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.

BENEFICIAL REUSE

What is Beneficial Reuse?

"Beneficial reuse" is defined by the EPA as reusing a material in a manner that makes it a valuable commodity. Spent caustics are generally byproducts of a refinery or chemical process that would ordinarily be treated as wastes. When beneficially reused without reclamation, the spent caustics are exempt from the solid waste definition and are categorized as a product (or valuable commodity) under the EPA regulations.

Value as a Merichem Customer

Merichem's beneficial reuse of spent caustic, without reclamation, is more environmentally friendly than disposing of the material as a waste. As such, these materials are no longer a part of your waste generation statistics.



MERICHEM COMPANY 70th ANNIVERSARY 1945-2015

5455 Old Spanish Trail Houston, Texas 77023 | 713.428.5000 | www.merichem.com

BENEFICIAL REUSE

SPENT CAUSTIC • NON-WASTE • MERICHEM

At Merichem, we bring more than 50 years of experience in the handling of caustic effluent streams to the petroleum refining and petrochemical industries. Our technical expertise allows us to recommend the right caustic treating needs for your specific processes and, if needed, handle most resulting caustic solutions.

Our beneficial reuse of caustic streams helps our customers achieve ***waste minimization*** goals and eliminates labor intensive waste handling protocols such as manifesting, waste record keeping, etc. Your spent caustic is used as a substitute for other commercially available products or as a feedstock in our, or other customer, production processes. In either case, Merichem will utilize your spent materials in a non-waste, environmentally responsible, manner.

Merichem's advanced logistics system allows us to transport caustic solutions to our chemical plants and terminals in a safe, efficient and cost effective manner. Additionally, our adherence to the American Chemistry Council's **Responsible Care®** program ensures compliance to the highest industry standards.

It's true! Merichem is the partner of choice for **non-waste utilization** of your secondary materials.



Non-waste Utilization of Your Secondary Materials

www.merichem.com/Beneficial-Reuse

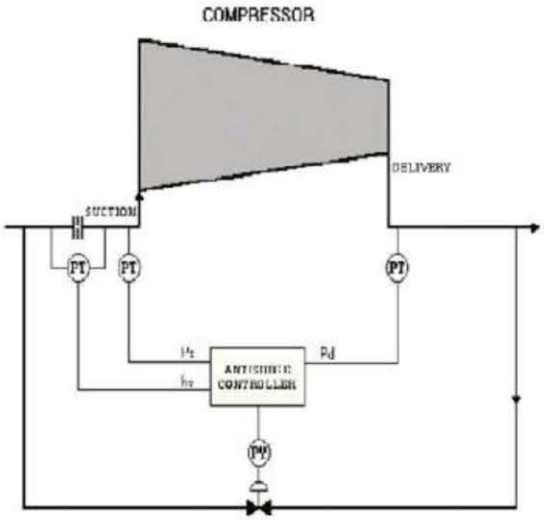


Figure 1. A typical plant layout where there is a recirculation line that includes an anti surge valve.

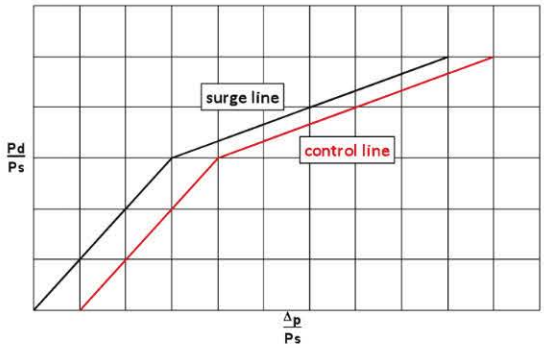


Figure 2. An example of a surge limit line (SLL) and a surge control line (SCL) that is usually calculated with a 10% flow safety margin.

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.

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

JACOBS®

Comprimo® Sulfur Solutions



Gas Treating & Sulfur Technology

With more than 500 units built during the last 40 years, we are a global leader in the gas treating and sulfur recovery technology





Total Project Solutions

We are one of the world's largest and most diverse providers of professional technical services. Our global network includes more than 200 offices in more than 25 countries

From our gas treating & sulfur technology centers of expertise in Leiden, The Netherlands and Calgary, Canada, we provide engineering, procurement and construction services to our clients around the world



Visit our webpage to learn more about all our products >

www.jacobscomprimo.com

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

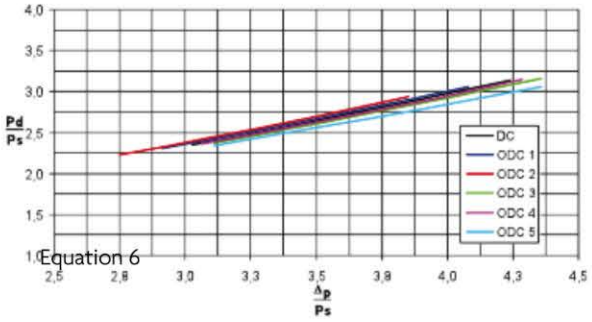


Figure 3. Surge limit lines obtained with different inlet conditions for compressor working with low pressure suction condition.

- 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:

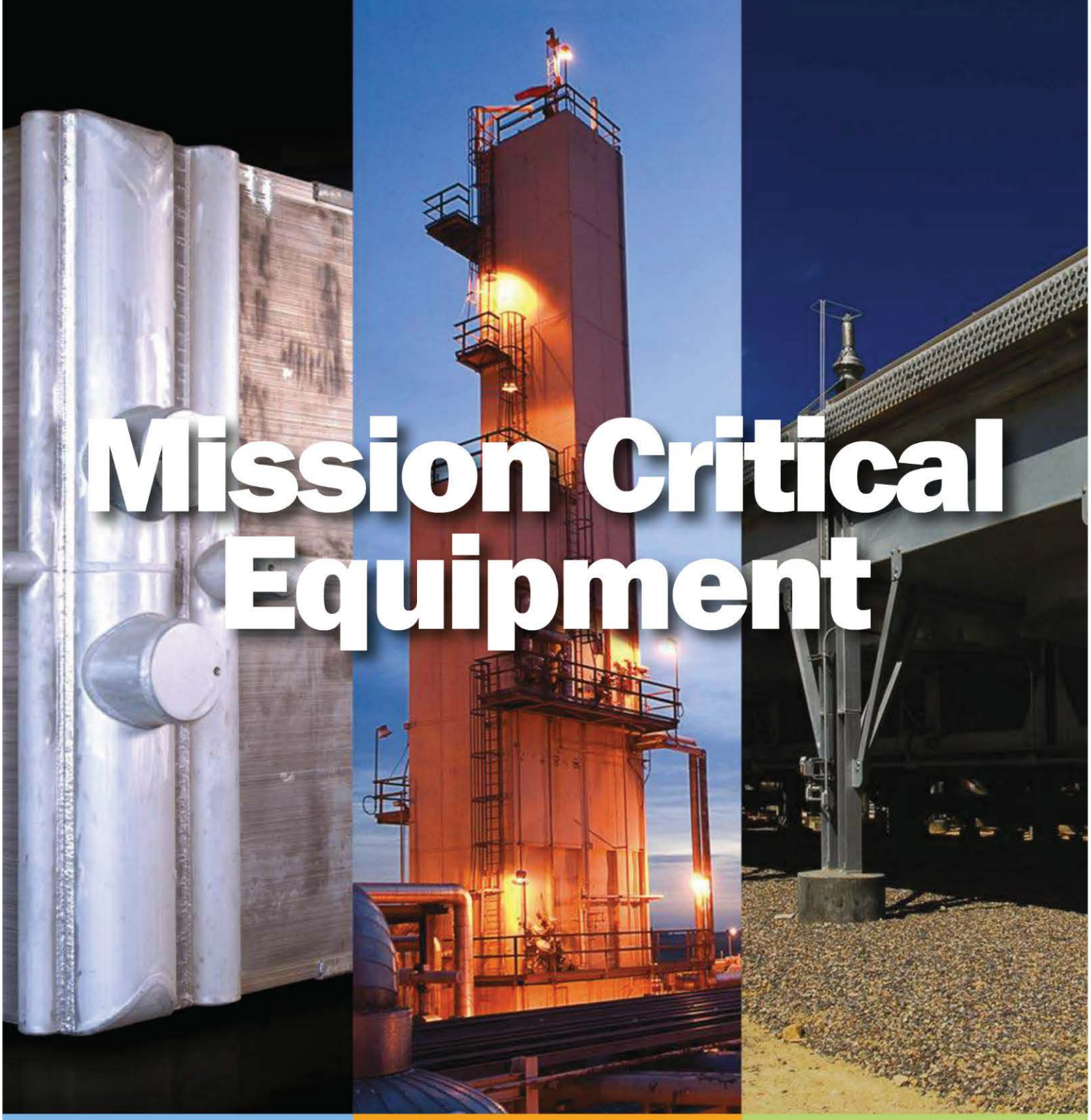
- Availability of compressor design conditions performance map.
- Derivation of the surge line $\beta - \frac{\Delta p}{p_1}$.
- Calculation of compressor off design performance map.
- Analytical determination of the surge points for each operative speed.
- Derivation of the numerically evaluated surge 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:

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

Where:
Pd = Discharge pressure
Ps = Suction pressure
$\dot{V}$ = Volume flow

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



Mission Critical Equipment

Brazed Aluminum Heat Exchangers

Cold Box Assemblies

Air Cooled Heat Exchangers

Chart is at the heart of gas processing

Nitrogen rejection, NGL recovery, natural gas liquefaction and helium recovery all require custom equipment engineered and built by Chart.

CHART®

Innovation. Experience. Performance.®

chartindustries.com

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

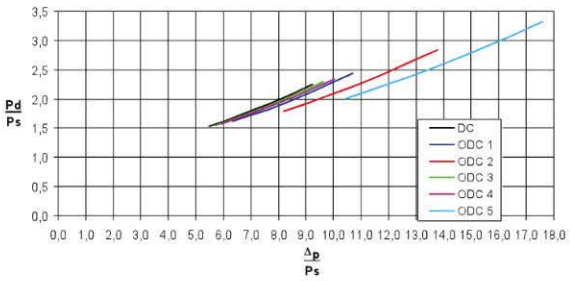


Figure 4. Surge limit lines obtained with different inlet conditions for compressor working with high pressure suction condition.

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 $\frac{\Delta p}{Ps}$ 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).

Devco

Sulfur Forming and
Handling Experts

devcousa.com



Lowest Capital Cost

Proven Marketability

Lowest Operation, Utility
and Maintenance Cost

Highest Operational
Reliability

Safety is Vital

Smallest Footprint

HOUSTONINTERESTS

PROCESS PLANT SERVICES

Devco Process Heaters

Devco

RIVER CONSULTING

S & R Technical Services

Case study 2

Also in this case study a centrifugal compressor 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 4 shows the surge limit lines obtained with different inlet conditions.

Table 4 compares the DC versus the ODC. 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 18.6 %. If the variation on the inlet conditions is applied simultaneously on pressure, temperature and mix, the maximum error calculated is 31.2% (with compression ratio of the 2.7). It is interesting to note that the correct surge flow line moves to the right with respect to the initial (design) surge line. This fact implies that the control system is underestimating the surge flow, and that the compressor could be potentially exposed to surge events.

Conclusion

The analysis developed indicates that, in a low pressure compressor, if the inlet conditions change it does not cause the problem of the surge but a reduction of the operating efficiency.

Instead, in a high pressure compressor, in varying the inlet condition the errors calculated (more than 30 %) are greater than the safety margin (usually 10 %).

Analysis proposed and described in this article can allow for affirmation that the actual centrifugal compressors protection systems based on simplified hypothesis such as the ideal gas law, validity of hydraulic affinity laws are valid only in a certain range of application. For a high pressure compressor it varies the inlet condition the errors calculated are greater than safety margin. Consequently, the protection become inefficient and potentially can cause damage to the compressor.

The software developed by IPC allows one to predict the performances of a centrifugal compressor under varying thermodynamic conditions of inlet gas. The prediction of compressor performances is accurate even at high pressures, where the ideal gas theory commonly used introduces considerable errors and implements advanced protection from surge, overcoming limits of the current technology.

References

1. *LEE, B.I., KESLER, M.G., 'A generalized thermodynamic correlation based on three-parameter corresponding states', AiChE Journal 1975, 21 (3), 510 - 527.*
2. *PLOCKER, U., KNAPP, H., PRAUSNITZ, J., 'Calculation of high-pressure vapor-liquid equilibria from a corresponding-states correlation with emphasis on asymmetric mixtures', Ind. Eng. Chem. Process Des. Dev. 1978, 17 (3), 324 - 322.*
3. *LEE & KESLER, AIChE Journal (Vol 21 No 3).*
4. *KOUREMENOS & ANTENOPOULOS, 'Isentropic Exponents of Real Gases and Application for the Air at Temperatures From 150 K to 450 K'.*
5. *MARIC, Flow Measurement and Instrumentation, 16(2005).*
6. *LÜDTKE, K.H., Process Centrifugal Compressors.*
7. *CENGEL & BOLES, 'Thermodynamics An Engineering Approach'.*
8. *DI FEBO, PAGANINI, PEDONE, ESPOSITO, 'Prediction of centrifugal compressor performance and application for test, surge protection and machinery diagnostic' (2012).*

