Cascading Failures:
Tube Ruptures in Cooling Water Systems

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Abstract:

Over the past two decades, units using hydrogen to sweeten products (hydrotreaters) or to crack heavy intermediates (Hydrocrackers) have been gradually increasing in pressure. Within most of these units a cooling water system with multiple connected heat exchangers is used to cool the process. A tube rupture, in any one of the high-pressure exchangers, could lead to extremely high pressure in the overall cooling water system, resulting in the overpressure of the remaining cooling water exchangers. *(Smith & Burgess recently presented this information to the AIChE and the research can be found on our website titled, "Living with Oversized Relief Valves.")*

This paper will show that for the high pressure units, with gas or two phase cooling water exchanges, a dynamic analysis of the consensus of a tube rupture effects are needed to look at the entire cooling water system, not just the exchanger with the tube rupture concern. Furthermore, if the high-pressure exchanger is designed so that the design pressures of both sides are the same, tube rupture is still an applicable scenario due to the effect on the cooling water system.

Example Unit:

The equipment in these systems are similar and for the purposes of this paper, we will focus solely on the hydrocrackers. The following is a simplified hydrocracker process:

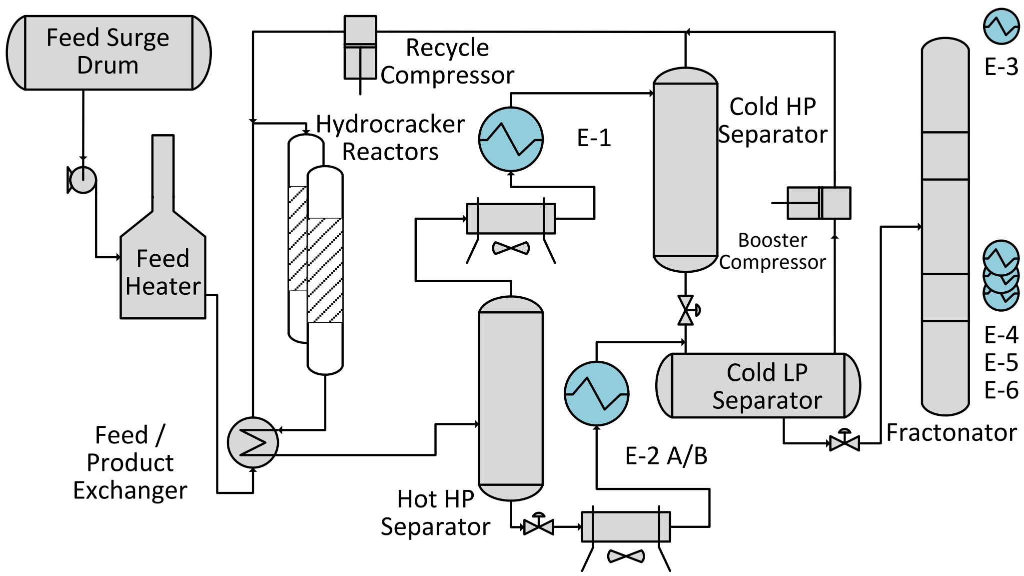

Figure 1: *Simplified Flow Diagram for a Hydrocracker*

In Figure 1, The cooling water exchangers are denoted with a blue tint, whereas the rest of the system equipment is grey. The reaction portion for hydrocrackers can operate with pressures exceeding 3,000 psig, but for this example, let's assume that the reaction runs with more moderate pressures (less than 2,500 psig.) Table 1 lists each of Figure 1's cooling water exchangers and provides a brief description of the various exchangers' functions.

Table 1: System Cooling Water Exchanger

Tag	Function	Cooling Water Side MAWP*	Process Side MAWP
E-2 A/B	Low Pressure Reactor Product Cooler	150	500
E-1	High Pressure Reactor Product Cooler	2,500	2,500
E-3	Fractionator Trim Condenser	75	150
E-4/5/6	Fractionator Product Coolers	75	150

**All pressures in psig and MAWP = Maximum Allowable Working Pressure.*

In Figure 2 below, we redrew Figure 1 to highlight the cooling water's flow and the pressures reflected in Table 1. From this view, we can easily visualize how a tube rupture in E-1 could impact the lower pressure MAWP exchangers (those in blue), as they are all on the same cooling water supply and return headers.

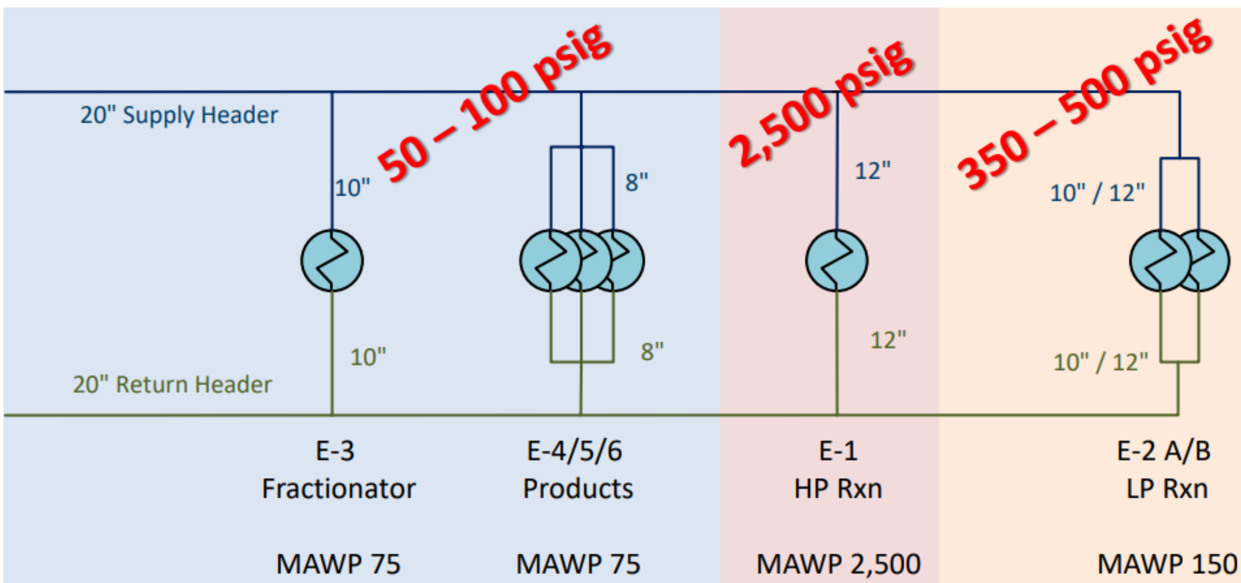

Figure 2: *Cooling Water Flow Diagram for the Sample Unit*

Even though we have designed E-1 for a tube rupture to not overpressure itself, a tube rupture may overpressure the low-pressure MAWP exchanges, depicted in the blue section of Figure 2.

To determine the effects of a tube rupture in E-1 on the system, we need to perform a dynamic model.

Dynamic Modeling:

The dynamic response of the cooling water system is based on the model presented by Sumaria et al. [1] which is further described in Appendix 1: Description of Model. The Sumaria model incorporates dynamic hydraulic pressure and flow changes to the cooling water network arising from the tube rupture induced pressure waves, as well as, bulk modulus related incompressible fluid effects. The model does this by using a series of differential equations that describe the following interactions:

Control Volumes - The calculation of the pressure in each control volume, based on the flow into and out of the control volume and the fluid and pipe/vessel properties.

Inertial Segments - The calculation of the mass flow into/out of each control volume based on the pressure differential between control volumes and the resistance of flow between the control volumes.

Per the work done by the HSE, this model has been validated and shown to be reasonable, but conservative, et al. [2]

The results shown here are for a rupture in E-1 with a high side pressure of 2,500 psig and tubed with ¾ BWG 12 tubes.

Results:

Figure 1 and Figure 2 predict the effects of a Tube Rupture in E-1 on the entire cooling water system.

Effects on the Cooling Water Piping

The pressures in the cooling water lines leading up to and away from E-1 exceeded 500/400 psig, respectively, in the initial 100 ms of the tube rupture. These pressures remained high, with pulses exceeding 300 psig for the first second, then pressures reduced to below 300 psig. Depending on the age and condition, the cooling water pipe may need to be replaced with stronger pipe.

The pressures further away from the exchanger changed significantly less. This is consistent with past modeling that shows significant pressure increases only occurring near the exchanger with the tube break. Figure 3 shows the pressures for a break in E-1 near the cooling water header. This system was modeled with more headers than just the one shown in Figure 2. Like the pressures shown in Figure 3 for the cooling water supply and return, pressure pulses in the other exchangers not depicted on Figure 2 were mild and the design parameters of most cooling water systems.

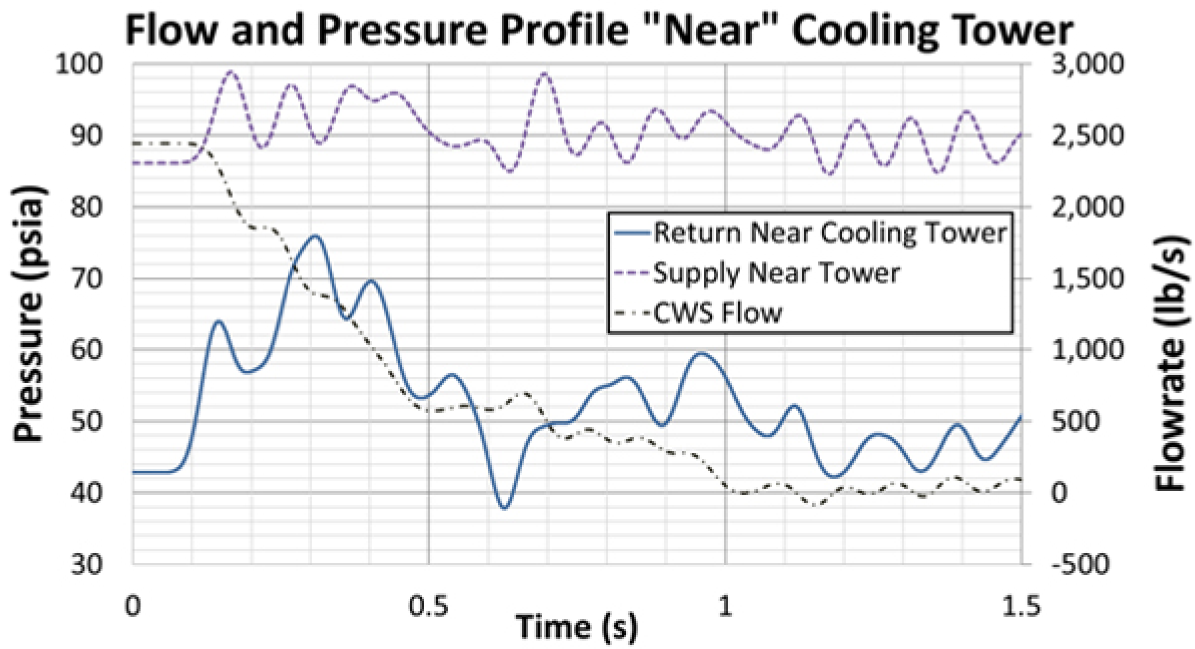

__Figure 3:__ Flow and pressure changes near the cooling water tower.

System Exchangers

The dynamic pressure trace for the system exchangers shown in Figure 2 is graphed below (Figure 4).

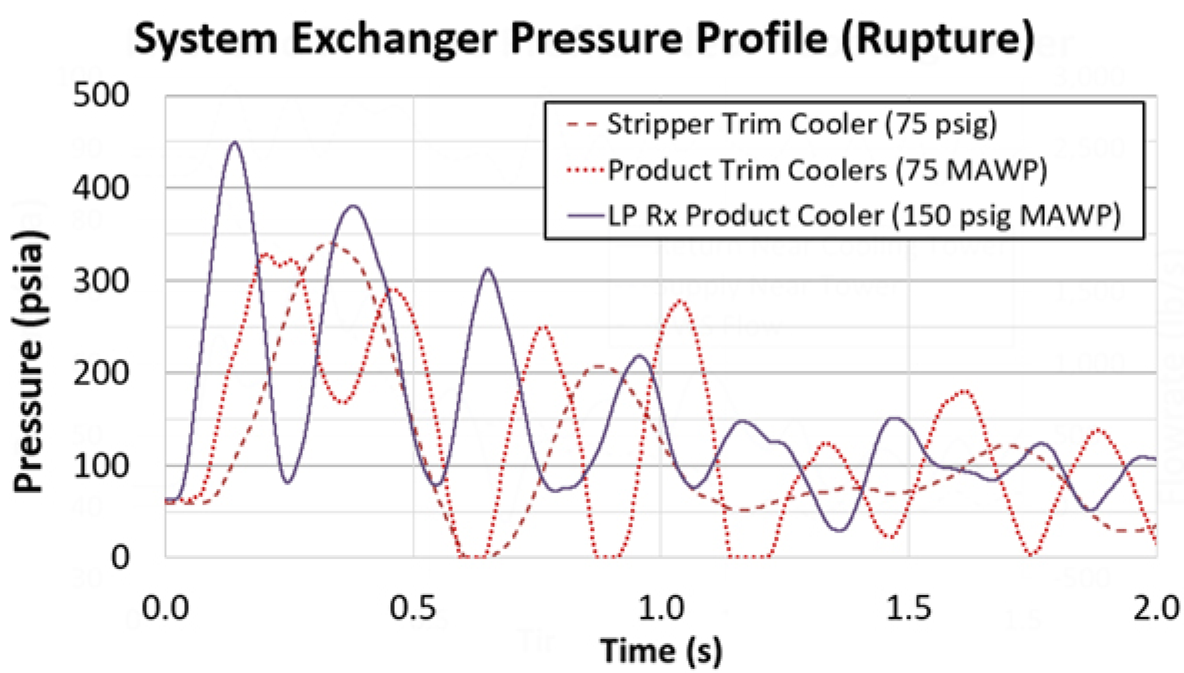

__Figure 4:__ System Exchanger Pressures, Tube Rupture in E-1

Illustrated in Figure 4, the Maximum Allowable Working Pressure (MAWP) for the trim coolers is probably unacceptable. A mechanical analysis of the LP Rx Product Cooler may show that while the high-pressure pulses are short, the allowable exchanger stresses are not exceeded. This would require a mechanical analysis of the exchanger and is outside of the scope of this paper.

Conclusions:

As systems continue to become more integrated and pressures in operating units continue to increase, the holistic effects of a tube rupture on the system needs to be considered. The specific conclusions of this paper are:

1. Systems with high pressure cooling water exchangers need to be modeled to ensure that in the event of a tube rupture, the cooling water system does not experience a secondary failure. This is true even if the tube rupture is not a scenario for the exchanger itself (see also API STD 521 6^{th} Ed. §4.4.14.2.1)
2. Piping leading to the high pressure exchanger may require upgrading (e.g. not 150# Class Piping) due to relatively long pulses of pressure in excess of the requirements in B31.3 §302.2.4.1. Piping built to other standards would similarly need to be verified.
3. Piping not on the same header has flow rate changes, but the pressure changes are mild and probably not a concern for most facilities. This is shown in Figure 3 above.
4. Low pressure exchangers on the same cooling water headers as the high-pressure exchanger need to be included in the model as pressures hydraulically close to the rupture become quite elevated. This is shown in Figure 4 above.

In the event that pressure limits are exceeded, mechanical design considerations or relief protection can be added to mitigate any identified concerns. In extreme cases, the tube bundle in the high-pressure exchanger can be replaced with one that has smaller tubes or tubes with thicker walls.

References:

[1] Sumaria, V.H., Rovnak, J.A., Heitner, I, Herbert, R.J. 'Model to Predict Transient Consequences of a Heat Exchanger Tube Rupture, API Proceedings – Refining Department', Vol 55. 1976. Pp 631-654.

[2] 'Guidelines for the Safe Design and Operation of Shell and Tube Heat Exchangers to Withstand the Impact of Tube Failure', Published by Energy Institute, Second Edition, Nov. 2015

Appendix 1: Description of Model

The model is an implementation of the one presented by Sumaria et al. [1], consisting of a defined network of control volumes connected via inertial segments. The pressure within each control volume is defined by a single average value across the control volume. One or more segments are identified as the location where a tube rupture occurs.

The flow entering the system via the ruptured tube is modeled based on an orifice flow calculation using the tube internal diameter, upstream pressure and physical properties, and the pressure in the control volume in which the rupture occurs. Flow from a single orifice was introduced to the both inlet and outlet channels; thus, from an overpressure protection standpoint the system was modeled with high pressure vapor inlet flow from 2 orifices.

The differential equation governing a control volume is:

$$\left(\frac{V_l}{B_l}+\frac{V_g}{kP}+\frac{VD}{TE}(1-u^2)\right)\frac{dP}{dt}=\frac{W_i-W_o}{\rho_l}+\frac{W_g}{\rho_g} \qquad \text{Eq. (1)}$$

Where:

V_l = Liquid phase volume

V_g = Vapor phase volume

V = Liquid phase volume

B_l = Bulk modulus

k = Isentropic coefficient

D = Diameter

T = Material thickness

E = Modulus of elasticity

u = Poisson ratio

W_i = Flow into control volume

W_o = Flow out of control volume

W_g = Gas flow into control volume

P = Pressure

ρ_l = Liquid density

ρ_g = Vapor density

t = Time

The differential equation governing an inertial segment is:

$$\frac{L}{Ag_c}\frac{dW}{dt} = P_i - P_o - \Delta P_{flow} \qquad \text{Eq. (2)}$$

Where:

L = Actual length of fluid mass

A = Cross-sectional area of fluid mass

g_c = Gravitation conversion constant

P_0 = Pressure at time zero

P_i = Pressure at time step i

The pressure nodes, associated control volumes, and linking inertial segments were chosen to suit the layout of the system under analysis. The main cooling water supply and return headers were treated as infinite reservoirs at the stated supply and return pressures. Each segment was solved to obtain a steady state prior to the introduction of the tube rupture. The resulting system of differential equations was solved using a classical fourth-order Runge-Kutta method.