Holding Back The Surge

Alex Biggs and Wayne Jacobson, Compressor Controls Corp., USA, consider the issues operators need to be aware of when using CO_2 compressors in urea plants.

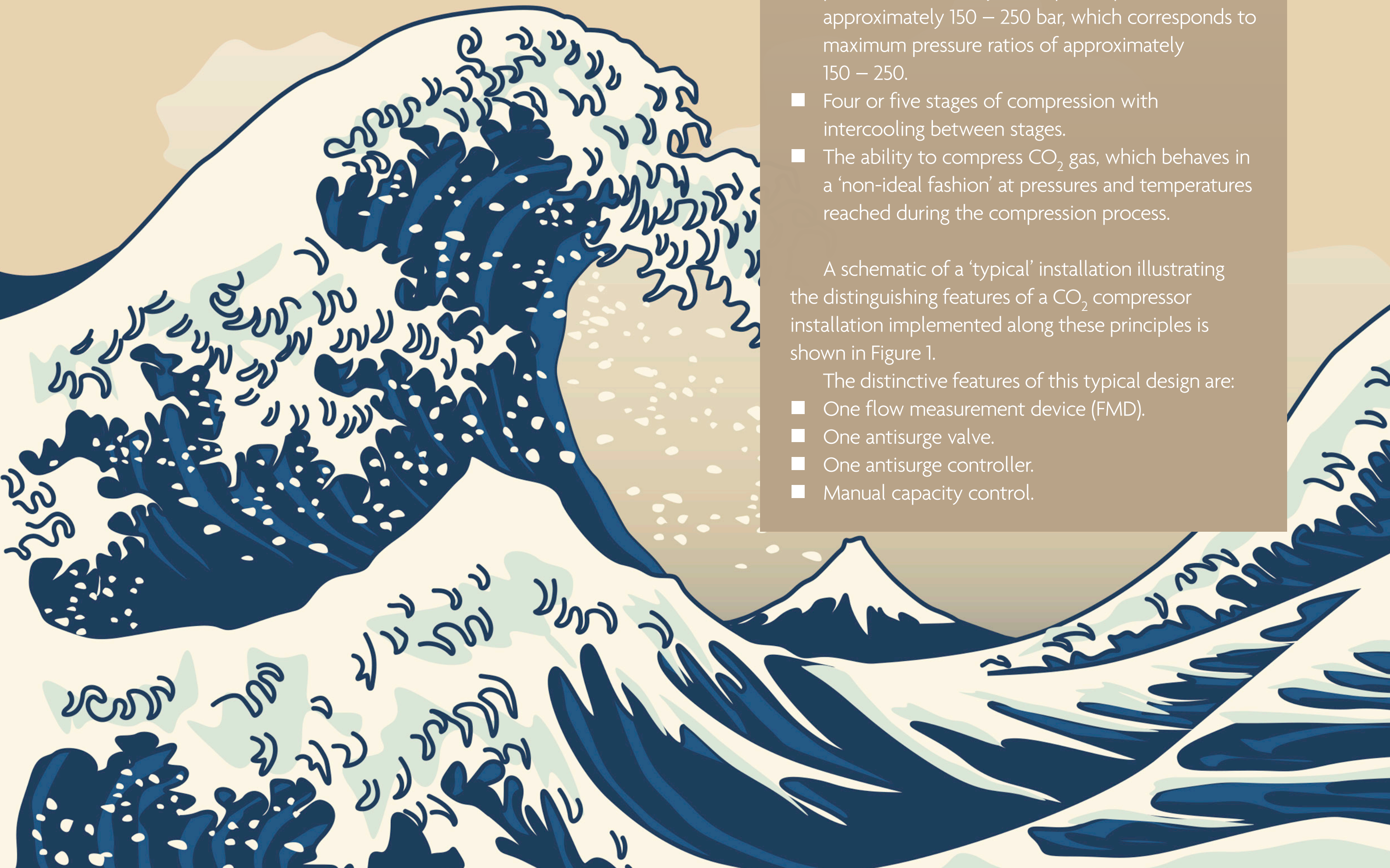
Urea and associated production typically requires the compression of carbon dioxide (CO_2) gas that is derived as a byproduct of ammonia production. Centrifugal compressors are often used in this service. These compressors are complex machines with the following distinguishing characteristics:

- High pressure ratios dictated by the need to raise pressure from nearly atmospheric pressure to approximately 150 – 250 bar, which corresponds to maximum pressure ratios of approximately 150 – 250.
- Four or five stages of compression with intercooling between stages.
- The ability to compress CO_2 gas, which behaves in a 'non-ideal fashion' at pressures and temperatures reached during the compression process.

A schematic of a 'typical' installation illustrating the distinguishing features of a CO_2 compressor installation implemented along these principles is shown in Figure 1.

The distinctive features of this typical design are:

- One flow measurement device (FMD).
- One antisurge valve.
- One antisurge controller.
- Manual capacity control.



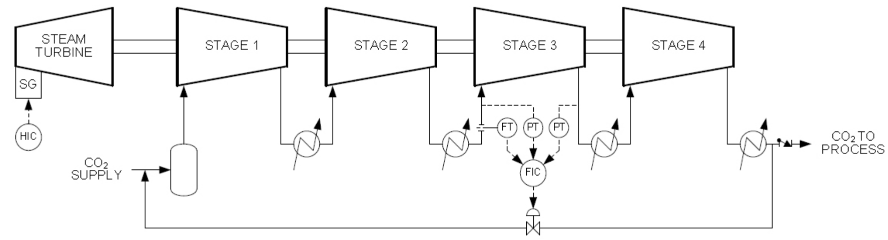


Figure 1. A common configuration including only a single antisurge controller, manipulating an antisurge valve.

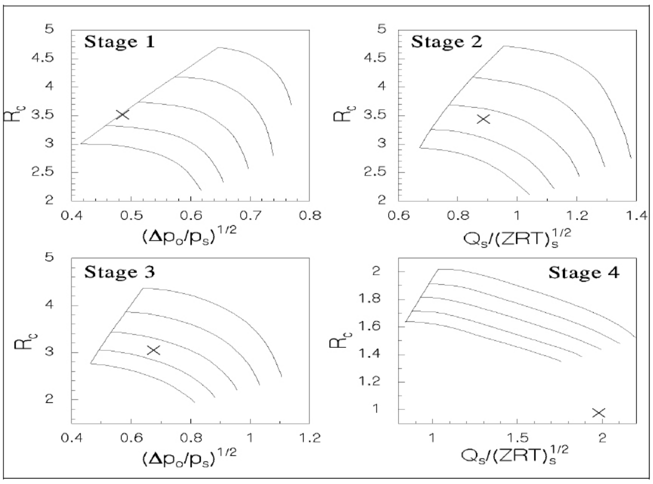


Figure 2. Operating points for each of the stages of compression. Note that stage 1 is on its surge line while stage 4 is in choke.

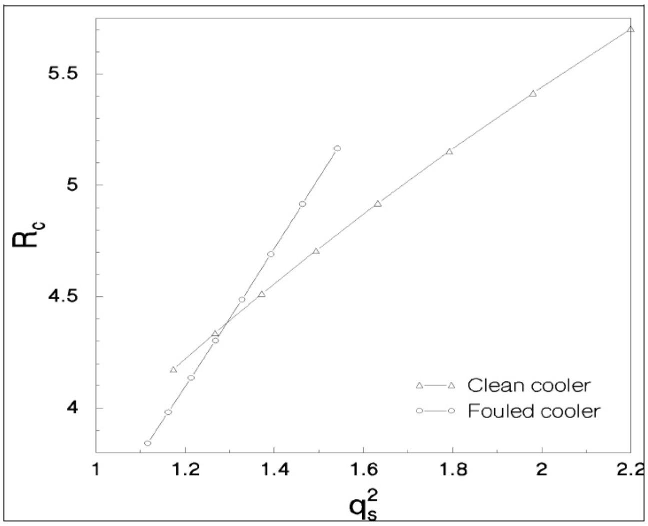


Figure 3. Shift in the surge line due to variation in intercooling. The compressor that surges first changes with the fouling of the cooler.

Issues with traditional design

Stage mismatch

The example in Figure 1 presents a control system for a four-stage CO_2 compressor.

It is difficult for a manufacturer of a four stage compressor to achieve matching stages with an overall pressure ratio of 150. The design of this type of compressor must consider the limitation of the operating envelope by events of surge and choke. Compressor Control Corp. (CCC) have studied a number of CO_2 compressors. Findings from this enquiry, are illustrated in Figure 2, and show that for a variable speed compressor at moderate to low speeds, the fourth stage may limit the flow through the entire compressor because it is in choke. This increases the danger of damage from a surge in stage 1 of the compressor. Alternatively, at higher speeds stage 4 is running dangerously close to surge, whereas other stages are entirely safe.

Intercooling

The temperature of gas rises together with a rise in pressure, meaning that there are practical limits 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.

If a single antisurge controller is used for protection of a multistage compressor with coolers between stages, a situation often arises where the temperature in one of the stages of the compressor rises due to fouling of an intercooler. Since information reflecting these changes is not entering the control system, it is completely unaccounted for by the control application. Alternatively, the surge line of the compressor stage downstream of the intercooler that fouled up can shift, as shown in Figures 3 and 4. This shifting in the surge line may result in the change of the order of surging between stages, and more generally it results in the change of the surge line of the overall compressor.

Non-ideal gas

Under the pressures and temperatures CO_2 is exposed to in the process of compression it does not, in general, behave as an ideal gas. This further affects the ability to obtain flow measurement and the ability to provide for an effective recycle for the typical design system.

Flow measurement

Compressors commonly have an orifice plate or similar 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.

For a CO_2 compressor, because of the great variation in the compressibilities, 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.

Multiphase flow

The combination of a high compression ratio in a multistage compressor with the peculiar behaviour 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. As a result of the extreme pressure at the discharge of the compressor, the possibility of internal and external freezing of the antisurge valve must be considered.

Absence of capacity control

CCC has observed 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 achieved mostly by the throttling of the CO_2 stream at the place of production.

This unfortunately leads to several negative consequences:

- Energy is wasted in the compressor operating at, for example, maximum speed – a lesser speed might suffice.
- Uncoupling capacity and antisurge controls can lead to poor and competing performance in both control loops.

Solutions

To remedy the problems outlined above, the following requirement should be considered for a satisfactory CO_2 compression system (Figure 5):

- At least two antisurge recycle loops.
- At least two antisurge controllers.
- One FMD dedicated to each antisurge controller.
- Performance control integrated with the antisurge controllers.

Case study

A urea plant has a CO_2 compressor comprising four stages with a single overall recycle line and is driven by a steam turbine. The control system consists of an antisurge control system designed for overall compression control, with the single flow measurement located in the third stage suction. Performance control is based on discharge flow control. An antisurge controller, FIC-3, can be placed on route to the urea reactor in systems with a compressor that has a high discharge pressure, in order to limit the pressure via a control loop pressure indicating controller (PIC) acting on pressure control valve PV-2, which is in parallel to recycle valve FV-2.

Analysis of existing control system

The overall recycle piping and single overall antisurge control design produces challenges and limitations during operation of the CO_2 compressor. The four compressor stages are not matched evenly. At lower operating speeds, stages 1, 2 and 3 can be at or very near their respective surge limit lines, while the fourth stage is in choke. While operating in this region, it limits the flow through the entire compressor. One of the events reviewed showed this to be the case, with the second stage at the surge limit line and the fourth stage near or in choke.

The overall recycle design also introduces delays in the system response time. Even though the recycle take off and recycle valve FV-2 are located very close to the fourth stage discharge, the first and second stages do not benefit from this because of the large volume associated with the downstream coolers and knockout drums, as well as the volume in the downstream compressor stages. This volume creates a delay in reducing the resistance through the first two stages and

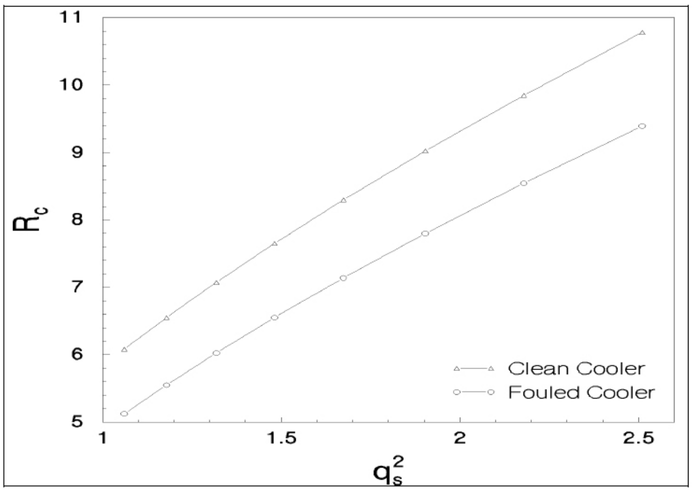


Figure 4. Shift in the surge line due to variation in intercooling. Here, the same stage surges first each time.

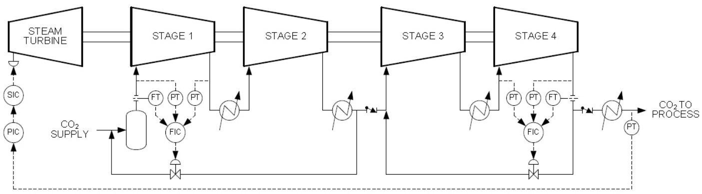


Figure 5. The recommended configuration with at least two antisurge controllers and two antisurge valves with performance control.

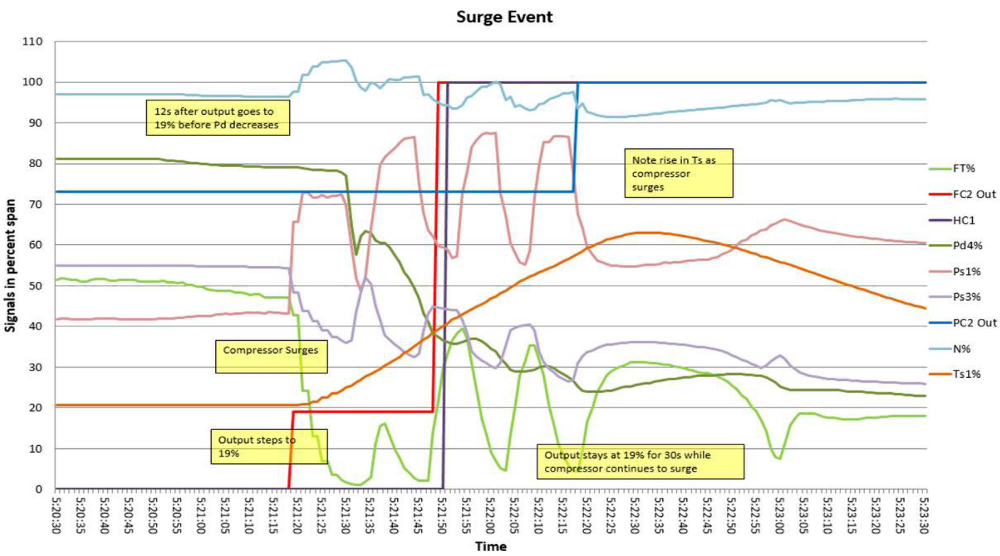


Figure 6. Plot of a surge event. Even with operator intervention surge events can occur with poorly performing control systems.

therefore a delay in moving these stages away from the surge when the recycle valve is opened.

The location of the single flow-measuring device in the suction of the third stage produces inaccuracies in calculating proximity to surge in the antisurge controller. This measurement is converted to compressor (first stage) inlet conditions by using temperature and pressure measurements and by assuming that compressibility remains relatively constant. As mentioned for CO_2, compressibility varies considerably with pressure and temperature, which can produce inaccuracies in the antisurge control system.

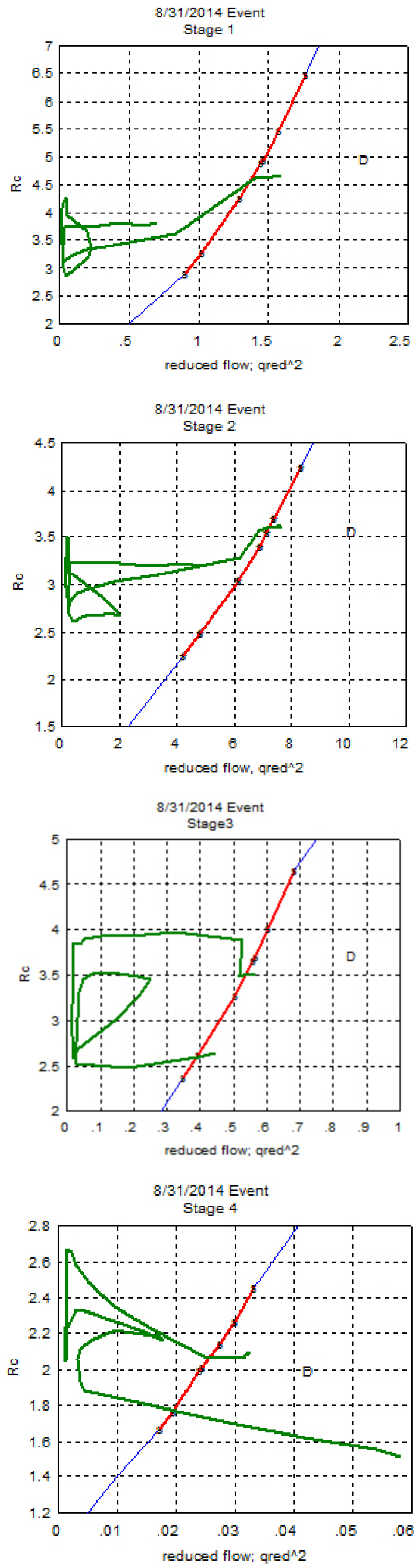


Figure 7. Surge events for each stage. The surge line for each stage was determined from the OEM individual compressor maps.

Analysis of reported events

Operational data as well as several events of instability were provided and reviewed. The next section discusses results from one of the five events analysed.

Surge event

Figure 6 is a plot of the surge event. The antisurge control loop steps the output by 19% at nearly the same time as the compressor surges. The controller maintains the output at 19% for 30 seconds while the compressor remains in surge. The output then steps to 100% open, followed by the HC-2 opening to 100%. Both of these actions are assumed to be by the operator. The compressor continues to surge for another 30 seconds since both valves are slow to open.

Figure 7 contains graphs showing the surge event for each stage. The graphs are in reduced flow vs Rc coordinates. The surge line for each stage was determined from the original equipment manufacturers' (OEM) individual compressor maps.

Existing control system issues and solutions

The antisurge valve strokes open too slowly – ideally this takes 2 seconds or less to open, and 3 – 5 times that to close. Volume boosters may need to be added, though actuators or positioners may also require replacement.

The existing system lacks monitoring for valve performance and the ability to alarm (i.e. in the event of valve sticking). Adding valve position feedback signals are of great help in troubleshooting because of their ability to monitor these outputs.

The transmitter impulse tubing length is too long, and includes numerous horizontal runs, with pockets that can accumulate condensate, which can yield poor signal performance. Further, some signal filtering is present, which is not preferable. Relocation of transmitters above tapping points, to minimise tubing length and ensure continuously sloped tubing for free draining, is highly recommended.

The surge limit and control lines do not appear to be implemented correctly in the distributed control system (DCS). The control line is very close to the actual surge line. Furthermore, the existing system performs slowly enough that operators are forced to manually adjust control valves. Two possible corrections here are: a) reconfiguring the DCS control line to be more conservative (if clear data is available); or b) replacing this control loop with a dedicated, high-speed control system (40 msec. or less), with proven and properly tested algorithms. A control system vendor should also perform surge testing along with a high-speed data recorder.

The compressor operating point along with the surge and control lines are not easily interpreted with running conditions. Further, trend archive resolution is limited at 1 second, which is too slow for proper troubleshooting for many dynamic events. In the advent of the second option listed above, it is also advantageous to include a human machine interface (HMI) that is capable of archiving with resolution of 200 msec. or better, as well as including proper and accurate operational displays.

Suggested control system options utilising dedicated special purpose controllers

Since major piping changes are often not practical to implement in the next scheduled shutdown, the two options below were suggested, with option 2 being the preferred option. These options require minimal-to-no changes to existing piping. In the future, an analysis can be carried out to determine the cost savings associated with changing the piping and control design to allow for a larger operating envelope and range of speed.

Option 1: overall antisurge control with integrated discharge flow control

This option uses a dedicated antisurge controller, FIC-2, that provides high discharge pressure limiting and controls both PV-2 and FV-2 in a split range arrangement, with PV-2 opening first. The existing PIC-2 control loop in the DCS is replaced by the secondary limiting loop within FIC-2. HIC-2 is the operator override to FIC-2 output for both PV-2 and FV-2. The discharge flow controller FIC-3 is a dedicated controller that is integrated with FIC-2 for loop decoupling and flow control. During turndown operation, FIC-3 coordinates with FIC-2 to control PV-2 and FV-2, maintaining discharge flow demand.

This option requires valve PV-2 to be modified to meet the same opening and closing recommendations as FV-2.

There are no piping modifications with this option. However, this option does not address the problem with protecting the first and second stages using overall antisurge control and recycle.

Option 2: individual antisurge control for LP section and for HP section with integrated discharge flow control

This option is similar to option 1 except for the addition of the second antisurge controller, FIC-1. FIC-1 provides antisurge control for stages 1 and 2 using existing valve HV-1, whereas FIC-2 provides antisurge control for stages 3 and 4 instead of overall antisurge control. This option allows for better antisurge control because direct flow measurement can be used without adjusting to suction conditions, which removes errors associated with assuming the ratio of compressibility is relatively constant. More importantly, using HV-1 for antisurge control will better protect stages 1 and 2 from surge as it will reduce the system response time, which in turn allows for tighter surge control margins than option 1.

In this option, FIC-1 and FIC-2 would be designed to decouple from each other to minimise loop interaction and to ensure the opening of HV-1 does not drive the third stage into surge. HIC-1 is the operator override to FIC-1 output for HV-1.

In addition to the modifications explained for option 1, option 2 also recommends the following:

- Adding a new FMD in the second stage discharge, and a new flow transmitter.
- Relocating transmitters so that they are above the tapping points and impulse tubing length is minimised.
- Modifying HV-2 actuation to meet the same opening and closing recommendations as FV-2.
- Considering adding small interstage bleed/recycle between the third and fourth stages to alleviate stage mismatch at low speeds.

Conclusion

Centrifugal CO_2 compressors are highly complex machines which require a carefully studied approach in controls design for robust operation. With experience gained in system design, incorporating best practices for compressor piping, valves and instrumentation, and properly configured, dedicated control applications, traditional challenges in CO_2 compression can be overcome and performance optimised. **WF**

Bibliography

1. MIRSKY, S., *Control of CO_2 Compressors in Urea Plants* (2008).