Distillation column relief loads—Part 2

The conventional method is expanded and a series of guidelines are developed

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In the first part of this article, a comparison between the two methods for distillation column relief load calculations was made. In this part, the conventional method will be expanded and a series of guidelines to predict relief loads for distillation columns in upset conditions will be developed.

The presented here is based mainly on the mass and energy imbalance at upset conditions. This method relies heavily on detailed analysis of the contingencies that must be executed on a case-by-case basis. It also is based on several assumptions that simplify the complex behavior of distillation columns and make it possible to determine relief loads through a series of simple calculations and by using regular steady-state process simulation software.

**Basic assumptions.** There are several suppositions that must be made to enable determining relief loads:

1. At relieving conditions, feeds, products and reflux compositions as well as top-tray liquid and bottoms compositions are unchanged. Note that for multi-feed columns this is valid only if all the feed rates, at relief conditions, vary proportionally to the normal rates. This method cannot be used if the said condition is not applicable.

2. The column trays are at vapor/liquid equilibrium at relief pressure.

3. Except for the feeds, all streams entering and leaving the column are at vapor/liquid equilibrium at relieving pressure.

4. Vapors may not be accumulated in the column after reaching relieving pressure and must leave the system via the relief valve. Liquids could accumulate in the system by means of rising and falling liquid levels.

5. The liquid phase of feeds can absorb or release heat whether they leave or stay in the system.

6. Credit may be taken for the difference between liquid feed enthalpies and the enthalpies of the liquid products and accumulated liquids. That is if the total enthalpy of the liquid feeds is less than the total enthalpy of the liquid products and accumulated liquids. The difference must be converted to relief load if the total enthalpy of the liquid products and accumulated liquids is less than the total enthalpy of the liquid feeds (liquids enthalpy imbalance).

7. Energy imbalance, resulting from an upset, is converted to the relief load using top-tray liquid latent heat of vaporization, calculated at relieving conditions.

8. The vapor portions of the feed streams, flashed adiabatically at relieving pressure, directly contribute to the relief load.

9. The vapor distillate control valve, if applicable, stays at its position. Credit may be taken for the vapor distillate flowrate unless its path is blocked.

10. Credit may be taken for reboiler temperature pinch, if light materials can not reach the column bottom.

11. Any safety margin used in the design of equipment must be considered in the relief load calculations.

12. The properties of the vaporized top-tray liquid at bubble point and relief pressure are used to size the relief valve.

The orifice area of any relief valve in vapor service, using API RP-520 equations, is a function of the relieving fluid temperature, molecular weight and compressibility factor. All of this plus top-tray liquid latent heat of vaporization change with time during a relief event. The orifice area would be at maximum value when the following function is at maximum:

\[
f(T, Z, M, \lambda) = \sqrt{\frac{TZ}{M}}
\]

where:
- \( T \) = Relieving fluid temperature, °R
- \( Z \) = Relieving fluid compressibility factor, dimensionless
- \( M \) = Relieving fluid molecular weight, lb/lb-mol
- \( \lambda \) = Latent heat of vaporization, Btu/lb

In order to conservatively size a relief valve, one might calculate the maximum value of the function, \( f \), over the boiling range of the top-tray liquid and use corresponding properties, including top-tray liquid latent heat of vaporization, in sizing calculations.

**Relief load calculation.** Based on the above assumptions the relief rate can be defined as:

\[
W = W_R + W_F - W_V - W_C - W_H
\]

where:
- \( W \) = Relief rate
- \( W_R \) = Load contribution from reboilers and side-reboilers
- \( W_F \) = Feed streams vapor contributions
- \( W_V \) = Vapor product credits
- \( W_C \) = Condenser and pumparound credits
- \( W_H \) = Liquids enthalpy imbalance credit/contribution.

**Load contributions from reboilers.** Heat input from the reboilers and side-reboilers is converted to relief load using top-tray liquid latent heat of vaporization:
PROCESSING DEVELOPMENTS

TABLE 1. Column parameters, feed and product properties

<table>
<thead>
<tr>
<th>Column parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating pressure (top), psig</td>
<td>175.0</td>
</tr>
<tr>
<td>Relief valve set pressure, psig</td>
<td>200.0</td>
</tr>
<tr>
<td>Relieving pressure, psig</td>
<td>220.0</td>
</tr>
<tr>
<td>Normal condenser duty, million Btu/hr</td>
<td>29,890</td>
</tr>
<tr>
<td>Condenser duty at relief, million Btu/hr</td>
<td>0.000</td>
</tr>
<tr>
<td>Normal reboiler duty, million Btu/hr</td>
<td>35,000</td>
</tr>
<tr>
<td>Reboiler duty at relief (clean U), million Btu/hr</td>
<td>47,230</td>
</tr>
<tr>
<td>Top-tray liquid latent heat, Btu/lb</td>
<td>123.5</td>
</tr>
</tbody>
</table>

**Feed properties**

<table>
<thead>
<tr>
<th></th>
<th>Liquid</th>
<th>Vapor</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed normal flowrate, lb/hr</td>
<td>264,864</td>
<td>123,236</td>
<td>388,100</td>
</tr>
<tr>
<td>Feed rate at relieving conditions, lb/hr</td>
<td>294,564</td>
<td>93,536</td>
<td>388,100</td>
</tr>
<tr>
<td>Specific enthalpy at normal conditions, Btu/lb</td>
<td>466.7</td>
<td>12.1</td>
<td></td>
</tr>
<tr>
<td>Specific enthalpy at relief conditions, Btu/lb</td>
<td>-417.1</td>
<td>8.2</td>
<td></td>
</tr>
<tr>
<td>Bubble point specific enthalpy at relief, Btu/lb</td>
<td>-141.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Product properties**

<table>
<thead>
<tr>
<th></th>
<th>Prod. 1</th>
<th>Prod. 2</th>
<th>Prod. 3</th>
<th>Prod. 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal flowrate, lb/hr</td>
<td>121,000</td>
<td>98,361</td>
<td>168,100</td>
<td>639</td>
</tr>
<tr>
<td>Flowrate at relieving conditions, lb/hr</td>
<td>135,500</td>
<td>0</td>
<td>168,100</td>
<td>0</td>
</tr>
<tr>
<td>Specific enthalpy at normal conditions, Btu/lb</td>
<td>110.6</td>
<td>-90.0</td>
<td>-697.2</td>
<td>-6,972.1</td>
</tr>
<tr>
<td>Specific enthalpy at relief conditions, Btu/lb</td>
<td>106.0</td>
<td>-75.0</td>
<td>-677.6</td>
<td>-6,956.4</td>
</tr>
<tr>
<td>Phase</td>
<td>Vapor</td>
<td>Liquid</td>
<td>Liquid</td>
<td>Liquid</td>
</tr>
<tr>
<td>Bubble point specific enthalpy at relief, Btu/lb</td>
<td>-22.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ W_R = \frac{Q_R}{\lambda} \] (3)

where: \( Q_R \) = Reboilers and side-reboilers total duty, Btu/hr
\( \lambda \) = Top-tray liquid latent heat of vaporization, Btu/lb.

Credit is allowed for reboiler temperature pinch if light materials cannot reach the column bottom at relieving conditions. The heat transfer coefficients of the reboilers and side-reboilers, however, must be adjusted to clean (zero fouling factors) values.

**Feed streams vapor contribution.** The vapor portions of the feeds, flashed adiabatically at relief pressure, directly contribute to relief load. The compositions of those vapors, however, are different from that of the relief stream. The latent heat contents of the vapor portions of the feeds must be calculated and converted to relief load.

The assumption is that as the rising vapor feeds come in contact with tray liquids they are partially condensed while vaporizing some of the tray liquids. This happens all the way to the top tray. The heat content of each vapor feed, which contributes to relief load, is equal to the feed heat-of-vaporization at relief pressure. This heat is simply the difference between dew point and bubble point enthalpies of the vapor feed at relieving pressure.

\[ Q_{FV} = \sum \left( H_{FV,i} - H_{PV,i} \right) F_{FV,i} \] (4)

where: \( Q_{FV} \) = Vapor feeds total heat of vaporization, Btu/hr
\( H_{FV,i} \) = Specific enthalpy of vapor feed \( i \) at dew point and relief pressure, Btu/lb
\( H_{PV,i} \) = Specific enthalpy of vapor feed \( i \) at bubble point and relief pressure, Btu/lb
\( F_{FV,i} \) = Flowrate of vapor feed \( i \) at relief conditions, lb/hr

The relief load contribution from vapor feeds is equal to the total heat of vaporization of the vapor feeds divided by the top-tray liquid latent heat.

\[ W_F = \frac{Q_{FV}}{\lambda} \] (5)

**Vapor product credits.** If the vapor products and the relieving fluids are of different compositions, the same method used for the vapor feeds should be applied to convert vapor product (latent) heat contents to a relief load credit:

\[ Q_{PV} = \sum \left( H_{PV,i} - H_{PV,i} \right) F_{PV,i} \] (6)

and

\[ W_P = \frac{Q_{PV}}{\lambda} \] (7)

where: \( Q_{PV} \) = Vapor products total heat of vaporization, Btu/hr
\( H_{PV,i} \) = Specific enthalpy of vapor product \( i \) at dew point and relief pressure, Btu/lb
\( H_{PV,i} \) = Specific enthalpy of vapor product \( i \) at bubble point and relief pressure, Btu/lb
\( F_{PV,i} \) = Flowrate of vapor product \( i \) at relief pressure, lb/hr.

**Condenser and pumparound credits.** Similar to the reboilers and side-reboilers, the condenser and pumparound

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duties are converted to relief load credit using the top-tray liquid latent heat of vaporization:

$$W_C = \frac{Q_C}{\Lambda}$$  \(8\)

where:  
$$Q_C = \text{Condensers and pumparound total duty, Btu/hr}$$

Although the temperature difference (LMTD) in the condensers and pumparound tends to increase during relief, it is hard to justify additional credit for the increased duties of the condensers and pumparound exchangers.

**Liquids enthalpy imbalance.** The assumption that the product compositions stay unchanged at relieving conditions logically concludes that the feeds, if continued, will partition into the same product compositions as in normal conditions. The products will be formed in the column whether they leave or accumulate in the system. Since the compositions of the products are the same as the normal compositions, the product rates at relief should be proportional to the normal product rates.

The heat absorbed or released by the feeds to form products (at their liquid phase) is the enthalpy imbalance and is equal to the sum of the enthalpies of liquid products and accumulated liquids minus the sum of the liquid feed enthalpies at relieving conditions. Credit may be taken for the liquids enthalpy imbalance if the sum of the feed enthalpies is smaller than the sum of the product and liquid accumulation enthalpies. If the reverse is true, the enthalpy difference must be converted into and added to the relief load.

It is important to understand that the liquids enthalpy imbalance is the heat required (with a positive or a negative sign) to form products at their liquid bubble point status. Note that the relief load calculations are based on the heat input to the system and the latent heat of vaporization, which is the heat required changing bubble point liquids to dew point vapors. In short, liquid feeds form bubble point liquid products (using liquids enthalpy imbalance) and bubble point liquid products form relief load or vapor products (using latent heat of vaporization). It is important to ensure that while all the input and output heats are accounted for, they are not double dipped in the calculations.

The basis for enthalpy imbalance, however, must be a balanced mass and applies only to the liquid portions of the feeds. The vapor phase is directly converted to relief load as previously explained. The method used to calculate the mass of liquid bubble point products and accumulations is:

1. The total rate of all feeds (liquids plus vapors) at relieving conditions is distributed to product streams, proportional to the normal product rates. Obviously, if the feed rates are not changed the results would be the same as normal product flowrates.
2. The products are sorted by specific enthalpies in a descending order. A rate equal to the sum of vapor portions of all feeds at relieving conditions is subtracted from the product

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TABLE 2. Liquid product adjusted rates and enthalpies

<table>
<thead>
<tr>
<th>Description</th>
<th>Prod. 1</th>
<th>Prod. 2</th>
<th>Prod. 3</th>
<th>Prod. 4</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Product normal flowrates, lb/hr</td>
<td>121,000</td>
<td>98,361</td>
<td>168,100</td>
<td>639</td>
<td>388,100</td>
</tr>
<tr>
<td>(2) Feed vapor phase total flowrate, lb/hr</td>
<td>93,536</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>93,536</td>
</tr>
<tr>
<td>(3) Adjusted rates, (1) – (2)</td>
<td>27,464</td>
<td>98,361</td>
<td>168,100</td>
<td>639</td>
<td>294,564</td>
</tr>
<tr>
<td>(4) Bubble point specific enthalpies at relief, Btu/lb</td>
<td>-22.4</td>
<td>-75.0</td>
<td>-677.6</td>
<td>-6,956.4</td>
<td></td>
</tr>
<tr>
<td>(5) Total enthalpies of products (3) x (4), Btu/hr</td>
<td>-615,194</td>
<td>-7,377,075</td>
<td>-113,904,560</td>
<td>-4,445,140</td>
<td>-126,341,969</td>
</tr>
</tbody>
</table>

rates, starting with product 1 (highest specific enthalpy) and moving to the next product subtracting the balance of the vapor feed rates. The results are the adjusted liquid product rates the sum of which should be equal to the total rate of the liquid portions of the feeds. The adjusted rates and the liquid feed rates are the mass basis for the liquids enthalpy imbalance calculation. Note that the adjusted [product] rates are independent of the actual liquid product rates at relieving conditions. Once again, the assumption is that liquids can accumulate in the column by the rise or fall of the liquid level.

3. The liquids enthalpy imbalance is the sum of the enthalpies of the adjusted products minus the sum of the enthalpies of liquid feeds:

\[ Q_{L} = \sum H_{PL} j \times F_{PL} j - \sum H_{PL} i \times F_{PL} i \]  \hspace{1cm} (9)

and

\[ W_{H} = Q_{H} / \lambda \]  \hspace{1cm} (10)

where:

- \( Q_{L} \) = Liquids enthalpy imbalance, Btu/hr
- \( H_{PL} j \) = Specific enthalpy of liquid product \( j \) at bubble point and relief pressure, Btu/lb
- \( F_{PL} j \) = Adjusted flowrate of the liquid product \( j \) lb/hr
- \( H_{PL} i \) = Specific enthalpy of the liquid phase of the feed \( i \) at relief pressure, Btu/lb
- \( F_{PL} i \) = Flowrate of the liquid phase of the feed \( i \) at relief conditions, lb/hr

A numerical example. A typical distillation column is evaluated for a condenser failure scenario. The column parameters, feed properties and product properties are summarized in Table 1.

Contingency analysis. The reflux drum liquid level drops quickly. Both reflux and liquid distillate product streams will be lost regardless of either being on level or flow control. The difference is timing and sequence. The one on level control stops first, and pretty quickly. The feed is on flow control and its rate stays constant. The vapor distillate control valve stays at its position (constant Cv). At relieving pressure, it can pass 135,500 lb/hr (an extra 12%) vapor product. With no liquid distillate product, the lights in the feed could get to the column bottom; therefore, no credit may be taken for the reboiler temperature pinch.

Load calculations: Load contribution from reboilers and side-reboilers:

\[ W_R = Q_R / \lambda \]

\[ W_R = 47,230,000 / 123.5 = 382,429 \text{ lb/hr} \]

Feed streams vapor contribution:

\[ Q_{FV} = \sum \left( H_{FVD} j - H_{FVB} j \right) F_{FV} j \]

\[ Q_{FV} = \left[ 8.2 - (-141.5) \right] 93,536 = 14,002,339 \text{ Btu/hr} \]

\[ W_p = Q_{FV} / \lambda \]

\[ W_p = 14,002,339 / 123.5 = 113,379 \text{ lb/hr} \]

Vapor product credits:

\[ Q_{PV} = \sum \left( H_{PVD} j - H_{PVB} j \right) F_{PV} j \]

\[ Q_{PV} = \left[ 106.0 - (-22.4) \right] 135,500 = 17,398,200 \text{ Btu/hr} \]

\[ W_p = Q_{PV} / \lambda \]

\[ W_p = 17,398,200 / 123.5 = 140,876 \text{ lb/hr} \]

Condenser and pumparound credits:

\[ W_C = Q_C / \lambda \]

\[ W_C = 0.0 \text{ lb/hr} \]

Liquids enthalpy imbalance:

\[ Q_H = \sum H_{PL} j \times F_{PL} j - \sum H_{PL} i \times F_{PL} i \]

The liquid product specific enthalpies and adjusted rates as well as the sum of the product total enthalpies, \( \sum H_{PL} j \times F_{PL} j \), are summarized in Table 2. HP

\[ \sum H_{PL} j \times F_{PL} j = 126,341,969 \text{ Btu/hr} \]

\[ \sum H_{PL} i \times F_{PL} i = 294,564 (-417.1) = 122,862,644 \text{ Btu/hr} \]

\[ Q_H = -3,479,325 \text{ Btu/hr} \]

\[ W_H = Q_H / \lambda \]

\[ W_H = -3,479,325 / 123.5 = -28,173 \text{ lb/hr} \]

\[ W = W_R + W_P - W_C - W_H \]

\[ W = 382,429 + 113,379 - 140,876 - 0 = -28,173 \]

\[ W = 383,105 \text{ lb/hr} \]

Piruz Latifi Nezami is a process engineering section manager with Jacobs Engineering in Houston, Texas. He holds a BS degree in chemical engineering from Sharif University of Technology in Tehran, Iran, and has more than 30 years of experience in the design and engineering of chemical, petrochemical and refining projects.