Part 1

Evaluate Heat-Exchanger Tube-Rupture Scenarios Using Dynamic Simulation

Applying dynamic simulation models to tube-rupture scenarios can help ensure more accurate sizing and hazard assessments

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IN BRIEF

FIGURE 1. Heat exchangers in many CPI applications can experience tube rupture, and these scenarios must be evaluated and addressed in order to ensure continued safe operations

Tube rupture in heat exchangers is an extremely serious issue in the chemical process industries (CPI; Figure 1). Heat-exchanger tube-rupture scenarios can be evaluated by various means, including dynamic and steady-state process simulation. Performance of reliable dynamic simulations of tube-rupture scenarios requires suitable experience, expertise and significantly higher effort than steady-state evaluations. This article discusses a number of heat-exchanger tube-rupture scenarios, including: the requirements for scenario evaluation; tube-rupture flow estimation; selection and sizing of relief devices and associated piping; and guidelines for identification of situations where a dynamic evaluation is appropriate.

In addition, several dynamic-simulation case-study summaries are presented, illustrating the utility of this method in the proper selection and sizing of relief systems. Special emphasis is given to liquid-filled systems, which see very rapid pressure-rise rates upon tube rupture. These cases show that dynamic evaluation can lead to better relief-device selection and sizing, as well as improved materials selection for various conditions, including some that do not require dynamic evaluation under American Petroleum Institute (API; Washington, D.C.; www.api.org) guidelines.

TABLE 1. SUMMARY OF TUBE-RUPTURE SCENARIO DYNAMIC EVALUATION CASES

HP Fluid/ LP Fluid		Natural gas/ Propane evaporator	Natural gas/ Propane condenser	Natural gas/ LP steam [8]	Hydrotreater effluent/ Stripper bottoms [6]	Natural-gas condensate / Liquid propane	Ethylene / Liquid propylene [7]	Ethylene / Liquid methanol [7]
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Design pressure (HP/LP)	barg	89 / 17	89 / 17	149 / 5.5	183 / 128	89 / 17	111 / 18.9	111 / 17.2
Operating pressure (HP/LP)	barg	69 / 1	67 / 8	113 / 3.5	158 / 19	43 / 7.2	101 / 11.9	101 / 36
Operating temperature (HP/LP)	°C	–16 to –20 / –24	2 to 10 / 18	3 to 80 / 147	275 to 310 / 230 to 290	–20 / 18	–26 to 11 / 25	11 to 15 / 64
Blocked-in pressure-rise rate	bars/s	0.16	0.92	5	74	67	28	64
Set pressure, P_{set}	barg	17	17	5.5	23/24.1	17	16.2	11.8
Relief device		PSV	PSV	PSV	PSV (3)	Rupture disk	PSV	PSV
Peak pressure, P_{max} P_{max}/P_{set}	barg	18.4 8.2%	18.2 7%	6 9%	37.7 64%	17.05 0.3%	20.5 26%	16 36%
Peak rupture flow	kg/s	3.7	3.6		17.1	5.7	13.4	7
Peak relief flow	kg/s	4.6	7.8	12.5	338.9	165.2	Not reported	Not reported

Note: Cases 4 through 7 refer to exchangers that are liquid-filled on the LP side

Evaluation criteria

Process-hazard analyses for shell-and-tube heat exchangers call for evaluation of tube-rupture scenarios if the difference in maximum allowable working pressure (MAWP) between the low-pressure (LP) and high-pressure (HP) sides is greater than that covered by the 10/13 (or 2/3 rule, as may be applicable). This is based on ASME Boiler and Pressure Vessel Code Section VIII, Div.1 [*1*], which requires a system to be hydro-tested at 130% of its MAWP.

This code requirement eliminates the need to evaluate a tube-rupture scenario, as the LP side is protected if its design pressure is no less than 10/13 of the HP side's design pressure. API-521 6th Ed. [*2*] notes that "Pressure relief for tube rupture is not required where the low-pressure exchanger side (including upstream and downstream systems) does not exceed the criteria noted above. The tube-rupture scenario can be mitigated by increasing the design pressure of the low-pressure exchanger side (including upstream and downstream systems), and/or assuring that an open flow path can pass the tube-rupture flow without exceeding the stipulated pressure, and/or providing pressure relief."

This option is often used to eliminate a tube-rupture scenario evaluation. However, for an exchanger with a large pressure difference between the HP and LP sides, uprating the LP side design pressure can be expensive, and a tube-rupture scenario evaluation is necessary. The required activities in a tube-rupture scenario evaluation are detailed in the following sections.

Tube-rupture flow estimation

API 520, Part 1 [*3*] provides the necessary guidelines and equations for single- and two-phase flow estimation. For two-phase flow, API-521 [*2*] recommends the following: "A two-phase flow method should be used in determining the flowrate through the failure for flashing liquids or two-phase fluids. The flow models developed by DIERS (the Design Institute for Emergency Relief Systems) and others can be adapted for this purpose. In cases where the fluid flashes at the low-pressure side of the heat exchanger, two-phase flow methods based on the homogenous equilibrium model (HEM), such as those proposed by DIERS, may be used for the flow through the tube to the break."

Darby's work in this area [*4*] also presents a good summary of these steady-state sizing methods, including the homogenous direct-integration (HDI) method.

Relief-device selection

In systems where the shellside-tubeside pressure difference is high, the pressure rise on the LP side can be very rapid. In those cases, relief valves provided to protect the LP side from overpressure may not respond quickly enough to protect the system. Such a scenario may call for the installation of a rupture disk.

Many companies have developed their own practices for identifying scenarios that require protection with rupture disks. Some companies prefer that the rupture disk is mounted directly on the exchanger — not on the inlet or outlet piping — because the disk might not react fast enough with the intervening pipe. This is not always practical to implement, since other factors must be considered, such as layout constraints or free-draining requirements for two-phase or liquid-relief lines. Thus, it is recommended that rupture disks be installed as close as possible to, if not directly on, the heat exchanger.

Liquid-filled systems, especially those filled with an incompressible liquid, such as water on the LP side, can experience a very rapid high-pressure spike upon tube rupture. Even a rupture disk may not be able to respond. Multiple disks at different locations on the exchanger itself may be required. Depending on the toxicity, flammability and reactivity of the fluids, consideration of tube-rupture-relief contingency may be advisable, even if the 10/13 rule is followed. The acoustic pressure wave that occurs

RECOMMENDATIONS ON DYNAMIC MODELING FROM API-521 [*1*]

> "A one-dimensional dynamic model can be used where the approach is to simulate the pressure profile and pressure transients developed in the exchanger from the time of the rupture. These methods generally include the dynamic model of the tube-rupture relief scenario and the response time of the relief device, the accuracy of which is critical in calculating the accuracy of pressures generated. The opening time for the device used should be verified by the manufacturer and should also be compatible with the requirements of the system.
>
> This type of analysis is recommended, in addition to the steady-state approach, where there is a wide difference in design pressure between the two exchanger sides [for example, 7,000 kPa (~1,000 psi) or more], especially where the low pressure side is liquid-full and the high-pressure side contains a gas or a fluid that flashes across the rupture. Modeling has shown that under these circumstances, transient conditions can produce overpressure above the test pressure, even when protected by a PRD (pressure-relief device). In these cases, additional protection measures should be considered."

in the case of incompressible-liquid-filled systems results in a waterhammer-type effect that cannot be simulated with the dynamic simulation tools commonly used for analysis of these scenarios. Sometimes a rupture pin is also considered, allowing faster open times than rupture disks. Typical opening times for relief devices are 50–100 milliseconds (ms) for spring-loaded pressure safety valves (PSVs) and around 1–10 ms for graphite rupture disks [*5*].

The capacity of a relief device handling high pressure-rise rates can be estimated using Equation (1), taking into account the pressure relief device's (PRD) opening capacity (*OC*), set pressure (*SP*), allowable overpressure (*AOP*) and relief-valve opening time (*T*).

$$OC = SP \times AOP/T \qquad (\mathbf{1})$$

For example, for a PSV with a set pressure of 5.5 bars, with 10% overpressure allowed, and an opening time of 100 ms (0.1 s), *OC* = 5.5 bars × 0.1/0.1 s = 5.5 bars/s.

The blocked-in pressure-rise rate (where no credit is taken for any flow out of the exchanger) calculated in dynamic runs can be compared with the PRD opening capacity to determine the suitability of the selected type of relief device. If the PRD's opening capacity is lower than the blocked-in pressure-rise rate, the device may not be able to open sufficiently in time to capture the pressure rise.

Relief-device sizing

The steady-state calculation procedures described previously are applicable to tube-rupture flow estimation. However, sizing of the relief device itself and its inlet and outlet lines requires relief-flow estimation. The API-521 [*2*] guideline states that for steady-state relief device sizing, "PRD size should be based on the gas and/or liquid flow passing through the rupture."

The volumetric flowrate of the LP fluid equivalent to the volumetric flowrate of the HP fluid passing through the rupture location should be used when the fluid properties at the relief location are significantly different from those at the rupture location, or when the relief device is located at some distance from the exchanger. Alternately, API-521's recommendations with regard to dynamic modeling are shown in the box above.

In summary, API-521 recommends that for exchangers with differential pressures of less than 70 bars, relief-device sizing should use the tube-rupture flow estimate. For exchangers with differential pressures greater than 70 bars, use a dynamic simulation of the system to estimate relief flows and relief-device sizing.

Other situations where a dynamic evaluation is sometimes considered are the following:

- Exchangers with liquid-filled shells
- Sizing of relief piping, because steady-state methods can lead to oversized relief piping, especially for short, sharp-peak relief flows, as pipe holdup effects are not considered
- Long shells with baffles on a tight pitch
- For existing units where the overpressure protection was mounted on the relief piping
- For existing units with high differential pressures where a relief valve was used

Examples

Several tube-rupture dynamic-simulation studies are presented in the following sections. Cases 1 through 5 are recent tube-rupture studies that utilize commercial dynamic-simulation software. In these cases, the heat exchanger's LP side is split into several volume segments to facilitate the observation of the physical phenomena occurring during the rupture event. The details of this approach are discussed in Ref. *6*. Cases 6 and 7, as reported by Ennis and others [*7*], are also discussed here for comparison with these results for liquid-filled tube-rupture cases. Table 1 gives a summary of the cases.

Case 1: Natural-gas propane chiller. Natural gas is cooled in a chiller to reduce the hydrocarbon dewpoint, where liquid propane evaporates at 1 barg and –24°C on the shellside. The natural gas is on the tubeside at 68 barg pressure and temperatures around –16 to –20°C. The exchanger in this example is specified as type AKL based on Tubular Exchanger Manufacturers Association (TEMA; Tarrytown, N.Y.; www.tema.org) standards. TEMA exchanger-type codes, such as AKL, provide a shorthand for basic designs and manufacturing methods of heat exchangers. For more information on TEMA standards and codes, see Specifying Shell-and-Tube Heat Exchangers, *Chem. Eng.*, May 2013, pp. 47–53. Dynamic evaluation of a single-tube, full-bore rupture in this exchanger indicated a slow pressure-rise rate of 0.16 bars/s in the shell, as the pressure rises from 1 barg operating pressure to 17 barg relief pressure in 100 s. A spring-operated safety valve is adequate to protect the LP side of the exchanger for this scenario.

Figure 2 shows the exchanger shellside segmentation considered for the simulations. Figure 3 shows the temperature, pressure and flow transients for the run. In this run, the rupture was considered at the extreme left of the exchanger in segment V1. The gas cools as it expands

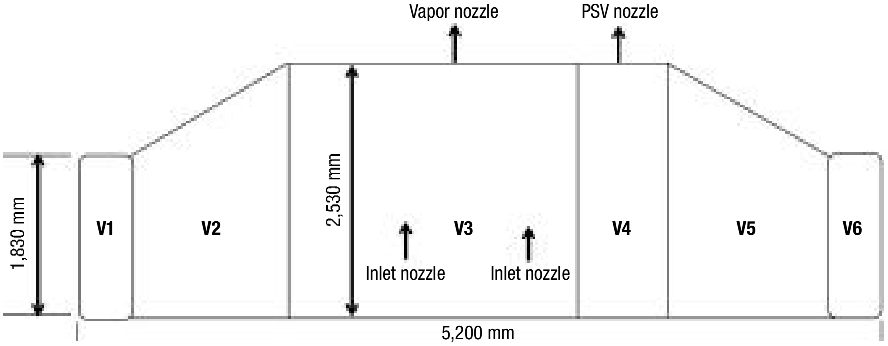


FIGURE 2. This schematic shows an exchanger shellside segmented into several volumes to facilitate the observation of the physical phenomena occurring during the rupture event. In this case, HP gas flows from left to right, the propane liquid level in the shellside is 1,800 mm and the tubes are not shown

on the LP side upon flowing across the tube rupture, resulting in its temperature dropping to –67°C immediately after rupture, and subsequently increasing as the shellside pressure rises. While the fluid temperature in the shellside is estimated to drop to a minimum of –48°C near the rupture location, direct impingement of the rupture fluids on the intact adjacent tubes, shell and tubesheet is possible. Conservative design practices led to a selection of the minimum design metal temperature (MDMT) for the exchanger based on the minimum rupture fluid temperature. These calculations did not consider the thermal inertia of the metal mass in the system, inclusion of which can allow a higher MDMT selection.

Case 2: Natural-gas-cooled refrigerant condenser. A propane-refrigerant-based natural-gas dewpointing plant utilizes the cooled, dewpointed gas to condense refrigerant discharging from compressors. Refrigerant at 5–8 barg condenses on the shellside, whereas HP natural gas at 67 barg flows on the tubeside of the exchanger, which is TEMA type BEM. Dynamic evaluation of a single-tube, full-bore rupture in this exchanger indicated a relatively slow pressure-rise rate of 0.92 bars/s in the vapor-filled shellside, as the pressure rises from 8 barg operating pressure to 17 barg relief pressure in 9.8 s (Figure 4).

A spring-operated safety valve is adequate to protect the LP side of the exchanger. The dynamic simulation indicated that a PSV size based on the tube-rupture flow is inadequate to limit the pressure rise to be within the required 10% overpressure. The PSV size was increased, and while this leads to an increased peak relief above the tube-rupture flow, the peak pressure rise can now be contained to the prescribed limit.

Case 3: Natural-gas heating with LP steam. This study's work [*8*] focused on HP natural gas on the tubeside of an exchanger heated with condensing LP steam on the shellside in a TEMA-type BEM exchanger. The natural gas is at 113 barg pressure and the temperature ranges from 3.2 to 80°C. The LP steam is at 3.5 barg and 147°C. The set pressure on the relief device protecting the LP side is 5.5 barg.

Dynamic evaluation of a single-tube, full-bore rupture in this exchanger indicated a shellside pressure-rise rate of 5 bars/s, increasing from 3.5 barg operating pressure to 5.5 barg relief pressure in 0.4 s. Upon relief valve opening, the pressure-rise rate drops to 0.27 bars/s. It was determined that this pressure-rise rate is acceptable for the installation of a spring-loaded relief valve. The study also indicated that the PSV set pressure should be set lower than the exchanger design pressure, as the pressure near the tubesheet can be higher than at the PSV inlet due to inlet line losses.

Case 4: Hydrotreater effluent stripper-bottoms exchanger. A hydrotreater effluent stream is cooled against the stripper bottoms stream of the unit in a shell-and-tube heat exchanger. The exchanger comprises two shells in series, with the HP hydrotreater effluent on the tubeside at 158 barg and temperatures of 275–310°C. The stripper bottoms pressure on the shellside is 17–19 barg and the temperature is 230–290°C. The shellside design pressure was originally selected as 128 barg, based on the 10/13 rule. Dynamic evaluations for single and multiple tube-rupture scenarios were executed [*6*]. On tube rupture, a very rapid pressure rise in the liquid-filled shell was estimated at 74 bars/s, with pressure rising from 18.9 barg operating pressure to 23 barg relief-valve set pressure in just 55 ms. Peak pressure rise in the shell protected with one, two or three spring-loaded relief valves was estimated. The dynamic runs indicated that the peak pressure rise can be limited to 37.7 barg, 50.1 barg and 81.4 barg using three, two, and one PSVs, respectively. Thus, a significant margin for shell design-pressure reduction is available below the originally selected design pressure of 128 barg. The study showed that despite the rapid pressure-rise rate, PSVs with a set pressure selected well below the design pressure to capture the pressure rise can, in fact, be used to lower the LP design pressure.

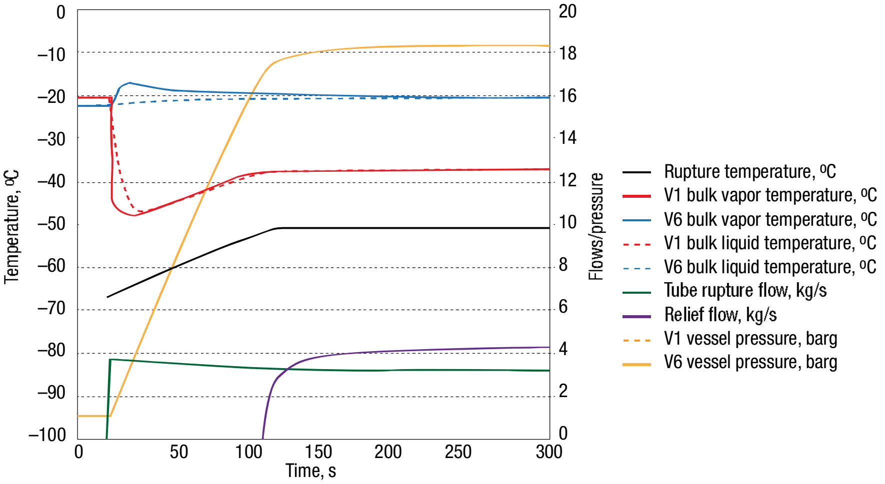


FIGURE 3. Case 1's tube-rupture event occurs 18 s into the run, while relief flow starts at 118 s into the run. Note that the temperature rises in segment V6 due to pure compression without exposure to cold rupture fluids

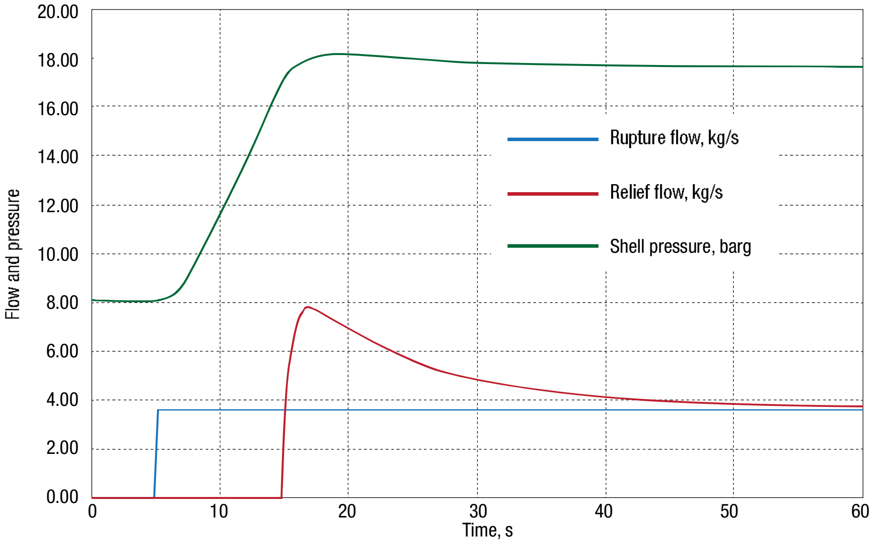


FIGURE 4. For Case 2, this transient diagram shows the exchanger LP shellside pressure rise on tube rupture, rupture flows and relief flows, for a PSV set pressure of 17 barg

Case 5: Liquid propane cooled by natural-gas condensate. A propane-refrigerant-based natural-gas dewpointing plant uses natural-gas condensate to sub-cool liquid refrigerant. Liquid propane at around 5–8 barg pressure is on the tubeside, and HP natural-gas condensate at 43 barg flows on the shellside of the exchanger, which is TEMA type AEL. The condensate state is two-phase, vapor-liquid in and out of the exchanger. Dynamic evaluation of a single-tube, full-bore rupture in this exchanger indicated a fast pressure-rise rate of 65 bars/s in the liquid-filled tubeside. The pressure rises from an operating pressure of 7.2 barg to 17 barg relief pressure in 0.15 s.

A rupture disk was selected as the relief device. Dynamic simulation of this scenario was carried out, and shows that the peak relief flow on disk rupture in liquid-filled systems can be an order of magnitude higher than the associated tube-rupture flow driving the event, as shown in Figure 5. The dynamic model was used for sizing the rupture disk's inlet and outlet lines based on the transient relief flows, with the criteria that the LP side must stay below the allowable design overpressure.

Accurate modeling of this system involving two-phase choked flow in pipes is a challenge, even with the advanced dynamic simulations packages available commercially. A commercial simulation model, which uses a momentum conservation equation based on Darcy's law, was used in this study to model the rupture disk's inlet and outlet lines. The exchanger tubeside was modeled using three volume segments, one each for the channels, and one to account for the volume of the intact tubes. Figure 6 shows the simulation process flow diagram (PFD) used for the transient analysis.

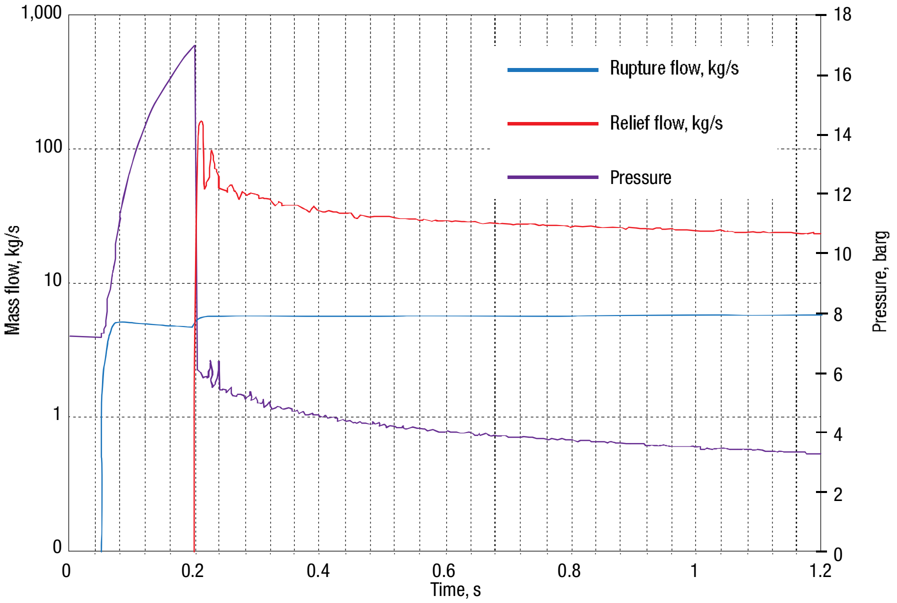


FIGURE 5. Case 5's rupture occurs 0.05 s into the run, followed by rapid pressure rise to rupture disc burst pressure of 17 barg at 0.2 s. Initial relief flow can be seen to be significantly higher than the rupture flow

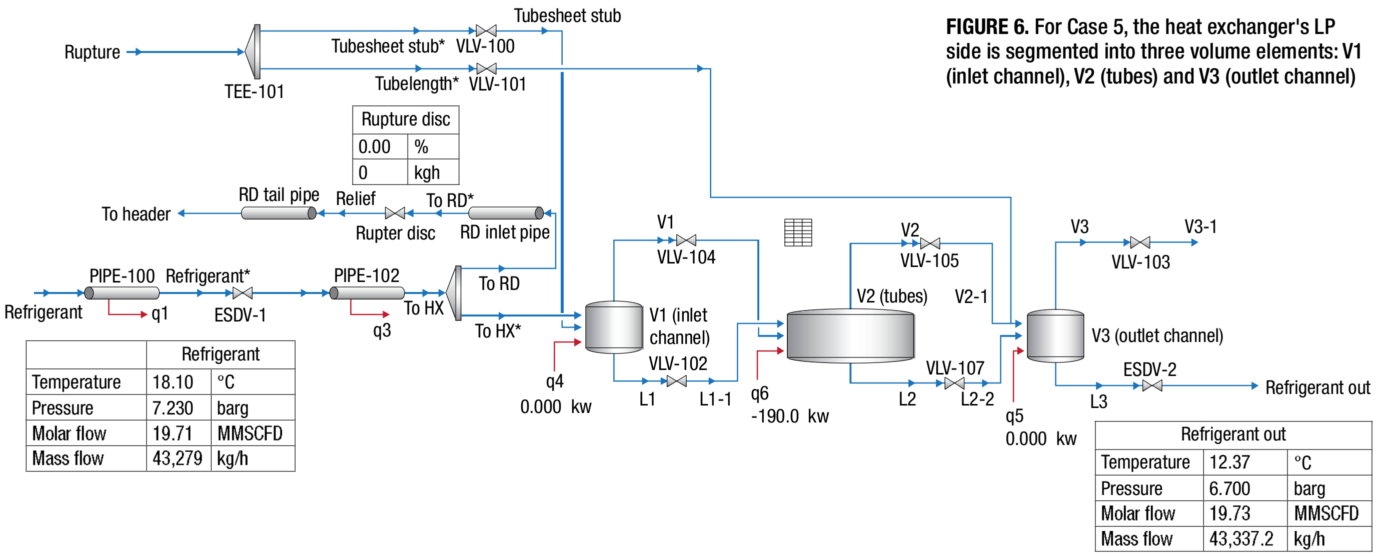
Cases 6 and 7: Liquid-filled exchangers in an ethylene plant. Ennis [5] presented dynamic simulation results for two liquid-filled exchangers, the first with liquid propylene, and the second with methanol on the LP side. Table 1 provides further system details. For both exchangers, the HP-LP pressure differential is >70 bars. The study used models that solve one-dimensional partial differential equations for the conservation of mass and momentum for the liquid-filled riser to the PSV attached to the exchangers. This method is a more rigorous approach for two-phase pipe flow than available in some dynamic-simulation software packages.

The blocked-in pressure rise calculated was 28 bars/s for the propylene-filled system, and 64 bars/s for the methanol-filled system. PSVs were proposed as the relief device for both cases. Note that as in Case 4, the PSV set pressure was significantly below the LP design pressure, allowing pressure to rise to above 10% of the PSV set pressure.

Closing thoughts

The following are some conclusions that can be drawn based on the information presented in this article:

- Dynamic simulations can allow for more accurate PSV sizing for tube-rupture scenarios than steady-state methods
- Based on dynamic simulation studies, PSVs can be used to protect liquid-filled exchangers with high pressure differentials of over 70 bars
- Dynamic simulation should be considered for evaluating tube-rupture scenarios of liquid-filled systems for relief-device selection and sizing, even when exchanger differential pressures are less than 70 bars, if the exchanger LP side is not pro-



Rupture disc	
0.00	%
0	kgh

	Refrigerant	
Temperature	18.10	°C
Pressure	7.230	barg
Molar flow	19.71	MMSCFD
Mass flow	43,279	kg/h

	Refrigerant out	
Temperature	12.37	°C
Pressure	6.700	barg
Molar flow	19.73	MMSCFD
Mass flow	43,337.2	kg/h

FIGURE 6. For Case 5, the heat exchanger's LP side is segmented into three volume elements: V1 (inlet channel), V2 (tubes) and V3 (outlet channel)

tected by the 10/13 rule

- Line sizing for the rupture disk's inlet and outlet should be based on the transient relief flows, with the criteria that the LP-side pressure rise is limited to the allowable design overpressure
- Dynamic simulations allow evaluations of suitable exchanger minimum metal design temperatures
- Dynamic evaluation of the heat-exchanger tube-rupture scenario is often simplified by looking at the exchanger in isolation from the larger system of which it is a part, since the assumption of instantaneous closure of inlet and outlet isolation valves and emergency shutdown valves (ESDVs) on tube rupture will give the fastest, and thus most conservative, pressure-rise estimate. Hazard analysis should, however, consider the impact of actual ESDV closure rates on the system beyond the ESDVs, especially for liquid-filled systems, which see very rapid pressure-rise rates

For further guidance, Figure 7 presents a decision chart for evaluating tube-rupture scenarios based on API-521 guidelines. Figure 7 and the cases discussed above show that dynamic evaluation can lead to better relief-device selection and sizing, and materials selection for various conditions, including some that do not require dynamic evaluation under the API guidelines. ■

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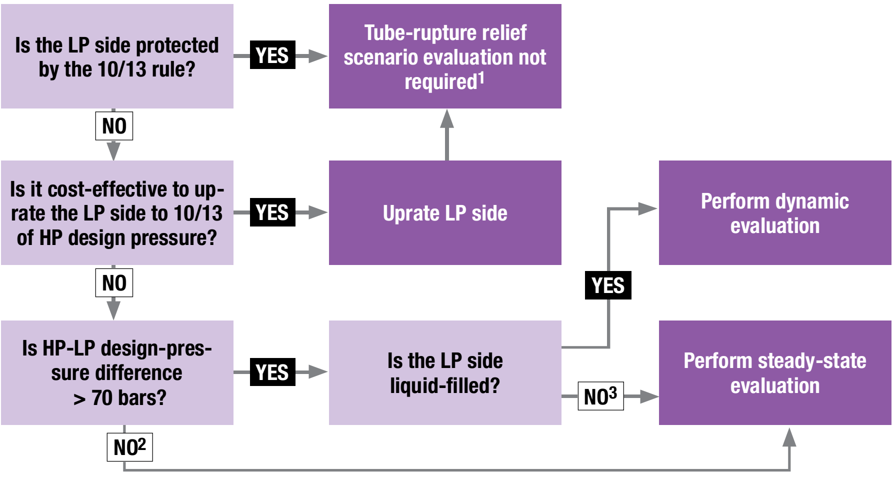

Notes:

1. Evaluation may still be required for reacting systems
2. As illustrated in Case 4, even for scenarios where the HP-LP pressure differential is <70 bars, dynamic simulation may be required if the LP side is liquid-filled. The pressure rise could still be too rapid for the PSV opening capacity. Even if a rupture disc is installed, inlet and outlet line sizing based on steady-state tube-rupture flow calculations may not be accurate
3. As illustrated by Case 2, dynamic simulation can allow for more accurate PRD sizing

FIGURE 7. Based on API-521 guidelines, this decision chart for evaluating tube-rupture scenarios can help engineers determine if steady-state or dynamic evaluation is most suitable

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