Evaluation of Anti-Surge Control Concepts during ESD
Simulation of dynamic process behaviour with PULSIM

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Abstract

This paper describes the potential of *dynamic* process simulation for operators and engineering contractors as a tool to analyse and solve operational and (front-end) engineering issues. The possibilities are illustrated by a typical project involving system dynamics. The objective of this project was to evaluate the effectiveness of several alternatives to prevent surge and overheating in a compressor system during emergency shutdown (ESD).

1. Simulation of Process Dynamics

1.1 Introduction

Safety, availability, operability and product specification are key performance indicators for operators of industrial processes and pipeline installations and the engineering contractors who design these facilities. Increasingly, operational criteria related to plant performance are assessed at dynamic operating conditions by simulation (e.g. Lamey, 1999).

Simulation plays an important role in the analysis of process dynamics both during *transient* operations (e.g. start-up, shutdown, trip and change of feedstock) and at *steady-state* operating conditions (e.g. regarding stability and controllability). The TNO Flow and Structural Dynamics department has performed integrated dynamic response analyses for oil & gas production facilities, (petro)-chemical plants and metallurgical installations. These so-called *system dynamics studies* (SDS) have been used in (conceptual) engineering, commissioning and troubleshooting projects.

The TNO Flow and Structural Dynamics department has assisted clients in the oil & gas and petrochemical industries for more than 30 years to prevent and solve problems regarding the dynamic behaviour of flow in process installations. Historically these services have been directed to a large extent at installations containing reciprocating compressors. Pulsation and mechanical response analyses are executed according to API standard 618 to identify potential pulsation and vibration problems and to recommend corrective measures. The pulsation studies are performed using PULSIM (Egas, 2001), a TNO proprietary simulation tool developed to solve industrial problems regarding the dynamic behaviour of flow in complex pipe systems, process installations and fluid machinery. Typical examples of the operational issues that can be analysed using PULSIM are:

- Analysis of flow-induced pulsations (FIPs) in Gas Metering and Control Stations (Peters, 2001)
- Pulsation analysis of installations containing positive displacement machinery
- Pulsation analysis of Hyper-compressors (Bokhorst, 2001)
- Stability analysis of centrifugal compressor systems

The frequency range of interest in case of pulsation studies lies roughly between 1 Hz and 500 Hz. Pulsation studies mainly focus at the process dynamics around a specific *steady-state* operating point. The operating range of interest is delimited for pressure by a margin of roughly plus or minus 10% of the operating point. The temperature profile along the system can be considered constant in time. Variations of fluid compositions are handled by simulating distinct *duties*. The *method of characteristics* is used to solve the model equations with sufficient accuracy in this operating envelope to meet the project objectives. Uncertainties in the model and process conditions are handled by a sensitivity analysis.

1.2 SDS Simulation Tool

For some years now, a growing number of s*ystem dynamics studies* has been performed successfully to investigate various issues in (front-end) engineering, commissioning and troubleshooting, such as:

- System layout and equipment selection.
- Process control (e.g. evaluation of controllability, stability and capacity control).
- Plant availability.
- Dynamic operating procedures (such as emergency blow down, start-up, shutdown or variation of feed gas composition).
- Analysis of a trip response and review of safeguarding actions as included in the *cause and effect diagrams* (e.g. response of a HIPPS system).
- The effect of *failure on demand* of (instrumented) safeguarding functions during emergency situations. Failure modes could relate for instance to ESD valves, depressurisation valves or instrument malfunction.
- The effect of *revealed failures* such as a spurious trip of a single piece of rotating or static equipment, a valve or instrument.

In order to deliver this new range of services to our customers, a special simulation tool called PULSDS is developed within the PULSIM simulation environment. PULSDS uses an integrated approach to predict dynamic process behaviour and includes the following physics and elements.

- Heat transfer between the fluid flow, the pipe wall and the environment
- Compositional tracking of the fluid components
- Process controllers
- Models of fluid machinery and fired equipment

Driven by the needs recognised in the market, the capabilities of PULSDS are continuously being expanded and improved.

Generally speaking, the relevant variations of the process conditions are relatively slow compared to a pulsation study and occur at a frequency range from 0.001 to about 10 Hz. The dynamic operating range of interest is relatively large. Pressure and flow vary in a range of about 0 to 200% of the nominal operating condition. The temperature and compositional profiles are calculated continuously. A solution method for SDS studies is currently developed in order to meet these new demands.

2. Evaluation of Anti-Surge Control Concepts during ESD

2.1 Background and Summary

The project presented here illustrates a typical system dynamics study (SDS). The SDS concerns the performance of a compressor system in a gas conditioning plant. The experience of the operator with existing gas compressors shows that the performance of the basic anti-surge control (ASC) system can be insufficient to prevent surge during emergency shutdown (ESD) events. In order to improve the response of the ASC system in emergency situations, implementation of a so-called *hot bypass* or a *cold bypass* can be considered. The TNO Flow and Structural Dynamics department has performed a dynamic response analysis with PULSIM to evaluate the effectiveness of these concepts to prevent surge and overheating of the compressor during ESD.

The compressor system that has been analysed can be described as follows. A fixed speed booster compressor is used to pressurise lean gas supplied by a turbo-expander/recompressor. The gas is subsequently cooled and delivered to the suction manifold of existing pipeline compressors. Both compressors are equipped with regular ASC recycle lines and pressure equalising lines. Depressurisation lines are located at the discharge side of both compressors. A schematic overview of the process that has been modelled and analysed, including all relevant valves, is presented in figure 2.1.

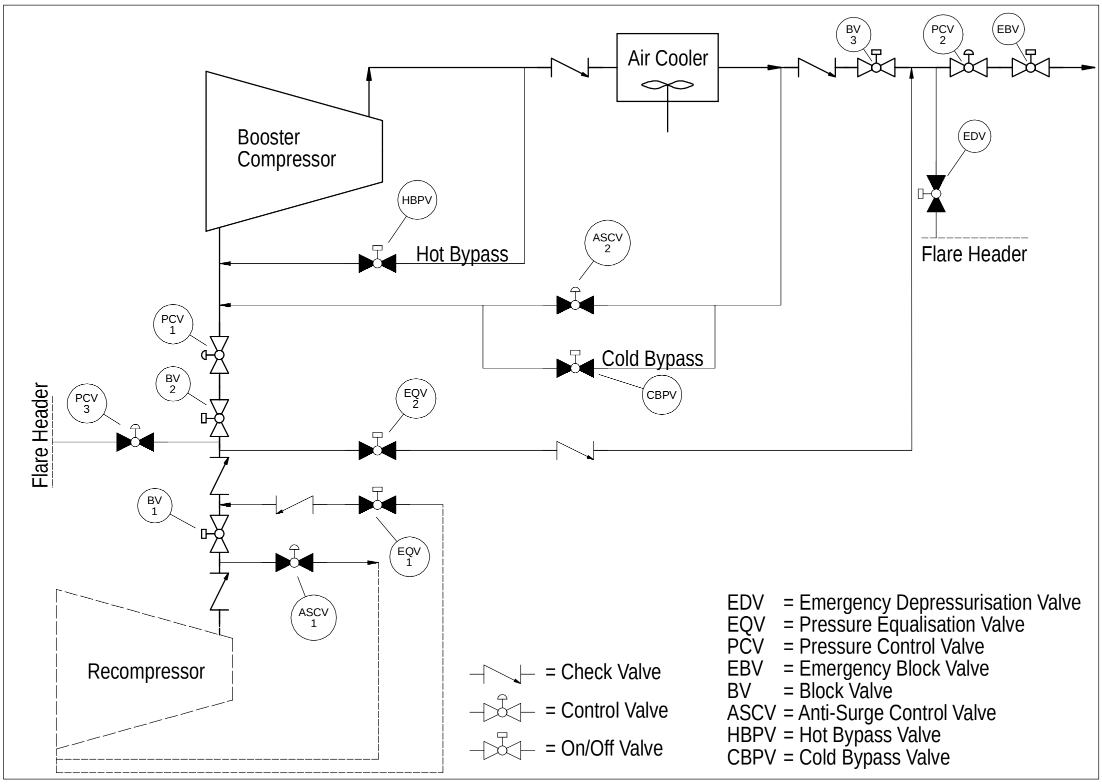

Figure 2.1 – Schematic overview of booster compressor system as simulated with PULSIM.

The hot bypass was perceived to be the preferred concept to prevent surge due to the proximity to the compressor. To prevent overheating, the compressor vendor recommended limiting the capacity of the hot bypass valve to 50% of the ASC valve capacity. The capacity of the cold bypass valve was recommended to be equal or twice the ASC valve capacity. Dynamic simulation helped to quantify the effect of these recommendations. Alternatively, simulation can be used as a design tool to specify cost-effective valve sizes, characteristics and required opening times.

Analysis of the dynamic system response showed that implementation of the *hot bypass* and/or the *cold bypass* can be effective to avoid surge during ESD. The improvement of the response is only marginally better for the hot bypass concept (when comparing identical valves). The temperature response both for the hot bypass and the cold bypass remained well within specifications, even when a hot bypass valve capacity of 100% of the ASC valve was selected.

3.2 Description of the Hot/Cold Bypass Concept

Prevention of Surge

The ASC system uses recycling of the compressed medium to reduce the differential pressure over the compressor and to increase compressor throughput. However, operator experience shows that surge may still occur during ESD, when the ASC system uses a control valve only. A compressor manufacturer stated that this problem can be aggravated by a large compressor discharge volume, which is the case when air-cooled after coolers are used. For this reason the hot bypass and the cold bypass concepts have been developed to prevent surge when a fast response is required in emergency situations (see figure 2.1).

The *hot bypass* is in fact a recycle line located very close to the compressor. The gas that is recycled via this line has not been cooled. The *cold bypass* is a line parallel to the regular ASC valve, thereby retaining the after cooler in the recycle loop. Both the hot and the cold bypass contain on/off valves with a quick opening characteristic. The 'stem travel' speed of these valves is about twice as fast as the ASC valve.

The central idea of both concepts is:

1. To increase the *speed* of response of the recycle flow. A faster response is realised by implementing valve-actuator combinations, which open much faster than a regular anti-surge control valve. This can be achieved by reducing 'stem travel time' and by selecting a quick opening valve characteristic instead of the linear characteristic that is used for the ASC valve.
2. To increase the recycling *capacity* during emergency situations. The extra valve will increase the total recycling capacity during emergency shutdown, which will help to reduce the pressure difference across the compressor at a faster rate.
3. A third way to increase the speed of response of the ASC system in case of emergencies is to limit the effective volume of the compressor suction and/or discharge side. This may be realised under certain conditions by the implementation of a (non-slam) check valve downstream of the hot bypass at the compressor discharge side. This set-up will only be effective when the capacity of the hot bypass exceeds compressor throughput.

Prevention of Overheating

Recycling will lead to heating whenever the compressed gas cannot be cooled to the initial operating temperature at the compressor suction side. This is the case both for the hot bypass and cold bypass concept. *Overheating* is defined as the occurrence of temperatures within the compressor exceeding 180 °C. The actual temperature response at the inlet of the Booster Compressor during an ESD event will depend on a variety of factors, such as:

- The amount of gas recycled via the hot/cold bypass and the regular anti-surge valve
- The decay rate of the speed of the relevant compressors
- The response of the after cooler (air fans)
- The speed of response of all valves actuated upon ESD, with respect to flow.

3.3 Problem Description and Objective

In order to perform a system dynamics study, the objective has to be clearly specified in operational terms. The objective could for instance relate to safety, availability or operability. Consequently, the relevant part of the process, including control and safeguarding functions, should be determined and modelled in sufficient detail. The operating cases should be defined in terms of the state variables of the process, equipment, actuators and controllers. Uncertainties (e.g. valve opening times) have to be identified and should be addressed in a sensitivity analysis.

Objective

The main objective of the analysis is to evaluate the effectiveness of both the hot and cold bypass concept to prevent surge and overheating of the compressor, during a pre-defined ESD event.

Operating Case and Initialisation

The dynamic response of the system is determined starting at a steady-state operating condition. Specific cases have been selected based on data provided by the EPC contractor. The model has been tuned to reproduce the initial stationary process conditions, such as the pressure and temperature profiles.

Process Disturbance

The simulation is started at a steady state operating condition. At t=1 second, several safeguarding actions are executed *simultaneously* as a result of the ESD event. The safeguarding actions are listed below:

- Trip of compressor drivers following an exponential decay curve.
- Opening of the ASC valves, pressure equalisation valves and the hot/cold bypass valve(s).
- Closure of (emergency) block valves.
- No action on control valves and depressurisation valves.

Model Assumptions for Base Case and Sensitivity Analysis

Various assumptions have been made for the base case and the sensitivity analysis.

- Opening/closing time of valves following an ESD, valve characteristics and capacity.
- Trip response of booster compressor speed and recompressor throughput following an ESD
- Pressure response of existing compressor suction manifold
- (Emergency) depressurisation will not occur
- Heat exchange between the gas and the pipe wall is neglected at the time scale of interest
- Cooling of the recycled gas by expansion cooling/Joule Thompson effect is neglected

The sensitivity analysis has been performed for various model parameters. These parameters include the response time and capacity of the anti-surge valve and the hot/cold bypass valves and the compressor decay rates. The principal objective of the sensitivity analysis is to determine the effect on the simulation results, conclusions and recommendations when key parameters are varied within a specific range.

3.4 Simulation Results

The dynamic response of the operating point of the booster compressor as a function of time is presented in figure 2.2. The trajectory has been plotted for 4 anti-surge concepts (combinations of regular ASC, hot and cold bypass) and several valve capacities.

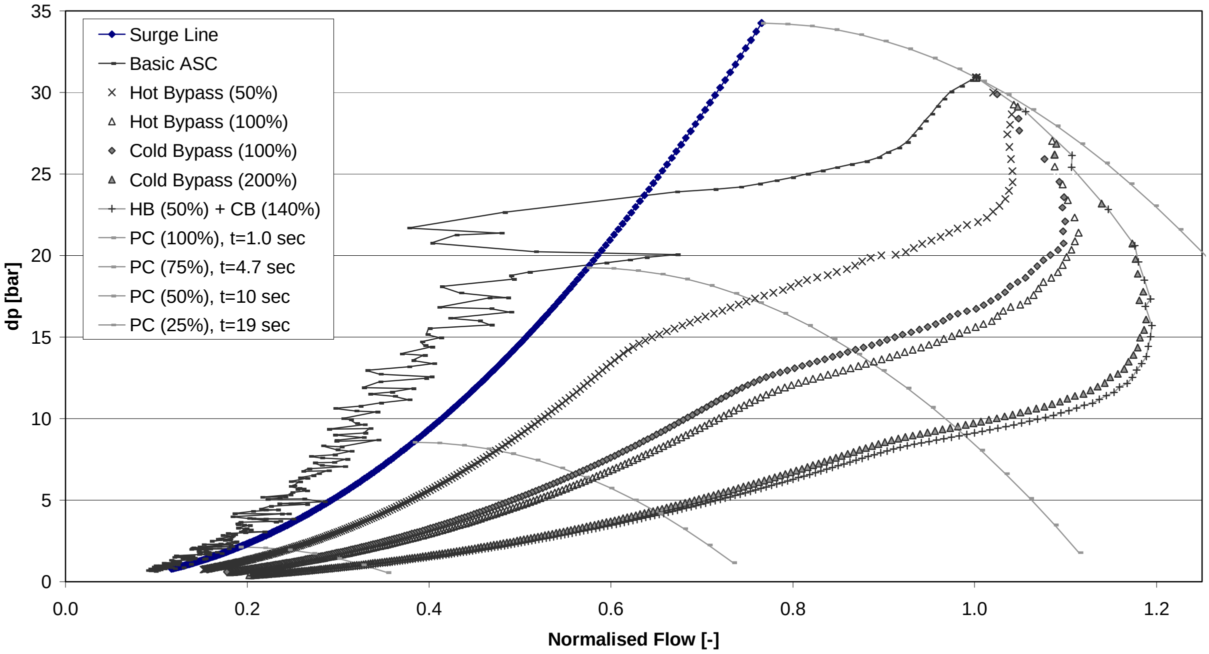

Figure 2.2 - Response of compressor operating point during ESD for various anti-surge concepts. Percentages in the legend indicate the capacity of the Hot/Cold Bypass valves relative to the ASC valve. The capacity of the ASC valve is 65% of rated compressor flow. The performance curves are shown for 100%, 75%, 50% and 25% of rated speed. Total simulation time is 25 seconds.

ASC = Anti-Surge Control; HB = Hot Bypass; CB = Cold Bypass; PC = performance Curve.

As shown in figure 2.2, simulation confirms that the compressor system will go into surge during ESD when only relying on the basic ASC system. Implementation of a hot bypass, a cold bypass or a combination of these will avoid surge during the specified ESD case, if the valve capacity is sufficient. It is interesting to note that the effect of the hot bypass and the cold bypass on the system response is comparable when identical valve capacities are selected. This can be seen when comparing the 100% trajectories of the hot bypass and the cold bypass. Alternatively, the 200% trajectory of the cold bypass is roughly identical to the ‘190%’ trajectory of the combined hot (50%) and cold bypass (140%).

The resemblance can be explained as follows. The discharge piping of the Booster Compressor can be seen to act as a single volume, as the pressure drop along the discharge piping is relatively small due to the large pipe diameter. As a consequence, the tie-in point of the anti-surge line or bypass lines does not significantly affect the response of the compressor operating point for a given valve capacity. When comparing the effectiveness of the hot and cold bypass to avoid *surge*, it can be concluded that both concepts perform similar during the ESD event.

Furthermore it is observed that the check valve at the booster compressor discharge side does *not* close upon ESD. This is the case even when the capacity of the hot bypass valve equals the anti-surge valve capacity. The reason for this is that the regular ASC valve will open relatively fast and simultaneously with the hot bypass valve, upon ESD. The capacity of the hot bypass valve is insufficient to cause backflow in the discharge piping.

Conclusions

As the effectiveness to avoid surge is roughly identical for both concepts, it is recommended to implement the cold bypass concept, even though heating of the recycled gas is only slightly less for the cold bypass concept during ESD.It should be noted that this conclusion is based on a single pre-defined ESD case only. Other operational cases, involving events such as failure of (check) valves or different ESD actions may affect the selection process.

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