8.3143 J/(mol.*^{o}K) for SI units)
R = Gas constant, Ru/MW.
T = Temperature, (absolute)
Q = Volumetric flow rate, actual cubic feet per minute, (acfm, or m^3/hr)
R_C = Compression Ratio across the compressor (or compressor stage)
Z = Compressibility
σ = Polytropic factor ((n-1)/n)

Subscripts

act = actual operating condition
actual = actual operating condition
_corr = Corrected to Reference map conditions
corrected = Corrected to Reference map conditions
s = Suction
d = Discharge
f = Flowmeter
ref = Reference map conditions
reference = Reference map conditions
ss = Sidestream
1 = 1st Stage
2 = 2nd Stage
3 = 3rd Stage

Acronyms

FPSO = Floating Production Storage and Offloading
FE = Flow Element
FV = Flow Control Valve (Antisurge valve)
FY = Flow control signal
FT = Flow transmitter
LNG = Liquefied Natural Gas
OEM = Original Equipment Manufacturer
PI = Proportionl and Integral
PT = Pressure transmitter
PV = Process Variable
SC = Surge controller
SP = Set Point
SLL = Surge Limit Line

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