Memo

Practical procedure for LNG RPT risk-assessment

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1 RPT peak pressure and explosive yield

In Aursand and Hammer [1], we developed the following step-by-step procedure for LNG RPT risk assessment for a given LNG mixture:

1. Approximately specify the LNG mixture in question in terms of the first four alkanes,

$$z = [z_1, z_2, z_3, z_4], \tag{1}$$

where each number represents the molar fraction of methane (C1), ethane (C2), propane (C3), and n-butane (C4), respectively. If the mixture is given in terms of mass fractions w_i, the molar fractions may be found from

$$z_i = \frac{w_i/M_i}{\sum_j w_j/M_j}, \tag{2}$$

where M_i is the molar mass of species i.

2. Calculate the **Alkane factor**,

$$\zeta(z) = \frac{M_2 z_2 + M_3 z_3 + M_4 z_4}{M_2(1 - z_1)}, \tag{3}$$

which is essentially the average molar mass of the non-methane part of the mixture, relative to the molar mass of pure ethane (M_2). Typical LNG mixtures generally yield values in the range $\zeta \in [1.1, 1.4]$.

If ζ is less than 1.1 we predict that delayed RPT will not occur, and the risk-assessment stops here.

3. Calculate the **Leidenfrost fraction**,

$$z_\mathrm{L} = 1 - \frac{0.36}{\zeta - 0.73}, \tag{4}$$

which is the methane fraction that the mixture must boil down to before meeting the criterion for delayed RPT triggering. One may also calculate the **reduction factor**,

$$\nu = (1 - z_1)\frac{\zeta - 0.73}{0.36}, \tag{5}$$

which is the fraction of initial moles remaining at the time when the triggering criterion is reached.

4. Calculate the predicted **peak pressure**,

$$p^* = \left[1 - \mathrm{e}^{-5.6(\zeta-1)}\right] \cdot 62\,\mathrm{bar}, \tag{6}$$

which is the estimated maximum explosive pressure close to the source of the RPT event.

5. Calculate the predicted **explosive energy yield**. In terms of triggered moles of LNG, it is found from

$$E = \left[4.731\zeta^3 - 24.65\zeta^2 + 41.75\zeta - 20.60\right] \cdot 1\,\mathrm{kJ\,mol^{-1}}. \tag{7}$$

The yield in terms of triggered mass may then be found from

$$E^{(\mathrm{mass})} = \frac{E}{z_\mathrm{L} M_1 + \zeta(1 - z_\mathrm{L}) M_2}. \tag{8}$$

2 Risk assessment for an axisymmetric continuous spill

In Ref. [2], we present a simple set of equations for predicting the radius, time, and potential mass of a delayed RPT event for an idealized case of an unbounded, axisymmetric continuous spill of LNG onto water. It is assumed that the spill has a constant mass rate S (kg s^{-1}) within a spill radius $r < r_0$. The spilled LNG has composition $z = (z_1, z_2, z_3, z_4)$. We assume that only the methane is evaporation and we approximate the specific enthalpy of evaporation ΔH by the methane value ΔH_1, which is listed in standard chemical tables. Furthermore, we assume that the heat flux $\dot{q}$ from sea water into LNG is roughly independent of position and composition.

With the above assumptions, we find that the radius of RPT is

$$r_\mathrm{RPT} = \sqrt{\frac{S(1 - \hat{z}_\mathrm{L})\,\Delta H_1}{2\dot{q}}}, \tag{9}$$

where $\hat{z}_\mathrm{L}$ is given by Eq. (4) except in terms of mass fractions. The time of RPT is then given by

$$t_\mathrm{RPT} = \frac{r_\mathrm{RPT}}{u_\mathrm{LE}}, \tag{10}$$

where u_LE is the spill leading-edge velocity and is approximately given by

$$u_\mathrm{LE} \simeq 1.05\sqrt[3]{\frac{S g_\mathrm{eff}}{4\pi\rho r_0}}. \tag{11}$$

Here $g_\mathrm{eff} = \delta g$ is the effective acceleration of gravity, and δ is the a buoyancy factor based on the densities of water and LNG, $\delta = (\rho_\mathrm{w} - \rho)/\rho_\mathrm{w}$.

Finally, the following is a worst-case estimate of the total mass of LNG that at any time $t > t_\mathrm{RPT}$ may trigger in an RPT event,

$$M_\mathrm{RPT} = \hat{z}_\mathrm{L} S(t - t_\mathrm{RPT}). \tag{12}$$

References

[1] E. Aursand and M. Hammer. “Predicting triggering and consequence of delayed LNG RPT”. In: Journal of Loss Prevention in the Process Industries 55 (2018), pp. 124–133. DOI: `10.1016/j.jlp.2018.06.001`.

[2] K. Y. Lervåg, H. L. Skarsvåg, E. Aursand, J. A. Ouassou, M. Hammer, G. Reigstad, Å. Ervik, E. H. Fyhn, M. A. Gjennestad, P. Aursand, Ø. Wilhelmsen, and S. T. Munkejord. A coupled fluid-dynamical, heat-transfer, and thermodynamical model to predict the onset of rapid phase transitions in spills of cryogenic liquids. Journal article to be submitted early 2020.