CONTROL OF CO_2 COMPRESSORS IN UREA PLANTS

Saul Mirsky, P.E.

COMPRESSOR CONTROLS CORPORATION

Des Moines, IA USA

1. BACKGROUND

Urea and associated production usually requires compression of CO_2 gas that is derived as a by-product of ammonia production. Centrifugal compressors are usually used in this service. These compressors are complex machines with the following distinguishing characteristics:

- high pressure ratios dictated by the need to raise pressure from nearly atmospheric pressure to levels of approximately 150-250 bar, which corresponds to maximum pressure ratios of approximately 150-250;
- four or five stages of compression with intercooling between stages;
- CO_2 is a gas that behaves in a "non-ideal fashion" at pressures and temperatures reached during compression process.

Traditionally, CO_2 compressors utilized in the fertilizer production plants are centrifugal compressors of a rather sophisticated design. As a result of many years of operation, certain customs existing in the fertilizer industry have lead to a design approach that is simplified to a point where even the simple practical solutions are substituted by even more simple, but by now, impractical solutions. In our opinion, there is presently a situation where in many plants the simplicity of the design solutions is no longer adequate given the complexity of the machine and the process. Understandably, the fertilizer industry has always been under pressure to deliver acceptable economic results, often it is forced to reduce capital investment. As a result, installations of CO_2 compressors have acquired over time certain characteristics that are viewed by a large number of users as acceptable minimum control system features. Despite the existing potential for savings in operation that can be paid by a minimum increase in the initial investment, the designs of present day CO_2 compressor control systems still follow these traditions.

A schematic of a "typical" installation illustrating distinguishing features of a "typical CO_2 compressor installation" implemented by these traditions is shown in Figure 1.

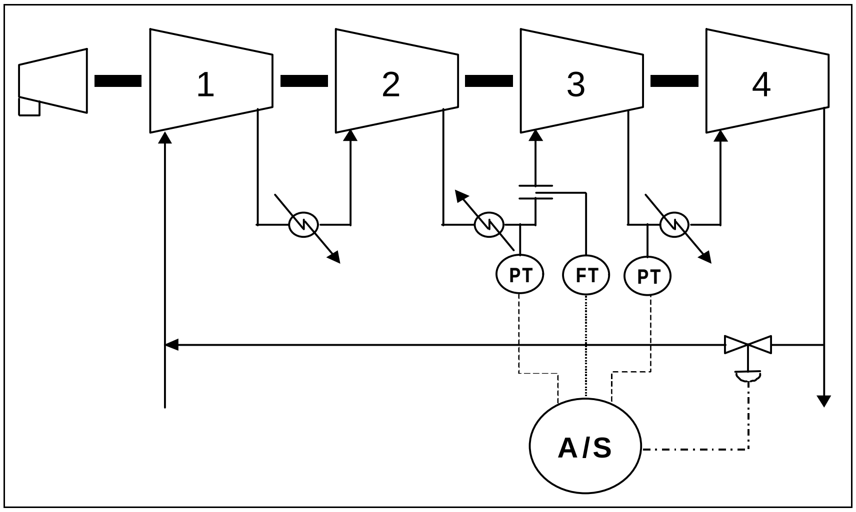


Figure 1: A common configuration including only a single antisurge controller manipulating the single antisurge valve.

The distinctive features of this "typical design by tradition" are:

- one flow measurement device;
- one antisurge valve;
- one antisurge controller;
- manual capacity control.

The intent of our presentation is to discuss these deficiencies of design "by tradition" and to describe solutions to improve the system to allow achievement of savings in the operation of these compressors.

2. ARGUMENTS AGAINST USE OF ANTISURGE CONTROL SYSTEM BASED ON A SINGULAR CONTROLLER WITH A SINGULAR RECYCLE VALVE

The design "by tradition" has lead to a situation where there is a number of typical and commonly accepted flaws in the systems of Antisurge Control for these sophisticated machines. We would like to disclose some of these most critical defects. In our opinion, these defects can be classified into two groups: (1) defects that are reducing the ability of the control system to *detect* surge and pre-surge conditions and, (2), defects that are reducing the ability of the control system to *execute* the protection of the compressor from the imminent surge event. The review of the problems described below must be applied to the analysis of a control system of any design, manufacturer, etc.

2.1 STAGE MISMATCH

The example on Fig. 1 above presents a control system for a four-stage CO_2 compressor. Matching stages of a four-stage compressor with an overall pressure ratio of 150 is a difficult problem for the manufacturer of the compressor. Design of this type of compressor must consider the limitation of the operating envelope of the compressor by events of surge and choke. We studied a few CO_2 compressors. Our findings (illustrated in Fig. 2 and Fig. 3) show that for a variable speed compressor, at moderate to low speeds, the fourth stage may be limiting the flow through the entire compressor because it was in choke. This increases the danger of damage from surge in stage 1 of the compressor. On the other hand, at higher speeds stage 4 is running dangerously close to surge, whereas other stages are perfectly safe.

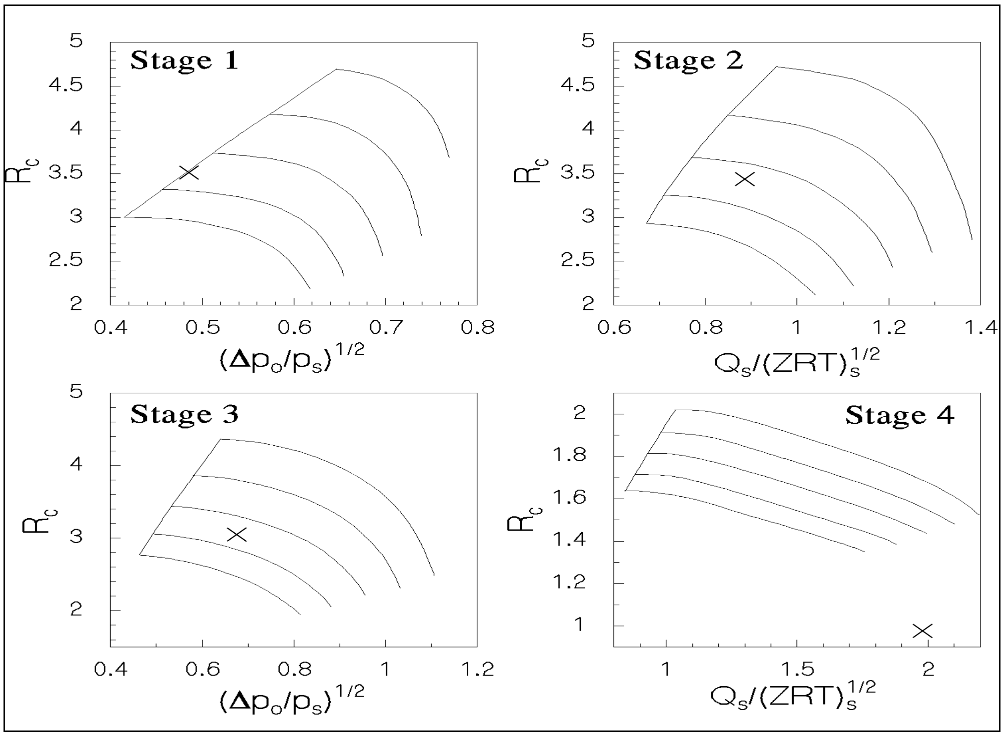


Figure 2: Operating points for each of the stages of compression. Note that stage 1 is on its surge limit while stage 4 is in choke.

Figure 2 shows that at approximately 93% speed (85% correspond to minimum governor), stage 1 reached its surge limit line, while stage 4 was choked. As it is well known, the event of choke limits the flow through the compressor stage when velocities near sonic are reached by this stage. Because the flow through the compressor is limited by the choke flow through stage 4, this compressor should not be operated below 93% speed if only a single recycle loop is provided. The reason for this statement is quite clear: this single recycle valve will not be able to provide flow necessary to protect stage 1 at speeds below 93%. In fact, it will be difficult to provide adequate protection from surge of stage 1 until sufficient margin away from surge will not be established, and, therefore, a more conservative value of speed, like 95%, will have to be used. This operating condition is depicted in Fig. 2 where each of the four compressor maps for each compression stage is shown with its operating point displayed as an “x.”

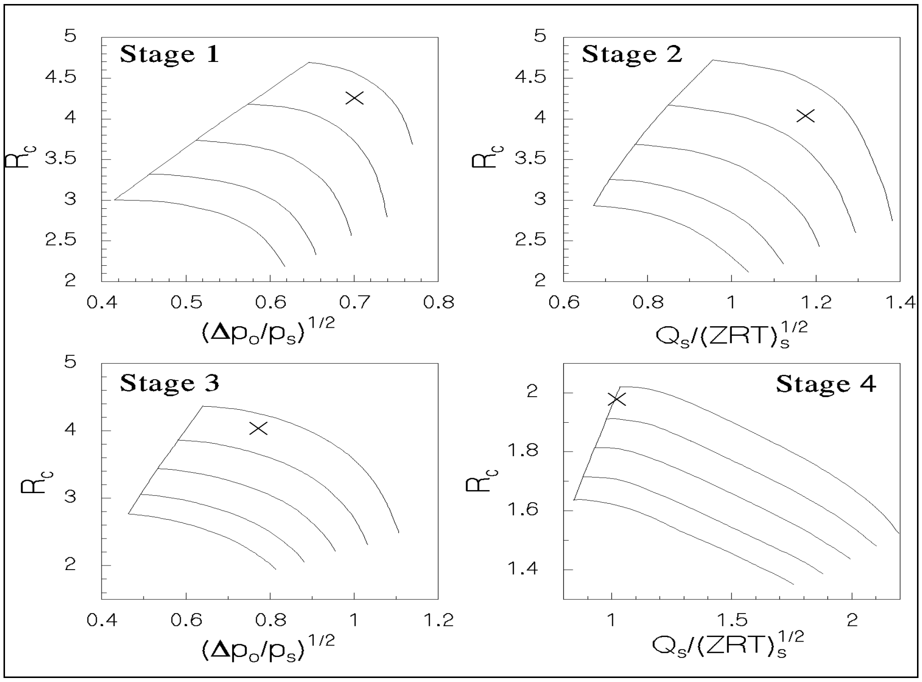


Figure 3: An operating condition where stage 4 reaches its surge limit first.

In Figure 3, the picture almost reverses itself. The fourth stage of the same compressor reaches the surge line before any other stage at a speed approximately equal to 103% (again, 85% corresponds to minimum governor.) If we combine observations for Figures 2 and 3, we would reach a conclusion that protecting this compressor on the basis of an antisurge controller that is focused on one stage and using one common recycle valve is impossible.

From a theoretical standpoint, it can be shown that the required turndown of the fourth stage for the above-described compressor is exceptionally high. Our investigations [1] found that for the compressor studied in the example above, the flow at the rightmost end of the performance curve at a speed corresponding to the minimum governor for the fourth stage must be over 300% of the surge flow at maximum governor speed.

The observations above were further confirmed in field testing of a few CO_2 compressors. In these field tests, our field engineers collected data from a surge test recorded during the commissioning of the control system for an actual CO_2 compressor. The invariant coordinates reduced flow and pressure ratio, respectively, were calculated from the recorded data, and are displayed in Figures 4 and 5 as:

$$q_r = \sqrt{\frac{Dp_o}{p_s}} \quad \text{and} \quad R_c = \frac{p_d}{p_s} \qquad (1)$$

where:

q_r is reduced flow,
Dp_o is pressure drop across flow measuring device
R_c is compression ratio of the stage
p_d is absolute pressure in the discharge of the stage
p_s is absolute pressure in the inlet of the stage

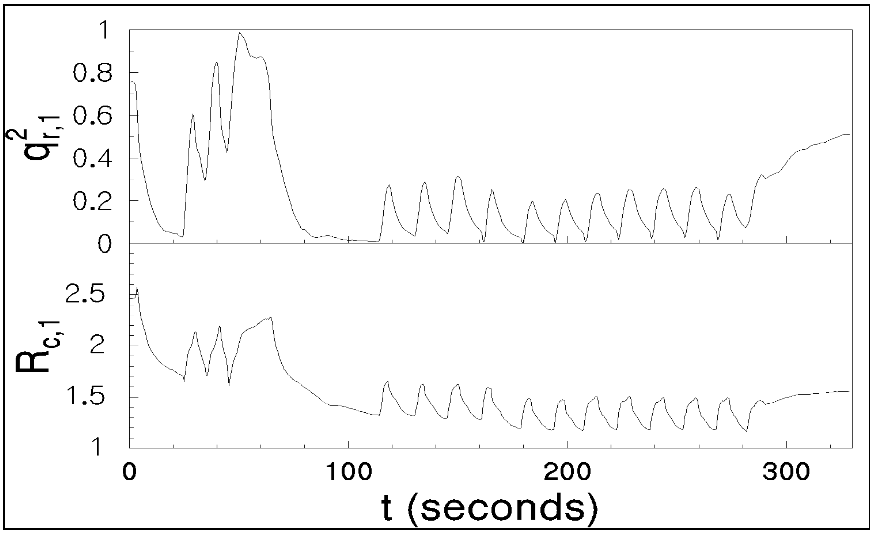


Figure 4: Trends of the reduced flow squared (q_r^2) and pressure ratio (R_c) for the first stage during the surge event at N=7300

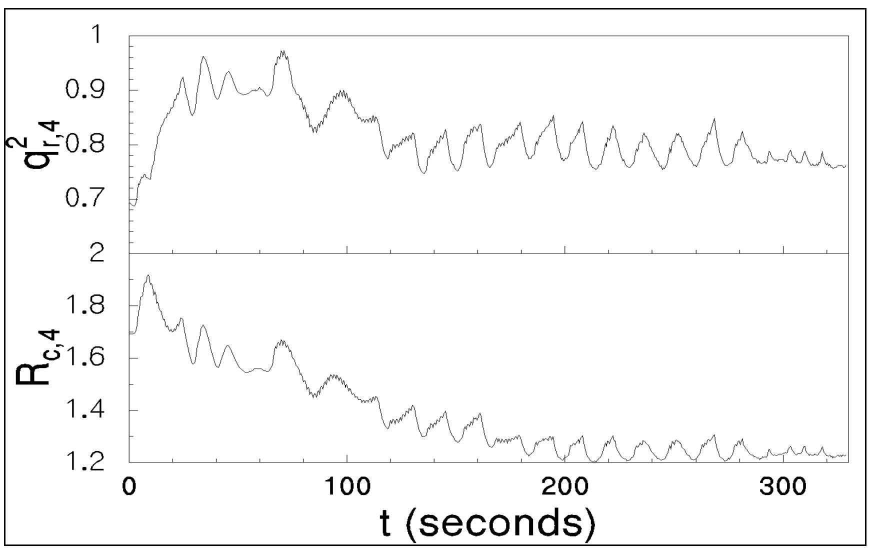


Figure 5: Trends of reduced flow squared (q_r^2) and pressure ratio (R_c) for the fourth stage during the surge event at N=7300.

The main conclusion that one can make from these trend plots of the surge event is that at the start of the record the first stage encountered surge and continued to surge repeatedly, while the fourth section was in choke. Surge is apparent in the first stage as the reduced flow drops off to near zero repeatedly, but, at the same time, it is apparent that the fourth stage is in choke because the reduced flow actually increased from its initial (stable) state going into the first stage's surge event.

The choke of the fourth stage is encountered as a result of opening the antisurge valve that is required to get the first stage out of surge. The fact that it took nearly five minutes for the first stage to come out of surge indicates that the flow supplied to the first stage of the compressor via the overall recycle valve was insufficient to permit efficient termination of surge.

2.2 INTERCOOLING

Compressors that are used for compression of CO_2 employ multiple stages of compression to deliver gas to the plant at the desired level of pressure. The temperature of gas rises together with rise in pressure and, therefore, there are practical limits as to how high the pressure can be raised within one compression stage. To continue the increase of pressure, the gas must be cooled between stages in intercoolers, and compressed further, repeating this process, until the desired pressure level is reached. Typically, a CO_2 compressor requires 4-5 stages of compression with 3-4 intercoolers between stages.

Presence of intercoolers in the system affects operation of the antisurge control system. If a singular controller is applied for protection of a multistage compressor with coolers between stages, there is often a situation where, due to fouling of an intercooler, the temperature in one of the stages of the compressor rises. Since the information reflecting these changes is not entering the control system, it is completely unaccounted for by the antisurge control system. On the other hand, the surge line of the compressor stage downstream of the intercooler that fouled up is shifting as shown in Figures 6 and 7. This shifting in the surge line may result in the change in the order of surging between stages, and, more generally, it results in the change of the surge line of the overall compressor.

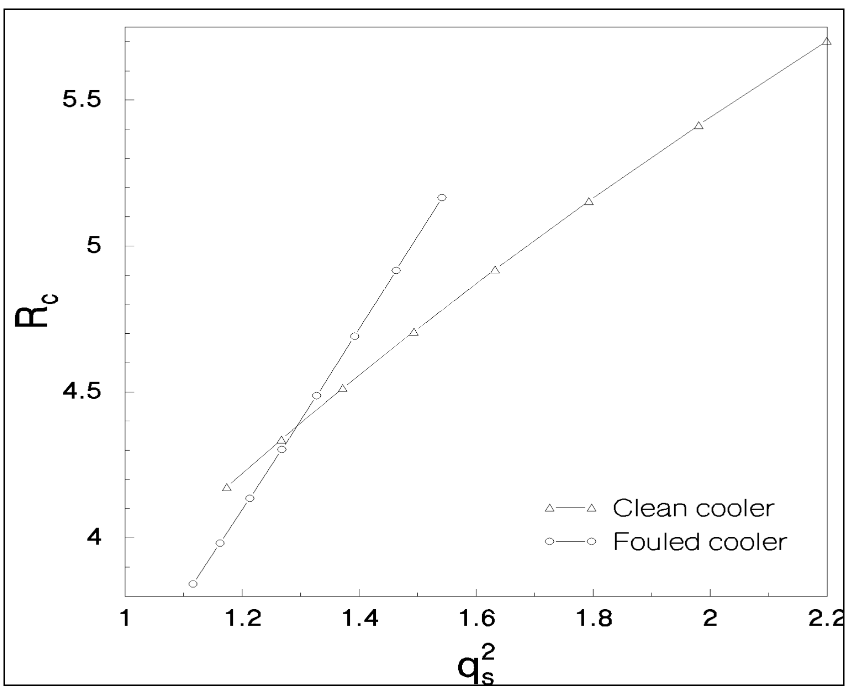


Figure 6: Shift of the surge limit line due to variation in intercooling. The compressor which surges first changes with the fouling of the cooler.

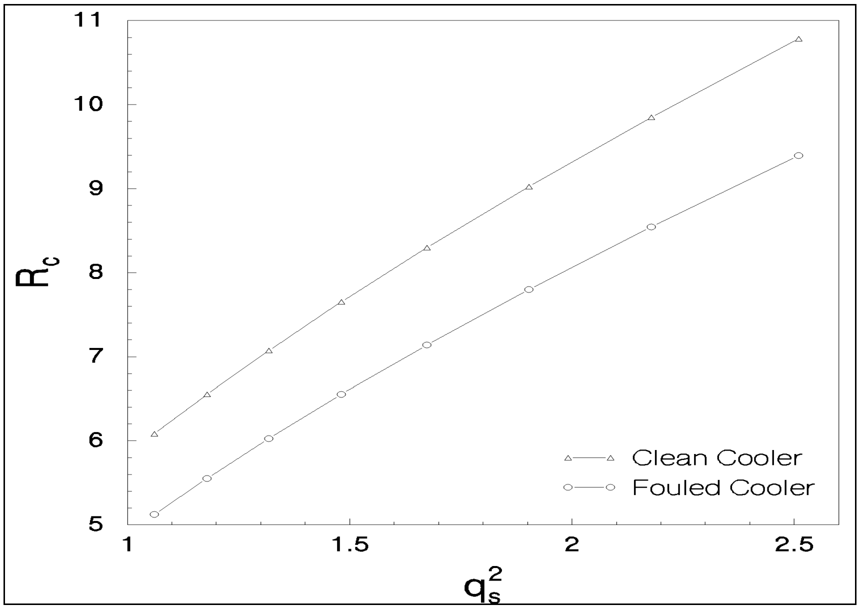


Figure 7: Shift in the surge limit line due to variation in intercooling. Here, the same stage surges first each time.

In all truth, the overall compressor map of the multistage compressor is valid only as long as the temperature in the inlet of every stage of compression is the same as it was assumed for the original overall compressor map. If the inlet temperature(s) to one or more of the stages change as a result of fouling up of the intercoolers, the previously derived overall compressor map can not be applied any more to the same compressor. This statement is correct even if the inlet temperature to the compressor (inlet to the first stage) remains the same. In essence, changes in temperature to inlets of one or more of the compression stages, due to fouling up of intercoolers, may have more affect on the performance of the compressor than the change of the temperature of gas entering the inlet of the compressor.

Application to the overall compressor of a surge control system based on a singular measurement disregards this effect and idealizes the picture assuming that intercoolers do not foul up. Experience shows that this expectation is absolutely groundless, and machines in many cases are operating with either no protection or with unjustified high margins of safety, thus wasting energy.

2.3 Non-ideal Gas

Under the pressures and temperatures CO_2 is exposed to in the process of compression in the compressor, it does not, in general, behave as an ideal gas *(Z=1)*. This further impacts the ability to obtain flow measurement and the ability to provide for an effective recycle for the “typical design system”.

Flow Measurement

Commonly, compressors have an orifice plate or similar flow measurement device (FMD), which is used to figure out the flow through the compressor. The differential between the pressures across this FMD is measured and then used to compute the flow in a format necessary for the control algorithm. The relationship between the differential pressure and flow is given by the equation

$$\Delta p_o = \frac{1}{A}\frac{\dot{m}^2}{\rho} = \frac{1}{A} Q^2 \rho \qquad (2)$$

where: Δp_o is pressure drop across flow measuring device
m is mass flow rate
Q - volumetric flow rate
A - flow coefficient of the FMD used
ρ - density.

For many compression systems in other applications, it is possible to calculate an equivalent flow signal for a location other than that of the existing FMD. In other words, if the FMD is located in the suction of the first stage of a two-stage compressor, an equivalent flow signal can be calculated as if there was an FMD in the suction of the second stage. To apply Equation 2, we need to know the densities at the location of the FMD, and also at the location for which the flow needs to be calculated. Knowledge of densities requires that we know the pressures, temperatures, and compressibilities at both locations. Typically, compressors are sufficiently instrumented with pressure and temperature transmitters, but compressibility still must be calculated from these values, with the knowledge of the gas composition. Calculation of compressibilities is definitely not a trivial task and requires extensive computing capability especially considering that it must be done in real time at a high speed of execution.

We conclude that, for a CO_2 compressor, because of the great variation in the compressibilities, Z calculation of equivalent differential pressure signals is not practical. For individual surge protection of multiple stages, each antisurge controller requires a dedicated FMD in the suction or discharge of the stage(s) under protection.

Note that despite the great variation in the compressibilities the differential flow measurement signal from an actual FMD at some point in the system (not calculated) is quite applicable to the antisurge system of this stage(s) regardless of the value of or the variation in the compressibility at that point.

MULTIPHASE FLOW

The combination of a high compression ratio in a multistage compressor with the peculiar behavior of the gas being compressed, CO_2, leads to unusual effects that must also be taken into account when considering the protection of such a machine by a single recycle valve. Because of the extreme pressure at the discharge of the compressor, the possibility of internal and external freezing of the antisurge valve must be considered.

This situation can arise with a gas temperature below approximately 100ºC, as seen in Figure 8. If, for example, the gas trapped in the recycle piping is permitted to cool to this point (or lower), CO_2 can condense inside the valve, reducing its capacity to pass sufficient flow to protect the compressor from surge.

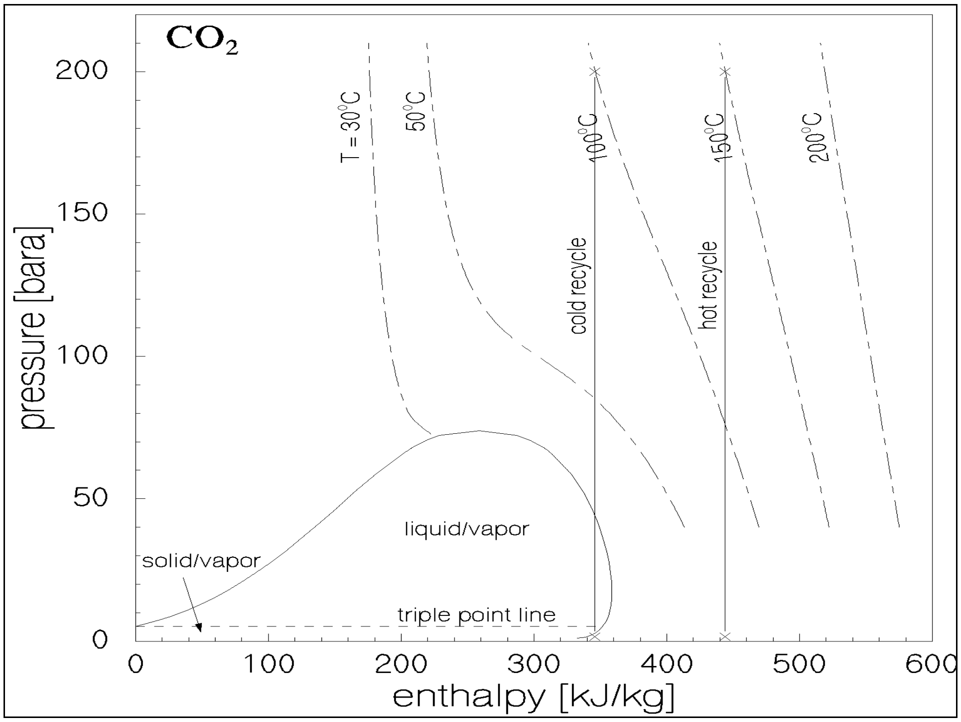


Figure 8: Pressure-enthalpy plot for CO_2 showing paths of expansion through the recycle valve when the gas is "hot" and when it is "cold."

Continuous leakage of the antisurge valve might cause the valve body to drop to below 0ºC and, thus, result in freezing outside of the valve if the ambient air is humid. The result can be a frozen valve actuator and the inability to protect the compressor from surge.

An additional problem to be considered, is "bombardment" of the impeller of stage 1 by frozen CO_2, causing possible erosion and damage to the impeller.

2.4 ABSENCE OF THROGHPUT (PERFORMANCE) CONTROL

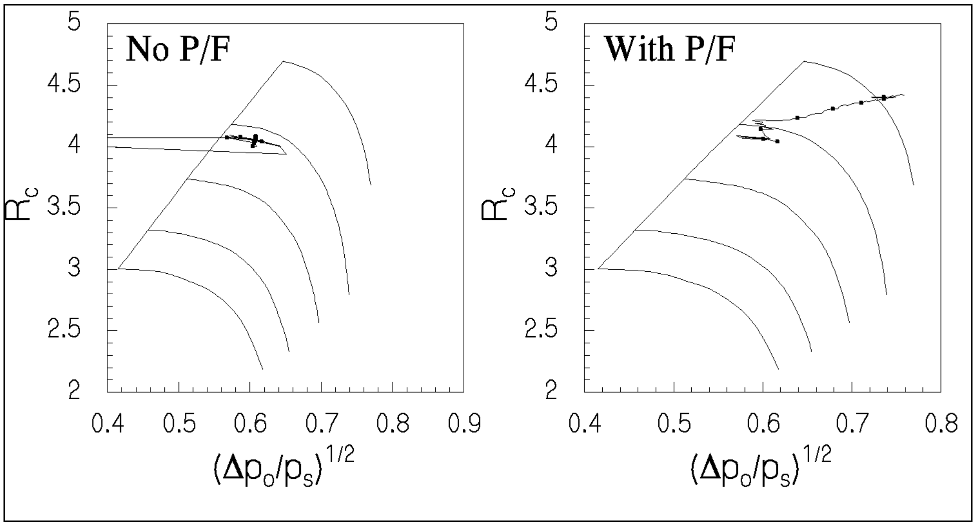
It is our observation that the majority of CO_2 compressors in the industry are operated without sufficient means of adjusting the throughput (performance) of the compressor to the available mass flow of gas to be compressed. Compressors are operated mostly at maximum speeds, variable speed mode is disregarded, and adjustment to the flow is done mostly by the throttling of the CO_2 stream at the place of production.

In our opinion this leads to unfortunate negative consequences:

- Energy is being wasted in the compressor operating at, for example, maximum speed where a lesser speed may suffice.
- As we will show below, simultaneous operation of throughput (performance) control and the antisurge control improves both: the quality of the antisurge protection of the compressor, and the quality of pressure control and operating comfort.

Using simulation, a comparison was made between using performance control (integrated with the antisurge control loops) and not using performance control. In each case, two antisurge controllers sharing a single antisurge valve were installed. As may be seen on

Figure 9a, representing operation with no performance control the system surges, whereas in Figure 9b, there is no surge for a similar disturbance in a system that utilizes performance control that is properly integrated with the antisurge control (more about this below).



Fugure 9a **Figure 9b**
Stage 1 without (a) and with (b) performance control (P/F)

3 RECOMMENDED SOLUTIONS

To remedy the problems outlined above, the following should be considered requirements for a satisfactory CO_2 compression system:

- At least two antisurge recycle loops
- At least two antisurge controllers
- One flow measurement device dedicated to each antisurge controller
- Performance control integrated with the antisurge controllers

These requirements are depicted in Figure 10.

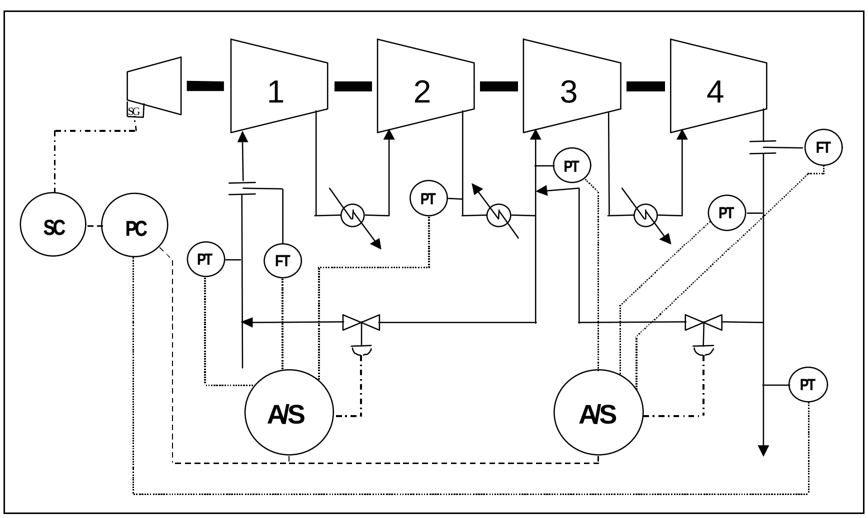


Figure 10: The recommended configuration with at least two antisurge controllers and two antisurge valves with performance control.

3.1 MULTIPLE ANTISURGE RECYCLE VALVES

Ideally, each stage of compression should be protected by an antisurge valve that is dedicated to that stage. However, in most instances, installing more than two recycle loops is not practical.

Multiple antisurge recycle valves provide better dynamics of the system (because of shorter piping lengths), and a two-valve system greatly reduces the problems associated with stage mismatch and non-ideal gas behavior.

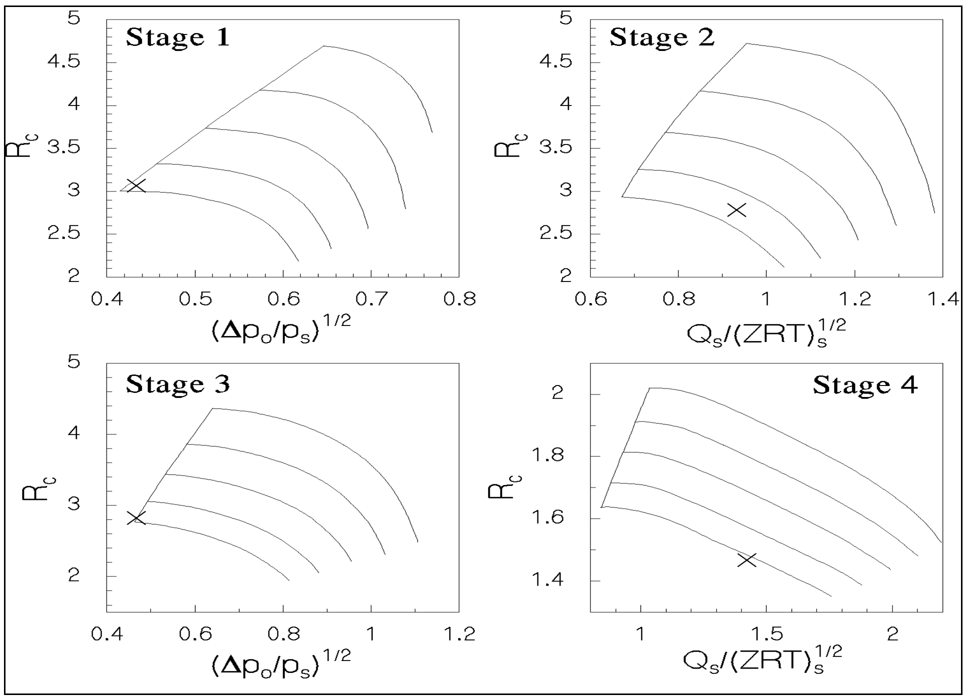


Figure 11: Operating points for each of the stages of compression with two antisurge valves. Minimum governor can be reached without choking stage 4.

To show the advantage of two valves for stage mismatch resolution, compare the single valve situation in Figure 2 to the two-valve case in Figure 11. As may be seen, the two-valve configuration allows for adjusting the flow to stages 1 and 2 independently from flow to stages 3 and 4. This means that the antisurge protection of stage 1 now does not depend on whether the flow is being choked off by stage 4 and that the sufficient flow can be supplied from discharge of stage 2. As an illustration of the capability of this concept, on Figure 11 we show operation at speed 85%, whereas on Figure 2, with a single recycle line it is impossible to operate this compressor below 93% speed without surging when in complete recycling.

Both problems of non-ideal location of the flow measuring device and that of the multi-phase flow are also resolved:

With two recycle valves there are two antisurge controllers, each with the associated flow measuring device, see Figure 10. Although the problems associated with the compressibility of a very "non-ideal" CO_2 gas remain, the amount of guessing is substantially reduced because in every case flow measurement is closer to the point to be monitored.

The problem of the multi-phase flow is resolved by distributing the overall compressor pressure ratio across two recycle valves. The low-pressure recycle loop would be in no danger of multiphase flow. The high-pressure loop could still expand the gas into saturated liquid but only if it were allowed to cool upstream of the valve. To avoid cooling, the high-pressure recycle valve should be located as close to the compressor discharge flange as possible. A valve which can tolerate two phase flow is recommended as well as a knockout drum to keep the liquids from being ingested into the compressor suction. The high-pressure antisurge loop should never be located so it draws gas from downstream of an aftercooler. In each case, care should be taken to ensure that the suction temperature does not become excessive when recycling fully around the high-pressure stages.

3.2 Modification of Controls

The modification of controls away from the "traditional design" involves both antisurge control and performance control. Both are required to provide an overall package that will result in superior control of the compression system. Note that the integration of these two functions is of utmost importance.

ANTISURGE CONTROL

Ideally, each stage of compression would be monitored for surge control and prevention. Even if the recycle valves are shared between two stages, having antisurge controllers that are dedicated to single stages reduces or eliminates the uncertainties. The main uncertainties originate from the intercooling between stages.

A less costly, and also less precise alternative, is to use two antisurge controllers — each being dedicated to the control of the two stages sharing the recycle line, as shown on Figure 10.

Instrumentation for these antisurge controllers includes

suction pressure, p_s,

discharge pressure, p_d, and

differential pressure flow measurement, Δp_0.

for each antisurge controller. The proximity to surge S_s is calculated on the basis of measured variables, as:

$$S_s = K \frac{f(R_c)}{q_r^2} \qquad (3)$$

where: $f(Rc)$ is a function responsible for linearization of the surge line

K is the slope of a linearized surge line

$q_r^2 = \Delta p_o / p_s$ is the reduced volumetric flow

The slope of the surge line K is calculated so that the distance to surge S_s goes to unity on the surge limit line and is less than one in the safe region. Details of the CCC approach to antisurge control are given in [2].

An important element of the system: two antisurge control functions must be decoupled between themselves. The idea in here is that if decoupling would not be used when one antisurge controller opens, the corresponding recycle valve improves the antisurge status of the compression stage the controller protects, but, at the same time, it makes the situation worse for the other compression stage protected by the other controller. Therefore, decoupling between stages must be used to send a feedforward signal that will open the recycle valve of the other stage in advance, thus, avoiding the interaction between stages.

PERFORMANCE CONTROL

Control of a process parameter like, for example, discharge pressure, via changes in the rotational speed of the CO_2 compressor is highly recommended. If the compression train is equipped by a constant speed driver, the performance control should be applied to the inlet throttling valve. The benefits of performance control are realized in the system regardless of the type of the compressor train driver. Performance control will:

- help stabilize the process,
- reduce the occurrence of operator error,
- reduce the chance of surge,
- save energy in operation of the compressor.

To reduce the chance of surge, the two control loops (antisurge and performance) are *decoupled*. When an antisurge loop takes action to open its antisurge valve, it will send a feedforward signal to the performance controller, which will increase the speed of the driver. Correctly tuned, this will provide the extra speed boost needed to keep the stage(s) from surging. Figure 9 shows that the system with performance control that is properly decoupled from the antisurge controllers' action is more successful in avoiding surge. For the same disturbance, the system in Figure 9b does not surge, whereas the system without performance control in Figure 9a is surging.

8. CONCLUSIONS

To adequately protect these complex CO_2 compressors from surge, a more aggressive approach than used in "design-by-tradition" is required.

Singular recycle loop is not adequate to control these machines, and multiple loops are highly desirable, with a minimum of two — one for stages one and two, and one for stages three and four.

For retrofits, the recommended and preferred solution is to modify the piping, and, in our experience, quite often the existing piping can be utilized very effectively.

For retrofits where piping modification is too costly, even though this is a less desirable solution, a single valve may be used. But even for this we suggest utilizing multiple antisurge controllers and performance control, as discussed above, integrated with the antisurge controller.

The valves should be sized adequately. The high pressure recycle valve must be placed as close to the hot compressor discharge line as possible to reduce the chance of forming liquids when the gas is expanded. This same valve should be designed and sized to handle liquids, and a knockout drum may need to be placed so that liquids will not be ingested into the compressor.

Antisurge controllers must be provided for more than one stage. It is preferable to protect each stage separately, but a minimum of two antisurge controllers is required. Applying antisurge control across pairs of stages can cover both stages with sufficient precision (no stage is left unprotected), but variation in intercooling may still cause uncertainties of an acceptable magnitude in the location of the surge limit, requiring a larger but acceptable safety margin.

A flow measurement device must be dedicated to each antisurge controller and be placed to accurately indicate the flow through the stage or stages being protected.

Performance control manipulating the turbine speed set point is required in all scenarios for decoupling with the antisurge system.

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2. CCC 1997. *Series 3 Plus Antisurge Controller for Centrifugal and Axial Compressors*. Compressor Controls Corporation Publication IM301(5.0).