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Consider new analysis for flares

Applying dynamic models in designing safety systems can reduce capital costs

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Application of dynamic modeling for relief system design can substantially lower capital expenditure (CAPEX) while simultaneously improving plant safety. This article considers using dynamic analysis to two areas: vessel depressurization (or "blowdown") and flare network design. New modeling methods can accurately quantify relief loads and metal temperatures to enable informed safety and CAPEX decision support.

CASE HISTORY 1: VESSEL DEPRESSURIZATION

Detailed dynamic analysis of the rapid depressurization (blowdown) of high-pressure vessels is a key element of the safety analysis of oil and gas facilities and other high-pressure installations.

Event description. Depressurization of a vessel usually results in cold gas venting into the flare system. The cold gas can significantly lower the temperatures within the process equipment metal walls and pipework, as well as the relief system pipework immediately downstream of the blowdown valves (BDVs). Low temperatures can lead to embrittlement of the equipment and pipework metal walls, and the difference in temperature between adjacent metal sections can result in high thermal stresses. This condition has implications for the integrity of process vessels, pipework and sections of the relief system, as well as for CAPEX.

Accurate analysis of likely relief scenarios is essential to determine:

- **Relief loads entering the flare network.** For new designs, accurate information is needed to achieve an optimal design that minimizes the piping diameters required to meet Mach number and back-pressure constraints. Minimizing the piping sizes also provides benefits in terms of reduced support infrastructure, which can be particularly important in the case of offshore platforms where additional weight is heavily penalized. For revamps or expansions to an existing process plant, accurate data can help determine whether the current flare system can handle the new loads acceptably. In either design scenario, CAPEX savings can be considerable.
- **Temperature throughout the process and pipework metal walls** to identify areas of potential embrittlement, and where (and when) unacceptable thermal stresses are likely to arise. Such information can be used to mitigate potential problems either by controlling the relief rates or by rerouting the relief flows.
- **Temperature of the relieving "gas" streams** (which may actually contain evaporating entrained liquids). This provides essential information for choosing the appropriate material of construction for the critical sections of pipework immediately downstream of the BDV.

The effects of low temperature can usually be addressed by using suitable materials of construction. Unfortunately, in some cases, such materials can be expensive, and it is highly desirable to minimize their use without compromising safety considerations. This requires accurate quantification of flowrates and temperatures of the relieving stream, as well as the minimum temperatures reached in the metal walls.

Complex phenomena. Depressurization of a vessel involves a complex set of coupled physical phenomena that must be characterized accurately to understand behavior and provide suitable design values.

Current depressurization modeling is often performed with off-the-shelf process flowsheeting simulators that use an equilib-

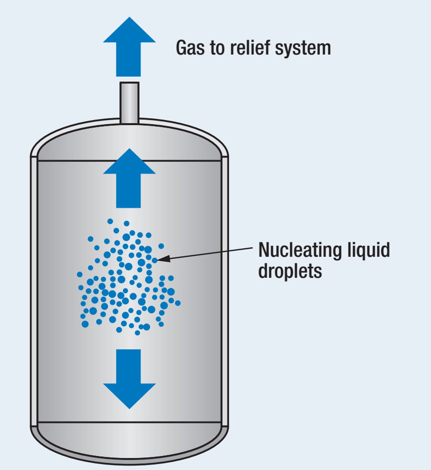

FIG. 1 Formation of droplet phase in blowdown event.

rium thermodynamic approach. The latter provides some indication of the flow and temperature, but by no means adequately describe the complex thermodynamic and kinetic phenomena occurring as a result of rapid decreases in pressure. The fact that multiple phases can form within the vessel, and that these may not be in equilibrium with each other or with the vessel wall, can have a significant effect on both the relief flows and metal temperatures of the vessel and relief system pipework.

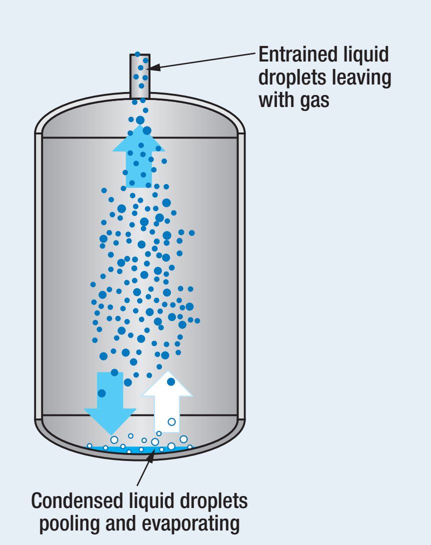

FIG. 2 Droplets exiting in the gas stream and forming a continuous liquid phase on the vessel bottom.

The sudden decrease in pressure in a gas-filled vessel results in a rapid change in the thermodynamic state of the gas within the vessel. This can result in nucleation of liquids within the gas bulk to form a "droplet phase" as shown in Fig. 1. Some of the nucleated liquid leaves as entrained droplets in the high-velocity gas exit stream (Fig. 2). Downstream of the vessel, and as the pressure further reduces, this exiting entrained liquid evaporates into the bulk gas stream, lowering the temperature of the cold exiting stream even further. This creates a risk of brittle fracture of the flare system pipework.

Some proportion of the liquid remaining in the vessel drops to the vessel floor. Initially, this evaporates instantly due to the warm temperature of the metal it encounters. The effect is similar to a drop of water falling on a hotplate. However, once the metal has cooled sufficiently (typically after a few tens of seconds), liquid begins pooling (Fig. 2) and forming a continuous liquid phase.

The pool boils vigorously, cooling and reducing in size, and, in turn, reducing the temperature of the metal beneath it. This event can lead to significant temperature differences between the metal immediately below the pool and its surroundings—presenting a very real threat of brittle fracture and rupture of the vessel base.

The effect of the phenomena can be seen graphically in Fig. 3, which shows the results of depressuring a vessel filled with light-hydrocarbon gas at 120 bar. In the initial phase of depressurization, the gas temperature (black line) drops rapidly. The temperature of the metal wall in contact with the gas (green line) begins to drop, but much more slowly because of the resistance to heat transfer between between wall and gas and heat conduction within the wall. After about 80 seconds, a droplet phase begins to form throughout the gas. Initially, droplets in contact with the metal heat up rapidly and vaporize (red spike). When cool liquid droplets (at a temperature close to that of the bulk gas) begin to pool on the vessel floor, the liquid temperature increases further above the bulk gas temperature as the liquid is heated by the metal wall and changes in composition. After a while, the gas bulk temperature begins to rise because of heat influx from the metal wall.

The items of most concern are the rapidly decreasing temperature of the metal in contact with the liquid pool (blue line) and the difference between the temperature of this metal and the adjacent metal contacting with the gas (green line). The metal temperature can be seen to drop to nearly –30°C, approaching the brittle fracture temperature for carbon steel. The temperature difference between vessel floor and sides rapidly increases to over 20° and is nearly 40° by the end of the blowdown, which may give rise to unacceptable stress.

Because of the rapid change of conditions, the three phases coexisting in the vessel (gas, droplet and a pool of liquid,) and the vessel walls are not in equilibrium with each other throughout most of the blowdown event. In comparison, the dotted line shows the equivalent temperature curve obtained using an equilibrium model for the same blowdown, which predicts a much less severe drop in temperature. This model fails to identify the most significant safety-related aspect—the cooling effect of the liquid on the vessel bottom.

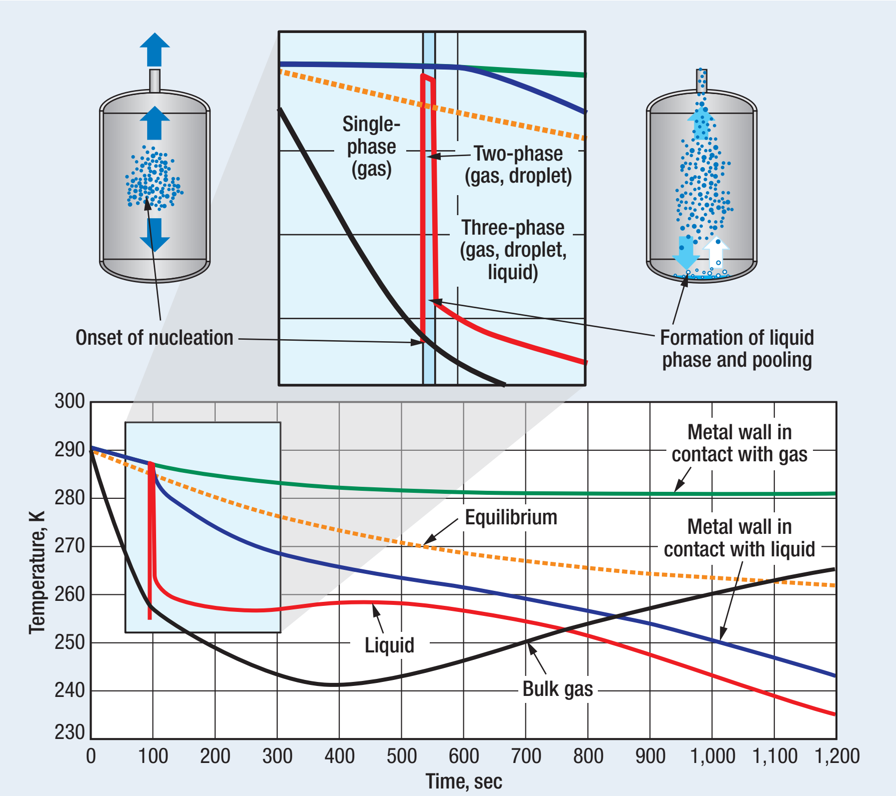

FIG. 3 Temperature profiles over the duration of the blowdown event.

Fig. 4 shows the resulting vessel wall temperatures and associated thermal stresses for the vessel vertical walls as color temperature plots. This information would not be available without rigorous modeling of the nonequilibrium mass and energy transfer between phases. This example describes just one scenario. Other scenarios may develop depending on the initial inventory and state of the material in the vessel. For example, there may be "bubblet" nucleation in super-critical fluid, rather than the droplet nucleation described here.

CASE HISTORY 2: FLARE NETWORK Conventional flare header design techniques use peak relief flows in steady-state simulation to assess system capacities and determine back-pressures downstream of blowdown valves (BDVs) and pressure safety valves (PSVs), Mach number in the headers, and radiation at the flare tip.

This steady-state assumption is highly conservative. While conservative approaches may be desirable in safety system design, they can nevertheless lead to gross overdesign throughout the system. Key areas of over design include:

Oversized flare header. Sizing the header for the sum of the maximum flows takes no account of effects such as:

- System packing, where the gas pressurizes the available volume in the flare network
- Potential for sequencing of flare events. For example, depressurization initiated deliberately by an operator may be complete well before a fire causes PSVs to lift. Steady-state peak flow analysis, on the other hand, assumes that all events occur simultaneously.

Reducing the peak flows used as the design basis by judicious analysis can significantly reduce pipe sizes and materials and fabrication costs, which can be substantial for large-diameter headers. Reducing the size also creates knock-on savings related to the support structure and flare stack size.

Oversized flare stack. The flare stack sizing depends on radiation emitted by the flame, which is a function of the volumetric gas flowrate through the flare tip. Using unrealistically high flowrates determined from peak flows results in an overlong stack, creating weight problems in offshore facilities or adding stack support costs (or unnecessary additional header length) in onshore facilities. Similarly, a lack of accurate temperature information leads to a wide span between the minimum and maximum design temperatures used for gas arriving at the stack, resulting in unrealistic allowances for thermal expansion and contraction.

Over-use of expensive alloys. Although flare system pipework may be in contact with gas at extremely low temperatures, this typically occurs for a relatively short duration. The use of steady-state flows does not consider the duration of such exposures to low temperature, which may result in very conservative and expensive application of alloys.

It can be argued that a good flare network design is one that minimizes capital expenditure while meeting all safety constraints. Overdesign should be avoided wherever possible.

By making simple dynamic analyses using data that is mostly already available in some form, it is often possible to refine network designs to arrive at systems with a significantly lower capital cost while demonstrably meeting safety requirements. Similarly, it is often possible to find additional capacity during retrofits, thus removing the need for additional capital expenditures.

Typical examples of where dynamic analysis can bring significant new information that has an impact on capital cost are:

Peak flowrates. The actual relief flow through any PSV is at the maximum only for a short period. Using steady-state methods based on peak flows is equivalent to making the assumption that all relief flows start at the same time and go on forever. In reality, it is often possible to take credit for staged or staggered relief. Shifting depressurization of certain units by a few tens of seconds can make a significant difference to the peak flows through the system—an effect that cannot be represented at all by steady-state simulation.

Packing. Steady-state approaches make the implicit assumption that the flare system has no volume—what goes in comes out, instantly. For larger systems, the impact of relief flows is partially "absorbed" by pressurization of the flowing lines and the dead volumes in non-flowing parts of the system. This "packing" effect can reduce both the calculated peak back-pressures or Mach numbers and

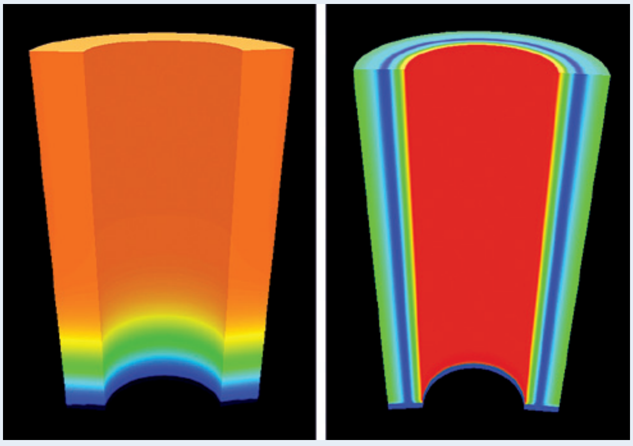

FIG. 4 4a. Wall temperatures at the end of the blowdown; 4b. Wall thermal stresses from the effects of pooling liquid.

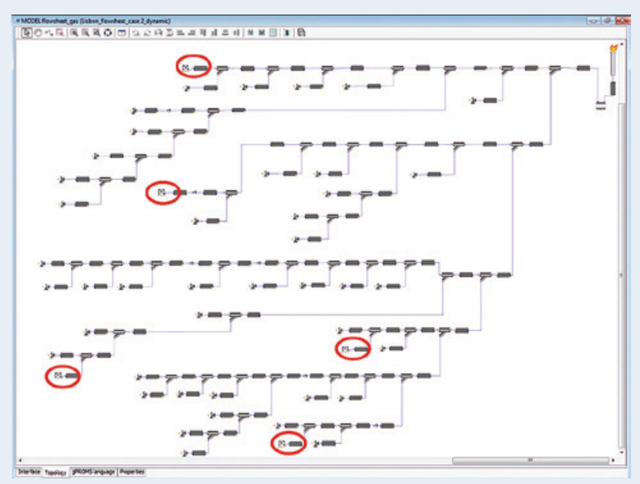

FIG. 5 Example of a flare network showing active sources.

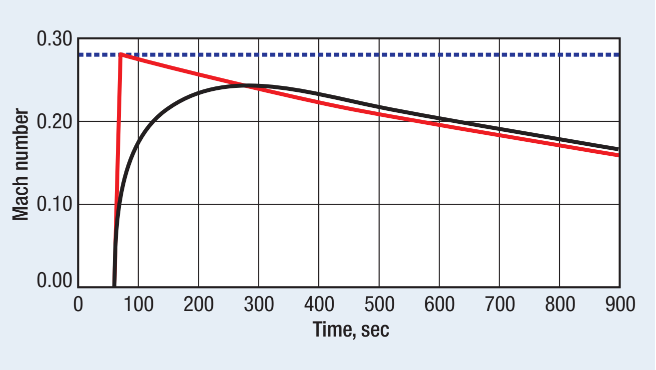

FIG. 6 Mach numbers of 24-in. header in a flare system.

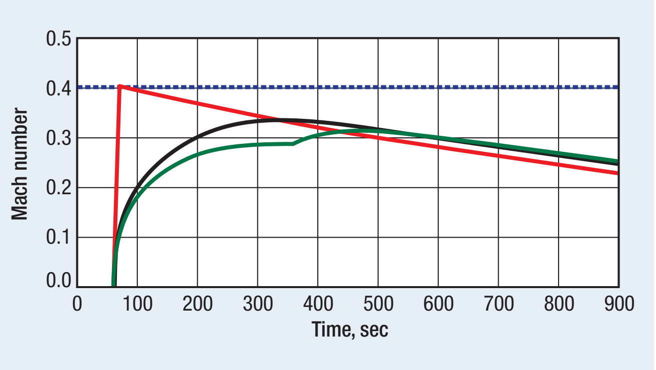

FIG. 7 Mach numbers of 20-in. header in a flare system using a staggered blowdown.

TABLE 1. Back-pressures for 24-in. header case

Inlet source	Back-pressure, bar
Train_1_DP	1.63
Train_2_DP	1.75
Train_3_DP	1.63
Train_4_DP	1.79
Train_5_DP	1.68

TABLE 2. Back-pressures for 20-in. header case

Inlet source	Back-pressure, bar
Train_1_DP	2.23
Train_2_DP	2.32
Train_3_DP	2.23
Train_4_DP	2.34
Train_5_DP	2.27

the peak flows seen at the flare tip, allowing reduction in header and tailpipe diameters and flare stack lengths, respectively. Dynamic simulation allows this important buffering effect to be taken into account in the design.

Duration. Equally important, dynamic simulation can be used to determine the duration of peak flare loads. Engineering judgment can then be used to assess the risks of any infringements. For example, a 5-second violation of back-pressure or radiation constraints may well be acceptable, especially given the capital costs of oversizing the flare system to avoid such a contingency.

Temperature. Relief system pipework that is likely to encounter low temperatures needs to be constructed from expensive alloys such as Inconel to avoid the possibility of embrittlement and consequent fracture. The true extent of pipework that truly needs to be constructed of such materials is impossible to gauge with steady-state simulation, as low-temperature flows are considered to continue forever, ensuring that calculated metal temperatures reach their minimum. In reality, such flows may only last for a few minutes; the thermal inertia of the pipework metal and heat gain from the environment prevent the pipework from reaching the gas temperatures during this time (a similar effect can be seen in the bulk gas and metal temperature plots in Fig. 3). It is frequently possible to reduce the usage of alloy significantly based on the more accurate information from the dynamic analysis. One oil company reported saving $1.5 million on a single vessel this way.

Flare-stack temperatures. Dynamics can also help provide a true picture of the temperature of gas arriving at the flare tip. Proper calculation of the effect of low-temperature gas over a short time taking into account metal-thermal inertia and ambient heating provides much more accurate minimum and maximum design temperatures, allowing the designer to make sensible decisions on stack length and support mechanisms.

Example. Consider the flare system shown in Fig. 5, where the header sizes are set primarily by a depressuring scenario from five units simultaneously, as highlighted in the figure. One of the key questions is the size of the long main-header pipe leading to the flare stack. Typically, such a system is designed by working back from the flare tip, sizing all the lines based on velocity constraints until reaching the relief valves, and then confirming that other constraints, such as back-pressure constraints at the relief valves and limits on noise, are not violated.

In this study, a system has been designed using steady-state techniques using a velocity heuristic requiring a Mach number between 0.25 and 0.35 in the main lines. A conventional steady-state approach calculates the Mach number using the sum of the peak flowrates. The maximum Mach number at the pipe outlet is represented by the dotted line in Fig. 6. At 0.29, this is well within the 0.25–0.35 range. The back-pressures at the five blowdown valve sources are listed in Table 1; these are well below the limit.

For illustration, it is useful to do a "pseudo-dynamic" run, using relief flow curves but taking no account of the flare system volume. This shows a Mach number profile over time that has the characteristic sharp-peaked shape of relief flow curves (red line in Fig. 6). As expected, the peak Mach number from this run is the same as for the steady-state case, at the sum of the individual peak flows. Although this case adds no new information to the design, it does provide some indication of the length of the blowdown event, allowing judgment to be applied in the case of constraint violation.

If a full dynamic simulation is done, taking the volume of the system (both for active and inactive branches) into account, it can be seen that the effect of flare system packing significantly reduces the peak Mach number observed, to about 0.25. It is evident from these results that there may be potential to reduce the diameter of the 24-in. header, as the Mach number is nowhere near its limit.

A new series of calculations is performed with a 20-in. header diameter to see the effect of reducing the flare system line sizes. As expected, the Mach number obtained using steady-state peak flows (0.4) violates the system design constraints, indicating that the design is not viable (Fig. 7, dotted line). The corresponding pseudo-dynamic case shows (Fig. 7, red line) that the value is out of range for about three minutes, which is also unacceptable. However, a full dynamic simulation taking into account line packing shows that the peak Mach number is within the 0.35 limit (Fig. 7, black line); the back-pressures (Table 2) remain well within the limits. The added information provided by the dynamic simulation thus indicates that the design is indeed viable.

If further mitigation is required, it is possible to investigate the dynamic effects of staggering the depressurization, so that units depressure in sequence. The green line in Fig. 7 shows the effect on Mach number of delaying the blowdown of Unit 2 by several minutes. Similar approaches can be applied to retrofit cases, often demonstrating that it is possible to accommodate additional sources in an existing flare system that is ostensibly operating close to its limits.

Conclusion. The dynamic simulation capabilities of modern software tools provide a number of options for analyzing both the depressurization event—to determine accurate relief flows and fluid thermodynamic conditions—and the flare header design itself. This enables engineers to design systems that comply with safety guidelines based on a much more realistic representation of behavior than traditional methods allow, and, at the same time, to identify opportunities for significant capital savings.

In the case of depressurization, rigorous dynamic simulation identifies potentially dangerous situations. For new flare system designs, it can lead—among other benefits—to a reduction in header size, resulting in significant capital savings. For existing headers, it provides a means to establish whether there is sufficient capacity to accommodate new sources, thereby avoiding the need for a new header and flare. **HP**

BIBLIOGRAPHY

Haque, M. A., S. M. Richardson, and G. Saville, "Blowdown of Pressure Vessels. I—Computer Model," *Transactions of the Institute of Chemical Engineers Part B: Process Safety Environmental Protection,* 70(BI), 1, 1992.

Mafgerefteh, H. and S. M. A. Wong, "A numerical blowdown simulation incorporating cubic equations of state," *Computer Chemical Engineering,* Vol. 23, p. 1309, 1999.

Gruber, D., D.-U. Leipnitz, P. Sethuraman, M. A. Alos, J. M. Nougues and M. Brodkorb, "Are there alternatives to an expensive overhaul of a bottlenecked flare system?" *Petroleum Technology Quarterly* Q1, 2010.

Chen, F. F. K., R. A. Jentz and D. G. Williams, "Flare System Design: A Case for Dynamic Simulation," Offshore Technology Conference, May 4–7, 1992, Houston.

Goyal, R. K. and E. G. Al-Ansari, "Emergency Shutdown devices and relief system sizing and design in oil refineries," *Hydrocarbon World,* Vol. 4, No. 1, Touch Briefings, 2009.

Speranza, A. and A. Terenzi, *Blowdown of Hydrocarbons pressure vessel with partial phase separation,* Series of Advances in Mathematics, available from http://www.i2t3.unifi.it/upload/file/Articoli/animp_2004.pdf, 2005.

Szczepanski, R., "Simulation programs for blowdown of pressure vessels," IChemE SONG Meeting, 1994.

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