Risk and Consequences of Rapid Phase Transition for Liquid Hydrogen

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Safe handling of liquid hydrogen (LH_2) has gained extra attention over the last years due to an increase in usage to mitigate climate changes. Rapid phase transition (RPT) is a potential safety concern when cryogens, like LH_2 and liquefied natural gas (LNG), are accidentally spilled onto water. A theoretical assessment of the risk and consequences of LH_2 RPT has been conducted. The assessment is based on the RPT theory established from LNG research, as well as published reports on actual LH_2 spills. We give a review of the established theory on LNG RPT, examine the probability of an LH_2 RPT event, and give estimates on the theoretical consequence in terms of the peak pressure and the explosive energy yield. There are two main findings of this study. Firstly, the known theoretical pathways to LNG RPT are impossible or very unlikely when applied to LH_2 spills. Secondly, the theoretical consequences of an explosive LH_2 RPT event are low compared to LNG RPT. The expected peak pressure is about 25% of an LNG RPT, while the expected explosive energy yield is only about 10% of an LNG RPT, given the same volume of participating cryogen. Combined with the knowledge that LNG RPT events are only moderately dangerous, the hypothetical LH_2 RPT event is possibly characterized by a low destructive potential.

Keywords: Liquid hydrogen, Safe fuel handling, Cryogens, Rapid phase transition, Spill accidents, Risk and consequence analysis

1. Introduction

Hydrogen technology is pointed out as one of the solutions to reduce emissions in the transport and energy sectors. The high volumetric energy density of liquid hydrogen (LH_2) compared to gaseous hydrogen is an advantage for transport and storage of large quantities. LH_2 is considered a cryogen due to its extremely low boiling point (20 K). With an increase in usage, transportation and storage, the need for more knowledge of safe handling is important.

Liquefied natural gas (LNG) is another cryogenic fuel that has been widely used over the last decades. If LNG is accidentally spilled onto water it has been observed in some cases, seemingly at random, to undergo a localized explosive vaporization (Reid, 1983; Cleaver et al., 1998; Luketa-Hanlin, 2006; Melhem et al., 2006; Koopman and Ermak, 2007). This is known as a rapid phase transition (RPT) and has the potential to have devastating consequences (Luketa-Hanlin, 2006; Havens and Spicer, 2007; Pitblado and Woodward, 2011; Forte and Ruf, 2017). Predicting triggering and consequence of LNG RPT was subject to a recent study by Aursand and Hammer (2018). The literature on LH2 RPT is very limited, and to the best of our knowledge, no RPT-like event as a consequence of an LH_2 spill has been reported. This does not mean that LH_2 RPT is impossible.

In this study, we examine the probability and consequences of the hypothetical LH_2 RPT event. The assessment is based on the RPT theory established from LNG research, as well as published reports on actual LH_2 spills. Our focus is RPT events caused by the cryogen being spilled onto water, since this is a likely scenario for transportation and storage in a marine environment. We recognize that other scenarios may also cause RPT events, e.g., when water is released onto a cryogenic pool. An introduction to RPT and a review of the established theory on LNG RPT is given in Sec. 2. This theory is then applied to LH_2 in Sec. 3. In particular, we apply the approach by Aursand and Hammer (2018) to estimate the consequences of an RPT event in terms of the peak pressure of the vapor-explosion and the explosive energy yield. Finally, we summarize the main conclusions of this study in Sec. 4.

2. LNG Rapid Phase Transition (RPT)

Natural gas is a common fossil fuel whose main component is methane (about 90%), with the remainder consisting of progressively smaller amounts of the heavier alkanes. For long-range

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transportation, natural gas is sometimes cooled down below its boiling point (−162 °C at atmospheric pressure) to form liquefied natural gas (LNG) (Kumar et al., 2011).

2.1. *The phenomenon of RPT*

When LNG is spilled onto water it will in the majority of cases eventually boil off without further incident. However, in some cases it is observed to suddenly, and seemingly at random, undergo a localized explosive vaporization. This is an RPT event, and is considered one of the main safety concerns of the LNG industry (Reid, 1983; Pitblado and Woodward, 2011). Still, the attention given to RPT risk in LNG safety reviews is highly variably, ranging from significant discussion (Pitblado and Woodward, 2011; Cleaver et al., 2007; Luketa-Hanlin, 2006; Shaw et al., 2005) to little more than a brief mention (Alderman, 2005; Hightower et al., 2005; Havens and Spicer, 2007; Raj and Bowdoin, 2010; Forte and Ruf, 2017).

RPT is not an explosion in the common meaning of the word, since it does not involve combustion or other chemical reactions. RPT events are what is sometimes called a vapor explosion or a physical explosion. It is still destructive in nature, and poses a danger to both people and equipment. Its peak pressures and released mechanical energy can be large enough to displace and damage heavy equipment (Luketa-Hanlin, 2006; Pitblado and Woodward, 2011; Forte and Ruf, 2017) and could theoretically cause secondary structural damage and cascading containment failures (Havens and Spicer, 2007). Whether or not an RPT event will occur in any given spill has been notoriously difficult to predict. From extensive tests performed by LLNL in the 1980s (Luketa-Hanlin, 2006; Koopman and Ermak, 2007; Melhem et al., 2006) it was found that RPT occurred in about one third of spills. It was also observed that a single spill may lead to more than ten distinct RPT events. The yields of single RPT events seem quite random, and may apparently have TNT equivalents of anything from a few grams to 6 kg (about 25 MJ) (Koopman and Ermak, 2007; Melhem et al., 2006; Cleaver et al., 1998; ABS Consulting, 2004; Hightower et al., 2004).

The general macroscopic chain-of-events of a marine LNG spill is as follows:

(i) *Containment breach*: Due to some unintended event, the containment of LNG in a tank or transfer line is broken. If the breach is above sea level, the LNG may fall towards the water surface in the form of a jet.
(ii) *Jet impact*: The LNG jet impacts the water surface, which will break it up into separate droplets.
(iii) *Droplet/water mixing*: If the momentum of the the jet is large enough, the droplets will initially penetrate the surface and become submerged in water. This forms a chaotic *mixing region*.
(iv) *Pool formation and spreading*: Since the density of LNG is about half of that of water, the droplets will be buoyant and will eventually rise to the surface. This forms an LNG pool that spreads on top of the water surface.
(v) *Boil-off*: The boiling point of LNG is at about −162 °C (at atmospheric pressure), while the water holds a temperature relatively close to 0 °C, so the spreading pool will start boil while spreading. Since methane is by far the most volatile component, the resulting vapor is almost purely methane. This causes a gradual compositional change, which increases the relative amounts of the heavier alkanes such as ethane, propane and butane.

See Fig. 1 for an illustration of the scenario. As indicated, there is an established distinction between two kinds of RPT events depending on when and where it occurs in a spill event (Luketa-Hanlin, 2006; Koopman and Ermak, 2007). An *early RPT* is defined as any RPT that occurs in the mixing region at any time during the spill event, while a *delayed RPT* is defined as any RPT that is not an early RPT, which means that it must occur somewhere in the spreading pool, not in the mixing region. Reports indicate that delayed RPT only occurs a considerable time (on the scale of minutes) after the start of the LNG spill event.

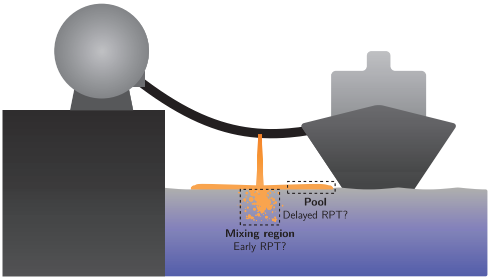

Fig. 1. An illustration of a spill-scenario, where a breach in a fueling line causes the release of cryogen in the form of a falling jet. Also shown are the origins of the two kinds of RPT event: *early RPT* from the mixing region, and *delayed RPT* from the spreading pool.

2.2. *The theory of RPT*

After the possibility of LNG RPT was discovered in the 1960s, a handful of research groups went to work on understanding the mechanisms behind the phenomenon. By the first half of the 1970s, they had arrived at a general consensus for a theory of RPT (Katz and Sliepcevich, 1971;

Katz, 1972; Nakanishi and Reid, 1971; Enger, 1972; Enger and Hartman, 1972a,b; Enger et al., 1973). This is a theory about what occurs on the small scales at the local time and position where a single RPT event is observed, and is relevant for both early and delayed RPT. The theory may be summarized by the following chain-of-events:

(i) *Film-boiling stage*: The temperature difference between the sea water and the LNG is so large that boiling occurs far into the *film boiling* regime, see Fig. 2. This means that the LNG pool or droplet is insulated from the water by a vapor film consisting mainly of methane. Because of this the heat flux stays relatively low and the evaporation stays in a quasi-equilibrium regime. All of the energy transferred into the LNG is spent on evaporation, and the LNG temperature stays close to the bubble-point, which is initially about $-162\,°\mathrm{C}$.

(ii) *Film-boiling collapse (liquid-liquid contact)*: For some reason there is a sudden and localized *film-boiling collapse*. The suggested mechanisms for film-boiling collapse will depend on whether one is considering early or delayed RPT. In either case, this means that there is considerable direct contact between the water and the LNG, which increases the heat flux by orders of magnitude.

(iii) *Rapid superheating to the superheat limit*: Because a liquid-liquid interface has relatively few nucleation sites, the evaporation rate is initially unable to keep up with the dramatic increase in heat flux. Instead, much of the heat is spent on *superheating* the LNG, which means that the liquid is heated significantly beyond its boiling temperature. The superheated liquid is in a meta-stable state, and may transition to its corresponding equilibrium state if disturbed. If not disturbed sufficiently, there is a maximum temperature at which the liquid must transition regardless of external disturbances. This is called the *superheat limit*.

(iv) *Homogeneous nucleation*: Once the liquid approaches its superheat limit, vaporization spontaneously occurs throughout its volume by *homogeneous nucleation*. This is the start of a rapid transition from a liquid state to a two-phase state.

(v) *Explosive expansion*: If in mechanical equilibrium with its surroundings, the new state would take up over 100 times the volume of the original superheated liquid state. The fluid is initially forced to fit in the original volume, so the pressure increases dramatically before it has time to expand. Since this transition happens fast, it is observed as a loud and destructive vapor explosion. The event involves high-pressure waves and considerable energy release through expansion work.

2.3. *Predicting triggering of RPT*

The main challenge when predicting the occurrence of RPT is predicting step two, the sudden film-boiling collapse and subsequent liquid–liquid contact. We refer to this as the *triggering event*. The approach depends on whether one considers early RPT (droplet boiling) or delayed RPT (pool boiling).

2.3.1. *Delayed RPT*

For delayed RPT, the relevant mode of boiling is *pool boiling*. This is usually quantified in terms of the *boiling curve* (Dhir, 1998). A general illustration of a boiling curve is shown in Fig. 2.

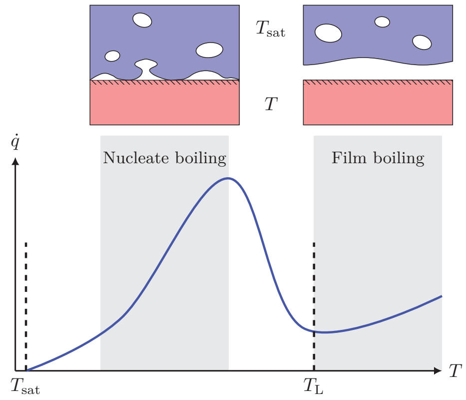

Fig. 2. Illustration of a typical boiling curve for saturated pool boiling, showing boiling heat flux ($\dot{q}$) as a function of surface temperature (T). In our case, the cryogen is the boiling fluid (blue shape), while water takes the role as the hot surface (red shape). Once $T > T_{\mathrm{sat}}$ the surface is considered superheated, and the difference $T - T_{\mathrm{sat}}$ is called the *surface superheat*. At moderate surface superheat we are in the conventional *nucleate boiling regime*. Once the surface superheat becomes very large there is a transition into a *film-boiling regime*, which comes with a dramatic drop in heat flux due to the formation of a continuous vapor film. The lower end of the film boiling regime is the Leidenfrost temperature (T_{L}), and crossing this from right to left is called *film-boiling* collapse.

In the present case, LNG takes the role of the boiling fluid and water takes the role of the hot surface. According to the theory described above RPT is triggered on film-boiling collapse, which for pool boiling is defined by the position on the boiling curve:

$$\begin{aligned} T_\mathrm{L} < T_\mathrm{w} &: \text{Film boiling (no RPT)}\\ T_\mathrm{L} > T_\mathrm{w} &: \text{Liquid-liquid contact (risk of RPT)}, \end{aligned} \tag{1}$$

where T_w is the temperature of the water. The Leidenfrost temperature of a fluid such as LNG is difficult to predict (or even measure) with good accuracy, but it has generally been found that it is close to, but slightly below, the fluid's critical temperature (Spiegler et al., 1963),

$$T_\mathrm{L} \approx \frac{27}{32} T_\mathrm{crit}. \tag{2}$$

The critical point of a typical LNG mixture is in the region of $T_\mathrm{crit} \approx 203\,\mathrm{K}$ ($-70\,^\circ\mathrm{C}$), yielding $T_\mathrm{L} \approx 171\,\mathrm{K}$ ($-102\,^\circ\mathrm{C}$). By comparison, since the water is normally not observed to freeze in large-scale LNG spills, the surface holds a temperature close to zero, $T_\mathrm{w} \approx 0\,^\circ\mathrm{C}$. Hence, we are safely in the "Film boiling (no RPT)" part of Eq. (1).

The above calculations are only true for LNG with its initial (stored) composition. As boil-off proceeds, the composition changes in such a way that the critical temperature of the mixture increases. According to Eq. (2), this means that the Leidenfrost temperature will also increase. Eventually it reaches the water temperature, which according to Eq. (1) gives a risk of RPT. See Fig. 3 for an illustration of this *LNG RPT boil-off* effect.

Thus, the challenge of predicting the triggering of delayed LNG RPT is reduced to the prediction of when and where the condition $T_\mathrm{L} > T_\mathrm{w}$ may be satisfied. In our previous work, Aursand and Hammer (2018), this was analyzed extensively in terms of the methane fraction necessary to satisfy the the triggering criterion. In short, the results can be summarized as follows. The LNG must boil down to approximately 30-50 mol% methane before meeting the condition for delayed RPT triggering ($T_\mathrm{L} \approx T_\mathrm{w}$). This depends on the relative amounts of the heavier alkanes. By the time the triggering condition is met, only 10-20% of the original amount of LNG is remaining.

2.3.2. *Early RPT*

As indicated in Fig. 1, so-called early RPT occurs in the chaotic mixing region beneath the point of LNG jet impact. This region contains film-boiling LNG droplets submerged in water, which initially move downwards due to inertia but eventually move back to the surface due to buoyancy. According to the general theory of RPT presented in Sec. 2.2, the triggering event is initiated by sudden significant liquid-liquid contact. Predicting this for early RPT is much more difficult than in the case of delayed RPT, since the degree of liquid-liquid contact is no longer governed by a simple boiling curve. In this case it would require a detailed multi-phase simulation of the mixing region over sufficiently long time-scales. This has to our knowledge not been achieved, and we consider early RPT an unsolved problem in the LNG industry.

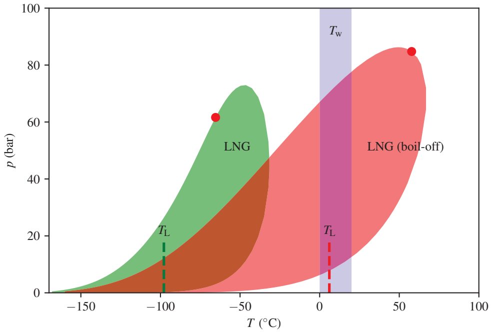

Fig. 3. An illustration of how the two-phase region (filled shapes) and the critical point (red dot) shifts to higher temperatures as methane is removed from the mixture due to boil-off. In this particular example the LNG boils down from 90 mol% methane to 40 mol% methane. This causes the Leidenfrost temperature (T_L), according to Eq. (2), to shift up into the typical seawater temperatures (blue bar), which satisfies the condition for delayed RPT triggering.

2.4. *RPT consequence quantification*

Our work in Aursand and Hammer (2018) also included a method of partially quantifying the consequence of RPT. According to the theoretical chain-of-events listed in Sec. 2.2, after film-boiling collapse (Leidenfrost transition) there is rapid superheating, homogeneous nucleation and explosive expansion. Here we enable consequence quantification by simplifying the final two steps in the chain-of-events (steps 4-5) by the following idealized two-step process:

(i) *Equilibration*: Calculate the energy and density of the the mixture exactly when it reaches the superheat limit after film-boiling collapse. The temperature of this state is the superheat limit (T_SHL) corresponding to the composition at the time when the triggering criterion was reached. Then, find the corresponding quasi-equilibrium state, with the same energy, density and composition. This yields a new high-pressure intermediate state (T^*, p^*).

(ii) *Isentropic expansion*: The intermediate state (T^*, p^*) is called a quasi-equilibrium state because while it is in local equilibrium, it is not in mechanical equilibrium with the surroundings ($p^* \gg 1\,\mathrm{atm}$). This leads to a rapid expansion, which is approximated as an isentropic process. The end-state of this expansion may then be found as the state at atmospheric pressure that has the same entropy as the high-pressure intermediate state.

There are two significant numbers to take away from such a calculation. Firstly, the *peak pressure* (p^*) is found as the pressure of the intermediate state before expansion. The value may be interpreted as an estimate for the peak pressure seen in the vapor-explosion event very close to the source. Secondly, the *explosive energy yield* (E) is found as the mechanical work done by the expansion process. Since the process is assumed to be isentropic (reversible and adiabatic), it follows from classical thermodynamics that the work done by the process is simply the difference in total enthalpy between the initial and final states of the expansion. Note that this merely yields an energy per amount triggered (i.e. per mole or kilogram), not a total amount.

Even with these simplifying assumptions, performing this calculation involves a set of quite complex thermodynamic algorithms. Firstly, an algorithm to calculate the superheat limit (T_{SHL}). Here we use the method described in Aursand and Hammer (2018). Secondly, an algorithm to calculate the two-phase equilibrium state, given either values for energy and density or values for entropy and pressure. Here we use the implementations in SINTEF's in-house software (Wilhelmsen et al., 2017), which are based on algorithms described by Michelsen and Mollerup (2007).

The result of such a calculation is shown in Fig. 4. This result will depend on the initial LNG composition, which will vary some. In Aursand and Hammer (2018) the range of outcomes given a plausible range of LNG compositions was explored, and the conclusions were the following. The predicted explosive yield from LNG RPT (E) is in the range of $50\text{–}80\,\mathrm{kJ/kg}$, which is equivalent to about $12\text{–}20\,\mathrm{gTNT}$ per kg LNG. In terms of spilled liquid volume, this is about $5\text{–}10\,\mathrm{gTNT}$ per litre. The predicted peak pressure from LNG RPT (p^*) is in the range of $20\,\mathrm{bar}$ to $60\,\mathrm{bar}$.

Note that the predicted yield is only found in terms of energy per liquid amount that participates in the event. Since there is currently no way of predicting how much liquid will participate in a single event, the explosive yield of single RPT events cannot be predicted. However, the calculations give useful upper bounds on the explosive potential of an LNG pool. They also give numbers that may be compared with other substances, such as LH_2.

3. Assessment of LH_2 RPT

To our knowledge, no RPT-like incident has ever been reported in relation to LH_2 spills. Pritchard and Rattigan (2010) reported in 2010 that "…no record of a RPT resulting from a LH_2 spill has been found", and subsequent reports addressing hydrogen safety does not mention RPT (Batt, 2014; Royle and Willoughby, 2014; Ekoto et al., 2014; Kotchourko et al., 2014; Rivkin et al., 2015; Ruiz, Vega, del Mar Arxer, Jimenez, and Rausa, Ruiz et al.; Keller et al., 2016). Furthermore, experimental activity on LH_2 spills on water is limited to the BAM trials in 1994 (Verfondern and Dienhart, 1997, 2007), were no RPT-like events was observed. In this section we will assess the probability and consequences of a hypothetical LH_2 RPT event based on the theory for LNG RPT presented in Sec. 2.

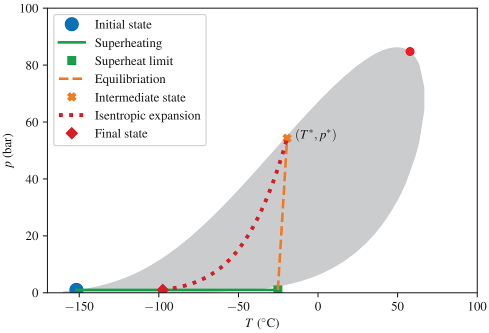

Fig. 4. The result of an RPT consequence calculation, as described in Sec. 2.4, for an LNG mixture that is triggered after boiling down to 40 mol% methane. In this particular example the theoretical explosive yield (E) is $20\,\mathrm{gTNT}$ per kg LNG, or about $10\,\mathrm{gTNT}$ per liter of spilled LNG. The predicted peak pressure (p^*) is about $55\,\mathrm{bar}$.

3.1. *Triggering of LH_2 RPT*

3.1.1. *Delayed RPT*

If we assume that the basic principles and theories for LNG RPT also apply for the hypothetical LH_2 RPT, the triggering criterion Eq. (1) for delayed RPT should still hold. In other words, triggering may only occur if the Leidenfrost temperature (T_{L}) is at or above the water temperature. According to the approximate model in Eq. (2), the Leidenfrost temperature of hydrogen is about $28\,\mathrm{K}$. This is somewhat consistent with the value of $24\,\mathrm{K}$ reported by Wang et al. (2016). In either case, the triggering criterion is far from being satisfied:

$$T_{\mathrm{L}} \ll T_{\mathrm{w}} \implies \text{No triggering.} \qquad (3)$$

Furthermore, a pure fluid like H_2 has no compositional shift as boil-off proceeds. This is in contrast to LNG, where the initial stable situation like Eq. (3) is eventually lost due to methane depletion. In terms of Fig. 2, LH_2 will be far into the film-boiling regime throughout the boil-off process, which will prevent RPT. The conclusion is the following: As long as the surface (water) temperature stays anywhere near $0\,°\mathrm{C}$, delayed LH_2 RPT is impossible given that the applied theory is valid.

3.1.2. *Early RPT*

We should also consider the possibility of early RPT, as described for the case of LNG in Sec. 2.3.2. As illustrated in Fig. 1, early RPT occurs in the mixing-region below the location where the cryogen jet penetrates the water surface. As mentioned in Sec. 2.3.2, there is no satisfactory method for quantifying the probability of early RPT. From experience of LNG spills, it seems to be an event of quite high probability, occurring in about one third of spills. In contrast, no early RPT has ever been observed in LH_2 spills, and we may speculate why this is the case:

- *Small mixing region*: This relates to the mixing region illustrated in Fig. 1, where all early RPT events occur by definition. LNG on water has a density-ratio of about $1/2$, which allows for an appreciable mixing region. In contrast, LH_2 on water has a density-ratio of less than $1/10$. Unless the jet has a very high velocity, it is unlikely to have enough inertia to penetrate the water and create an significant mixing region. Additionally, if a droplet is submerged, it will be brought to the surface by buoyancy very quickly.
- *Stable film-boiling droplets*: As mentioned the Leidenfrost temperature is very low compared to the water temperature. While this value is usually measured for pool boiling, the stability of film boiling around submerged droplets is likely quite related to this. This suggests that even if an LH_2 droplet is submerged in water, it will likely stay separated from the water by a vapor film, and thus not satisfy the fundamental criterion for RPT triggering (film-boiling collapse).

3.1.3. *Hypothetical pathways to LH_2 RPT*

Note that the above argument is based on the assumption of no ice-formation, i.e. a situation where the LH_2 is spilled on top of liquid water that holds an approximately constant temperature of $0\,°\mathrm{C}$. Moreover, we neglect other triggering criteria such as water waves, that could increase the mixing region and hence possibly facilitate an RPT. For large-scale (unconfined) LNG-on-water spills very little or no ice-formation is usually reported (Luketa-Hanlin, 2006; Cleaver et al., 2007), despite the very low LNG temperature ($-162\,°\mathrm{C}$). It appears that the film-boiling heat transfer is not sufficiently strong to overcome the convective heat transfer in the water, and thus is unable to create the sub-cooling necessary to nucleate and grow solid ice. However, LH_2 is considerable colder ($-253\,°\mathrm{C}$), which presumably could be enough to cause noticeable ice-formation. The formation of continuous and thick (several mm) layers of ice when LH_2 is spilled on water has been reported in experiments (Verfondern and Dienhart, 1997, 2007). This may be important for (at least) the following reasons:

- *Sub-cooled ice*: The presence of an ice sheet allows for a new potential mechanism for the triggering of delayed RPT. If there is no freezing, the surface temperature would essentially be locked to a constant $T_\mathrm{w} \approx 0\,°\mathrm{C}$, leading to the conclusion that the only way to satisfy Eq. (1) is to increase the Leidenfrost temperature, which is not possible for LH_2. However, the formation of ice allows for the further cooling of T_w. If the ice surface cools all the way down to T_L, the triggering criterion can be satisfied despite T_L being constant. The maximum heat flux achieved after film-boiling collapse (*critical heat flux*) is quite high ($1 \times 10^5\,\mathrm{W/m^2}$ (Wang et al., 2016)), despite the temperature difference being less than $10\,\mathrm{K}$ at that point. This is almost as high as the critical heat flux of methane (Sciance et al., 1967).
- *Jet-on-ice impact*: The presence of an ice sheet makes the incoming jet impact a solid surface instead of a liquid surface. One could imagine this leading to a new kind of early RPT.

Both of the above hypothetical pathways lead to liquid-solid contact after film-boiling collapse. This may make RPT unlikely, as the fundamental theory outlined in Sec. 2.2 often stress the importance of a liquid-liquid interface between the cryogen and the hot substrate. A liquid-liquid interface has no nucleation sites, which allows the sudden heat-flux increase to be spent on superheating instead of rapid heterogeneous nucleation. Sudden liquid-solid contact after film-boiling collapse may merely lead to normal (but rapid) nucleate boiling instead of an explosive RPT event.

It is also worth mentioning that the temperature of LH_2 ($20\,\mathrm{K}$) is below the freezing points of both oxygen ($54\,\mathrm{K}$) and nitrogen ($63\,\mathrm{K}$). This means that there is a potential to both condense and freeze oxygen gas and nitrogen gas from the air and mix it into the LH_2 pool. Such mixing may have unpredictable consequences, and should be studied further.

3.2. *Consequences of LH_2 RPT*

Regardless of the actual probability of triggering, we may apply the procedure described in Sec. 2.4 to quantify the consequence of LH_2 RPT assuming that it does occur. The results of such a calculation are shown in Fig. 5, which is the equivalent of what Fig. 4 showed for LNG. Note that in this case, as opposed to the case of LNG, a single calculation is representative for all scenarios because there is no composition variable in a pure fluid. The results are summarized and compared with LNG in Tab. 1.

Table 1. The predicted consequences of LH_2 RPT compared to LNG RPT. The energy yields per volume were calculated using densities of $450\,\mathrm{kg/m^3}$ for LNG and $71\,\mathrm{kg/m^3}$ for LH_2.

	LNG	LH_2	LH_2 compared to LNG
Peak pressure (p^*)	20–60 bar	7 bar	12% – 35%
Yield (energy per mass)	50–80 kJ/kg	38 kJ/kg	48% – 76%
Yield (energy per volume)	22000–36 000 kJ/m^3	2700 kJ/m^3	7.5% – 12%

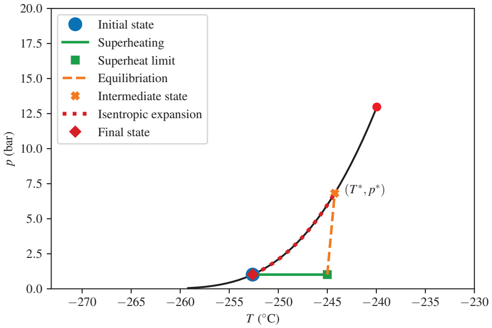

Fig. 5. The result of an RPT consequence calculation, as described in Sec. 2.4, applied to pure hydrogen. Theoretical explosive yield (E) is 9.2 gTNT per kg LNG, or about 0.65 gTNT per liter of spilled LNG. The predicted peak pressure (p^*) is about 6.8 bar.

4. Conclusions

The probability and consequence of a hypothetical RPT event caused by a LH_2 spill (release) onto water has been evaluated based on established LNG research. We may draw the following conclusions from this assessment.

The probability of an explosive LH_2 RPT event similar to the well known phenomenon of LNG RPT seems to be low. The theoretical pathways to RPT known from LNG research seem unlikely due to the very low Leidenfrost temperature of hydrogen, the lack of a shift in the Leidenfrost temperature due to boil-off, and the presumably very small mixing region at the point of jet impact in the absence of waves. The formation of an ice sheet could theoretically allow the triggering of RPT, but this would require the ice to have time to cool down to extremely low temperatures. This theoretical risk assessment is supported by the fact that no RPT incidents have ever been reported from real LH_2 spills.

In a hypothetical LH_2 RPT event, the estimated consequence of the vapor explosion is considerably smaller than an LNG RPT event. The predicted peak pressure is only about 25% of that from LNG RPT. The predicted explosive energy yield is about 60% by mass (or about 10% by volume) compared to LNG RPT.

Based on these arguments, we judge the hypothetical LH_2 RPT to be an issue of only minor concern. It should be noted that there have been relatively few LH_2 spills on water, experimental or accidental, when compared to LNG spills. Thus, the fact that no LH_2 RPT has been reported is not conclusive evidence for it being impossible and additional experiments is recommended. Experimental activity on LH_2 spill on water designed to investigate triggering and consequences of LH_2 RPT is planned to be conducted as part of the project ”Safe H_2 fuel handling and Use for Efficient Implementation (SH$_2$IFT)”.

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