BETA
Machinery Analysis

THE BETA BULLETIN

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Reciprocating Compressors: Maximizing Productivity through Economic Analysis

Reciprocating compressors are key production assets in many organizations. Compressor performance has a direct impact on the financial bottom line. Maximizing production of reciprocating compressors requires optimum performance attributes including capacity, efficiency and energy consumption.

And "you can't improve what you don't measure".

So it is important to measure performance characteristics and deviations from normal or optimum behavior. Even better, these measures should be expressed in economic terms. Then we will have information for making production and maintenance decisions based on sound economic considerations.

Economic Analysis

Typical predictive maintenance ... short of ... condition and ... in economic terms. Consequently these programs have failed to deliver the benefits promised.

Operations, maintenance and engineering decisions should be driven by ROI (return on investment) considerations. Standard behavior has been driven by technological considerations - the valve is leaking, so we should replace it. A better approach is to assess the cost of replacing it now versus at some future time.

We will discuss four possible economic measures:

- recirculating gas
- excessive valve and passage losses
- pulsation
- deviation in fuel consumption

Note that the economic measures discussed here do not include any lost production cost and can be, therefore, very conservative.

Cost of Recirculating Gas

Gas recirculation refers to leakage and slippage past compressor valves and rings. Analysis of a compressor pressure-volume curve yields the following information:

- flow balance which is the ratio of measured suction capacity (Q_s) to discharge capacity (Q_d); ideally, this ratio is 1.0 for a healthy compressor cylinder.
- brake horsepower (BHP)
- capacity (MMSCFD)
- cost of producing one HP per day ($/BHP/day) from fuel metering information or baseline fuel curves
- volume of recirculating flow derived from deviation in flow balance

The daily cost of recirculating gas is calculated from the cost required to develop one horsepower per day:

$$\text{Cost of recirculated Gas}\left(\$/_{day}\right)$$

$$\text{recir gas (MMSCFD)}\ \frac{\text{BHP}}{\text{MMSCFD}}\ \text{fuel cost}\left(\$/_{\text{BHP - day}}\right)$$

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                ECONOMIC CONDITION REPORT

                  PIPELINE COMPANY LTD
Location :KANSAS
Unit Mfr :CLARK                                  Model  :TCVC-16
Unit name:624                                    Date   :22-Jul-93

Load Step     :  0
Percent Load  :  95.12 %

UNIT COSTS
Fuel Cost                                   2437.51 $/day
Total BHP                                   7560.65 BHP
Cost of Each BHP                                .32 $/BHP-day

ENGINE COSTS
Actual Fuel Consumption                     7293.56 BTU/BHP-Hr
Predicted Fuel Consumption                  6798.01 BTU/BHP-Hr
Deviation From Predicted                     495.55 BTU/BHP-Hr
Cost of Deviation                            165.61 $/day
                                            5040.89 $/month
                                           60490.70 $/year

COMPRESSOR COSTS
                                              Estimated
                                              Cost of Loss
Valve & Passage Losses      541.39 BHP        174.54 $/day
Pulsation                      .00 BHP           .00 $/day
Gas Recirculation             3.42 MMSCFD      17.33 $/day

Total Cost                                    191.87 $/day
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Figure 1: An economic performance report indicates the cost of losses and inefficiencies on a daily, monthly or yearly basis.

Cost of Valve & Passage Losses

The pressure-volume curve is used to determine the horsepower consumed by valve and passage losses.

We can determine the cost of valve and passage losses from:

- pressure-volume curves
- measured suction and discharge nozzle traces
- horsepower from measured curves
- cost of one HP per day ($/BHP/day) from fuel metering information or baseline fuel curves

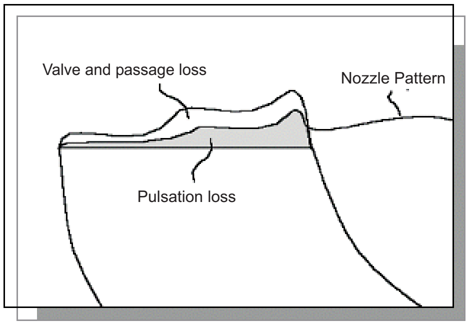

Figure 2: If pressure is measured at the nozzle in addition to the cylinder ends, the total system losses are resolved into valve and passage losses and losses due to pulsation.

Cost of Pulsation

Pulsation in suction and discharge passages tends to increase the horsepower required to move a given amount of gas - sometimes by a lot. To quantify the effect we need the same data as for valve and passage losses. When the pulsation horsepower losses are known, we can multiply by the cost of developing one horsepower to determine the cost of the loss.

Compressor losses

Suction and discharge losses represent a significant portion of the total power consumed. Losses through valves can be substantial, but there is a trade-off between valve efficiency and durability. Generally, the more efficient a valve is, the less durable it will be.

How losses are determined

We need to measure pressure in the suction nozzle just prior to the gas entering the cylinder and in the discharge nozzle just after the gas leaves the cylinder. Then we can quantify the pulsation and valve and passage losses.

If we combine these "nozzle traces" with the P-V curve as in Figure 2:

- the area between the nozzle trace and a straight line from the terminal pressure is the loss due to pulsation.
- the area between the nozzle trace and the PV curve is the valve and passage loss.
- the area between the P-V curve and a straight line from the toe pressure is the total loss.

Figure 3 shows an example where there is a significant pulsation loss on the discharge side, but very low losses on the suction side.

True valve losses can only be measured by collecting a pressure trace on a tapped valve cap which is then overlaid on the cylinder pressure-volume curve.

If neither nozzle traces nor valve cap traces are measured, we can only quantify the total of pulsation plus valve and passage losses.

Losses can be evaluated either in horsepower units or as percentage of total horsepower. Using a percentage of horsepower provides a quick method of evaluating potentially excessive losses. As a rule of thumb, we look for ways of reducing valve losses that exceed 5% per corner (10% per end) by either adjusting or changing valves to improve dynamics or reducing pulsation.

Summary of performance loss causes and effects

Behaviour	What happens	Net effect
Suction valve leaks	trapped gas leaks back to suction instead of being delivered to the discharge increase suction gas temperature as hot compressed gas leaks from the cylinder into the suction passage	loss of capacity progressive HP reduction
Discharge valve leaks	compressed gas is lost back into the cylinder instead of being discharged increases gas temperature	loss of capacity progressive HP reduction
Packing leaks	trapped gas flows through the packing and is lost instead of being delivered to the discharge passage less gas is being delivered to the discharge line only affects the crank end of a double-acting compressor	reduces capacity
Piston ring leak	capacity loss due to compressed gas leaking from one compressor end to the other instead of being delivered to the discharge line partially compressed gas leaking past the piston increases temperatures and reduces the gas density usually increases suction volumetric efficiencies (calculated capacity increases)	loss of capacity progressive decrease in HP
Valve and passage restrictions	suction terminal pressure reduced discharge terminal pressure increased suction and discharge pumping work increased temperature increases due to non-reversibility	decreases capacity increases HP
Late valve closure	volume and mass of residual gas increases mass of gas compressed decreases reverse flow causes slamming of plates	capacity decreases horsepower decreases reduced valve life
Valve flutter/multiple openings	tends to increase average pressure drop final closure before the dead center position reduces the amount of gas drawn into/discharged from the cylinder	little performance effect reduced valve life
Delayed valve opening	large pressure differential required to initiate opening increases P-V area and work done	increases HP
Pulsation	usually lowers suction pressures and raises discharge line pressures causes valves to fully or partially close when they should be open affects terminal pressures. They may be higher or lower than normal. This will increase or decrease the mass of gas trapped and hence compressor capacity	usually increases HP can increase static pressure drop significantly can reduce valve life
Heat transfer in the suction passage	suction gas temperature increases as it flows through the suction passage reduces mass of gas to be compressed	decreases compressor capacity no change in compressor power reduces efficiency
Pressure drops external to cylinder	pulsation control devices, orifices and choke tubes, impose pressure drops dynamic effects increase static pressure drop	increased horsepower decreased capacity

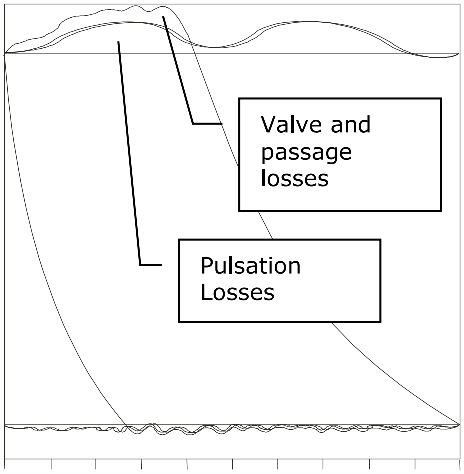

Figure 3: Example showing large discharge losses and small suction losses

Cost of Deviation in Fuel Consumption

To determine the cost of excess fuel consumption, we must have a reliable baseline curve of BSFC vs. torque. The cost of fuel consumption is determined from the deviation in actual BSFC from baseline BSFC.

The analysis determines:
- % torque (from compressor calculations)
- measured BSFC from fuel metering information
- difference between measured BSFC and baseline BSFC

We can then calculate the cost of the difference in BSFC from the fuel cost.

Causes and effects of losses

The actual power required to compress gas is always somewhat larger than theoretical. The main power loss is due to pressure drops as the gas flows through choke tubes, orifices, suction passages, suction valves, discharge valves, and discharge passages.

Valve losses cause the cylinder pressure to drop below the suction toe (suction line) pressure during the suction stroke and the cylinder pressure to rise above the discharge toe pressure during the discharge stroke.

Heat transferred to or from the gas also reduces compression efficiency and requires extra power.

Compressor losses that affect horsepower and/or capacity are:
- valve and passage restrictions
- piston ring leakage
- packing leakage
- discharge valve leakage
- suction valve leakage
- pulsation
- heat transfer in the suction passage
- heat transfer in the cylinder

Summary

In conclusion, optimizing performance for maximum production is essential. In this article we have addressed the challenge of maximizing the economic performance of compressors. Predictive maintenance programs and machinery analysis techniques generally play a vital role:
- current mechanical condition can be determined non-intrusively, since most common faults can be detected
- deviations in performance, and the cost thereof, can be measured
- conditions leading to premature failure can be detected

Economic analysis provides a basis for operations and maintenance practices that will deliver:
- maximum availability
- maximum sustainable throughput rate
- lowest operations and maintenance cost pe*r unit of throughput*

Compressor Valve Dynamics

Valves have a very large influence on performance and reliability. They are the heart of the compressor. Improving the performance of the compressor valve should be a goal of any optimization program. To achieve this goal, the compressor valve should be the ideal type and design for the application.

Valve life depends significantly on the velocity of the valve plate as it hits the back guard and valve seat when opening and closing. Excessive spring load causes valve plate flutter which results in efficiency loss and premature valve plate breakage. Inadequate spring load can result in the valve plate slamming against the seat and can cause late closure. Valve failures can result from foreign matter in the gas, liquids, pulsation, and corrosion. Valve failures can cause further internal damage to the compressor.

Optimizing valve design

Many different variables affect valve design; some of the most important variables are:
- gas density
- capacity (flow velocity)
- driver speed
- cylinder size

These and other factors determine the size of the valves, how many valves are used, materials selected and type of valve used.

Minimize losses

A primary design goal is to minimize losses through the valves. Flow areas in the guard and seats are designed to give the least restriction to the gas flow possible. Generally the more flow area the valve has, the less resistance to flow the valve will have.

Reducing gas turbulence in the flow area is another way to decrease the resistance. To minimize turbulence, the gas passages in the valve seat are bevelled. The shape of the valve elements can also help in reducing gas turbulence. Pyramid or moon shaped rings or the bullet shape of the poppet are used for this purpose.

Most of the energy lost in the gas flow occurs in the expansion process as the gas leaves the guard. Valves should be designed with guard passages that are larger at the exit areas than at the entrance area and with rounded exits.

Increasing valve durability

A second desired characteristic is high durability. The operating conditions that a valve must endure are severe. The valve material must be durable enough to take the beating. Valve bodies must be structurally sound while providing generous entrance and exit areas and allowing space for the moving elements.

Minimize clearance

Another design consideration is added clearance volume. High clearance in the valves will add to the total fixed clearance in the cylinder. Any increase in clearance decreases capacity.

Optimize valve for the application

Once the main characteristics of the valve are set, the designer then fine tunes the design to achieve highest reliability while delivering as much capacity as possible. There is a trade off between reliability and efficiency.

High reliability equates to lower efficiency; high efficiency equates to lower reliability.

Four factors that are critical to achieving the optimum performance are:

- plate lift
- gas velocity through the valve
- pressure drop across the valve
- spring tension

Pressure drop and gas velocity through the valve are influenced by the free lift area in the valve. The variable that can change the free lift area most readily is the plate lift. Increasing or decreasing the plate lift increases or decreases the free lift area and affects velocity and pressures losses accordingly.

The maximum allowable gas velocity through a valve is determined by the density of the process gas.

The following table illustrates the relationship between seven variables.

Lift	Velocity	Delta P	Reliability	Efficiency	Impact	Hp Loss

High lift can lead to high plate impact velocity, resulting in high stress and causing premature failure of the valve plates.

Spring tension has a some effect on reliability and efficiency. A function of springs is to slow the valve elements during opening, reducing slamming on the valve guard. It would appear that the stronger the spring the more cushioning provided and the more protection to the elements. However, there is a trade off. The gas has to expend energy to open the valve and keep it opened against spring tension. The stronger the spring the more energy is required, which increases the pressure loss across the valve. Excessively stiff springs can also contribute to valve flutter.

On the other hand, with low spring stiffness efficiency could be higher but reliability decreased due to the minimum cushioning effect of the springs and possible late closure.

Minimize wear and fatigue

Some wear is unavoidable due to the moving elements, plates and springs, contacting the stationary elements, the guard and seat.

To make sure that wear is not accelerated:

- ensure proper valve lift, spring tension and element material for the application
- maintain proper lubrication rates to the cylinder
- maintain proper cylinder and interstage cooling to minimize heat stress
- keep the gas stream free of foreign matter and liquids

Beta Machinery is pleased to announce that Rich Bennekemper has joined our company to lead business development in our Houston office. Rich brings over twenty years experience in the engineering, design and manufacturing of air and gas compressor packages, generator sets, pump packages and metering packages for onshore and offshore installations.

News & Notes

The 3rd European Forum for Reciprocating Compressors was held on March 27 & 28, 2003, in Vienna, Austria. Brian Howes attended and presented a technical paper titled “API 618 Forced Response Studies”.

Brian Howes attended the 68th Spring Refining Meeting held mid April in Seattle, Washington. The pulsation control subcommittee is working on a recommended practices (RP-688) document that will be published at the same time as the 5th Edition of API 618.

Mark Deutscher of Beta Machinery Analysis will be a presenter at the GMRC Engine Analyzer and Reliability Workshop, to be held in Nashville from July 29 - 31, 2003. For more information visit www.gmrc.org.

Beta will be at the annual Gas Machinery Conference planned for Salt Lake City from October 6 - 8, 2003. Please contact Marsha Short at mshort@southerngas.org for registration and program information.

Beta Engineers have presentations scheduled for the CMVA Annual Meeting and Trade Show to be held in Halifax from October 29 - 31, 2003. The theme of the conference is “21st Century Solutions for Condition Monitoring”. Please contact Val Zacharias at cmvaed@shaw.ca or go to their website at www.cmva.com for further information.

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