UNDER THE INFLUENCE

Massimiliano Di Febo and Paganini Pasquale, IPC, Italy, discuss the influence of inlet parameters on centrifugal compressor surge limit lines.

Actual centrifugal compressors anti surge protection systems are based on the surge limit line (SSL). SSL is the description of the surge points locus and, in current practice, is assumed to be invariant with centrifugal compressor inlet conditions. The main purpose of this article is to present the results of a numerical study aimed to investigate the effect of variations of centrifugal compressors inlet conditions on the surge limit line. The results presented will provide quantitative evaluation on how the surge line changes as a consequence of variations of the gas mixture composition and thermodynamic suction conditions (temperature and pressure).

After a preliminary introduction on the actual surge protection systems and SLL, the investigation method will be presented and results of two case studies will be provided. Case study results will show the effect of inlet conditions variation on the surge line at high and low operating pressures.

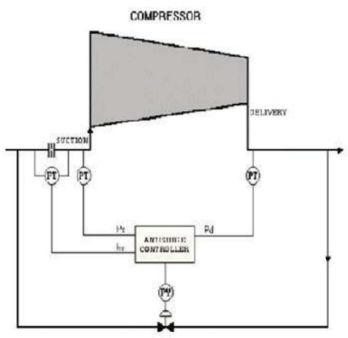

Figure 1. A typical plant layout where there is a recirculation line that includes an anti surge valve.

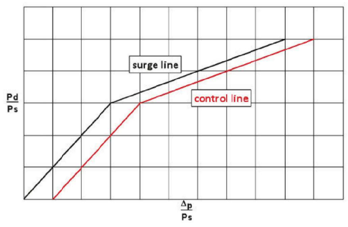

Figure 2. An example of a surge limit line (SLL) and a surge control line (SCL) that is usually calculated with a 10% flow safety margin.

This article will additionally provide some considerations about the effect that variations of compressed gas inlet conditions may cause on actual anti surge system protection effectiveness. Actual anti surge systems application validity range will then be discussed, and relevant considerations will be supported by numerical data.

All numerical evaluations reported have been developed using the most recent thermodynamic theories and machine aero mechanical models. Calculation algorithms used are able to predict both machine behaviour and thermodynamic real gas properties under different operative conditions.

All calculations in this study have been executed using a dedicated software tool (Cmap), developed at IPC research lab. Cmap has been designed to predict easily and quickly centrifugal compressors performance under different inlet conditions and with variable hydrocarbons gas mixtures composition.

Notes on compressor surge

Surge is a well known instability phenomenon that consists of a rapid oscillation of the mass flow elaborated by the compressor, accompanied by a characteristic noise and high vibrations.

During the surge, the flow is suddenly reverted from discharge to suction. This reverse flow through the compressor causes high mechanical stresses on the machine internal components. The surge is an abnormal operative condition, which can have a destructive nature, and could cause, when the machine remains in this condition without adequate protections, damages or failures of the compressor.

Actual protection methods have been designed with the intention to run the compressor safely far from surge points. Today, the 'state of the art' for anti surge systems provides a protection action consisting in opening, partially or totally, a special control valve (anti surge valve) located on a line that recycles the gas from the discharge to the compressor suction. In this way the control system reduces the overall line resistance and increases the elaborated flow, moving the compressor operative point to the right of the characteristic curve corresponding to the actual operative speed.

Figure 1 shows a typical plant layout where there is a recirculation line that includes a recycle control valve (anti surge valve). The anti surge valve is commanded by a dedicated proportional integral derivative (PID) controller, usually embedded in the protection system programmable logic controller (PLC). The surge protection logic embeds the SLL and the correlated surge control line (SCL).

Figure 2 shows an example of SLL and the SCL that usually is calculated with a 10% flow safety margin from the SLL. Using field readings, the protection logic calculates the actual operative compression ratio β and uses the stored SCL data to determine the corresponding actual flow limit parameter. This value is then used as set point for the anti surge valve PID controller. The process variable is instead the actual flow parameter, also obtained from the field readings.

From the above description, it is evident how actual surge protection systems rely completely on the concept of the SLL. This is basically the central element of the actual systems protection action.

At this point, it is important to recall that the SLL concept is based on some main hypothesis. In fact the SLL is a simplified correlation between the compression ratio β and the flow parameter that identifies the surge points. This simplified correlation is derived by applying:

- The hydraulic affinity laws (fan laws).

$$H_p = K_1 Q^2 \qquad \text{Equation 1}$$

- The expression of polytrophic head for perfect gas.

$$H_p = \frac{n}{n-1} z_1 R T_1 \left[\beta^{\frac{n-1}{n}} - 1 \right] \qquad \text{Equation 2}$$

- The expression of the volumetric flow rate trough the suction flow meter.

$$Q = K_0 \sqrt{\frac{\Delta p}{\rho_1}} \qquad \text{Equation 3}$$

Table 1. Case 1 low pressure suction condition

Operative conditions	p1, bar a	T1, °C	M, g/mole	Gas mix, %
DC	67.5	38.5	16.04	Mix design
ODC 1	67.5	38.5	19.24	Mix 1
ODC 2	67.5	38.5	23.79	Mix 2
ODC 3	83.0	38.5	16.04	Mix design
ODC 4	67.5	23.0	16.04	Mix design
ODC 5	83.0	23.0	23.79	Mix 2

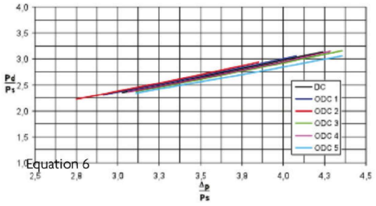

Figure 3. Surge limit lines obtained with different inlet conditions for compressor working with low pressure suction condition.

- The real gas state equilibrium.

$$\rho_1 = \frac{p_1}{z_1 R T_1} \qquad \text{Equation 4}$$

- Using the above hypothesis and introducing a simplifying approximation (conservative for the protection purposes).

$$\frac{n}{n-1}\left(\beta^{\frac{n-1}{n}} - 1\right) \cong \beta - 1 \qquad \text{Equation 5}$$

- It is possible to obtain the SLL final expression as correlation between the flow parameter $\frac{\Delta p}{p_1}$ and the compression ratio β:

$$\frac{\Delta p}{p_1} = K \cdot (\beta - 1)$$

This expression of the SSL seems to be invariant with gas inlet conditions (hence it is some time called 'universal surge line'), and being simple it gives the possibility to be easily implemented on process computers. This was a great advantage in the early stages of anti surge applications (the 1960s), when engineers were looking for a simple surge locus formulation, to be implemented with the very modest calculation capability available at that time. For this reason, it has been largely used in the past and is still used today on actual surge protection systems. But it has also some limitations, in fact recalling the base hypothesis it is possible to argue that:

- The H_p - Q flow curve depends from gas suction condition.
- The affinity law is valid for liquid flow, and can be considered applicable to gas for low compressibility flows i.e. low Mach flows.
- Also when applicable the affinity law is valid in a small range around a reference point and cannot be used to describe the overall range of the compressor surge point without violating the considered hypothesis applicability limits.
- Also the Equation 5 is valid for low β, even if it introduces conservative errors.

These considerations show how the SSL depends on inlet suction conditions. This is much more evident in compressible flow conditions. The first point and the Affinity laws appear to be the main hypothesis. These can be considered applicable for single stage compressors operating at low Mach numbers. For multistage compressors and for compressors running at higher Mach numbers it should be considered a surge locus different from the one obtained, extending the fan law validity on all surge points; also the real surge locus will depend on the real behaviour of the gas in the actual gas inlet condition i.e. inlet pressure, inlet temperature and inlet gas mix composition.

Numerical investigation calculation method

The purpose of the numerical investigation is to check the effect of variation of inlet parameters on the surge line and in particular check if the surge line remains constant or if it changes. Input data for the analysis are the compressor performance map in design conditions and the relevant inlet gas condition (gas mixture composition, inlet pressure and temperature).

Based on these inputs the calculation method proceeds with the following main steps:

- Availability of compressor design conditions performance map.
- Derivation of the surge line $\beta - \frac{\Delta p}{p_1}$.
- Calculation of compressor off design performance map.
- Analytical determination of the surge points for each operative speed.
- Derivation of the numerically evaluated surge line.
- Check between the surge line initial (point 2) and numerically evaluated (point 5).

The starting point is the availability of compressor performance map in design condition. From this map the surge locus is derived. The equation to calculate the surge points is:

$$\frac{\partial\left(\frac{P_d}{P_s}\right)}{\partial \overline{V}} = 0 \qquad (1)$$

Where:

Pd = Discharge pressure
Ps = Suction pressure
$\overline{V}$ = Volume flow

Table 2. Case 1: Low pressure suction condition

Comparison	Δp%	ΔT, °C	ΔM%	Pd/Ps	Error%
DC - ODC 1	0	0	+20	2.5 - 3.5	-1.1
DC - ODC 2	0	0	+48	2.5 - 3.5	-2.6
DC - ODC 3	23	0	0	2.5 - 3.5	+1.7
DC - ODC 4	0	-15.5	0	2.5 - 3.5	+0.9
DC - ODC 5	23	-15.5	+48	2.5	+4.0
				3.5	+7.0

Table 3. Case 2: High pressure suction condition

Operative conditions	p1, bar a	T1, °C	M, g/mole	Gas mix
DC	267.5	60	16.04	Mix design
ODC 1	267.5	60	19.24	Mix 1
ODC 2	267.5	60	23.79	Mix 2
ODC 3	285.0	60	16.04	Mix design
ODC 4	267.5	45	16.04	Mix design
ODC 5	285.0	45	23.79	Mix 2

Table 4. Case 2: High pressure suction condition

Comparison	Δp%	ΔT, °C	ΔM%	Pd/Ps	Error%
DC - ODC 1	0	0	+20	1.5	5.5
				2.7	6.8
DC - ODC 2	0	0	+48	1.5	16.2
				2.7	18.6
DC - ODC 3	+6.5	0	0	1.5	1.5
				2.7	2.1
DC - ODC 4	0	-15.0	0	1.5	3.4
				2.7	4.1
DC - ODC 5	+6.5	-15.0	+48	1.5	27.6
				2.7	31.2

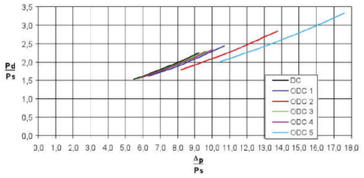

Figure 4. Surge limit lines obtained with different inlet conditions for compressor working with high pressure suction condition.

With the off design inlet conditions, the new compressor performance map is calculated. This step is developed using the Cmap software. Cmap allows the user to develop integrated aeromechanical and thermodynamic calculation useful to predict compressor performances in off design conditions. The software algorithm is characterised be the capability to consider the compressed gas mix as real gas. All mixture properties are then derived using the equation of state. In this analysis the Lee Kesler equation of state has been used. Also very important are the calculations for each performance point of the gas mixture compressibility and real gas polytrophic exponents. The availability of these accurate thermodynamic properties as a function of the gas mixture composition and inlet and outlet pressure and temperatures allows the software to run with higher precision the aeromechanical routines that provides final results for compressor performances. These calculations are not based on affinity law or other approximation, calculations are based on the availability of a non-dimensional model of the compressor based on correlations of work coefficient, flow coefficient parameterised by the mach number. Cmap software produced output performance maps are then analysed to find the surge points with the criteria (1) for several operative speed. This numerical process allows one to obtain the numerically evaluated surge line.

The surge line is then calculated from compressor performance map with reference to inlet off design conditions.

The two obtained surge lines (DC and ODC) are then drawn on a plan having as x axes the ratio between Δp across the orifice and the suction pressure (Ps) and as y axes the compression ratio (Pd/Ps).

The error between the design and off design universal surge lines is then calculated with reference to the compressor inlet volume flow: on equal compression ratio, it is calculated the percentage error between $\frac{\Delta p}{P_s}$ in case off design condition with respect to design condition.

Case studies

In the following section two real cases will be presented:

- Case 1 (C1): Compressor working with low pressure suction condition.
- Case 2 (C2): Compressor working with high pressure suction condition.

In each one of these cases two different compressor running conditions have been considered:

- Design condition (DC).
- Off design condition (ODC).

For the ODC many sub cases have been investigated with different inlet pressures, temperature and gas mix composition.

The following cases were then studied:

- C1-DC: Case 1, design condition.
- C1-ODC: Case 1, off design condition.
- C2-DC: Case 2, design condition.
- C2-ODC: Case 2, off design condition.

For both cases this study will show how the limit surge line changes when inlet conditions move from design values to off design values.

Case study 1

In this case study a centrifugal compressor is running in different inlet conditions.

Starting from the DC condition the surge line has been calculated changing respectively molecular weight (ODC 1 and ODC 2), pressure (ODC 3), temperature (ODC 4) and both properties (ODC 5). Figure 3 shows the surge limit lines obtained with different inlet conditions.

Table 2 compares the design conditions versus the off design conditions. In this table it can be noted that for the off design conditions considered (obtained varying separately the pressure, temperature or the molecular weight), the maximum error calculated is 2.6 %. If the variation on the inlet conditions is applied simultaneous on pressure, temperature and mix, the maximum error calculated is 7% (with compression ratio of 3.5).