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PROCESS CONTROL FOR GAS COMPRESSION SYSTEMS

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Abstract

The paper discusses the interaction between a centrifugal compressor and the process, and as a result, the control requirements for centrifugal compressor packages. The focus is on upstream and midstream applications, using variable speed drivers. The impact of the interaction between system characteristics and compressor characteristics, both under steady state and transient conditions is explained. Also considered are concepts to optimize and control the units. Special attention is given to the issue of surge avoidance.

The impact of the process behavior, and how the process dynamics impact the operation of the compressor and vice versa is analyzed, categorized, and explained.

Introduction

The purpose of the control of gas compressors is twofold: meeting the external process requirements and keeping the compressor within its operational boundaries. Within this scope, control scenarios that have to be considered are process control, starting and stopping of units, and fast or emergency shutdowns (Kurz and Brun, 2017).

The control of centrifugal compressors has to be considered both from the perspective of the compressor, the perspective of the control system and the perspective of the process.

Regarding the compressor, it is necessary to discuss the different control devices, such as variable speed, guide vanes, throttles or recycle valves. It is also important whether a steady state compressor map is still valid in the case of fast transients. Further different limiting aerodynamic operating regimes of the compressor, such as surge, stall, and choke have to be understood.

The control system has to be addressed with regards to instrumentation and device requirements, the system dynamics and the control methods of the drivers.

The process-compressor interaction is defined by suction and discharge pressure, and the flow. For the process, one must understand the relationship between the flow through the system, and the pressures imposed on the compressor. These relationships are different depending on their rate of change, in other words, one must expect different system responses for fast and slow changes as well as steady state conditions. Different upstream and midstream applications lead to different compression system characteristics and control requirements which, in turn, are the result of compressor requirements (such as high pressure ratio, wide operating range) and the process requirements. Multiple unit installations, installations with multiple compressors per train, and installation where the train has to serve multiple gas streams, require specific process control considerations to match the compressors with the process system behavior and the objectives of the station or system operator

Lastly, the discussion of compressor control is incomplete without a definition of the goal that the operator wants to achieve with a control system. The requirements to protect the process as well as the equipment have, of course, priority. But other goals need to be defined, too, in particular if the station involves multiple compression units, either in series or in parallel. Possible goals can be to minimize fuel consumption, to minimize maintenance cost or to maximize throughput.

The framework described above also defines the structure of this tutorial. The centrifugal compressor and its control, will be addressed first, and is followed by a description of the process behavior under various scenarios. A prominent role in these descriptions will be taken by surge avoidance considerations. The tutorial will close with considerations on how to control multiple units.

The behavior of compressors during emergency shutdowns will not be discussed in this tutorial. The control system’s function is simply to initiate the shutdown and to open the recycle valve as fast as possible. Furthermore, the behavior during emergency shutdowns has been covered in great detail in a number of papers, for example by Botros et al(2008,2011), Kurz et al (2004), Morini et al (2007) and Blieske et al (2011).

Compressor behavior and compressor controls

Centrifugal compressor behavior can be described by their head-flow-efficiency relationship. A centrifugal compressor at constant speed exhibits the relationship shown in Figure 1, with a distinct relationship between head and flow. In the case of machines with backwards bent impellers (the type in general used in upstream and midstream compression applications), the head of the compressor increases with reduced flow. When the compressor is operated at a condition different from its design point, the losses increase and the curve eventually becomes vertical for high flows, and horizontal, with a subsequent drop, at lower flows than the design flow. The curve section with a positive slope does usually not allow for stable operation. A more detailed treatment of this topic can be found in Kurz et al (2015).

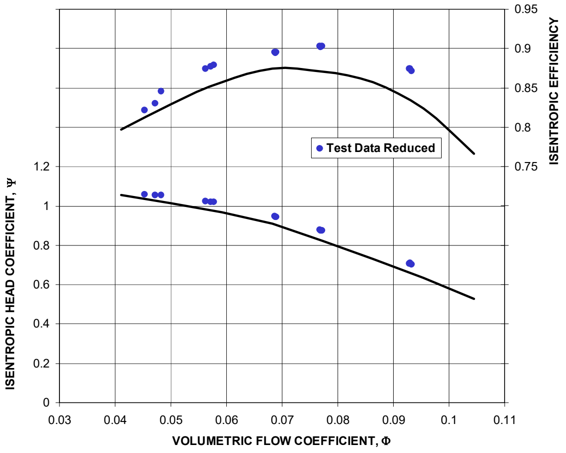

Figure 1: Head-Flow-Efficiency Characteristic of a Compressor at Constant speed

Applying different control mechanisms such as :
-Speed Variation
-Adjustable inlet vanes
-Adjustable diffuser vanes
allow the compressor to operate on a family of curves, as can be seen in Figure 2.

Of particular importance in upstream and midstream applications is the compressor that can be operated at varying speeds, since his is the most effective and efficient control method (Figures 2 and 3).

Additionally, compressors can be controlled by

-Suction or discharge throttling (Figure 2)
-Recycling (Figure 4)

Compressor Protection

Within the control system, subsystems protect the compressor. In general, process control will be enabled as long as the compressor stays within acceptable, predefined boundaries. These boundaries may include

-Maximum and minimum operating Speed
-Stability limit (aka surge line)
-Choke or Overload limit (on some machines)
-Pressure, temperature, torque limits

Station Level

Further, on the station level, if multiple units are used, control can be exercised by selecting the number of units in operation. Compressor configurations within a station can include: Single compressors, single compressors supplied from or delivering into multiple headers, multiple compressors operated in parallel, multiple compressors operated in series, multiple compressors, or compressors with multiple sections operated in a train. Variations may include multiple compressors in a train, with control of intermediate pressures, or multiple compressor trains in parallel (Figure 5).

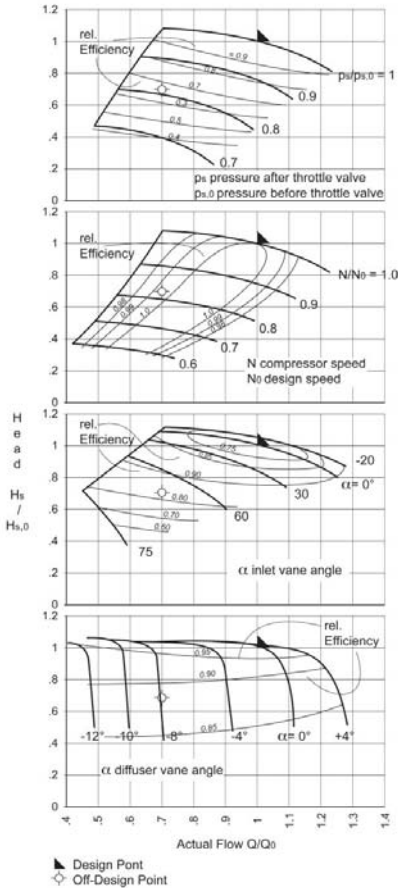

Figure 2: Control methods for centrifugal compressors:
Throttling, variable speed, and adjustable guide vanes (Rasmussen et al.,2009)

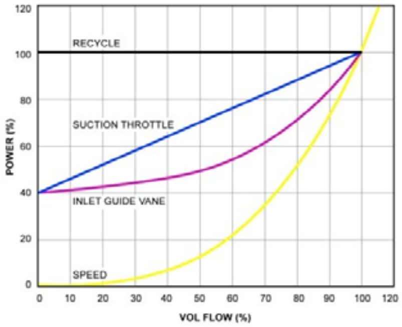

Figure 3: Power consumption for different control methods (Kurz et al, 2012a)

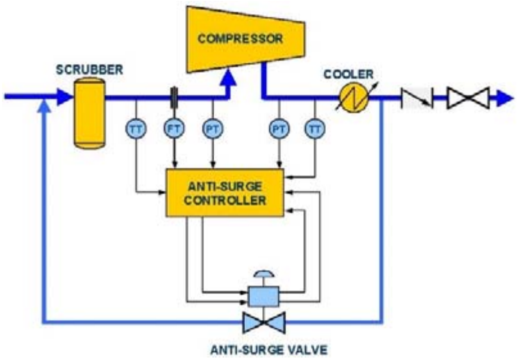

Figure 4: Recycle System

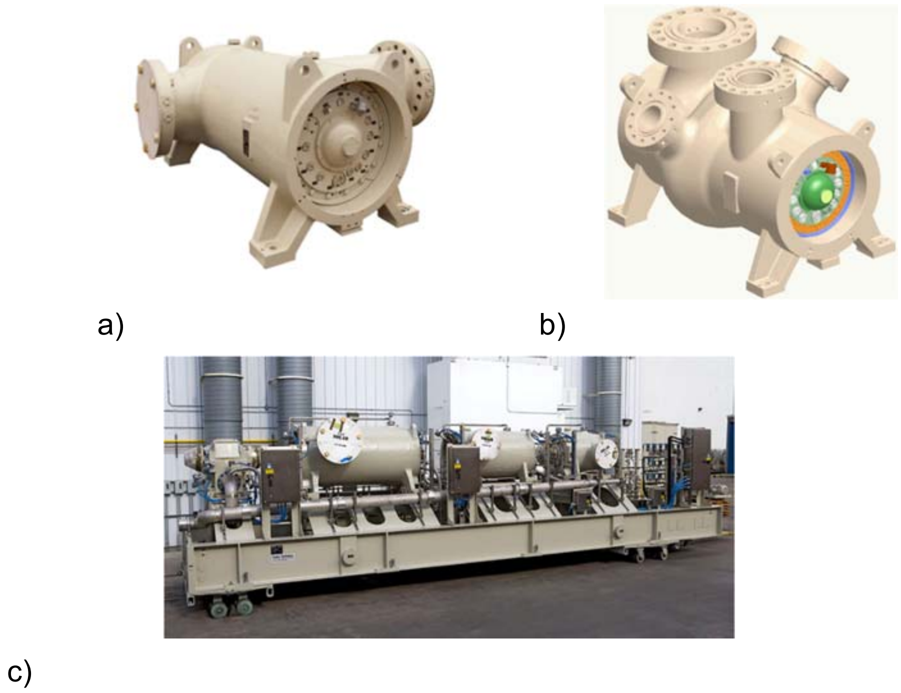

Figure 5: Different Compressor Configurations:
a) Single section, straight through Compressor, b) Multi Section Compressor, and
c) multi body tandem.

Control Concepts for multiple units in a station

With multiple units on a station, the question becomes how to control them to achieve certain objectives. These objectives may be minimizing the running hours of units, optimizing the capability to absorb load swings, minimizing fuel consumption or emissions. The first objective requires to run as few units as possible, while the second may require to run all or most units at part load for most of the time. Minimizing fuel consumption (which also equates to minimizing CO_2 production) will usually involve strategies to cover the load with as few units as possible running (i.e. running units as close to full load as possible or not running them at all). It then becomes a question whether it is better to run the operating units but one at full load, with the remaining unit at part load; or, to run all units at part load.

For two identical units running, the answer is virtually always to run both of them at equal part load. This is accommodated by operating the compressors at equal turndown or at equal gas turbine load (i.e. equal gas producer speed).

For more than two identical units running, the difference in fuel usage between N units running at the same load, and some running units at full load, and the remaining at part load, is usually very small. The optimum there is more often determined by the resulting operating points of the compressors.

For units that are not identical, it is usually better to load the more efficient unit and capture the load swings with the less efficient unit.

In many instances, it is desirable to limit the numbers of starts and stops of units, which may lead to strategies that approximate the optimum as close as possible, while avoiding starts and stops where possible. In some instances, these schemes are also dictated by the starting reliability of individual units, i.e., a low starting reliability may dictate operational schemes that are otherwise less fuel efficient.

Control of machines in series and parallel

The difference in operational behavior of machines in series versus machines in parallel is due to the different boundary conditions: In parallel operation, all units see the same suction and discharge pressure, but the flow will depend on the power that is fed into the compressor. In series operation, the flow has to be same through all machines (unless recycle is employed). Increasing the power for one of the machines will increase the amount of head that said machine will produce relative to the other machine, thus reducing its turndown. Many control schemes for multiple independent compressors use the approach to operate all compressors at the same turndown (turndown equalization). Turndown equalization for compressors in series works backwards from turndown equalization for compressors operating in parallel. In series operation, one has to increase the speed (and thus power) of the unit where turndown has to be reduced. For units in parallel, increasing the speed (and power) of the unit will increase its turndown.

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Series-Parallel Considerations

For some applications, for example for gas storage, it is advantageous to be able to switch two compressors from series to parallel operation and vice versa. In doing so, the operating range can be significantly increased. In series operation, the units can provide high head, while in parallel, the flow range is increased.

It is desirable to be able to switch from series to parallel operation, and vice versa, while the compressors are running at or near full load. This is possible with an appropriate arrangement of valves. The most elegant solution involves a control valve and two check valves (Figure 6). With the control valve open, the machines operate in series, while with a closed valve they operate in parallel. The check valve will automatically open and close based on the pressure differential over these valves, and therefore don't have to be controlled. In this arrangement, the opening and closing speed of the control valve is not particularly important

The same can also be applied for casings with two compressor sections. In particular for back-to-back machines, the requirement to balance the thrust load can impose additional limitations.

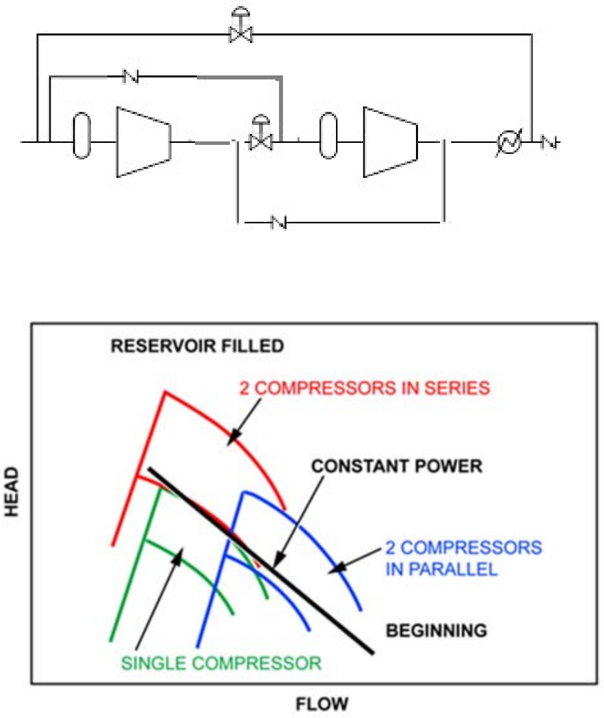

Figure 6: Compressors for series and parallel operation .Top : Schematic, bottom: resulting map.

Controls

Basic Process Control With a Gas Turbine Driver

Two-shaft gas turbines consist of two sections: the gas producer (or gas generator) with the gas turbine compressor, the combustor, and the high pressure portion of the turbine on one shaft and a power turbine on a second shaft . In this configuration, the high pressure or gas producer turbine only drives the gas turbine compressor, while the low pressure or power turbine, working on a separate shaft at speeds independent of the gas producer, can drive mechanical equipment. The power output of the gas turbine is primarily controlled by the fuel flow. The gas turbine control system will only allow an increase of fuel flow (and thus more power), when the gas producer does not exceed the maximum firing temperature or its maximum speed, and as long as the power turbine stays below its maximum speed. The amount of fuel flow determines the gas producer speed, and thus the power output (Kurz et al 2012).

The Control system for a gas turbine driver process control is set up to run the engine to maximum gas generator speed (i.e full load), unless it runs into another limit first. Limits can be compressor suction pressure, compressor discharge pressure or compressor flow. If, for example, suction pressure is controlled, the engine will run at full load unless the suction pressure drops below its set point. In that case, the gas producer speed is reduced. In the case of discharge pressure control or flow control, the engine will run at full load unless the discharge pressure or the compressor flow exceeds its setpoint.

Surge Avoidance

Surge avoidance , while the compressor is on line, is one of the process control for the left boundary of the compressor map. The intervention of surge control should be virtually unnoticeable. It should be as though the compressor has infinite turndown.

Understanding the principles of surge avoidance initially will make understanding the remaining process controls easier.

Some remarks about control dynamics and measurements

There are five essentials for successful surge avoidance (White et al, 2006):

1. A Precise Surge Limit Model: It must predict the surge limit over the applicable range of gas conditions and characteristics.
2. An Appropriate Control Algorithm: It must ensure surge avoidance without unnecessarily upsetting the process,
3. The Right Instrumentation: Instruments must be selected to meet the requirements for speed, range, and accuracy.
4. Recycle Valve Correctly Selected for the Compressor: Valves must fit the compressor. They must be capable of large and rapid, as well a small and slow, changes in capacity.
5. Recycle Valve Correctly Selected for the System Volumes: The valve must be fast enough and large enough to ensure the surge limit is not reached during a shutdown. The piping system is the dominant factor in the overall system response. It must be analyzed and understood. Large volumes will preclude the implementation of a single valve surge avoidance system.

Since this paper does not cover the behavior of surge control systems during emergency shutdowns, all that needs to be mentioned at this place is, that the volume of the pipes and vessels between the compressor discharge nozzle, the check valve and the recycle valve should be kept as small as possible. If concerns about surge during emergency shutdown arise, a separate hot recycle valve can be installed.

System Behavior

The system within which the compressor operates, that is, the piping valves, and vessels will show will show some relationship between the flow through the system and the pressure drop imposed by the system.

In the context of compressor applications, it is important to understand this relationship, since it has a profound impact on the selection of the correct compressor. Further, these relationships tend to be different in steady state operation versus transient operation.

The pipe system within which the compressor operates will impose its characteristic on the compressor. There are three fundamental steady state system characteristics that need to be considered (Figure 7):

A. Strong head-flow relationship
B. weak head-flow relationship
C. integrative relationship

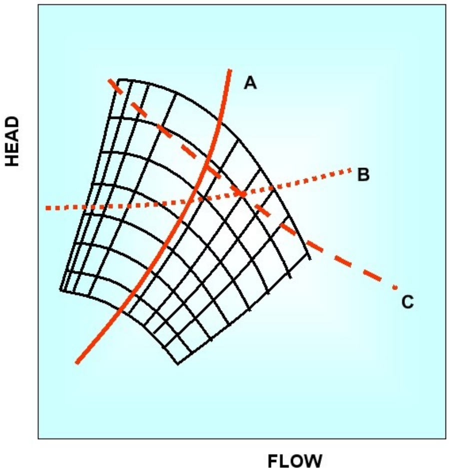

Figure 7: System Characteristics and Compressor Map

The case of strong head-flow relationship is, for example, seen in gas pipelines (Figures 7 and 8). Under steady state conditions, the pressure loss in the pipeline which imposes the suction and discharge pressure on the compressor station increases significantly when the flow through the pipeline has to be increased. The pressure levels are thus dictated by friction losses, which depend on the gas velocity in the pipe.

In a weak head flow relationship, the head requirement for the compressor head stays more or less constant with changes in flow. This behavior is found in refrigeration compressors, but also for situations where the process dictates a constant suction pressure (e.g., separator pressure), while the discharge gas is fed via a short pipe into a larger flowing pipeline, so the compressor discharge pressure is more or less dictated by the pressure in the large pipeline. Friction losses have therefore a very small effect.

In an integrative relationship, which exists for example in storage applications (Kurz and Brun, 2009), the compressor fills a large cavity. That means, the compressor discharge pressure is increased as a function of the cumulative flow into the cavity. Similar conditions can be found in gas gathering applications where (on a much slower scale) the field pressure declines as a function of the cumulative flow out of the gas field. These fields additionally also have a strong head-flow relationship, i.e., increasing the flow at any given time would lower the compressor suction pressure.

The interaction between compressor charateristic ansd system characteristic then becaomes a basic ingredient for the control approach. Figure 8 shows how the power input provided by the driver can be used to control the compressor operating point within the constraint of the system behavior.

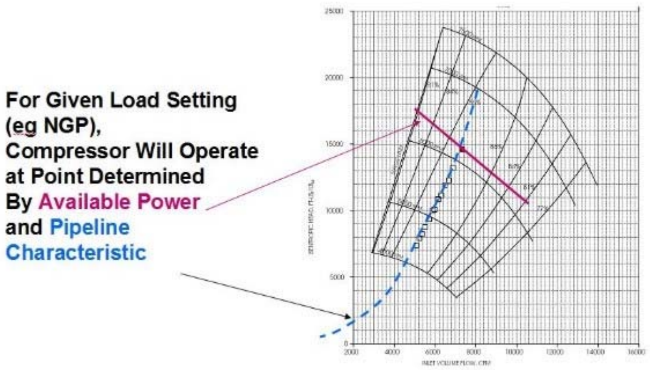

Figure 8: Available Power, Compressor Map and Pipeline Characteristic

Further, the transient system behavior must be considered (Figure 9). A pipeline for example can be operated in a transient condition by feeding more gas into the pipeline than what is taken off on the other end. This is usually referred to as line packing. In general, pipelines are operated under slowly changing operating conditions. While a pipeline under steady state conditions requires a unique station pressure ratio for a given flow (Figure 7), this is no longer true under transient conditions: If the pipeline operates under transient conditions, for example during line pack after a fast increase in driver power, or, if one of the compressors has to be shut down, the steady state relationships are no longer valid. Dynamic studies of pipeline behavior reveal a distinctly different reaction of a pipeline to changes in station operating conditions than a steady state calculation. In steady state (or, for slow changes), pipeline hydraulics dictate an increase in station pressure ratio with increased flow, due to the fact that the pipeline pressure losses increase with increased flow through the pipeline. However, if a centrifugal compressor receives more driver power, and increases its speed and throughput rapidly, the station pressure ratio will react very slowly to this change. This is due to fact that initially the additional flow has to pack the pipeline (with its considerable volume) until changes in pressure become apparent. Thus, the dynamic change in operating conditions would lead (in the limit case of a very fast change in compressor power) to a change in flow without a change in head. If the power setting is maintained, the compressor operating point would then start to approach the steady state line again, albeit at a higher speed, pressure ratio, flow, and power.

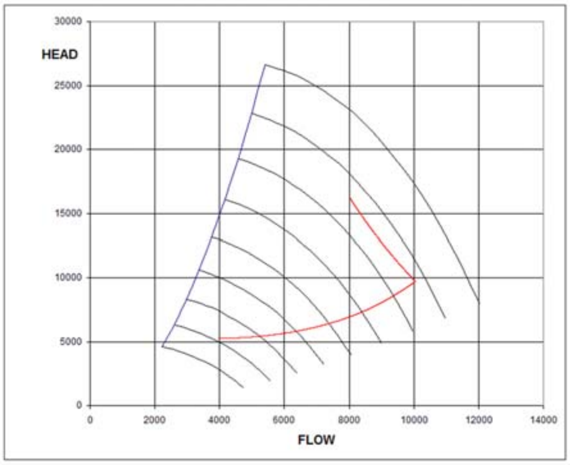

Figure 9: Typical Operating points if transient conditions are considered, in this case due to a fast engine acceleration from 50% to 100% load (Kurz et al.,2014).

Experimental data presented and analyzed by Blieske et al. (2011) indicates that the steady state compressor map is still usable even in transient situations.

Interaction between the system and the compressor

Since the goal of this paper is to discuss interactions between the process and the compressor or compressors, we have to look into how this interaction happens: For any situation, the process determines the suction and discharge pressure the compressor 'sees'. Based on some control setting (available power, speed, guide vane setting) the compressor will react to the situation by providing a certain amount of flow to the system. Thus, the flow into the system is a result of the compressor characteristic (it's map) and some external control setting.

Different controls elicit different scenarios in these control situations: If we control the compressor by the level of power that's supplied (Figure 8), then the speed at which the compressor runs is an outcome of the interaction between compressor and process. If we control the speed of the compressor, the required power is an outcome. The same is true for a constant speed machine (which in that sense is just a special case of a compressor that's forced to operate at a set speed).

Recycle control and throttle control (Figures 2 and 4)are essentially supplemental ways to control the compressor in certain situations. Recycling gas still maintains the system suction and discharge pressure as long as the compressor stays on line, but it allows the compressor to provide more flow than desirable or available from the system. Throttle control allows to reduce the system suction pressure or the system discharge pressure the compressor experiences.

There are obviously impossible outcomes: The compressor will not be able to operate at conditions where the speed is too high or too low, where the power demand is too high, or where the operation would cause an instability like surge. If the compressor due to constraints of power, speed, or flow range, is not capable to operate at the system imposed suction and discharge pressure, it will go into full recycle, i.e., it will operate within the constraints of a new system, that is a throttle valve controlled recycle loop.

It should be noted that the above principles also apply to transient situations, such as line pack in pipelines (Kurz et al. 2014), and even highly transient situations, such as during an emergency shutdown (Kurz and White, 2004; Moore et al.,2009). Again, the system (which is essentially the recycle loop as soon as check valves separate the recycle loop from the main system) imposes a certain suction and discharge pressure on the compressor, the available power comes from the inertia of the drive train, and the compressor speed is a result of the interactions.

Operation in a Pipeline System

In this example, the impact of different compressor characteristics on the efficiency achieved under operating conditions imposed by the system is highlighted. We compare a variable speed centrifugal compressor with a reciprocating compressor. Unlike a centrifugal compressor, a reciprocating compressor will deliver a lower efficiency when the pressure ratio drops (Noall and Couch, 2003).

The typical steady state pipeline operation (Figure 7) will yield an efficiency behavior as outlined in Figure 10. This is the result of evaluating the compressor efficiency along a pipeline steady state operating characteristic. Both compressors would be sized to achieve their best efficiency at 100% flow, while allowing for 10% flow above the design flow. Different mechanical efficiencies have not been considered for this comparison. The graph shows the impact of the increased valve losses at lower pressure ratio for reciprocating machines, while the efficiency of the centrifugal compressor stays more or less constant (Kurz et al., 2010).

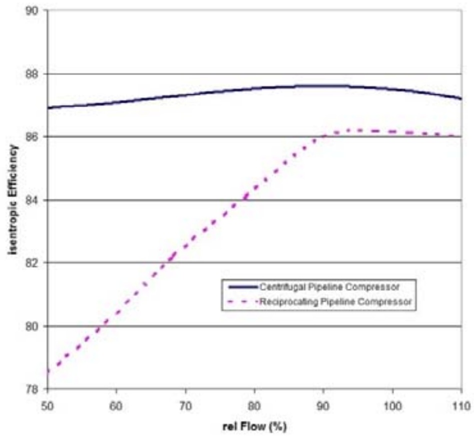

Figure 10: Compressor Efficiency at different flow rates based on operation along a steady state pipeline characteristic (pressure ratio at 100% flow = 1.4) .

The reciprocating compressor efficiency is derived from valve efficiency measurements in Noall and Couch (2003), with compression efficiency and losses due to pulsation attenuation devices added.. The efficiencies are achievable with low speed compressors. High speed reciprocating compressors may be lower in efficiency.

Control Objectives

In a discussion of control, one has to define the goal of a control system. The requirements to protect the process as well as the equipment have, of course, priority. But other goals need to be defined, too, in particular if the station involves multiple compression units, either in series or in parallel arrangements. Possible goals can be to minimize fuel consumption, to minimize emissions, to minimize maintenance cost (Lubomirsky et al, 2016) or to maximize throughput.

Each of these goals has to be translated into operations requirements for the compressors. For example, in a compressor station with 3 identical units, minimizing fuel consumption may be accomplished by running only the minimum number of units necessary for the duty. This generally also will minimize maintenance cost (since the cumulative running hours are minimized), unless the gas turbine incurs additional maintenance based on the number of starts.

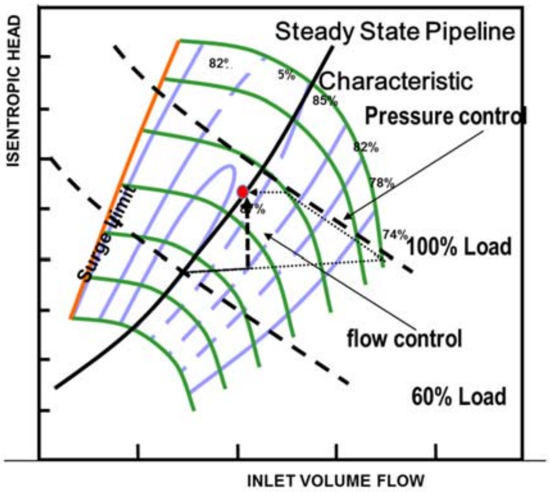

Figure 11: Flow and pressure control, load increase(Kurz et al, 2017)

We can set up system to control either pressure, power, speed and flow. For compression applications, we want to control variables that are relevant to the process, like flow or suction or discharge pressure. Speed and power are irrelevant from a process standpoint, except for machinery protection, or to maximize production (i.e., Operation at full load or full speed). Among the process variables in a compressor station, pressures tend to change relatively slowly, while flow can change fast. For compression applications, pressure (except as a limiting factor) is also often not that relevant, although there are applications where the control strategy requires pressure maintenance. Pressure control is often used for control purposes in pipelines, possibly because it’s easier to monitor, especially if reciprocating compressor are also used in the pipeline. Flow control is another method of process control, and is directly related to the process goal in a pipeline operation. Figure 11 shows how the compressor tends to react under different control scenarios. Kurz et al, 2014 showed that the fastest and most efficient way to get to a new operating point is to accelerate the engine to full power until the control objective is reached.

Both flow and pressure control will essentially make the engine operate at full load until the control objective is achieved. Pressure control will temporarily lead to a flow higher than the new steady state flow, while flow control will bring the engine to operate at part load earlier. In the case of a pipeline, pressure control will thus be a more efficient and faster way to execute changes.

The case where the unit is supposed to run at reduced flow is slightly more complicated, because it also requires to consider the anti- surge system (Figure 12). Upon setting the control setpoint to a lower flow (or pressure), the gas turbine will reduce power (by reducing gas producer speed). This will lead the compressor operating point to approach the surge control line. Under pressure control, the unit may actually cross the recycle control line, and thus the recycle valve will open to keep the compressor from surging. The combination of opened recycle valve and reduced power will bring the compressor to the new setpoint. Notably, there is no concern about interactions between power control and surge control (Kurz et al, 2017). For flow control, assuming the new flow point is still on the compressor map, the new operating condition will be reached without recycling gas.

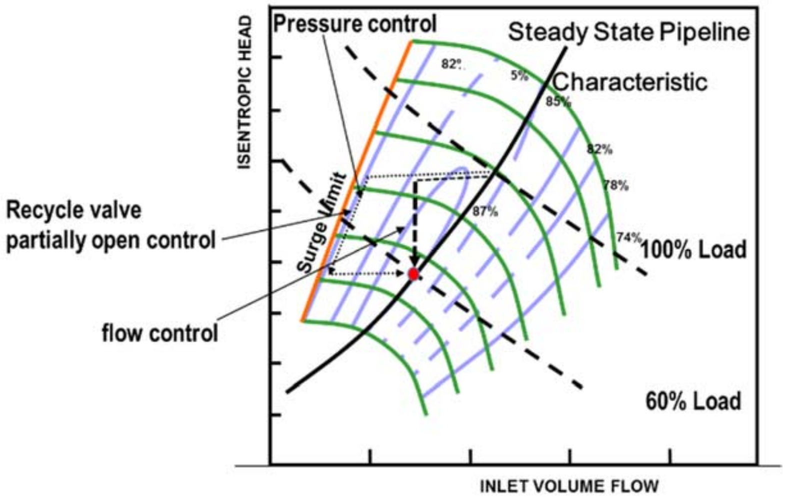

Figure 12: Flow and Pressure Control, load reduction (Kurz et al, 2017)

The examples in Figures 11 and 12 assume relatively large volumes in the piping upstream and downstream of the compressor station, typical of most pipeline operations. This means that the pressures will change slowly, because a large amount of gas is necessary to pack (or unpack) the lines. Smaller volumes, where the pressure increase is effected by smaller gas flows, will make the behavior of both control modes more similar.

Conclusion

There are two objectives for compressor control: meeting the external process requirements and keeping the compressor within its operational boundaries. Typical control scenarios that have to be considered are process control, starting and stopping of units, and fast or emergency shutdowns. The paper discusses the interaction between a centrifugal compressor and the process, and as a result, the control requirements for centrifugal compressor packages. The focus is on variable speed, upstream and midstream applications. The impact of the interaction between system characteristics and compressor characteristics, both under steady state and transient conditions is explained. Also considered are concepts to optimize and control the units. Special attention is given to the issue of surge avoidance.

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