Reciprocating Compressor Design Optimization

(to minimize cost and maximize efficiency, reliability, flexibility, and safety)

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Abstract

Three of the common design objectives for pipeline and midstream compressor owners are to minimize capital costs, maximize unit flexibility, and have the most efficient and reliable compressor possible. All these objectives are in conflict. Thus, achieving a well balanced design involves careful thought and new design methodologies and tools as current practices make it difficult to achieve a well balanced design.

A new System Performance Model^{TM} (SPM^{TM}) approach to reciprocating compressor and piping system design has been proven to be the most effective way to:

- Quickly compare alternatives by evaluating efficiency, performance, pressure drop, safety, capacity control and other key factors;
- Verify the selected design will meet the requirements over the full operating envelope; and
- Embed an accurate performance model into the control system to enable operations to improve the efficiency and reliability of the unit.

The SPM is an effective new approach for reciprocating compressor optimization. A number of examples are used to demonstrate how this optimization technique can save the owner millions of dollars in incremental throughput and reliability.

Introduction:

Beta Machinery Analysis (BETA) and ACI Services, Inc. (ACI) have collaborated over the past four years to help owners, EPCs, and packagers improve the design of reciprocating compressor packages. As a result of this research and development, BETA and ACI have developed a unique approach to optimize the design of reciprocating compressors for pipeline and midstream applications. Included in this initiative is the use of a System Performance Model (SPM) approach.

This is a condensed version of the technical paper presented at the Gas Machinery Conference in Atlanta, GA (Oct., 2009). For a full version of the paper, please visit www.BetaMachinery.com.

The paper outlines the key features to consider when optimizing a reciprocating compressor. Examples are provided based on actual projects, including a recent compressor station for Piedmont Natural Gas. The authors want to acknowledge, and thank, Adam Long of Piedmont for his contribution to this paper.

Optimization Goals

There are many documented cases where overall performance and design of a reciprocating compressor system falls short of the anticipated result. To the casual observer, it would seem these issues should be easily solved. Unfortunately, that is not the case.

Current practices make it difficult to optimize the compressor package design. Historically, no individual or team is evaluating the entire layout to assess improvement opportunities. In addition, until now, the industry has lacked proper modeling tools to accurately and efficiently evaluate the performance of the overall system, identify the best way to optimize the layout, and quantify financial benefits. As a result, many current designs can suffer from excessive pressure drop, limited flexibility when operating across a wide range, and uncertainty that the final design will meet the intended specification. Often the proposed design is not the best overall solution possible.

Figure 1: There is a Compelling Business Case for Compressor Design Optimization

Based on our survey of pipeline owners, we understand their ideal goals would include:

- Higher flow and efficiency;
- Better operating flexibility across the entire range of operating conditions;
- Reduced pressure drop through the piping system;
- Safe operation;
- Accurate predictions of power, forces, rod load limits, pin reversal, temperatures, emissions, and other parameters for all conditions, load steps and speeds; and
- Improved control of the compressor, including performance map for the SCADA system

Optimization is Hampered by Two Issues

To achieve the above design goals, an accurate performance model is required. Unfortunately, the standard performance models available in industry do not address this requirement for two reasons:

i). *Performance is predicted at the cylinder flange* (flange to flange as illustrated in Figure 2.a below). A generic assumption is then made about pressure drop through the piping, coolers, pulsation bottles, and other vessels. These assumptions lead to a wide margin of error. A better approach is to have accurate performance predictions from the inlet to outlet of the station (Fence to Fence).

"Flange to Flange" Performance
The standard approach used in OEM performance programs for initial sizing of compressor cylinders.

"Fence to Fence" Performance
An optimized design should include the analysis of the complete compressor piping system from fence to fence including piping, vessels, bottles, etc.

Figure 2.a: Standard Performance Programs Provide Accurate Results Based on Pressures at the Compressor Flanges
Figure 2.b: A System Performance Model includes effects of the piping system (from Fence to Fence).

ii). *Performance is assessed at a limited number of conditions*. These design points generally do not represent the breadth of operation and may result in some design compromises. If the entire range of operating conditions is included, the design team can evaluate different reciprocating compressor designs.

For example, a number of recent projects were designed based on only five operating conditions. This led to inefficient operation in other important areas of the operating envelope.

A System Performance Model

Accurately calculating performance and efficiency requires an understanding of total pressure drop through the piping system including inlet filters, pulsation bottles, coolers, and piping. Total pressure drop is the sum of static and dynamic pressure drop. Dynamic pressure drop is the result of non-linear dynamic flow phenomena in the piping. These non-linear effects are then included in the performance model, which gives a much more accurate picture of the efficiency, power, fuel requirements, rod load limits, temperatures, emissions, and other parameters. This entire database is part of the System Performance Model (SPM) approach.

The SPM overcomes the two limitations described above. First, it is more comprehensive than a standard performance program, because it includes the effects of the entire piping system (from Fence to Fence as shown in Figure 2.b). Second, it includes the entire operating envelope (Figure 5 below) rather than a few discrete points.

One benefit of the SPM is that it summarizes pressure drop in different regions of the system (Figure 3). This allows the team to highlight regions where high losses occur and evaluate alternative designs to economically reduce these losses.

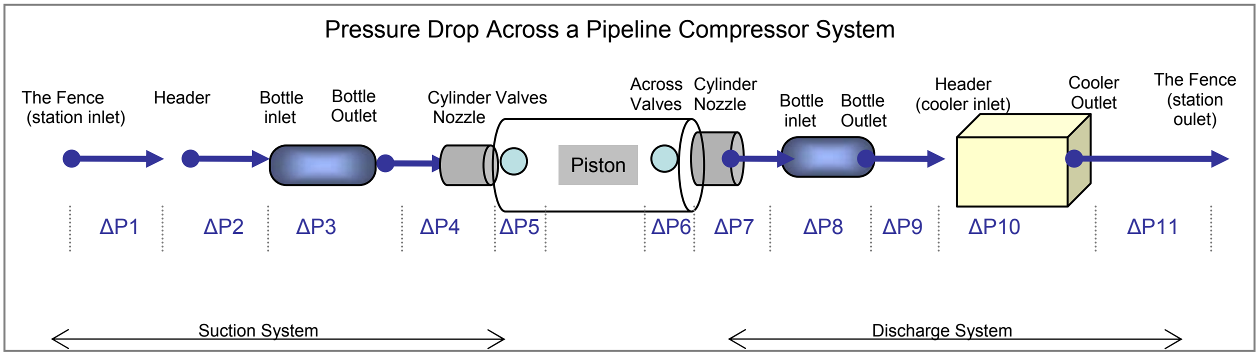


Figure 3: SPM Calculates Pressure Drop Locations at Different Locations in the Compressor System

Table 1 illustrates the pressure drop at these different locations and the percentage of the total losses for an existing pipeline compressor. In this example, the suction and discharge bottles represent a large component of the pressure drop. Modifying the system to reduce these losses can generate significant returns for the owner.

Evaluating performance from “fence to fence” using the SPM program provides a number of advantages:

- Includes accurate pressure drop estimates through piping, vessels, bottles, coolers, etc. (Note total pressure drop includes static plus dynamic effects.);
- Provides accurate flow, power, emissions, etc.;
- Verifies the design will meet the required performance specification;
- Identifies areas of excessive losses; and
- Allows comprehensive comparison of alternative designs.

To ensure adequate operating flexibility, the compressor design must accommodate the entire operating envelope. Running the SPM program across this envelope generates a powerful understanding of the overall system (Figure 5). To provide sufficient resolution, the SPM can include more than 500 different points, plus speed variation. With this mesh size, the team can now view the full map and understand trade-offs in the design.

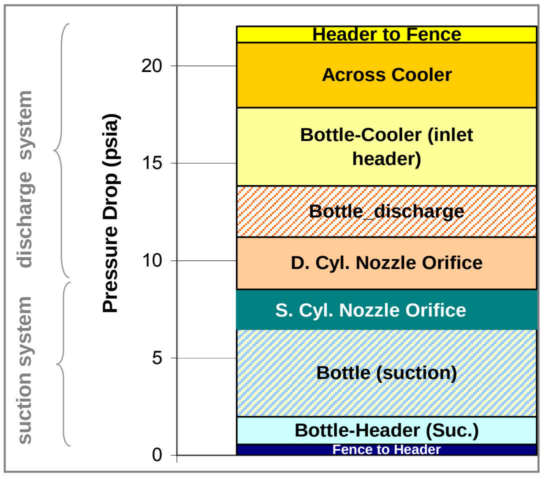


Figure 4: SPM Calculates Pressure Drop Locations at Different Locations in the Compressor System

Presure Drop Location	**Pressure Drop**	
Suction System	**(psia)**	**% of total**
S. Cyl. Nozzle Orifice	2.03	9.2%
Bottle (suction)	**4.51**	**20.5%**
Bottle-Header (Suc.)	1.42	6.4%
Fence to Header	0.56	2.5%
Total Suction	8.52	38.7%
Discharge Sysem		
D. Cyl. Nozzle Orifice	2.69	12.2%
Bottle_discharge	**2.63**	***11.9%***
Bottle-Cooler (inlet header)	4.01	18.2%
Across Cooler	3.35	15.2%
Header to Fence	0.83	3.8%
Total Discharge	13.51	61.3%
Total (psia)	**22.03**	**100.0%**

Table 1: Summary of System Pressure Drop (Fence to Fence)

Assessing the entire operating map is critical for owners to:

- Identify the optimal capacity control design;
- Pinpoint areas of unsafe operation;
- Optimize the pulsation control solution; and
- Check the performance in key locations.

Once the design is finalized the SPM operating map can be imported directly into the control system. This provides a much higher level of control, enabling operators to run the machine more efficiently.

To provide sufficient resolution, it is common for the SPM to include 500 conditions for the operating map. For each condition, the speed is evaluated at 50 speed increments, resulting in a total of 25,500 points.

Until recently, it was impossible to economically and efficiently assess the compressor over this many conditions. The recent development of the SPM program now makes this level of analysis (fence to fence performance, across the entire envelope) feasible.

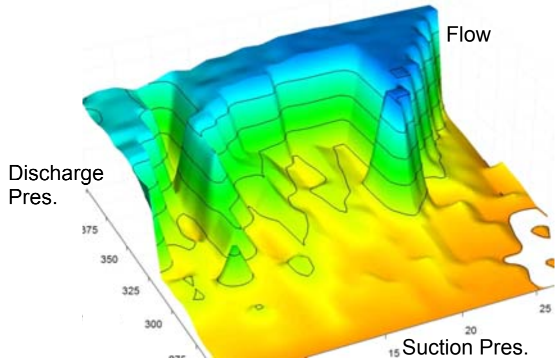


Figure 5: Assess Performance Across the Entire Operating Map

Six Examples of Evaluating Reciprocating Compressor Design Using the SPM Database

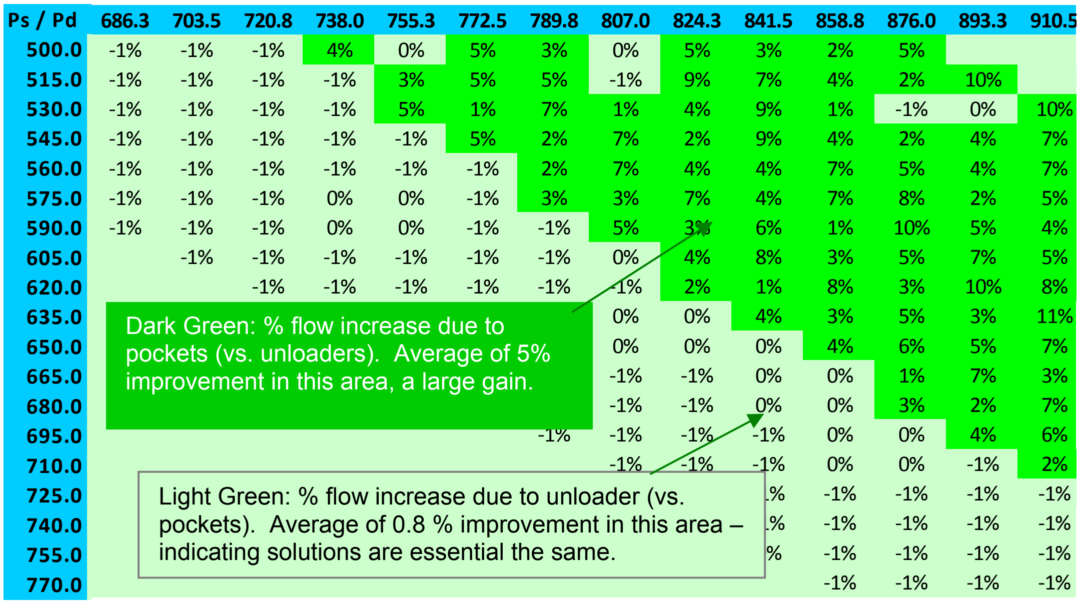
There are many specific ways that optimization will generate improved compressor designs. Using an actual situation, this paper includes six applications using the results from the SPM database.

(1) Optimized Capacity Control Strategy

One of the early steps in the design process is to define the capacity control strategy. Until now, it has been difficult to evaluate different unloading options and the impact on performance, efficiency, rod loads, and operating flexibility.

As often happens, the operating pressures for this station ended up substantially different from what was initially anticipated. Alternate loading scenarios for the existing (and future) units were investigated to address the rod load concerns and to look at optimizing loading over the wider range of operating conditions.

In this example, one solution to improve compressor loading is to replace the finger type valve unloaders (currently on four of six cylinders) with fixed volume pockets on all six cylinders. The SPM database is used to compare the calculated compressor capacity (flow) for the operating map. In Figure 6, the darker green areas are when the pockets-only option provides more flow. On average the darker green area has **5% more flow** (and up to 10% in some areas). The lighter green areas with data reflect areas where the unloaders-only option provides more flow (average of **0.8% improvement** over pockets).



Ps / Pd	686.3	703.5	720.8	738.0	755.3	772.5	789.8	807.0	824.3	841.5	858.8	876.0	893.3	910.5
500.0	-1%	-1%	-1%	4%	0%	5%	3%	0%	5%	3%	2%	5%		
515.0	-1%	-1%	-1%	-1%	3%	5%	5%	-1%	9%	7%	4%	2%	10%	
530.0	-1%	-1%	-1%	-1%	5%	1%	7%	1%	4%	9%	1%	-1%	0%	10%
545.0	-1%	-1%	-1%	-1%	-1%	5%	2%	7%	2%	9%	4%	2%	4%	7%
560.0	-1%	-1%	-1%	-1%	-1%	-1%	2%	7%	4%	4%	7%	5%	4%	7%
575.0	-1%	-1%	-1%	0%	0%	-1%	3%	3%	7%	4%	7%	8%	2%	5%
590.0	-1%	-1%	-1%	0%	0%	-1%	-1%	5%	3%	6%	1%	10%	5%	4%
605.0		-1%	-1%	-1%	-1%	-1%	-1%	0%	4%	8%	3%	5%	7%	5%
620.0			-1%	-1%	-1%	-1%	-1%	-1%	2%	1%	8%	3%	10%	8%
635.0								0%	0%	4%	3%	5%	3%	11%
650.0								0%	0%	0%	4%	6%	5%	7%
665.0								-1%	-1%	0%	0%	1%	7%	3%
680.0								-1%	-1%	0%	0%	3%	2%	7%
695.0							-1%	-1%	-1%	-1%	0%	0%	4%	6%
710.0								-1%	-1%	-1%	0%	0%	-1%	2%
725.0										%	-1%	-1%	-1%	-1%
740.0										%	-1%	-1%	-1%	-1%
755.0										%	-1%	-1%	-1%	-1%
770.0											-1%	-1%	-1%	-1%

Dark Green: % flow increase due to pockets (vs. unloaders). Average of 5% improvement in this area, a large gain.

Light Green: % flow increase due to unloader (vs. pockets). Average of 0.8 % improvement in this area – indicating solutions are essential the same.

Figure 6: Difference in Maximum Flow: Finger-type Unloaders (light green) vs. Fixed Volume Pockets (dark green).

Over the complete operating map, the pockets yield about a **2% increase** in flow compared to finger unloaders. In summary, the pockets allow the unit to be run efficiently across the entire map, with considerable performance gains as the station moves to the high discharge pressure condition.

There are times when each arrangement has an advantage over the other. However, across the entire operating map used in this study, the pocket-only proposal yields the best long term results.

(2) Optimized Pulsation Control
This existing pipeline compressor had a pulsation study performed based on a limited number of conditions. The pulsation bottle design was focused on minimizing pulsation forces in the bottles and minimizing pulsations leaving the bottles. The static pressure drop from the bottle internals was calculated to be 15% over the API 618 guideline for the highest pressure drop conditions.

The SPM was run on the existing (base) situation using a non-linear Time Domain pulsation algorithm.

Changes in the compressor capacity control from finger-type unloaders to pocket unloaders tend to reduce the pulsation energy generated by the compressor cylinders. This reduction in pulsation energy means that the pulsation bottle design can be relaxed.

The team investigated minor modifications to the pulsation filter (baffles and choke tube) while maintaining the existing pulsation bottle size. This modification can be easily installed in the existing installation.

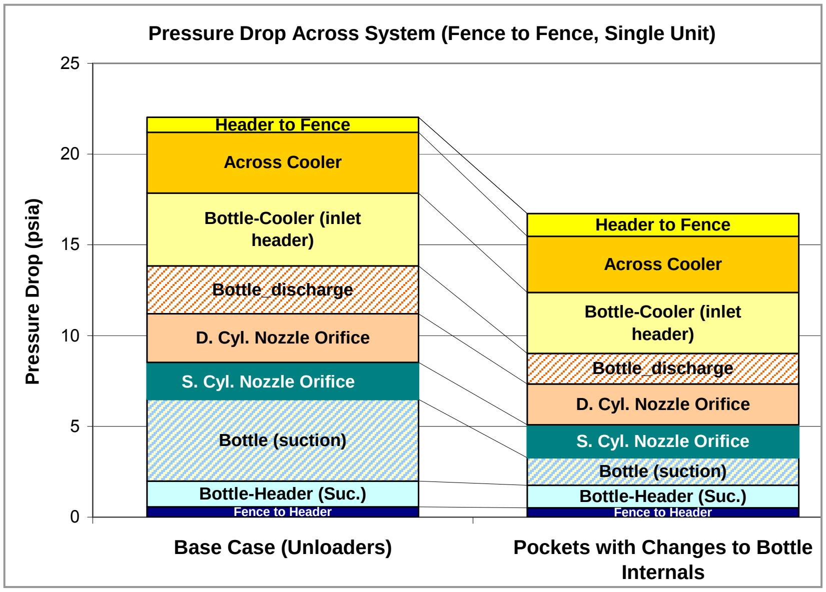


Figure 7: SPM Comparison of Existing Units (Base Case), and With Minor Adjustments to Pulsation Bottles and Pocket Unloaders.
Over 20% Reduction in Pressure Drop was Achieved.

The SPM was run and identified significant improvements in reducing total pressure drop while still maintaining acceptable control of pressure pulsations and shaking forces. It was determined that the suction and discharge bottle pressure drop could be reduced by 66% and 37% respectively. This relatively simple change in the bottle internal results in an overall reduction in the system total pressure drop of 20% (Figure 7).

(3) Incremental Flow and Net Profit
Following the above example, the minor changes to the bottle internals were modeled using the SPM approach. For discussion purposes the financial evaluation focused on a few discrete operating points including:

- Condition 1: Low compression ratio (1.16)
- Condition 2: High compression ratio (1.52)
- Condition 3: Higher Suction/Discharge pressures

A comparison was made of the calculated flow for the base case, or existing system (Case A), and the modified case, (Case B), which includes the pockets and new pulsation bottle internals). As shown in Figure 8.a and 8.b, there is no incremental benefit to Condition 1, but for the other conditions, there is a significant increase in flow varying between 8.5% and 11.5%.

Note: The SPM database can be used to evaluate other changes to the system. The pressure drop in the discharge piping and through the cooler was identified as significant and as a potential area for further investigation. It is also possible to determine alternative pulsation bottle designs and pulsation control devices which may result in further improvements in flow.

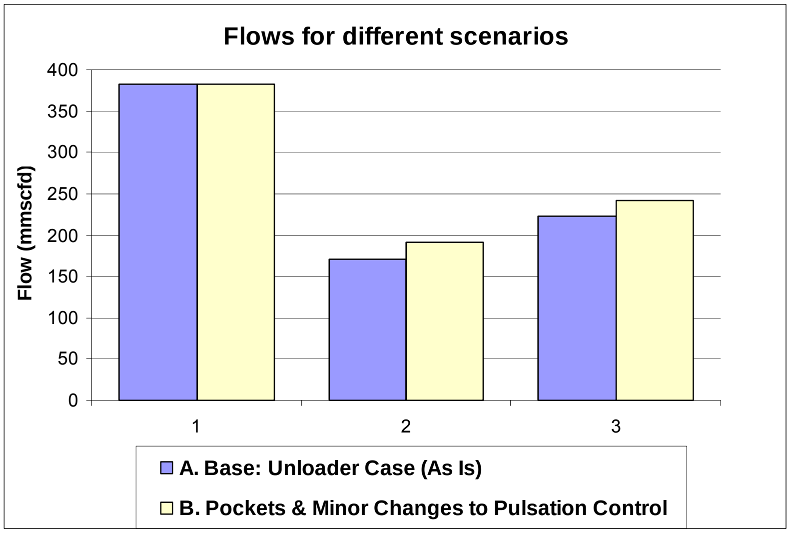


Figure 8.a: Flow Comparison of Base Case (A) and Modified Case (B) over 3 common conditions

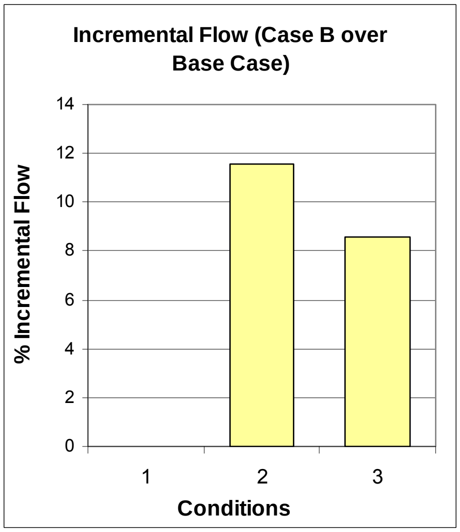


Figure 8.b: Incremental Flow (Case B vs. Base Case A in %)

The Net Profit financial metric [3] is an effective way to compare different design alternatives, based on the following:

- Gross Profit = Flow X Transportation Value
- Net Profit = Gross Profit – Expenses (maintenance and fuel costs)

For each of the three conditions evaluated, the financial analysis examines the INCREMENTAL net profit ($/year). The key assumptions include:

- A range of transportation fees were evaluated. The chart in Figure 9 illustrates the financial metrics for two prices: $0.06 and $0.18 per Dekatherm.
- $5.00/MMscf is applied for fuel gas cost.

When the unit is operating at points similar to conditions 2 and 3, the owner can realize over 1.1 million dollars per year.

The changes resulted in increased flows when evaluated over the entire map (average across all conditions). A common metric is Q/HP-hr to evaluate the improved capacity. The average increase was 2% for the minor changes in pulsation internals and modified control scheme. Additional improvements are available in different areas of the system.

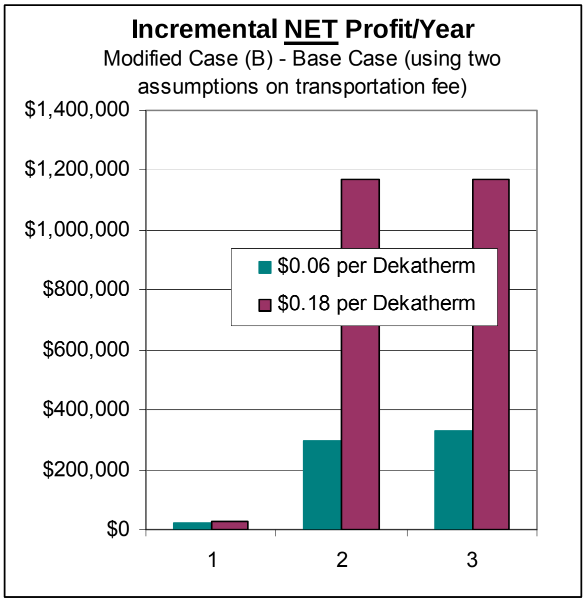


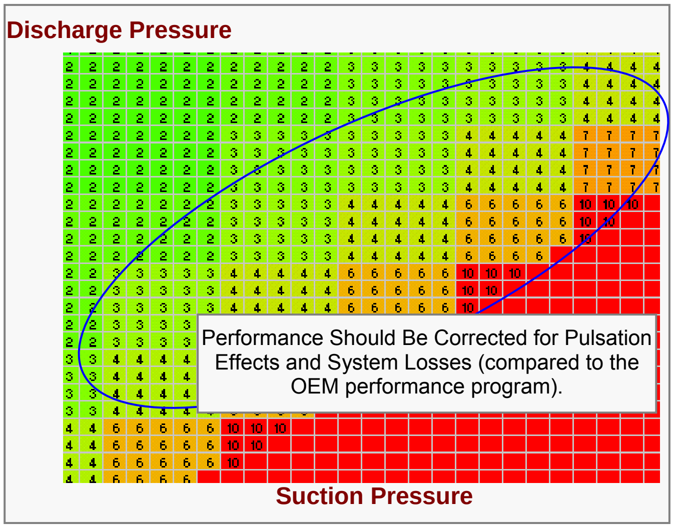
Figure 9: Incremental Net Profit/Year (Case B)

(4) Pulsation Effects Can Result in up to 10% Adjustments to OEM Performance Program

The SPM program identifies the required correction to the OEM performance program to account for system effects. This correction is due to predicted static and dynamic pressure drop through all components of the system (at each operating condition). The accurate pressure drop information is necessary to update the performance calculations. Also, pressure pulsations at the compressor valves impact the compressor performance. This effect can be quantified by the pulsation model.

Figure 10 illustrates the differences in the compressor performance for the full operating map when the pulsation effects are included. This example chart shows the percent (%) change in power or load. In many conditions, the adjustment is minor at 0% - 2%; however, other conditions show a more significant change in the order of 3% - 10%.

As a minimum, this more accurate compressor performance analysis can be used to make adjustments to the PLC control system so the compressor operation can be better controlled. A more powerful use for this information is to compare the compressor performance for different station or compressor package configurations. Higher capital costs for some designs may be justified given the improvements in compressor performance that could be realized.



Performance Should Be Corrected for Pulsation Effects and System Losses (compared to the OEM performance program).

Figure 10: Percent (%) Adjustments to OEM Performance Program to Account for Pulsation Effects

(5) Safety Map Improves Reliability

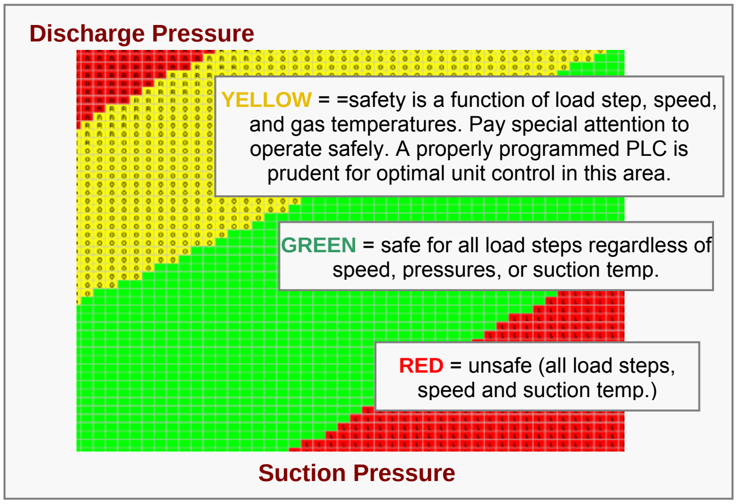
Another set of data that helps when comparing alternative solutions is a **Full Map Safety Check**. In this plot, "safe" means reliable compressor operation such as adequate rod load, allowable discharge temperatures, within pin reversal limits, and within volumetric efficiency limits. Excessive pulsation forces can also be included in the safety map.

This safety map (Figure 11) can be generated by the SPM database.

Green areas are safe for all load steps regardless of speed, pressures, or suction gas temperatures.

Red areas are unsafe for all load steps at any speed and any suction temperature.

Yellow areas identify areas where unit safety is a function of load step, speed, and gas temperatures requiring special attention to the control to operate safely. Thus, when maps show a lot of yellow area, then a properly programmed PLC is prudent for optimal unit control.



YELLOW = =safety is a function of load step, speed, and gas temperatures. Pay special attention to operate safely. A properly programmed PLC is prudent for optimal unit control in this area.

GREEN = safe for all load steps regardless of speed, pressures, or suction temp.

RED = unsafe (all load steps, speed and suction temp.)

Figure 11: SPM database used to generate Safety Map

(6) Compressor Control

Very often, the compressor's performance characteristics (for the entire operating envelope) must be imported into a PLC or compressor control system. A fully automated compressor with an accurate SPM database enables the unit to run more efficiently and generate higher throughput (e.g., reducing fuel, compressing more gas, lowering emissions and total carbon footprint, reducing wasted energy, avoiding areas of high rod load, etc.).

Conclusion

There are many challenges associated with optimizing the reciprocating compressor design. Various owners interviewed on this subject agreed that they would like to see improvements with the operation of their compressors.

Based on the authors' experience, the following suggestions have proven to be effective at optimizing the compressor design:

- Early in the design process, the engineering team utilizes a System Performance Model (SPM) to assess different capacity control schemes, pulsation solutions, cooler designs, and other factors that influence the system performance (e.g. fence to fence performance).
- Problems occur when only a few operating points are evaluated. It is recommended that the performance and operating factors are evaluated over the entire operating envelope. This allows the owner to ensure the system will meet the intended requirements.
- The SPM allows the team to quickly compare different design alternatives and implement an optimized design, before the package is tendered for fabrication. This optimization helps avoid costly changes or re-work later in the fabrication stage.
- Address the conflicting design goals and balance the need for lowest capital cost with operating flexibility and system efficiency.

There are significant benefits using this optimized design approach:

- Ability to operate across a much wider operating envelope.
- Improved flow in the key conditions (mid to higher discharge pressure) and equivalent efficiency in other conditions.
- Improved pulsation control (lower forces, less losses).
- More accurate control of PLC system.
- Significant financial improvement, often with relatively minor changes.

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