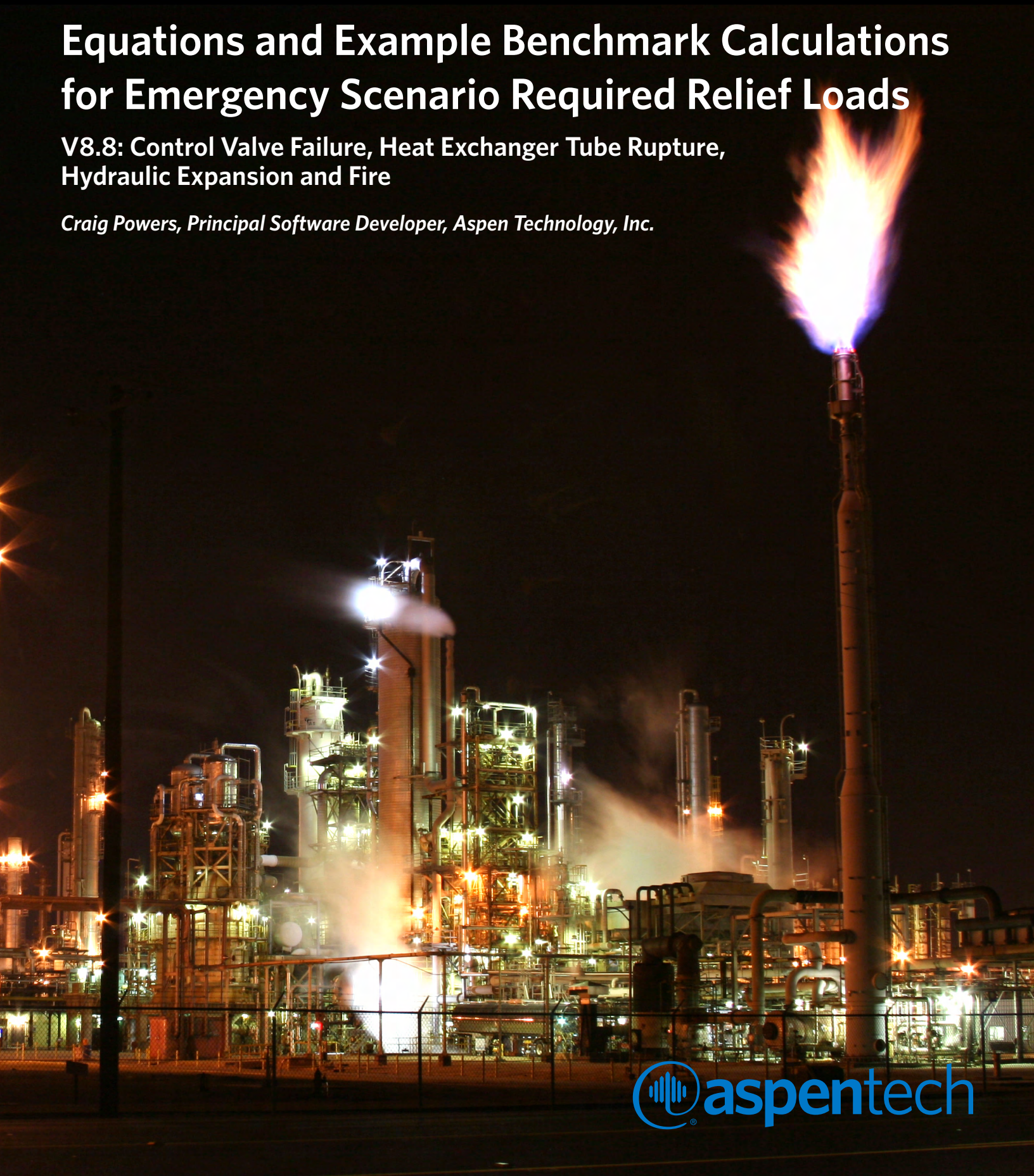
WHITE PAPER

Equations and Example Benchmark Calculations for Emergency Scenario Required Relief Loads

V8.8: Control Valve Failure, Heat Exchanger Tube Rupture, Hydraulic Expansion and Fire

Craig Powers, Principal Software Developer, Aspen Technology, Inc.



aspentech

Introduction

Introduced in Aspen HYSYS® V8.3, the Safety Analysis Environment provides a tool for adding pressure relief devices and calculating relief loads inside Aspen HYSYS. Leveraging this tool within the rigorous Aspen HYSYS simulator, and in combination with Aspen Flare System Analyzer, provides an integrated solution for pressure relief analysis (PRA) work.

This paper contains hand calculations for the relief loads inside the Safety Analysis Environment. This paper shows examples and equations for emergency scenarios, including control valve failure, heat exchanger tube rupture, hydraulic expansion, and fire, which will help you to validate the calculations of this tool located within Aspen HYSYS.

Control Valve Failure

For a control valve failure scenario, the required relief load is the maximum flow through the control valve at full open. API Standard 521 allows that credit for normal minimum flow may be taken under certain circumstances.[1]

PSV Plus Vapor Equations

The critical pressure drop for gas or vapor flow across a control valve is defined as below, where P_1 is the upstream pressure in psia, ΔP^* is the critical limit in psi, and C_f is a characteristic parameter of the control valve.

Eq. 1

$$\Delta P^* = 0.5 {C_f}^2 P_1$$

If the pressure drop across the control valve exceeds the critical limit, then the mass flow rate through the valve is given by Equation 2 below.

Eq. 2

$$w = 2.8 C_f P_1 C_v \sqrt{SG/Z}$$

Otherwise, the mass flow rate through the valve is given by Equation 3 below, where P_r is the downstream (relieving) pressure in psia, SG is the specific gravity relative to air at upstream conditions, Z is the compressibility of the stream at upstream conditions, and C_v is a characteristic parameter of the control valve.

Eq. 3

$$w = 3.22 C_v \sqrt{\frac{\Delta P^* (P_r + P_1) SG}{Z}}$$

The specific gravity may be calculated as below, where M is the molecular weight and T_r is the upstream temperature in °F.

Eq. 4

$$SG = \frac{M}{29} \times \frac{520}{T_r + 460}$$

PSV Plus Vapor Example with Unchoked Flow

The example is based on the following conditions:

Composition	40% isobutane, 45% isopentane, 15% n-hexane using the Aspen HYSYS SRK package for physical properties
Upstream conditions	320 psia / 320 F
Normal flowrate	9,000 lb/h
Relief pressure	260 psig set pressure + 10% allowable overpressure = 286 psig
Control valve	C_v = 20.0, $C_f = F_l$ = 0.75

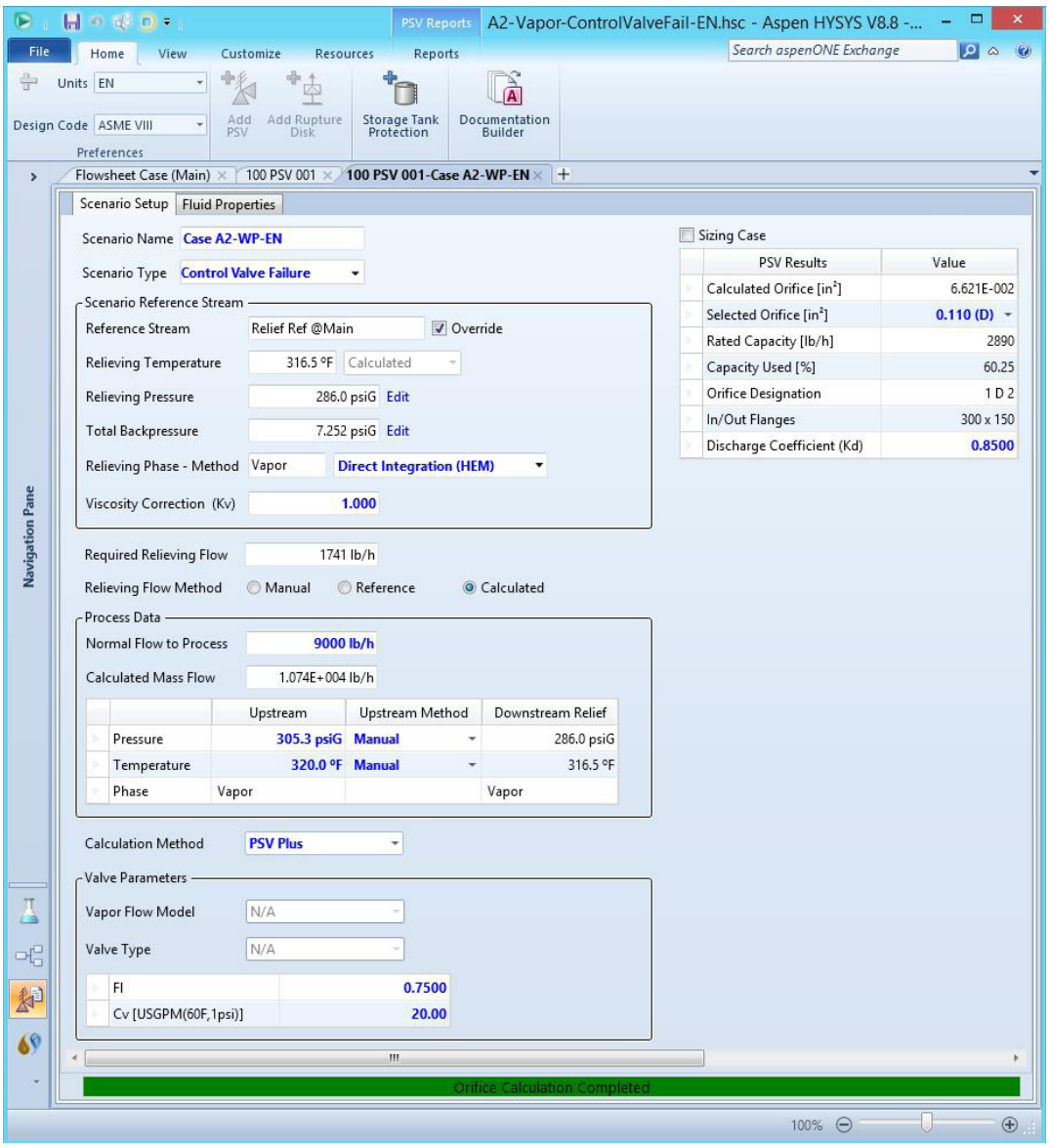


Figure 1: Subcritical vapor control valve case calculated in Aspen HYSYS using PSV Plus equations

Setting up a stream in Aspen HYSYS at the upstream conditions will yield the following properties:
M = 68.64
Z = 0.68

The critical pressure drop may be calculated using (Eq. 1):

$$\Delta P^* = 0.5(0.75)^2 320 = 90 \text{ psi}$$

The pressure drop across the valve at relieving conditions is only 19.3 psi, so the flow is subcritical.

The specific gravity may be calculated using (Eq. 4):

$$SG = \frac{68.64}{29} \times \frac{520}{320 + 460} = 1.578$$

The control valve capacity at relief conditions is calculated using (Eq. 3):

$$w = 3.22(20)\sqrt{\frac{19.3(286 + 14.7 + 320)1.578}{0.68}} = 10737 \text{ lb/h}$$

Subtracting the normal flowrate of 9,000 lb/h gives a required relief load of 1,737 lb/h.

The results calculated above are compared to results obtained in Aspen HYSYS in Table 1.

Variable	Units	Example Calculation	Aspen HYSYS
Inlet Pressure (P_1)		**320 psia**	**305.3 psig**
Normal Flow to Process	lb/h	**9,000**	**9,000**
Control Valve CV (C_V)		**20**	**20.00**
Critical Flow Factor (C_f)		**0.75**	**0.7500**
Molecular Weight (M)	lb/lbmol	**68.64**	
Compressibility (Z)		**0.68**	
Specific Gravity (SG)		1.578	
Critical Pressure Drop (ΔP^*)	psi	90.0	
Flow type		Subcritical	Subcritical
Full-open Flow (w)	lb/h	10,737	
Required Relieving Flow	lb/h	1,737	1,741
Blue = Calculation input Gray = Calculated value			

Table 1: Comparison of example calculation and Aspen HYSYS calculation for control valve failure with subcritical vapor flow

PSV Plus Vapor Example with Choked Flow

The example is based on the following conditions:

Composition	40% isobutane, 45% isopentane, 15% n-hexane using the Aspen HYSYS SRK package for physical properties
Upstream conditions	420 psia / 355 F
Normal flowrate	3,300 lb/h
Relief pressure	260 psig set pressure + 10% allowable overpressure = 286 psig
Control valve	C_v = 5.5, C_f = F_l = 0.75

Setting up a stream in Aspen HYSYS at the upstream conditions will yield the following properties:
M = 68.64
Z = 0.624

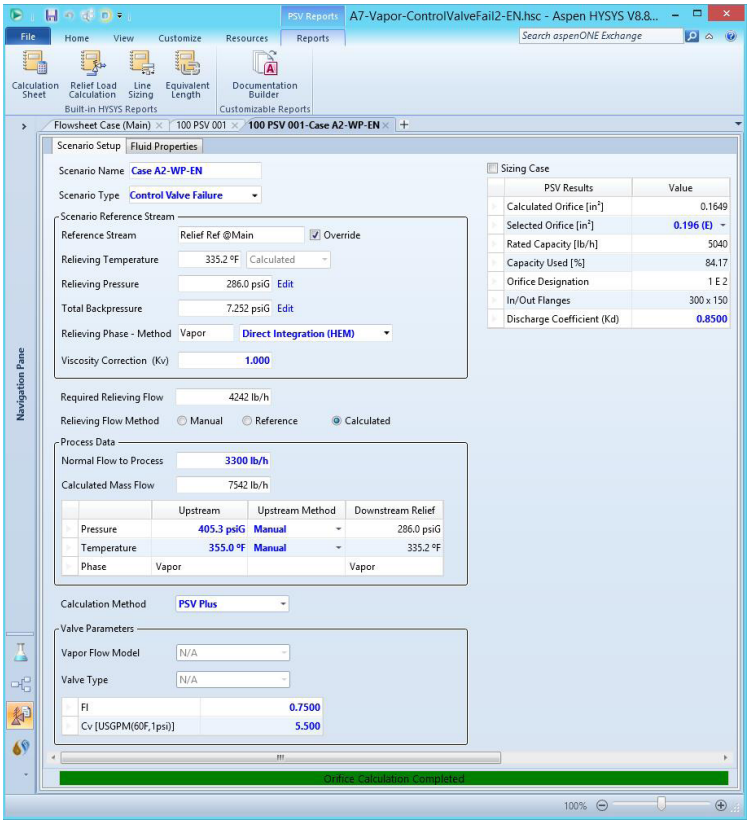


Figure 2: Critical vapor control valve case calculated in Aspen HYSYS using PSV Plus equations

The critical pressure drop may be calculated using (Eq. 1):

$$\Delta P^* = 0.5(0.75)^2 420 = 118.1 \text{ psi}$$

The pressure drop across the valve at relieving conditions is only 119.3 psi, so the flow is critical.

The specific gravity may be calculated using (Eq. 4):

$$SG = \frac{68.64}{29} \times \frac{520}{355 + 460} = 1.51$$

The control valve capacity at relief conditions is calculated using (Eq. 2):

$$w = 2.8(0.75)(420)(5.5)\sqrt{1.51/0.624} = 7{,}546 \text{ lb/h}$$

Subtracting the normal flowrate of 3,300 lb/h gives a required relief load of 4,246 lb/h.

The results calculated above are compared to results obtained in Aspen HYSYS in Table 2.

Variable	Units	Example Calculation	Aspen HYSYS
Inlet Pressure (P_1)		**420 psia**	**405.3 psig**
Normal Flow to Process	lb/h	**3,300**	**3,300**
Control Valve CV (C_V)		**5.5**	**5.500**
Critical Flow Factor (C_f)		**0.75**	**0.7500**
Molecular Weight (M)	lb/lbmol	**68.64**	
Compressibility (Z)		**0.624**	
Specific Gravity (SG)		1.51	
Critical Pressure Drop (ΔP^*)	psi	118.1	
Flow type		Critical	Critical
Full-open Flow (w)	lb/h	7,546	
Required Relieving Flow	lb/h	4,246	4,242
Blue = Calculation input Gray = Calculated value			

Table 2: Comparison of example calculation and Aspen HYSYS calculation for control valve failure with critical vapor flow using PSV Plus equations

PSV Plus Liquid Equations

The critical pressure drop for liquid flow across a control valve is defined as below, where F_F is a calculated critical flow parameter, P_v is the vapor pressure/bubble point pressure of the liquid in psia, and P_c is the critical pressure of the liquid in psia.

Eq. 5

$$F_F = 0.96 - 0.28\sqrt{\frac{P_v}{P_c}}$$

Eq. 6

$$\Delta P^* = {C_f}^2(P_1 - F_F P_v)$$

The volumetric capacity of the control valve may be calculated as shown below, where ΔP_{min} is actual ΔP or ΔP^*, whichever is smaller of the actual pressure drop across the valve and the critical pressure drop across the valve, SG is the specific gravity of the fluid at upstream conditions relative to water at 60 F (15.6 C), and Q is the capacity of the control valve in gpm.

Eq. 7

$$Q = C_v\sqrt{\frac{\Delta P_{min}}{SG}}$$

The required relief load in gpm may be converted to lb/h, as shown below:

Eq. 8

$$w = Q \times \frac{60\ \text{min}}{1\ \text{h}} \times \frac{1\ \text{ft}^3}{7.4805\ \text{gal}} \times \rho$$

PSV Plus Liquid Example with Unchoked Flow

The example is based on the following conditions:

Composition	15% propane, 30% isobutane, 30% n-butane, 25% isopentane using the Aspen HYSYS PR package for physical properties
Upstream conditions	275 psia / 195 F
No credit taken for normal flowrate across the valve	
Relief pressure	190 psig set pressure + 10% allowable overpressure = 209 psig
Control valve	C_v = 8, C_f = F_l = 0.75

Setting up a stream in Aspen HYSYS at the upstream conditions will yield the following properties:
P_c = 562.6 psia
P_v = 216.1 psia
ρ = 29.95 lb/ft^3 hence SG = 29.95/62.3 = 0.4807

The critical pressure drop is calculated from (Eq. 5) and (Eq. 6):

$$F_F = 0.96 - 0.28\sqrt{\frac{216.1}{562.6}} = 0.7865$$

$$\Delta P^* = 0.75^2(275 - 0.7865 \times 216.1) = 59 \text{ psi}$$

The pressure drop at relief conditions is 51.3 psi, which is less than the critical limit; therefore, the flow is unchoked. The required relief load is calculated from (Eq. 7) and (Eq. 8):

$$Q = 8\sqrt{\frac{51.3}{0.4807}} = 82.6 \text{ gpm}$$

$$w = 82.6 \text{ gpm} \times \frac{60 \text{ min}}{1 \text{ h}} \times \frac{1 \text{ ft}^3}{7.4805 \text{ gal}} \times 29.95 \text{ lb/ft}^3 = 19{,}840 \text{ lb/h}$$

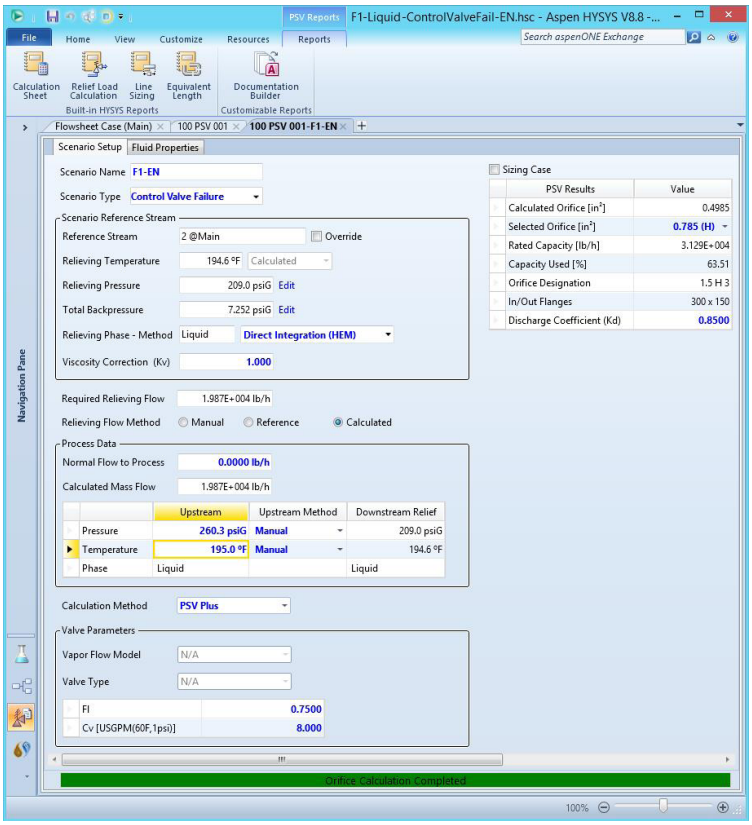


Figure 3: Unchoked liquid control valve case calculated in Aspen HYSYS using PSV Plus equations

The results calculated above are compared to results obtained in Aspen HYSYS in Table 3.

Variable	Units	Example Calculation	Aspen HYSYS
Inlet Pressure (P_1)		**275 psia**	**260.3 psig**
Normal Flow to Process	lb/h	**0**	**0.0000**
Control Valve CV (C_V)		**8**	**8.000**
Critical Flow Factor (C_f)		**0.75**	**0.7500**
Specific Gravity (SG)		**0.4807**	
Liquid Critical Pressure (P_C)		**562.2 psia**	
Liquid Vapor Pressure (P_V)		**216.1 psia**	
Critical Pressure Drop (ΔP^*)	psi	59	
Flow type		Unchoked	Subcritical
Required Relieving Flow	lb/h	19,840	19,870
Blue = Calculation input Gray = Calculated value			

Table 3: Comparison of example calculation and Aspen HYSYS calculation for control valve failure with subcritical liquid flow using PSV Plus equations

PSV Plus Liquid Example with Choked Flow

The example is based on the following conditions:

Composition	15% propane, 25% n-butane, 30% n-pentane, 30% n-heptane using the Aspen HYSYS PR package for physical properties
Upstream conditions	275 psia / 265 F
No credit taken for normal flowrate across the valve	
Relief pressure	105 psig set pressure + 10% allowable overpressure = 115.5 psig
Control valve	C_v = 120, $C_f = F_l$ = 0.75

Setting up a stream in Aspen HYSYS at the upstream conditions will yield the following properties:
P_c = 583.5 psia
P_v = 247.1 psia
ρ = 30.85 lb/ft^3 hence SG = 30.85/62.3 = 0.495

The critical pressure drop is calculated from (Eq. 5) and (Eq. 6):

$$F_F = 0.96 - 0.28\sqrt{\frac{247.1}{583.5}} = 0.778$$

$$\Delta P^* = 0.75^2(275 - 0.778 \times 247.1) = 46.6 \text{ psi}$$

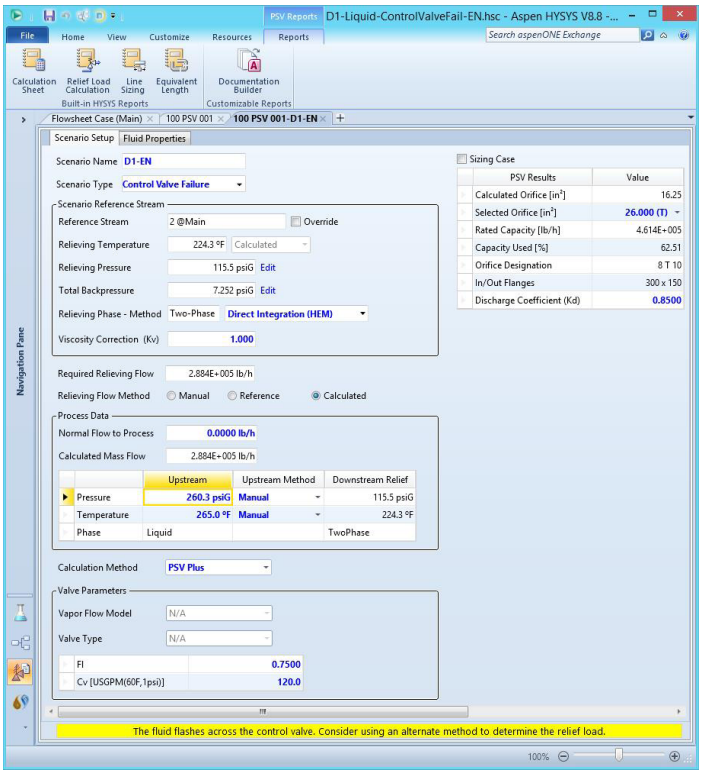


Figure 4: Choked liquid control valve case calculated in Aspen HYSYS using PSV Plus equations

The pressure drop at relief conditions is 144.8 psi, which is greater than the critical limit, therefore the flow is choked. The required relief load is calculated from (Eq. 7) and (Eq. 8):

$$Q = 120\sqrt{\frac{46.6}{0.495}} = 1164 \text{ gpm}$$

$$w = 1164 \text{ gpm} \times \frac{60 \text{ min}}{1 \text{ h}} \times \frac{1 \text{ ft}^3}{7.4805 \text{ gal}} \times 30.85 \text{ lb/ft}^3 = 288{,}100 \text{ lb/h}$$

The results calculated above are compared to results obtained in Aspen HYSYS in Table 4.

Variable	Units	Example Calculation	Aspen HYSYS
Inlet Pressure (P_1)		**275 psia**	**260.3 psig**
Normal Flow to Process	lb/h	**0**	**0.0000**
Control Valve CV (C_V)		**120**	**120.0**
Critical Flow Factor (C_f)		**0.75**	**0.7500**
Specific Gravity (SG)		**0.495**	
Liquid Critical Pressure (P_C)		**583.5 psia**	
Liquid Vapor Pressure (P_V)		**247.1 psia**	
Critical Pressure Drop (ΔP^*)	psi	46.6	
Flow type		Choked	Critical
Required Relieving Flow	lb/h	288,100	288,400
Blue = Calculation input Gray = Calculated value			

Table 4: Comparison of example calculation and Aspen HYSYS calculation for control valve failure with critical liquid flow using PSV Plus equations

Heat Exchanger Tube Break

For a heat exchanger tube break scenario, API Standard 521 states that the calculation should be based on a sharp break in one tube, at the back of the tube sheet, with high pressure fluid assumed to flow both through the stub in the tube sheet and through the long section of tube. A calculation basis of flow through two orifices is allowed as a simplifying assumption, because the resulting relief load is larger than would be calculated based on flow through a long tube.[1]

The tube rupture calculation in the Safety Analysis Environment uses a two-orifice calculation as described in the literature.[2 3]

Vapor Equations

As with control valves, vapor flow through a tube rupture is subject to a critical flow limit. The downstream critical limit pressure may be calculated as below, where P_{cfr} is the critical limit pressure in psia, P_1 is the high-pressure-side pressure in psia, and k is the ideal gas specific heat ratio $C_P/(C_P - R)$ at relief conditions.

Eq. 9

$$P_{cfr} = P_1 \left[\frac{2}{k+1}^{k/_{k-1}} \right]$$

The flow through the rupture is given by the calculation below, where w is the required relief load in lb/h, C is the orifice coefficient, A is the total rupture area in in^2, ΔP is the pressure difference between the P_1 and the greater of the downstream relief pressure or P_{cfr}, and ρ is the vapor density at upstream conditions in lb/ft^3.

Eq. 10

$$w = 2407.7\ C\ A\ Y \sqrt{\Delta P \cdot \rho}$$

For flow from the tube side into the shell side, the orifice coefficient used is typically 0.74 (so the product with the leading coefficient is 1,781.7), and the expansion coefficient Y may be calculated, as shown in Equation 11 below.

Eq. 11

$$Y = 1 - 0.4 \frac{\Delta P}{P_1}$$

For flow from the shell side into the tube side, the orifice coefficient used is typically 0.6 (so the product with the leading coefficient is 1,444.6), and the expansion coefficient may be calculated as shown below.

Eq. 12

$$Y = 1 - 0.317 \frac{\Delta P}{P_1}$$

Vapor Example with Unchoked Shell-Into-Tube Flow

The example is based on the following conditions:

Composition	30% propane, 70% n-butane using the Aspen HYSYS SRK package for physical properties
Upstream conditions	110 psia / 300 F
Normal flowrate	9,000 lb/h
Relief pressure	60 psig set pressure + 10% allowable overpressure = 66 psig
Tubes are 14 ga 7/8" tube with an inner diameter of 0.709 in	

Setting up a stream in Aspen HYSYS at the high-pressure side conditions will yield the following properties:
ρ = 0.7756 lb/ft^3

Flashing to relief conditions will yield the following properties:
k = 1.073

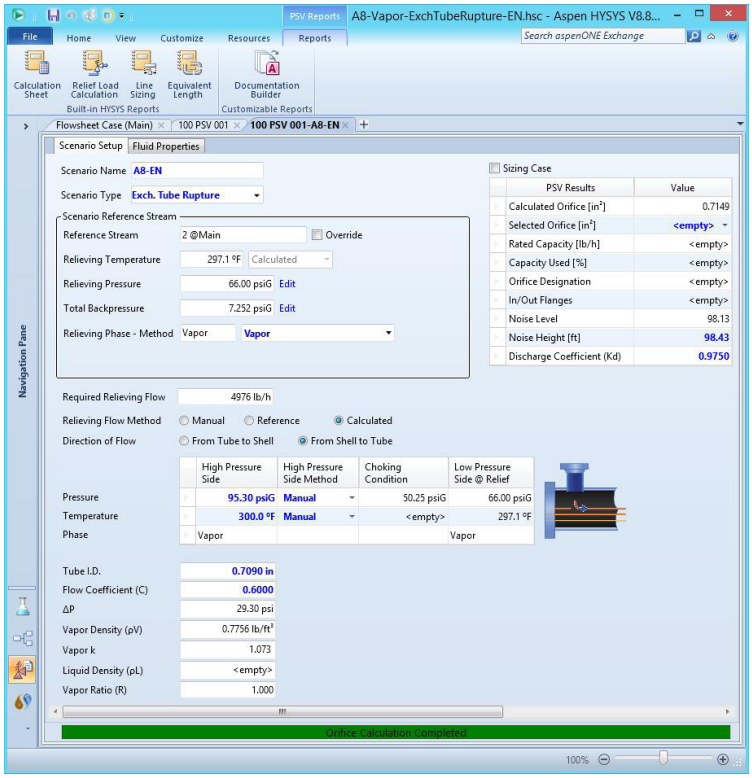


Figure 5: Subcritical vapor exchanger tube rupture case calculated in Aspen HYSYS

The critical flow pressure is calculated using (Eq. 9):

$$P_{cfr} = 110 \text{ psia} \left[\frac{2}{(1.073)+1}^{(1.073)/(1.073)-1} \right] = 64.9 \text{ psia}$$

Since the critical pressure of 64.9 psia is less than the low-pressure side relief pressure of 80.7 psia, flow is not choked and the pressure drops across the break ΔP = 29.3 psi.

The required relief load may be calculated using (Eq. 10) and (Eq. 12):

$$A = 2\frac{\pi}{4}(0.709 \text{ in})^2 = 0.7896 \text{ in}^2$$

$$Y = 1 - 0.317\frac{29.3}{110} = 0.9156$$

$$w = 1444.6(0.7896)(0.9156)\sqrt{(29.3)(0.7756)} = 4{,}979 \text{ lb/h}$$

The results calculated above are compared to results obtained in Aspen HYSYS in Table 5.

Variable	Units	Example Calculation	Aspen HYSYS
High Side Pressure (P_1)		**110 psia**	**95.3 psig**
High Side Temperature	F	**300**	**300.0**
Tube Inside Diameter	in	**0.709**	**0.7090**
$C_P/(C_P - R)$ (k)		**1.073**	1.073
Mass Density (ρ)	lb/ft^3	**0.7756**	0.7756
Critical Pressure (P_{cfr})		64.9 psia	50.25 psig
Flow Type		Subcritical	Subcritical
Expansion Factor (Y)		0.9156	
Required Relieving Flow	lb/h	4,979	4,976
Blue = Calculation input Gray = Calculated value			

Table 5: Comparison of example calculation and Aspen HYSYS calculation for exchanger tube rupture with subcritical vapor flow

Vapor Example with Choked Tube-Into-Shell Flow

The example is based on the following conditions:

Composition	30% propane, 70% n-butane using the Aspen HYSYS SRK package for physical properties
Upstream conditions	275 psia / 250 F
Relief pressure	60 psig set pressure + 10% allowable overpressure = 66 psig
Tubes are 20 ga 1 ¼" tube with an inner diameter of 1.18 in	

Setting up a stream in Aspen HYSYS at the high-pressure side conditions will yield the following properties:
ρ = 2.493 lb/ft^3

Flashing to relief conditions will yield the following properties:
k = 1.079

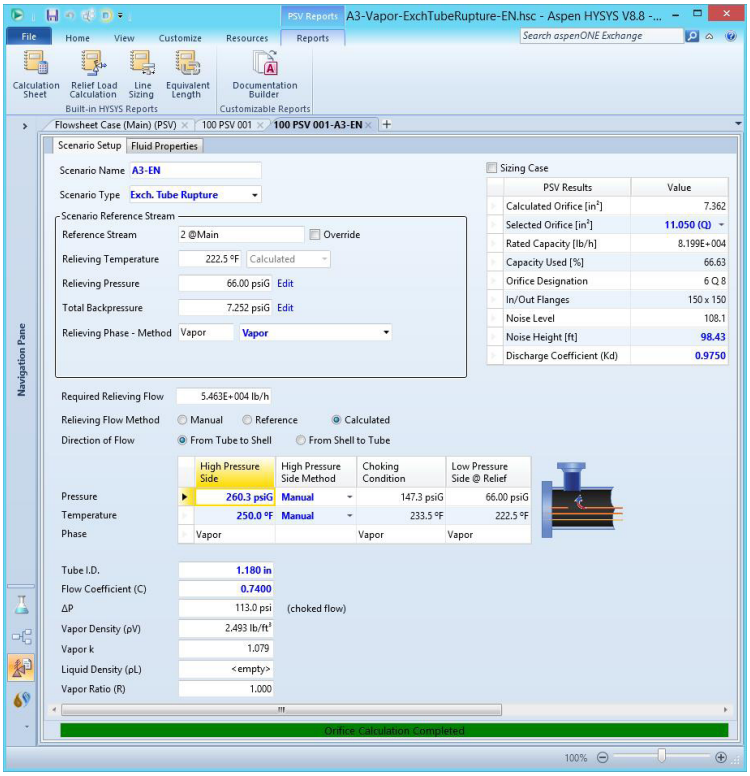


Figure 6: Critical vapor exchanger tube rupture case calculated in Aspen HYSYS

The critical flow pressure is calculated using (Eq. 9):

$$P_{cfr} = 275 \text{ psia} \left[\frac{2}{(1.079)+1}^{(1.079)/(1.079)-1} \right] = 162.0 \text{ psia}$$

Since the critical pressure of 162.0 psia is greater than the low-pressure side relief pressure of 80.7 psia, flow is choked and the pressure drops across the break ΔP = 113.0 psi.

The required relief load may be calculated using (Eq. 10) and (Eq. 11):

$$A = 2\frac{\pi}{4}(1.18 \text{ in})^2 = 2.187 \text{ in}^2$$

$$Y = 1 - 0.4\frac{113.0}{275} = 0.8356$$

$$w = 1781.7(2.187)(0.8356)\sqrt{(113.0)(2.493)} = 54{,}650 \text{ lb/h}$$

The results calculated above are compared to results obtained in Aspen HYSYS in Table 6.

Variable	Units	Example Calculation	Aspen HYSYS
High Side Pressure (P_1)		**375 psia**	**360.3 psig**
High Side Temperature	F	**250**	**250.0**
Tube Inside Diameter	in	**1.18**	**1.180**
$C_P/(C_P - R)$ (k)		**1.079**	1.079
Mass Density (ρ)	lb/ft^3	**2.493**	2.493
Critical Pressure (P_{cfr})		162.0 psia	147.3 psig
Flow Type		Critical	Critical
Expansion Factor (Y)		0.8356	
Required Relieving Flow	lb/h	54,650	54,630
Blue = Calculation input Gray = Calculated value			

Table 6: Comparison of example calculation and Aspen HYSYS calculation for exchanger tube rupture with critical vapor flow

Liquid Equations

Liquid flow is not checked for choking. The flow through the rupture is given by Equation 13 below.

Eq. 13 $$w = 2407.7CA\sqrt{\Delta P \cdot \rho}$$

As with vapor cases, for a tube-into-shell break, a value of 0.74 is typically used for the orifice coefficient, giving a combined leading coefficient of 1781.7. For a shell-into-tube break, a value of 0.6 is typically used for the orifice coefficient, giving a combined leading coefficient of 1444.6.

Liquid Example with Tube-Into-Shell Flow

The example is based on the following conditions:

Composition	35% n-heptane, 35% n-decane, 30% n-C13 using the Aspen HYSYS SRK package for physical properties
High-pressure side conditions	740 psia / 120 F
Relief pressure	400 psig set pressure + 10% allowable overpressure = 440 psig
Tubes have an inner diameter of 1.375 in	

Setting up a stream in Aspen HYSYS at the relief conditions will yield the following properties:
ρ = 44.13 lb/ft^3

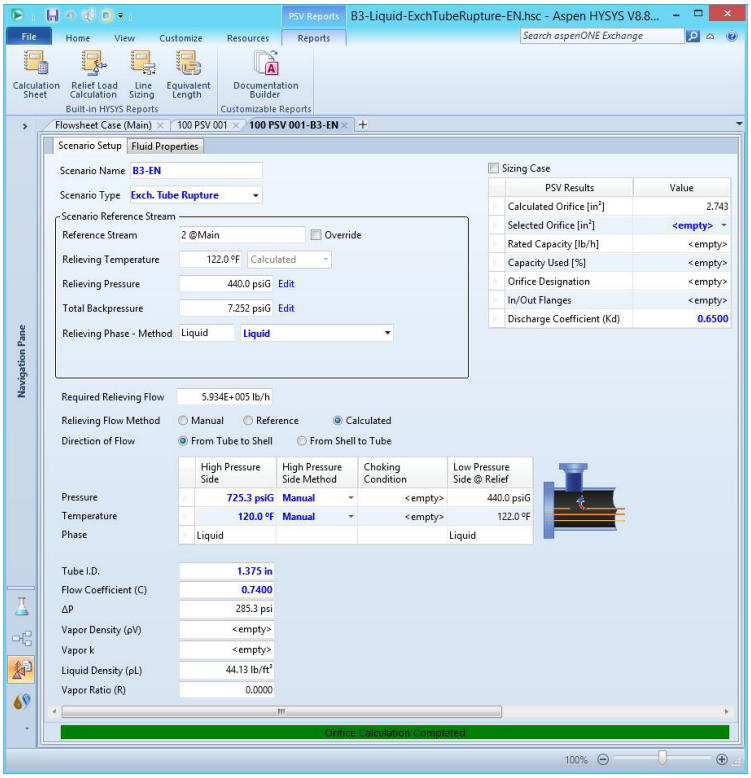


Figure 7: Liquid exchanger tube rupture case calculated in Aspen HYSYS

The required relief load may be calculated using (Eq. 13):

$$A = 2\frac{\pi}{4}(1.375\ \text{in})^2 = 2.97\ \text{in}^2$$

$$w = 1781.7(2.97)\sqrt{(740 - 455.3)(44.13)} = 593{,}132\ \text{lb/h}$$

The results calculated above are compared to results obtained in Aspen HYSYS in Table 7.

Variable	Units	Example Calculation	Aspen HYSYS
High Side Pressure (P_1)		**740 psia**	**725.3 psig**
Tube Inside Diameter	in	**1.375**	**1.375**
Mass Density (ρ)	lb/ft^3	**44.13**	44.13
Required Relieving Flow	lb/h	593,132	593,400
Blue = Calculation input Gray = Calculated value			

Table 7: Comparison of example calculation and Aspen HYSYS calculation for exchanger tube rupture with liquid flow

Mixed Two-Phase Flow Equations

For two-phase flashing flow, the calculation is performed based on a division of the total rupture area in order to obtain a ratio of mass flows that is equal to the mass fraction vapor of the high-pressure-side stream flashed isenthalpically to the low-pressure-side relief pressure. The choke condition is obtained for the vapor and applies to both phases. The downstream critical limit pressure may be calculated using (Eq. 9):

$$P_{cfr} = P_1\left[\frac{2}{k+1}^{k/_{k-1}}\right]$$

Here, k is taken at the low-pressure-side relief conditions.

Once the critical limit pressure is obtained, the vapor and liquid properties for calculating the required relief load are determined at the greater of the critical limit pressure and the low-pressure-side relief pressure (high-pressure-side conditions may be used if a vapor phase exists).

The fraction of the total flow area that is assigned to the vapor phase may be computed as shown below, where C is the orifice coefficient, typically 0.6 for shell-into-tube flow or 0.74 for tube-into-shell flow, Y is the vapor expansion coefficient computed using (Eq. 11) or (Eq. 12) as appropriate, ΔP is the pressure drop across the tube break subject to the downstream critical limit, ρ values are the respective phase densities, and x is the vapor mass fraction at the low-pressure-side pressure subject to the downstream critical limit.

Eq. 14 $$N_v = 2404.7CY\sqrt{\Delta P \cdot \rho_v}$$

Eq. 15 $$N_\ell = 2404.7C\sqrt{\Delta P \cdot \rho_\ell}$$

Eq. 16 $$f_v = \frac{x\,N_\ell}{(1-x)N_v + x\,N_\ell}$$

Then, the required relief load is calculated as the sum of the vapor and liquid flows, as shown below.

Eq. 17 $$w_v = f_v\,A\,N_v$$

Eq. 18 $$w_\ell = (1-f_v)\,A\,N_\ell$$

Eq. 19 $$w = w_v + w_\ell$$

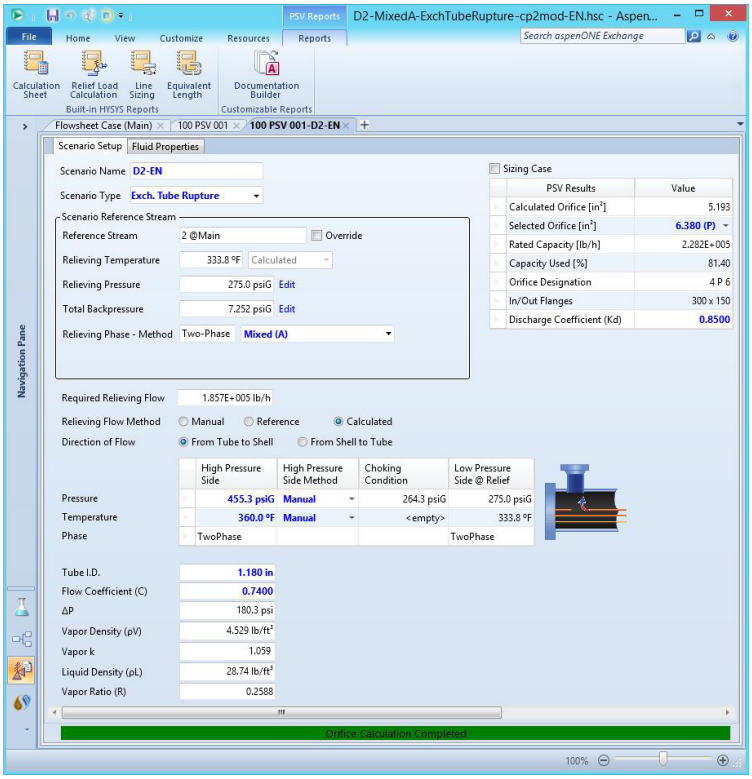


Figure 8: Mixed-phase, subcritical exchanger tube rupture case calculated in Aspen HYSYS

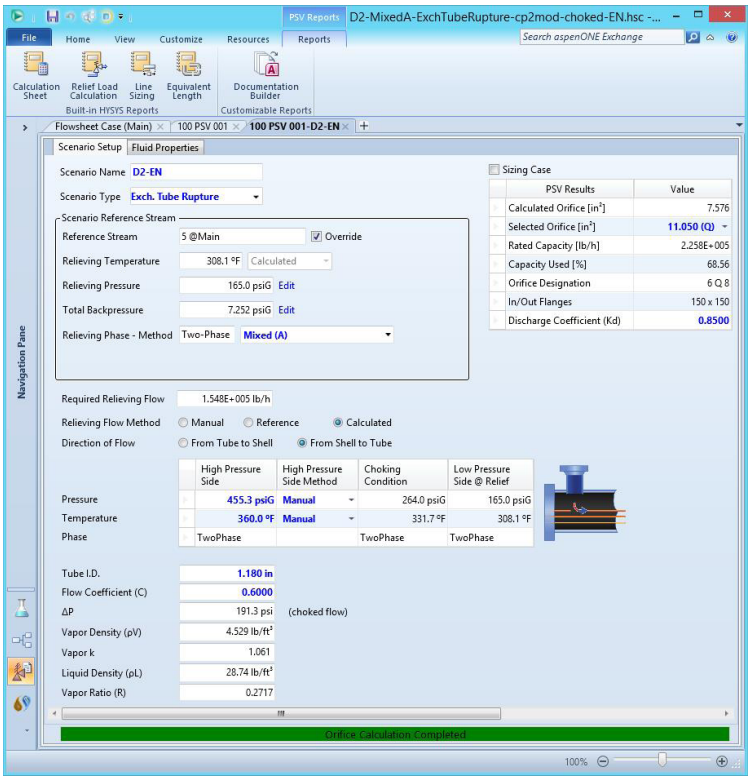


Figure 9: Mixed-phase, critical exchanger tube rupture case calculated in Aspen HYSYS

Mixed-Phase Example with Unchoked Tube-Into-Shell Flow

The example is based on the following conditions:

Composition	35% propane, 40% n-heptane, 25% CC6= using the Aspen HYSYS SRK package for physical properties
High-pressure side conditions	470 psia / 360 F
Relief pressure	250 psig set pressure + 10% allowable overpressure = 275 psig
Tubes are 20 ga 1 1/4" tube with an inner diameter of 1.18 in	

Setting up a stream in Aspen HYSYS at the high-pressure side conditions and performing an isenthalpic flash to relief pressure will yield the following properties:
T = 333.8 F
k = 1.059

The critical flow pressure is calculated using (Eq. 9):

$$P_{cfr} = 470 \text{ psia} \left[\frac{2}{(1.059)+1}^{(1.059)/(1.059)-1} \right] = 278.9 \text{ psia}$$

Since the critical pressure of 278.9 psia is less than the low-pressure side relief pressure of 289.7 psia, flow is not choked and the pressure drop across the break ΔP = 180.3 psi. Liquid and vapor properties may be obtained in Aspen HYSYS at the high side pressure using the previously-flashed stream, yielding:
ρ_l = 28.74 lb/ft^3
ρ_v = 4.529 lb/ft^3

The vapor fraction at relief conditions is:
x = 0.2588

The required relief load may be calculated using (Eq. 12) and (Eq. 14) through (Eq. 19):

$$A = 2\frac{\pi}{4}(1.18\text{ in})^2 = 2.187\text{ in}^2$$

$$Y = 1 - 0.4\,\frac{180.3}{470} = 0.8466$$

$$N_v = 1781.7(0.8466)\sqrt{(180.3)(4.529)} = 43103$$

$$N_\ell = 1781.7\sqrt{(180.3)(28.74)} = 128255$$

$$f_v = \frac{(0.2588)(128255)}{(1-0.2588)(43103) + (0.2588)(128255)} = 0.5096$$

$$w_v = (0.5096)(2.187)(43103) = 48{,}040\text{ lb/h}$$

$$w_\ell = (1-0.5096)(2.187)(128255) = 137{,}600\text{ lb/h}$$

$$w = w_v + w_\ell = 185{,}600\text{ lb/h}$$

The results calculated above are compared to results obtained in Aspen HYSYS in Table 8.

Variable	Units	Example Calculation	Aspen HYSYS
High Side Pressure (P_1)		**470 psia**	**455.3 psig**
High Side Temperature	F	**360**	**360.0**
Tube Inside Diameter	in	**1.18**	**1.180**
$C_P/(C_P - R)$ (k)		**1.059**	1.059
Vapor Mass Density (ρ_v)	lb/ft^3	**4.529**	4.529
Liquid Mass Density (ρ_l)	lb/ft^3	**28.74**	28.74
Critical Pressure (P_{cfr})		278.9 psia	264.3 psig
Flow Type		Subcritical	
Expansion Factor (Y)		0.8466	
Mass Fraction Vapor (x)		**0.2588**	0.2588
Required Relieving Flow	lb/h	185,600	185,700
Blue = Calculation input Gray = Calculated value			

Table 8: Comparison of example calculation and Aspen HYSYS calculation for exchanger tube rupture with subcritical mixed phase flow

Mixed-Phase Example with Choked Shell-Into-Tube Flow

The example is based on the following conditions:

Composition	35% propane, 40% n-heptane, 25% CC6= using the Aspen HYSYS SRK package for physical properties
High-pressure side conditions	470 psia / 360 F
Relief pressure	150 psig set pressure + 10% allowable overpressure = 165 psig
Tubes are 20 ga 1 1/4″ tube with an inner diameter of 1.18 in	

Setting up a stream in Aspen HYSYS at high-pressure side conditions and performing an isenthalpic flash to relief pressure will yield the following properties:
k = 1.061

The critical flow pressure is calculated using (Eq. 9):

$$P_{cfr} = 470 \text{ psia} \left[\frac{2}{(1.061) + 1}^{(1.061)/(1.061)-1} \right] = 278.7 \text{ psia}$$

Since the critical pressure of 278.7 psia exceeds the low-pressure side relief pressure of 179.7 psia, flow is choked and the pressure drop across the break ΔP = 191.3 psi. Liquid and vapor properties may be obtained in Aspen HYSYS at the high side pressure using the previously-flashed stream, yielding:
ρ_ℓ = 28.74 lb/ft^3
ρ_v = 4.529 lb/ft^3

The vapor fraction at the choke condition is:
x = 0.2718

The required relief load may be calculated using (Eq. 11) and (Eq. 14) through (Eq. 19):

$$A = 2\frac{\pi}{4}(1.18\text{ in})^2 = 2.187\text{ in}^2$$

$$Y = 1 - 0.317\,\frac{191.3}{470} = 0.8710$$

$$N_v = 1444.6(0.8710)\sqrt{(191.3)(4.529)} = 37036$$

$$N_\ell = 1444.6\sqrt{(191.3)(28.74)} = 107114$$

$$f_v = \frac{(0.2718)(107114)}{(1-0.2718)(37036) + (0.2718)(107114)} = 0.5191$$

$$w_v = (0.5191)(2.187)(37036) = 42{,}050\text{ lb/h}$$

$$w_\ell = (1-0.5191)(2.187)(107114) = 112{,}700\text{ lb/h}$$

$$w = w_v + w_\ell = 154{,}800\text{ lb/h}$$

The results calculated above are compared to results obtained in Aspen HYSYS in Table 9.

Variable	Units	Example Calculation	Aspen HYSYS
High Side Pressure (P_1)		**470 psia**	**455.3 psig**
High Side Temperature	F	**360**	**360.0**
Tube Inside Diameter	in	**1.18**	**1.18**
$C_P/(C_P - R)$ (k)		**1.061**	1.061
Vapor Mass Density (ρ_v)	lb/ft^3	**4.529**	4.529
Liquid Mass Density (ρ_l)	lb/ft^3	**28.74**	28.74
Critical Pressure (P_{cfr})		278.7 psia	264.0 psig
Flow Type		Critical	Choked Flow
Expansion Factor (Y)		0.8710	
Mass Fraction Vapor (x)		**0.2718**	0.2717
Required Relieving Flow	lb/h	154,800	154,800
Blue = Calculation input Gray = Calculated value			

Table 9: Comparison of example calculation and Aspen HYSYS calculation for exchanger tube rupture with critical mixed phase flow

Hydraulic Expansion

Equations

For a scenario where heat input causes hydraulic expansion in blocked-in, liquid-full equipment or process piping, API Standard 521 gives two equations for calculating the required relief load, one for U.S. customary units and one for SI units.[1] These equations may be combined and written as shown below, where q is the volumetric required relief load in m^3/s or gpm, N is a dimensional constant with a value of 1000 for SI units or 500 for U.S. customary units, α_V is the cubic expansion coefficient in 1/K or 1/R, φ is the total heat transfer rate in W or BTU/h, SG is the specific gravity of the fluid referenced to water at 60 F or 15.6 C (a reference density of 998.9 kg/m^3 or 62.3 lb/ft^3), and C_P is the fluid heat capacity in J/kg-K or BTU/lb-R.

Eq. 20

$$q = \frac{\alpha_V \, \phi}{N \, SG \, C_P}$$

Example

The example is based on the following conditions:

f = 500,000 kcal/h = 2,093,400 kJ/h = 581.5 kW
aV = 0.0085 1/K
SG = 0.63
CP = 0.591 kcal/kg-K = 2.474 kJ/kg-K

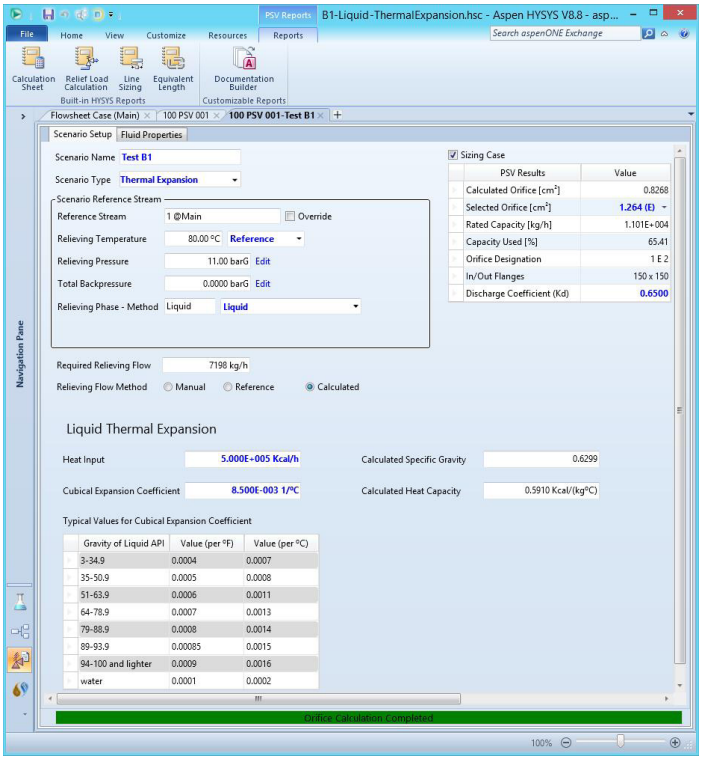


Figure 10: Hydraulic expansion case calculated in Aspen HYSYS

The required relief load is calculated using (Eq. 20), and converted to a mass flow rate:

$$q = \frac{(0.0085)(581{,}500)}{1000(0.63)(2{,}474)} = 0.00317\ \mathrm{m^3/s}$$

$$w = 0.00317\ \mathrm{m^3/s} \times \frac{3600\ \mathrm{s}}{1\ \mathrm{h}} \times (0.63)(998.9\ \mathrm{kg/m^3}) = 7182\ \mathrm{kg/h}$$

The results calculated above are compared to results obtained in Aspen HYSYS in Table 10.

Variable	Units	Example Calculation	Aspen HYSYS
Expansion Coefficient (α_V)	1/K	**0.0085**	**0.0085**
Heat Input Rate (φ)		**581,500 W**	**500,000 kcal/h**
Specific Gravity (SG)		**0.63**	0.6299
Mass Heat Capacity (C_P)		**2,474 J/kg-K**	0.5910 kcal/kg-K
Required Relieving Flow	lb/h	7,182	7,198
Blue = Calculation input Gray = Calculated value			

Table 10: Comparison of example calculation and Aspen HYSYS calculation for hydraulic expansion

Fire

Wetted Fire Equations

The required relief load due to vaporization of liquid inventory is calculated using equations obtained from API Standard 521.[1]

The required relief load is calculated using the following equations shown below, where Q is the rate at which heat is added to the vessel contents in W; C_{DF} is a constant to account for the presence or absence of adequate draining and firefighting, with a value of 43,200 when adequate drainage and firefighting are present or 70,900 when they are not; F is an environment factor to account for the presence of fireproof insulation, with a value of 1.0 for a vessel without fireproof insulation; A_{ws} is the exposed wetted surface area of the vessel, subject to certain conditions, in m².

Eq. 21 $$Q = C_{DF} F\ A_{ws}{}^{0.82}$$

Per the standard, for horizontal and vertical vessels, only the portion of the liquid inventory within 7.6 m of grade should be considered. For spherical vessels, the portion of the liquid inventory within 7.6 m of grade or up to the maximum horizontal diameter, whichever is greater, should be considered, where w is the required relief load in kg/h and l is the latent heat of the vessel contents at appropriate relieving conditions in kJ/kg.

Eq. 22 $$w = 3.6\ Q/\lambda$$

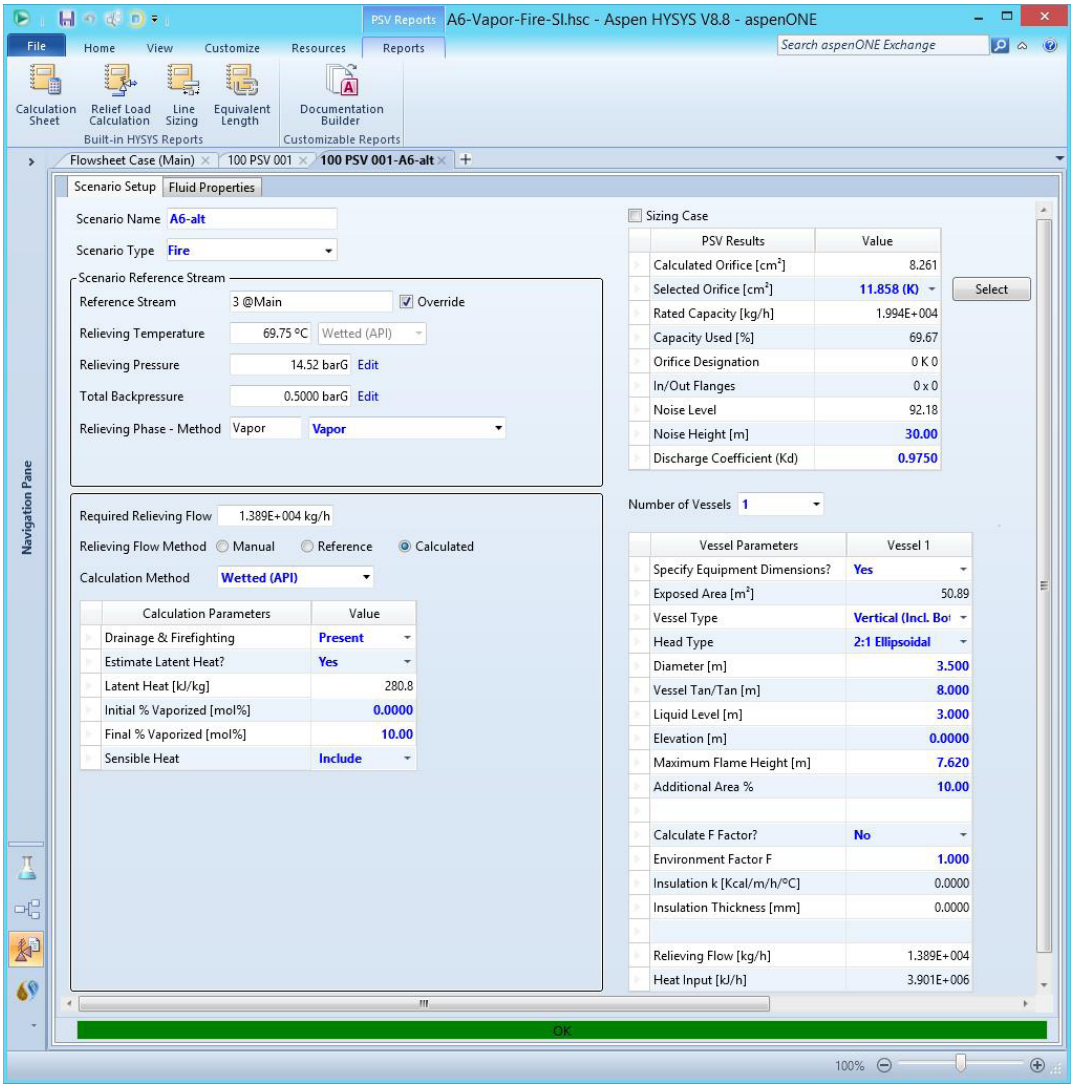


Figure 11: External fire case with a wetted vertical vessel calculated in Aspen HYSYS

Wetted Fire Example with a Vertical Vessel

The example is based on the following conditions:

Composition	50% propane, 50% isobutane using the Aspen HYSYS PR package for physical properties
Normal operating conditions	1000 kPaa, 85% vapor
Relief pressure	12 barg set pressure + 21% allowable overpressure = 14.52 barg
Vessel	Vertical with exposed bottom head, 3.5 m diameter, 8 m T/T height, with 2:1 ellipsoidal heads; 0 m above grade; normal liquid level is 3 m
Additional fire area	10% to allow for process piping
Insulation	No fireproof insulation is present
Drainage and firefighting	Adequate drainage and firefighting are present
Latent heat	The latent heat of the liquid at relieving conditions is estimated to be 280.8 kJ/kg

No correction needs to be made to the portion of liquid inventory that is considered, as the normal liquid level is less than 7.6 m above grade. The wetted surface area is computed as shown below.

$$A_{shell} = \pi\ D\ LL = 32.99\ \mathrm{m}^2$$

$$A_{head} = 1.084\ D^2 = 13.28\ \mathrm{m}^2$$

$$A_{ws} = 1.10 \times (A_{shell} + A_{head}) = 50.9\ \mathrm{m}^2$$

The required relief load is calculated using (Eq. 21) and (Eq. 22):

$$Q = (43200)(1.0)(50.9)^{0.82} = 1{,}084{,}000\ \mathrm{W}$$

$$w = 3.6\frac{(1{,}084{,}000)}{280.8} = 13{,}900\ \mathrm{kg/h}$$

The results calculated above are compared to results obtained in Aspen HYSYS in Table 11.

Variable	Units	Example Calculation	Aspen HYSYS
Vessel Type		**Vertical**	**Vertical**
Bottom Head Included?		**Yes**	**Yes**
Vessel Diameter (D)	m	**3.5**	**3.500**
Vessel T/T Length (L)	m	**8.0**	**8.000**
Vessel Liquid Level (LL)	m	**3.0**	**3.000**
Vessel Elevation Above Grade	m	**0.0**	**0.000**
Additional Area		**10%**	**10.00%**
Environment Factor (F)		**1.0**	**1.000**
Latent Heat (λ)	kJ/kg	**280.8**	280.8
Adequate drainage and firefighting present?		**Yes**	**Yes**
Heat Input Area (A_{ws})	m^2	50.9	50.89
Heat Input (Q)		1,084,000 W	3,901,000 kJ/h
Required Relieving Flow	kg/h	13,900	13,890
Blue = Calculation input Gray = Calculated value			

Table 11: Comparison of example calculation and Aspen HYSYS calculation for external fire on a vertical wetted vessel

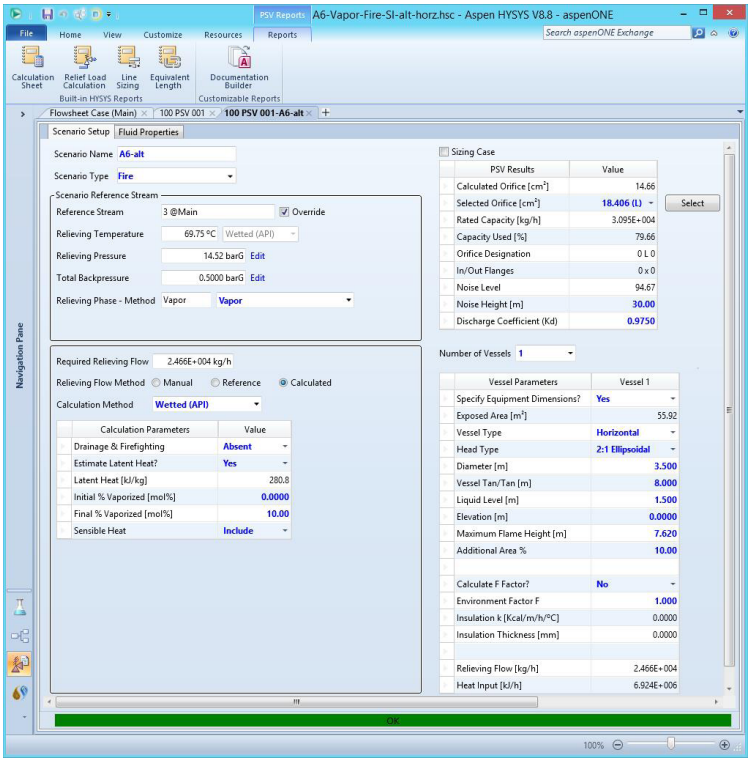


Figure 12: External fire case with a wetted horizontal vessel calculated in Aspen HYSYS

Wetted Fire Example with a Horizontal Vessel

The example is based on the following conditions:

Composition	50% propane, 50% isobutane using the Aspen HYSYS PR package for physical properties
Normal operating conditions	1000 kPaa, 85% vapor
Relief pressure	12 barg set pressure + 21% allowable overpressure = 14.52 barg
Vessel	Horizontal, 3.5 m diameter, 8 m T/T length, with 2:1 ellipsoidal heads; 0 m above grade; normal liquid level is 1.5 m
Additional fire area	10% to allow for process piping
Insulation	No fireproof insulation is present
Drainage and firefighting	Adequate drainage and firefighting are not present
Latent heat	The latent heat of the liquid at relieving conditions is estimated to be 280.8 kJ/kg

The fraction of the total area of the horizontal shell that is wetted may be computed as shown below.

$$\cos\theta = \frac{r-h}{r}$$

$$\theta = 1.427$$

$$f_{ws} = \frac{2\theta}{2\pi} = \frac{\theta}{\pi} = 0.454$$

$$A_{shell} = f_{ws}\,\pi\,D\,L = 39.97\ \mathrm{m}^2$$

$$B = \sqrt{1 + 12(h/D - 0.5)^2} = 1.030$$

$$A_{head} = 2\times\frac{\pi D^2}{8}\left[B(h/D-0.5) + 1 + 0.2887\ln\left(\frac{3.464(h/D-0.5)+B}{2-\sqrt{3}}\right)\right] = 11.89\ \mathrm{m}^2$$

$$A_{ws} = 1.10\times(A_{shell} + A_{head}) = 57.0\ \mathrm{m}^2$$

The required relief load is calculated using (Eq. 21) and (Eq. 22):

$$Q = (70900)(1.0)(57.0)^{0.82} = 1{,}952{,}000\ \mathrm{W}$$

$$w = 3.6\,\frac{(1{,}952{,}000)}{280.8} = 25{,}030\ \mathrm{kg/h}$$

The results calculated above are compared to results obtained in Aspen HYSYS in Table 12.

Variable	Units	Example Calculation	Aspen HYSYS
Vessel Type		**Horizontal**	**Horizontal**
Vessel Diameter (D)	m	**3.5**	**3.500**
Vessel T/T Length (L)	m	**8.0**	**8.000**
Vessel Liquid Level (LL)	m	**1.5**	**1.500**
Vessel Elevation Above Grade	m	**0.0**	**0.000**
Additional Area		**10%**	**10.00%**
Environment Factor (F)		**1.0**	**1.000**
Latent Heat (λ)	kJ/kg	**280.8**	280.8
Adequate drainage and firefighting present?		**No**	**No**
Heat Input Area (A_{ws})	m^2	57.0	55.92
Heat Input (Q)		1,952,000 W	6,924,000 kJ/h
Required Relieving Flow	kg/h	25,030	24,660
Blue = Calculation input Gray = Calculated value			

Table 12: Comparison of example calculation and Aspen HYSYS calculation for external fire on a horizontal wetted vessel

Wetted Fire Example with a Spherical Vessel

The example is based on the following conditions:

Composition	50% propane, 50% isobutane using the Aspen HYSYS PR package for physical properties
Normal operating conditions	1000 kPaa, 85% vapor
Relief pressure	12 barg set pressure + 21% allowable overpressure = 14.52 barg
Vessel	Spherical, 5 m diameter
Additional fire area	10% to allow for process piping
Insulation	No fireproof insulation is present
Drainage and firefighting	Adequate drainage and firefighting are present
Latent heat	The latent heat of the liquid at relieving conditions is estimated to be 280.8 kJ/kg

Five variations will be considered:

1	Elevation of 6 m, liquid level of 2 m
2	Elevation of 6 m, liquid level of 3 m
3	Elevation of 5 m, liquid level of 2 m
4	Elevation of 5 m, liquid level of 3 m
5	Elevation of 4 m, liquid level of 3 m

The wetted area exposed to heat input will be calculated using the equation below.

Eq. 23 $$A_{sphere} = \pi\, D\, h$$

The appropriate value for h depends on the variation of the example that we consider. In case 1, the liquid level is above 7.6 m above grade, but below the equator of the vessel, so the full level of 2 m is considered. In case 2, the liquid level is above 7.6 m above grade and above the equator of the vessel; the equator is higher, so that level of 2.5 m is used. In case 3, the liquid level is not above 7.6 m above grade nor above the equator of the vessel, so the full level of 2 m is considered. In case 4, the liquid level is above 7.6 m above grade and above the equator of the vessel; 7.6 m above grade is higher, so a level of (7.6 m – 5 m = 2.6 m) is used. In case 5, the liquid level is below 7.6 m above grade and below the equator of the vessel, so the full level of 3 m is considered.

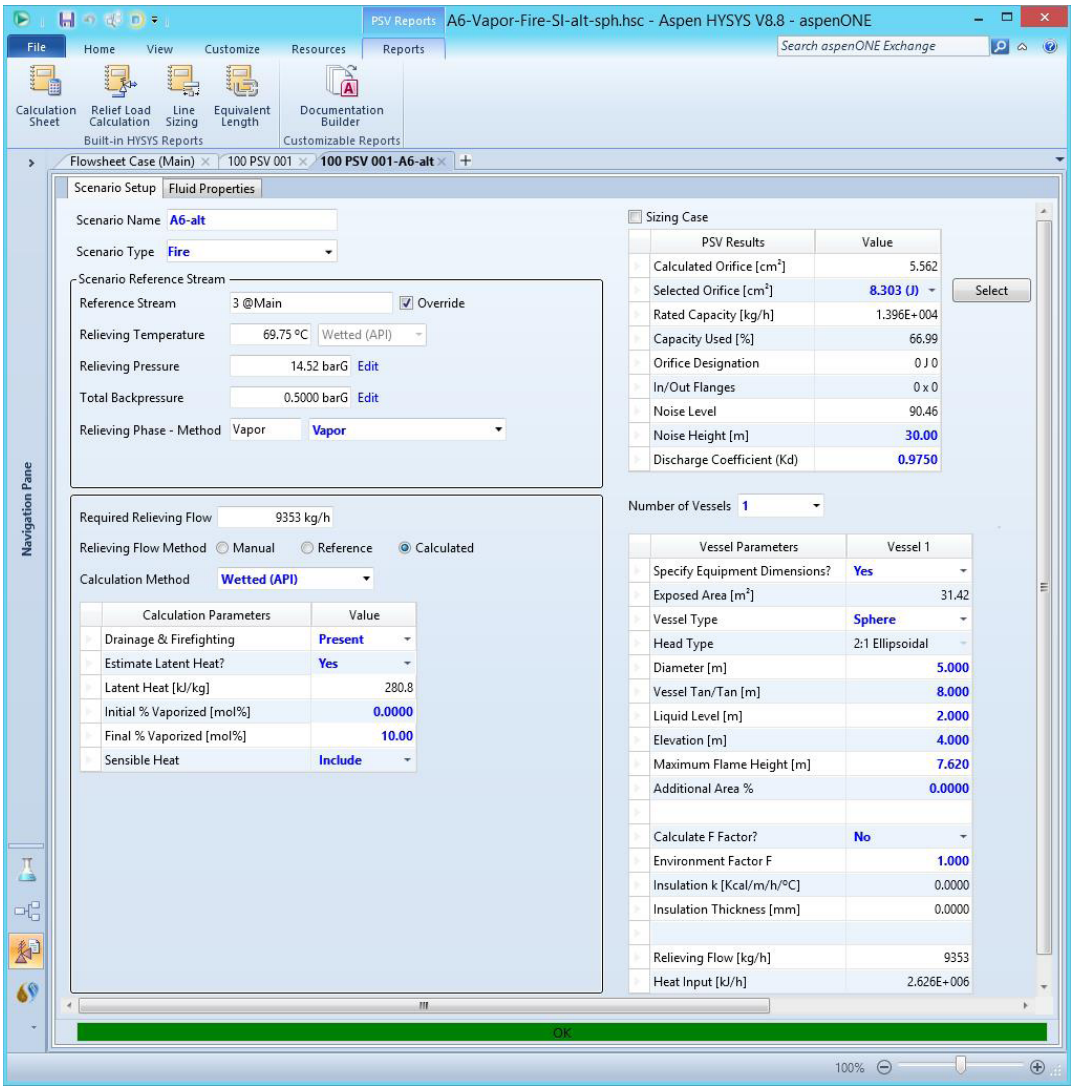


Figure 13: External fire case with a wetted spherical vessel calculated in Aspen HYSYS

The resulting wetted areas are:

1	$A_{ws}=\pi(5)(2)$	= 31.4 m²
2	$A_{ws}=\pi(5)(2.5)$	= 39.3 m²
3	$A_{ws}=\pi(5)(2)$	= 31.4 m²
4	$A_{ws}=\pi(5)(2.6)$	= 40.8 m²
5	$A_{ws}=\pi(5)(3)$	= 47.1 m²

The required relief loads are:

1	$w=(43200(31.4)^{0.82})/(280.8\times3.6)$	= 9,351 kg/h
2	$w=(43200(39.3)^{0.82})/(280.8\times3.6)$	= 11,240 kg/h
3	$w=(43200(31.4)^{0.82})/(280.8\times3.6)$	= 9,351 kg/h
4	$w=(43200(40.8)^{0.82})/(280.8\times3.6)$	= 11,590 kg/h
5	$w=(43200(47.1)^{0.82})/(280.8\times3.6)$	= 13,030 kg/h

The results calculated above for case 3 are compared to results obtained in Aspen HYSYS in Table 13.

Variable	Units	Example Calculation	Aspen HYSYS
Vessel Type		**Spherical**	**Spherical**
Vessel Diameter (D)	m	**5.0**	**5.000**
Vessel Liquid Level (LL)	m	**2.0**	**2.000**
Vessel Elevation Above Grade	m	**4.0**	**4.000**
Additional Area		**0%**	**0.0000%**
Environment Factor (F)		**1.0**	**1.000**
Latent Heat (λ)	kJ/kg	**280.8**	280.8
Adequate drainage and firefighting present?		**Yes**	**Yes**
Heat Input Area (A_{ws})	m²	31.4	31.42
Heat Input (Q)		729,400 W	2,626,000 kJ/h
Required Relieving Flow	kg/h	9,351	9,353
Blue = Calculation input Gray = Calculated value			

Table 13: Comparison of example calculation and Aspen HYSYS calculation for external fire on a spherical wetted vessel

Unwetted Fire Equations

The required relief load for a vessel filled with vapor (or vapor-like supercritical fluid) exposed to a fire are obtained from API Standard 521.[1]

The required relief load is calculated using the following equations, where for Equation 24, k is the ideal gas specific heat ratio $C_P/(C_P - R)$.

Eq. 24

$$C = 0.0395\sqrt{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}$$

For Equation 25, T_1 is the temperature at the upstream relieving pressure in K, T_n is the normal operating temperature in K, and p_1/p_n is the ratio of relief to normal operating pressure in kPaa.

Eq. 25

$$T_1 = \frac{p_1}{p_n}\,T_n$$

For Equation 26, T_w is the maximum wall temperature of the vessel in K and K_D is the coefficient of discharge of the relief valve (a value of 0.975 is typically used for preliminary design calculations).

Eq. 26

$$F' = \frac{0.2772}{C\,K_D}\left[\frac{(T_w - T_1)^{1.25}}{{T_1}^{0.6506}}\right]$$

A minimum value of 182 should be used for F'.

For equation 27, w is the required relief load in kg/h, M is the molecular weight of the fluid, and A' is the vessel area exposed to fire, which is calculated using the same method as the wetted area for a liquid-full vessel exposed to fire.

Eq. 27

$$w = 0.2772\sqrt{M \cdot p_1}\left[\frac{A'(T_w - T_1)^{1.25}}{{T_1}^{1.1506}}\right]$$

Unwetted Fire Example

The example is based on the following conditions:

Composition	100% water using the Aspen HYSYS NBS Steam package for physical properties
Normal operating conditions	2600 kPaa / 226.1 C
Relief pressure	25.17 barg set pressure + 10% overpressure = 27.7 barg = 2870 kPaa
Maximum wall temperature	866.5 K (from 1100 F)
Vessel	Horizontal, 1.016 m diameter, 3 m T/T length, with 2:1 ellipsoidal heads; 0 m above grade
Additional fire area	15% to allow for process piping

Relief temperature is calculated using (Eq. 25):

$$T_1 = \frac{2870}{2600}\,499.25 = 551.1\ \mathrm{K}$$

Flashing the contents at relief pressure and temperature in Aspen HYSYS yields the following properties:
$k = 1.210$

Then, the required relief load is calculated using (Eq. 24), (Eq. 26), and (Eq. 27):

$$C = 0.0395\sqrt{(1.210)\left(\frac{2}{1.210+1}\right)^{\frac{1.210+1}{1.210-1}}} = 0.0257$$

$$F' = \frac{0.2772}{(0.0257)(0.975)}\left[\frac{(866.5-551.1)^{1.25}}{551.1^{0.6506}}\right] = 242.1$$

This value is greater than 182, so no modification is needed to proceed.

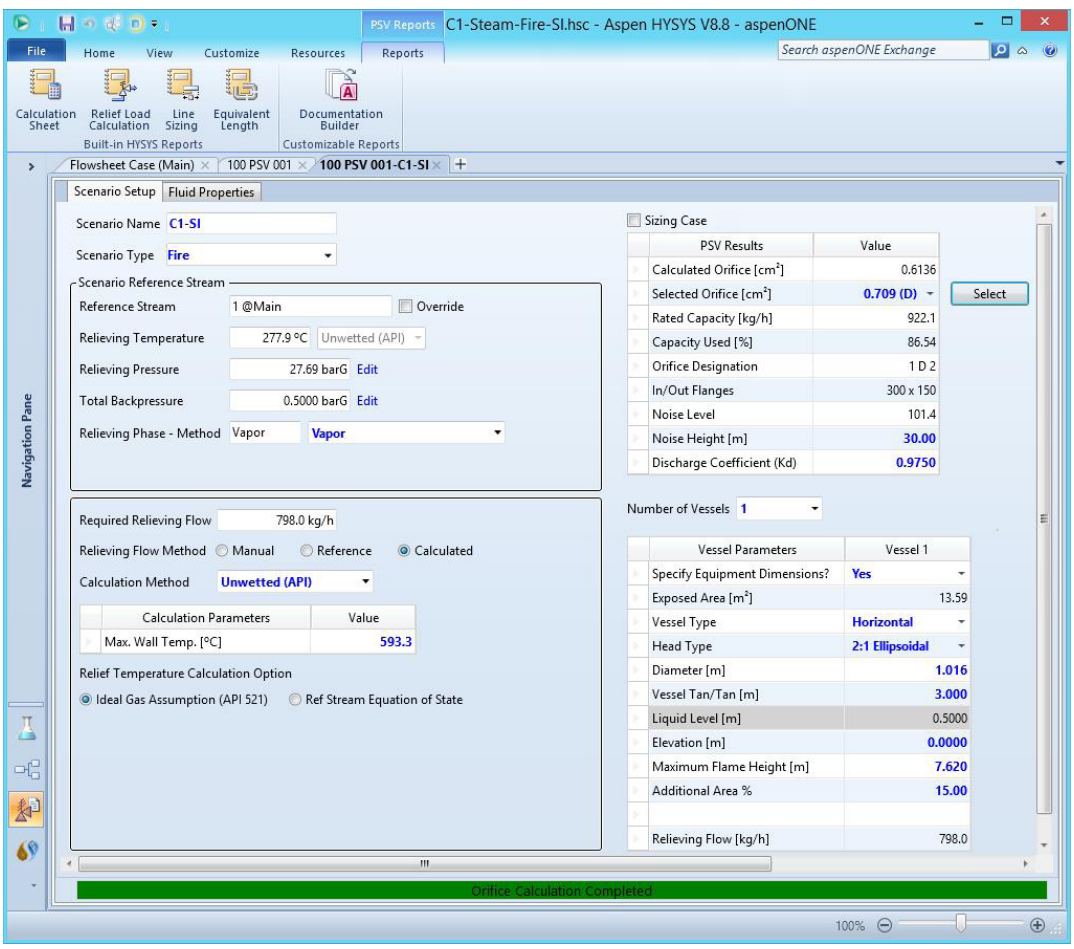


Figure 14: External fire case with an unwetted horizontal vessel calculated in Aspen HYSYS

$$A_{shell} = \pi DL = 9.58 \text{ m}^2$$

$$A_{heads} = 2 \times 1.084\, D^2 = 2.24 \text{ m}^2$$

$$A' = 1.15 \times (A_{shell} + A_{heads}) = 13.6 \text{ m}^2$$

$$w = 0.2772\sqrt{(18.02)(1600)}\left[\frac{13.6(866.5 - 551.1)^{1.25}}{551.1^{1.1506}}\right] = 799.1 \text{ kg/h}$$

The results calculated above are compared to results obtained in Aspen HYSYS in Table 14.

Variable	Units	Example Calculation	Aspen HYSYS
Maximum Wall Temperature		**866.5 K**	**593.3 C**
Operating Temperature	C	**226.1**	
Operating Pressure	kPaa	**2600**	
Vessel Type		**Horizontal**	**Horizontal**
Vessel Diameter (D)	m	**1.016**	**1.016**
Vessel T/T Length (L)	m	**3.0**	**3.000**
Vessel Elevation Above Grade	m	**0.0**	**0.000**
Additional Area		**15%**	**15.00%**
Heat Input Area (A')	m^2	13.6	13.59
C		0.0257	
F'		242.1	
Required Relieving Flow	kg/h	799.1	798.0
Blue = Calculation input Gray = Calculated value			

Table 14: Comparison of example calculation and Aspen HYSYS calculation for external fire on a horizontal unwetted vessel

In Conclusion

Safety is of the highest priority to every process, and ensuring accurate, validated calculations is a key component of this work. To view additional validation papers, access tutorial documents and videos, and learn more about the tools AspenTech provides to address process safety work, please visit the safety page on our company website, today!

References

1. American Petroleum Institute, API Standard 521 6th Ed.: Pressure-relieving and Depressuring Systems, Washington, DC: API Publishing Services, 2014.

2. W. Y. Wong, "PRV sizing for exchanger tube rupture," Hydrocarbon Processing, pp. 59-64, February 1992.

3. W. Y. Wong, "Correction to 'PRV sizing for exchanger tube rupture'," Hydrocarbon Processing, p. 44, May 1992.

AspenTech is a leading supplier of software that optimizes process manufacturing—for energy, chemicals, engineering and construction, and other industries that manufacture and produce products from a chemical process. With integrated aspenONE® solutions, process manufacturers can implement best practices for optimizing their engineering, manufacturing, and supply chain operations. As a result, AspenTech customers are better able to increase capacity, improve margins, reduce costs, and become more energy efficient. To see how the world's leading process manufacturers rely on AspenTech to achieve their operational excellence goals, visit **www.aspentech.com**.

Worldwide Headquarters
Aspen Technology, Inc.
20 Crosby Drive | Bedford, MA 01730 | United States
phone: +1-781-221-6400 | fax: +1-781-221-6410 | **info@aspentech.com**

Regional Headquarters
Houston, TX | United States
phone: +1-281-584-1000

São Paulo | Brazil
phone: +55-11-3443-6261

Reading | United Kingdom
phone: +44-(0)-1189-226400

Singapore | Republic of Singapore
phone: +65-6395-3900

Manama | Bahrain
phone: +973-13606-400

For a complete list of offices, please visit **www.aspentech.com/locations**

