Scaling Up Safely: Making Smarter Decisions about Rate Dependency

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1. Introduction

In the refining and chemical processing industries, increasing throughput through a processing unit is often considered as a means of maximizing value with existing capital or minimal additional investment. Often, the throughput will be increased many times over the lifetime of the facility. The pressure relief system for a process is designed in part based on the throughput of the unit; therefore, the change in the throughput may affect the adequacy of the pressure relief system design.

Verifying the design of the process unit's pressure relief system for these increased rates is typically done by identifying overpressure scenarios as either rate-dependent or rate-independent. A rate-dependent overpressure scenario is one whose required relief rate varies with changes in process throughput. A common example is a blocked outlet scenario on a separator. With higher the process throughput, the quantity of mass that must be relieved to limit the pressure to the allowable accumulation is expected to increase.

Conversely, rate-independence refers to overpressure scenarios whose required relief rate is independent of process throughput. A common example is exterior fire, where the required relief rate depends on the heat of vaporization of the liquid mixture inside the vessel, the density of the vapor and liquid phases, and the wetted area of the vessel the fluid is residing in. Changing the feed rate to the vessel is not expected to result in a change to the required relief area for the exterior fire scenario. In some circles, these scenarios may also be termed "equipment-dependent". While the equipment and piping remains constant, the required relief rate remains constant. However, as rate scale-up increases, the equipment and piping may be changed to accommodate the additional capacity.

Rate-Dependent v. Equipment - Dependent Scenarios

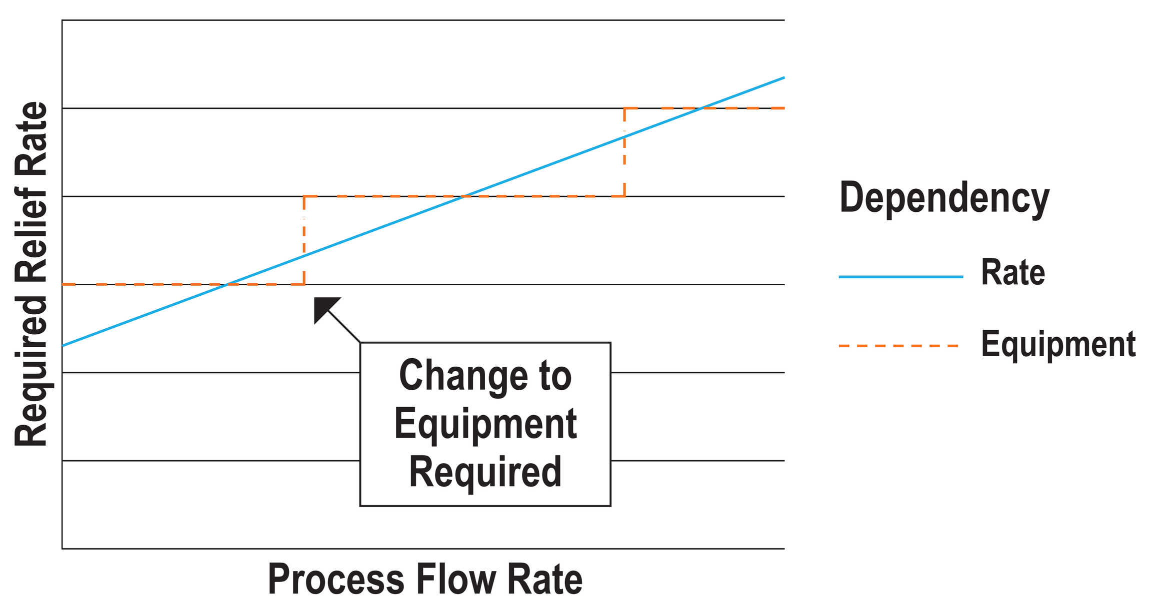

Figure 1: Rate-dependent scenarios increase in required relief rate (and therefore area) with process flow rate increase, while equipment-dependent scenarios are effectively constant until a change to equipment is required.

1.1 How Rate Dependency is used in Pressure Relief System Design

The common practice in pressure relief system design is to select a unit process basis that the user believes represents both the actual operation of the process as well as the worst case for the relief system design. Since process units can have a range of operating modes and rates, selection of these cases tends to favor the following:

- Modes of operation with lighter feed, as this can result in more vaporization and therefore larger vapor and two-phase relief loads
- Higher process throughput rates; often the peak rate achieved, or some percentage above the peak rate

The engineer performing the design will typically identify overpressure scenarios as rate-dependent to minimize the amount of recalculation that needs to be performed in the future, by only performing new calculations for the overpressure scenarios that are dependent on rates.

This has led to the following widespread practice:

1. The user takes the heat and material balance at the previous throughput rate
2. The user obtains a list of calculations that had been identified as rate-dependent
3. The user takes the percentage increase in flow and factors this value into the required relief rates
4. The user re-evaluates the pressure relief device requirements vs. capacity (along with other associated concerns where relevant, e.g. pressure losses if calculated at required relief rates)

This process rarely involves revalidating the process unit simulation to confirm the heat and material balance. Typically this practice has been followed for small changes to throughput rates. However, once the procedure has been implemented, the potential exists for repeated applications to increase the degree of deviation from a validated baseline even further. This poses a danger, as excessive extrapolation and repeated application of the scale-up process without carefully considered heat and material balance revalidation can quickly lead to larger and larger deviations, and the potential for undersizing the pressure relief system.

2. Proper Identification of Rate-Dependency

2.1 How to Identify Rate-Dependency

A general rule of thumb often passed around among novices in pressure relief system design is that overpressure scenario required relief rates that result from equations are rate-independent, and required relief rates that come from a heat and material balance (HMB) are rate-dependent. However, some engineers may take subsequent steps in the required relief rate calculation that can change the classification. These may include such actions as:

- Taking credit for an outlet that would not be blocked as a result of the scenario (including secondary causes like controller action and shut off systems)
- Reducing heat transfer into the system due to elevated bubble point temperatures
- Limiting flow rates based on the hydraulic limits of the piping, including valves and fittings
- Limiting flow rates to the maximum capacity of rotating equipment that can deliver the stated pressure at the point of relief

For example, if determining the required relief rate in the event of a blocked liquid outlet on an exchanger by taking the normal feed rate as the required relief rate is found to result in a required relief area greater than the currently installed relief area, the engineer may review the inputs and determine that when discharging against the relief pressure, the capacity of the feed pump is reduced below the normal feed rate, potentially making the existing installed relief area adequate. In this example, the overpressure scenario has changed from rate-dependent to equipment-dependent.

Table 1 shows common sources for determining the required relief rate for an overpressure scenario, and potential additional modeling choices that can change the classification.

Table 1. Examples of Dependency and Factors That May Change Classification†

Overpressure Scenario	Rate Commonly Derived From	Dependency for Common Derivation	Factors that may change Classification
Closed outlets	HMB/Simulation, Exchanger duty	Rate-Dependent	Limited by pump/compressor, valve, or pipe capacity
Reflux failure	HMB/Simulation, Exchanger duty	Rate-Dependent	
Cooling failure	HMB/Simulation, Exchanger duty	Rate-Dependent	
Overfilling	HMB	Rate-Dependent	Limited by pump or valve capacity
Inadvertent opening of manual valve	Line capacity	Equipment-Dependent	Credit taken for volume outflow
Failure open of inlet control valve	Valve capacity	Equipment-Dependent	Credit taken for normal minimum flow or outflow
Check valve failure	Valve or line capacity	Equipment-Dependent	
Abnormal heat input	Valve or exchanger capacity, HMB/Simulation	Rate-Dependent	
Exterior fire	Fluid properties, Vessel area	Equipment-Dependent	
Hydraulic expansion (pipe)	Fluid properties, Pipe area	Equipment-Dependent	
Hydraulic expansion (exchanger)	Fluid properties, Exchanger duty	Equipment-Dependent	Exchanger duty driven by hot side flow rate
Tube rupture	Exchanger properties, fluid properties	Equipment-Dependent	
Tube leak	Exchanger properties, fluid properties	Equipment-Dependent	
Plate weld failure	Exchanger properties, fluid properties	Equipment-Dependent	
Column power failure (Complex)	HMB/Simulation, Exchanger duty	Rate-Dependent	
Column power failure (Simple*)	Fluid properties, reboiler duty	Rate-Dependent	
Loss of Absorbent	HMB/Simulation	Rate-Dependent	

*** - Simple column failure includes overpressure scenarios where the required relief rate can be determined as a function of the reboiler duty and heat of vaporization of the residing fluid.***

† - Not a comprehensive list.

3. Rate-Dependent Factors Influencing Pressure Relief System Design

A quick review of three factors influencing pressure relief device sizing will aid in understanding the limits of scaling up the pressure relief system design basis: composition, operating conditions, and heat exchanger duties. Note that this list is intended for illustrative purposes of the effects and is not an all-inclusive list.

3.1 Composition

3.1.1 Composition and Pressure Relief System Design

- Composition can directly impact the determination of the required relief rate; for example, fire calculations use the latent heat of vaporization for a mixture, and depending on the particular modeling choices selected (e.g. inclusion of sensible heat, vaporization interval selected) may include further dependencies on heat capacity, bubble point temperature, vapor to liquid volume ratio, and other variables. Orifice flow calculations (such as are found in tube rupture calculations) depend on the density or molecular weight, compressibility, and specific heat ratio for the fluid.
- Composition of the fluid mixture directly impacts the relationship between the pressure of the fluid and the specific volume of the fluid, which governs the determination of the critical mass flux across the relief device nozzle.

3.1.2 How Scaling Up the Process Can Affect Composition

- Changes in operating temperature and pressure can have an impact on the composition by affecting the separation of the vapor and liquid phases within the process equipment. Increasing the operating pressure can raise the bubble point temperature of the fluid mixture, requiring additional heat to achieve the same separation point. Decreasing the operating pressure can reduce the bubble point temperature of the fluid mixture, possibly resulting in more vapor flashing off, with a higher molecular weight.
- In order to maximize the throughput for the specific process unit, feeds from multiple sources may be required. If the process unit has excess capacity but insufficient feed is available from on-site units, feed may be supplemented from offsite or from tankage. These feeds may have variations in compositions, and as the new feed is added, the blend ratio can change.

3.2 Operating Conditions

3.2.1 Operating Conditions and Pressure Relief System Design

- The operating conditions within equipment in the process unit can directly impact the pressure relief device sizing primarily through the temperature's effect on the fluid conditions (for overpressure scenarios that model the required relief rate using its operating temperature). Temperature also influences the maximum mass flux across the pressure relief device. Since the relief device is sized at the relief pressure, there is no similar direct effect of operating pressure.
- More significantly, changes in the normal operating temperature and pressure can affect the required relief rate calculations for overpressure scenarios that require these values as inputs, such as modeling flow across an orifice, flow through piping or valves, or where separation processes are occurring.
- The applicability of an overpressure scenario may be altered, where the existing operating conditions are already near the threshold of applicability – from either direction. Changing the operating pressure may affect the suction pressure of a pump or compressor, thereby altering the deliverable pressure to a downstream system, whose determination of applicability for a control valve failure or inadvertent opening of a manual valve overpressure scenario may depend on the comparison of this pressure to the downstream system maximum allowable working pressure.

3.2.2 How Scaling Up the Process Can Affect Operating Conditions

- The mechanical characteristics of rotary equipment – For example, for a given installed impeller diameter, as the flow rate is increased, the operating point of the rotating equipment must move out on the pump performance curve, resulting in a lower delivered pressure.
- Piping hydraulic limitations – As flowrate is increased, the pressure drop is expected to increase. With changes in the pressure drop between equipment, the operating pressure profile may be affected. For flow in the turbulent region, for the same diameter of piping, the pressure drop normally roughly follows a trend of proportionality with the square of the flowrate.

3.3 Heat Exchanger Duties

3.3.1 Heat Exchanger Duties and Pressure Relief System Design

- Heat exchanger duties can potentially cause deviations in the relief device sizing basis if the process duties are used as inputs in determining the required relief rates. Note that some users choose to use the design duties of the exchangers in lieu of the process duties. This may mitigate the impact of scale-up (up to the point where new heat transfer equipment is required).
- The other route through which heat exchanger duties can impact the pressure relief system sizing is by impacting the operating conditions of the process (see section 3.2.1).

3.3.2 How Scaling Up the Process Can Affect Heat Exchanger Duties

- Scaling up the process flow rate through an exchanger can significantly impact the exchanger heat duty if it is limited by flow instead of limited by heat transfer area and overall heat transfer coefficient ("UA-limited"). For the same heat exchanger, the flow pattern correction factor FT is expected to be constant. In these cases an increase in process fluid flow can result in increased duty, up to the point where the exchanger UA becomes limiting. Note that for forced convection, since the Nusselt number is a function of the Reynolds number, the value for the overall heat transfer coefficient U is not constant; rather, it is itself a weak function of flow rate (as well as composition and operating conditions). If the exchanger duty is limited by UA, then the exchanger heat transfer duty can be still changed by differences in log mean temperature difference (ΔT_{lm}).

3.4 Extent of Deviations and Overall Impact on Pressure Relief System Design

While it can be expected that minor changes in flowrate would have a correspondingly minor impact on composition, temperature and pressure, and heat exchanger duties, and therefore a minor impact on the pressure relief system design, it is important to recognize that the extent of deviation from linear behavior can increase with the extent of the process throughput scale-up. Additionally, repeatedly performing scale-ups on a previously scaled-up process, without revalidating the heat and material balance, can lead to the same result in a less obvious manner.

4. Conclusion

The economic driver for maximizing the production from process units is ever-present. However, it is vitally important to ensure that the techniques used to evaluate the pressure relief system design are appropriate and suitable to the task. Awareness of the assumptions inherent in rate-dependent classifications, and the potential to invalidate this classification with further "pencil-sharpening", is a starting point. Understanding the ways in which process throughput scale-ups can impact other factors in determining the design of the pressure relief system, such as affecting the fluid composition, operating conditions, and heat exchanger duties, and their impact on required relief rate determination or even scenario applicability, helps to illuminate potential problem areas when evaluating a process throughput scale-up, and informs the decision on whether a revalidation of the heat and material balance is appropriate. Altogether, these considerations should enable engineers to make smarter decisions about rate-dependency and ensure safer operation during process throughput scale-ups.

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