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Runefors, Marcus; Mcnamee, Robert

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Influence of Sprinklers on the Thermal Exposure of a Tank Exposed to a Hydrogen Jet Flame

Runefors, M.[1,*], McNamee, R.[1,2]

[1] *Division of Fire Safety Engineering, Lund University, Lund, Sweden.*
[2] *Fire and Safety, Research Institutes of Sweden (RISE), Lund, Sweden.*
**Corresponding author's email: marcus.runefors@brand.lth.se*

ABSTRACT

A high-pressure tank rupture is a challenging scenario requiring attention in most hydrogen applications. A common cause of rupture is an external fire heating the tank, causing increased internal pressure and/or reduction in the tensile strength of the tank material (with the relevance of each depending on tank material).

Most of the available methods for prevention of such ruptures have been developed, primarily, for buoyancy-driven flames from nearby combustible materials. However, in some applications, a rupture due to heating from a hydrogen jet, emanating from a leak on the system, also needs to be prevented. One method, that has been used in some sites in Sweden, is to use a deluge water spray system to cool the exposed tank. However, this approach has not yet been experimentally validated.

In this paper, a series of experiments are presented to assess the feasibility of such an approach. In the experiments a simulated tank is exposed to a small impinging hydrogen jet ($L_f \approx 1$ m) while simultaneously being cooled by a sprinkler system delivering water densities between 12.2 mm/min and 30.5 mm/min.

The results show that, although the temperature at most of the tank surface becomes significantly lower due to the sprinkler, temperatures can locally remain much higher ($\Delta T \approx$ 600-800K) which might still cause a rupture of a type-IV-tank. It is more likely that a sprinkler system can prevent rupture of a type-I-tank, but this has not been decisively proven.

KEYWORDS: Tank rupture; Jet fires; Plate-thermometers; Thermal exposure; Water film.

INTRODUCTION

The high storage pressures needed to compensate for the low volumetric energy density of hydrogen leads to a large amount of stored mechanical energy which will be released in case of a tank rupture. This energy release is further reinforced by the feedback from the hydrogen combustion feeding into the pressure wave, which typically occurs for hydrogen [1]. Together, this leads to tank rupture potentially being a very destructive scenario which, in most situations, needs to be prevented.

There are a number of techniques available to mitigate the risk of a tank rupture, such as the installation of a temperature-activated pressure relief device (TPRD), but these need to be installed where they are directly affected by fire and, to the authors' knowledge, there are no products on the market that satisfy the pressure vessel directive for fixed installations. Alternative ways, such as Leak-Not-Burst-design and intumescent painting of the tanks, has not yet been widely adopted.

All these methods have been developed primarily to prevent a rupture induced by a fire in nearby combustible material, but not for an impinging hydrogen jet flame which might in some situations be needed, at least for stationary application. One method, that has been used at some sites in Sweden, is to install a deluge water sprinkler system designed to 12.2 mm/min in water density. This density is based on the requirement in point 6.11.2.2 in NFPA 55-2020 [2], referring to Extra Hazard Group 1 according to NFPA 13 [3] for storage of flammable gases. This is used in combination with flow restriction in the hydrogen system that limits the size of potential jet flames. The underlying idea among the designers is that the water film formed on the tank surface provides enough cooling to prevent a potential impinging hydrogen jet from inducing a tank rupture.

However, a scientific underpinning of this approach is lacking. Indeed, to provide enough cooling of the tanks from hydrogen jets flames with a temperature of over 2000°C is certainly challenging. Also, the high storage pressures result in jets with potentially a very high momentum that might push the water film from the area of jet impingement.

In this paper, some experimental results are presented where a high-pressure hydrogen jet flame impinges on a metal cylinder constructed as a large plate thermometer equipped with a grid of 30 thermocouples. The influence of a deluge water sprinkler system, with different design densities, are investigated to assess whether it has a significant cooling effect on the temperatures at the area of jet impingement and if the effect is so substantial that it can affect the potential of a tank rupture.

THEORY

Hydrogen jet flames

Hydrogen jet flames have been extensively studied in the literature, and a broad range of correlations for flame length exist [4]. Also, there are several studies on thermal radiation emitted from such flames. However, few studies investigate the thermal structure of large-scale hydrogen diffusion flames, probably do to that this is generally less relevant for safety since the temperatures in the entire flame is high enough to provide a significant hazard for people and equipment.

Molkov [4] performed a literature review of axial temperature distribution based on three papers in the literature and found that the maximum axial temperature was 2180°C occurring at around 60-80% of the visible flame length. It can be noted that this value is very close to the theoretical upper limit which is the adiabatic flame temperature at 2254°C. No study on the radial temperature distribution of a large-scale hydrogen diffusion flame has been identified.

Also, the literature on impinging hydrogen jets is scarce. There are some studies on the pressure effects of delayed jet ignition of impinging hydrogen jets [5], but few studies are concerned about the thermal impact of impinging jets on structures. A notable recent exception is the SH2IFT-project currently performed by SINTEF in Norway together with partners. They performed a series of impinging hydrogen jets and presented their results on a webinar on June 22nd, 2021. A scientific publication is currently underway according to direct communication with the authors. From the webinar, it can be noted that the maximum temperature measured on steel plate walls backed with ceramic wool (i.e. similar to the tank used in the current study), was approximately 1200°C and, for large jets/short distances, a cool spot were be found around the stagnation zone due to impingement of unburned hydrogen. One study on the effect of sprinklers on impinging jets has been found and concluded that the sprinkler system had a moderate effect on gas temperatures, but high effect on exposed structures [6].

Temperature measurements using plate thermometers

The plate thermometer is a standardized measurement device used to regulate the thermal exposure during fire resistance testing in furnaces [7,8]. It is basically a 100 x 100 mm wide, and 0.7 mm thick, plate made of a nickel alloy. This plate is insulated with a 10 mm thick ceramic insulation on one side. In the centre of the metal plate the hot junction of a type K thermocouple is attached by spot welding or screwing. During fire resistance testing, the metal side of the metal/insulation sandwich is pointing away from the test specimen, i.e. the temperature registered by the thermocouple is measuring an effective exposure temperature. As the size of the plate is 100 x 100 mm the convective heat transfer coefficient of the plate is similar to larger objects that are typically tested.

The plate thermometer concept for controlling the exposure in fire resistance furnaces was originally developed by Wickström [9]. The use of plate thermometers has then been extended and are used on a regular basis in the fire research area. In this context, concepts for using the plate thermometer for estimation of incident radiation [10] and a related methodology for heat transfer calculations based on the so-called "adiabatic surface temperature" have been developed [11,12].

METHODS

The experiments were performed using a jet fire rig with a 0.6 mm nozzle connected to two 50 l bottles of hydrogen at approximately 176 bar pressure. The jet was directed towards a simulated tank in the form of a cylinder made of 1.5 mm stainless steel with a diameter of 440 mm. The diameter was intended to simulate a Hexagon Type IV-tank with a volume of 76 l. The cylinder was designed based on a plate thermometer design (see theory) with a backing of 25 mm ceramic insulation with a density of 80 kg/m^3. During all but one of the experiments, the cylinder was subjected to cooling with a sprinkler head delivering 12.2 to 30.5 mm/min. An overview of the experimental setup can be found in figure 1 below.

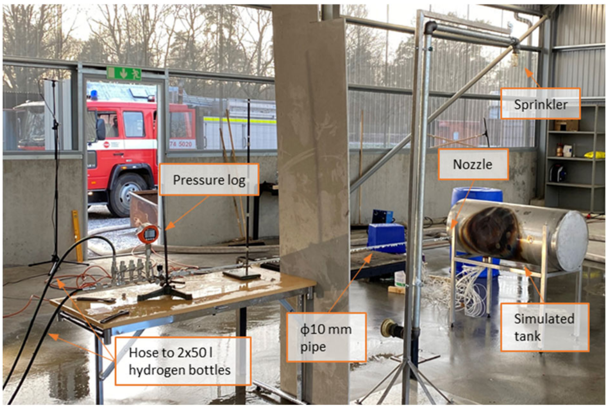


Fig. 1. Overview of the experimental setup.

In the simulated tank, 0.8 mm type KX ceramic fibre insulated thermocouples were welded on the inside of the cylinder with a distance of 100 mm both in the horizontal direction and along the circumference. The positions are labelled so that "A0" was located at the central point of jet impingement and then the labelling was according to figure 2. In total, 30 thermocouples were used labelled from A-4 to A+5, B-4 to B+4, C-3 to C+3 and D-2 to D+2. Of these, A+2 and B-2 failed at an early stage of the experimental campaign and was therefore not included in the analysis. The temperatures were logged with a frequency of one second using a datalogger (dataTaker DT85). The distances used in the test can be found in figure 2 below.

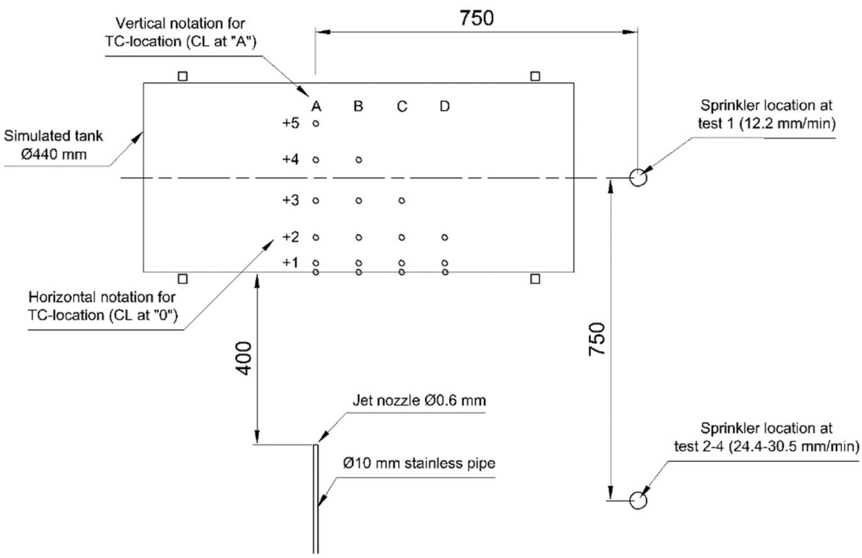


Fig. 2. Top-view of test setup with jet rig, simulated tank and sprinkler location.

As noted in figure 2, the sprinkler head was moved 750 mm after the first test to allow for a more direct impingement of the droplets on the most exposed location since it was found to be difficult for the sprinkler to affect that area. The sprinkler flow was based on nominal water densities in NFPA 13-2022 [3] ranging from 12.2 to 30.5 mm/min based on a 9 m^2 coverage area for Extra Hazard according to 10.2.4.2.1. The sprinkler system was fed from a fire truck and the flow was regulated using a needle valve and a magnetic-inductive flow meter (IFM Electronic SM9000). An overview of the test campaign and the actual densities at the point of jet impingement is found in the table below. The actual density was measured using a bucket test with a bucket of size 0.42x0.42 m^2 centred at the point of jet impingement and with a height of 0.6 m. The results can be found in table 1.

Table 1. Sprinkler heads used in the different tests, nominal water density based on a 9 m^2 coverage area and actual density at the point of jet impingement.

Test	**Sprinkler head**	**Nominal water density** (based on a 9 m^2 coverage area) [mm/min]	**Actual density at the location of jet impingement** [mm/min]
1	Standard pendent K115 (V3406)	12.2	6.3
2 & 3	ESFR K-17 [a] K240 (TY7226)	24.4	13.0
4	ESFR K-17 [a] K240 (TY7226)	30.5	17.6
5	None	N/A	N/A

[a] These sprinklers were intended to be standard pendent K160, but due to wrong delivery, noticed only after the experiments, an ESFR sprinkler was tested instead. This will cause the droplets to be slightly larger than intended, but the flow will be according to specification.

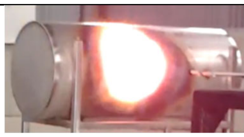
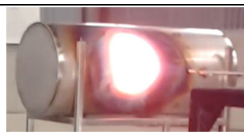
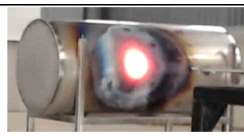
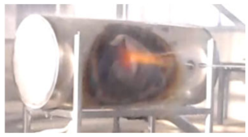
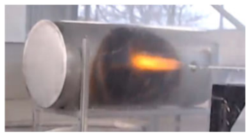
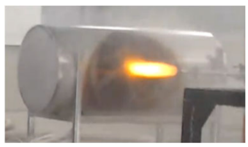
RESULTS

First, some visual observations from the tests are presented, and, after that, quantitative results are shown.

Visual observations

Snapshots of the tank at different times are given in table 2 below.

Table 2. Snapshots of the tank mock-up at different pressure levels during the tests.

	150 bar	**100 bar**	**50 bar**
	t = 68 s	t = 282 s	t = 688 s
No sprinkler			
12.2 mm/min[a]	*N/A*		
24.4 mm/min			
30.5 mm/min			

[a] Note that in this test, the sprinkler was placed along the tank centreline and not displaced by 750 mm as in the remaining tests.

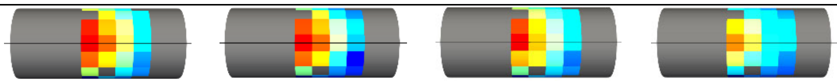
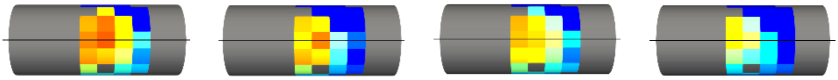
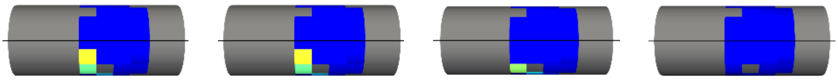
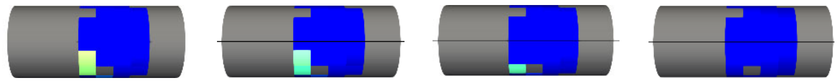
A few things can be noted from the pictures above. At first, for the sprinkled cases at 150 bar, the point of highest temperature appear to be shifted downwards and left (i.e. away from the location of the sprinkler). Secondly, the flame length at 50 bar just barely reaches the tank, and, finally, it appears that the flame becomes more luminous as the sprinkler density increases.

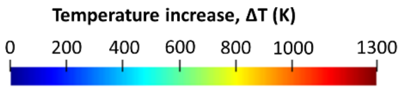
Temperature profile

The target temperature at the different locations is presented at three different pressures during the tank blowdown – 150 bar, 100 bar and 50 bar. This is complemented by the maximum temperature at each location throughout the experiment.

First, an overview of the temperature profile is given in table 3 through a visualization of the front view using ParaView. For increased readability, only the first of the two iterations at 24.4 mm/min sprinkler flow is presented. A comparison with the second iteration is presented in the discussion chapter. Parts of the tank that have colours different from the legend are not equipped with thermocouples (or the thermocouples were damaged during the experiments).

Table 3. Overview of the temperature profiles of the tank at 150 bar, 100 bar and 50 bar as well as maximum temperature for the different tests

	Maximum	150 bar	100 bar	50 bar
		t ≈ 68 s	t ≈ 282 s	t ≈ 688 s
No sprinkler				
12.2 mm/min[a]				
24.4 mm/min				
30.5 mm/min				



[a] Note that in this test, the sprinkler was placed along the tank centreline and not displaced by 750 mm as in the remaining tests.

While the profile above gives a reasonable overview of the results, the results are reiterated below in figure 3 to allow for a more quantitative comparison. The results shown are the temperatures in the vertical direction where "0" represent the point where the hydrogen jet impinges on the simulated tank.

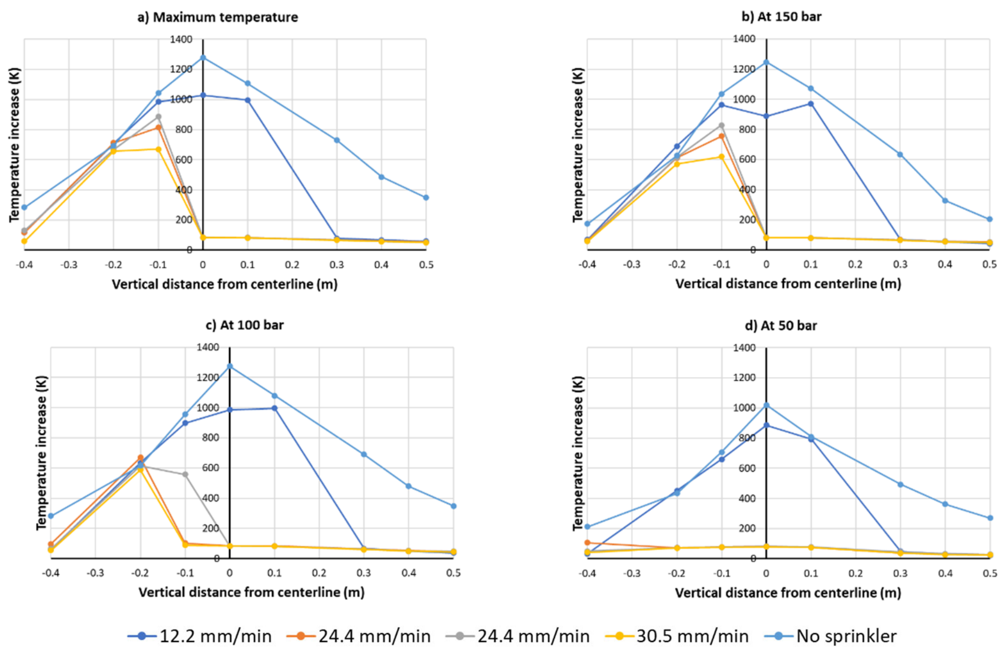


Fig. 3. Temperature increases along the vertical axis with zero at the point of jet impingement. Presented are maximum values for the entire experiment (a) and for three different pressures (b-d)

For the case without sprinklers, the temperature profile was quite axisymmetric, and the maximum temperature increase was 1278K which is roughly similar to the 1200K presented at the SINTEF-webinar mentioned in the theory section.

It can be noted that for the case with the lowest density (12.2 mm/min) and the sprinkler located along the centre axis of the tank, the influence on the temperature was quite high near the top of the cylinder, point 0.3-0.5, while the effect is smaller closer to the point of jet impingement. Is in line with observations during the experiment where it could be seen that the momentum from the jet acted to push away the water film formed on the tank.

For the remaining sprinkled cases, where the sprinkler was moved 750 mm to allow the droplets to more directly impinge on the front side of the tank, the effect is more substantial down to the point of jet impingement at 150 bar and slightly below at 100 bar. Below that point, the effect is neglectable at those pressures. For 50 bar, the temperature is quite low, which is likely to be due to the jet barely touching the tank and did no longer have the necessary momentum to push away the water film.

Figure 3 and table 3 show that either a measuring location is protected by a water film, causing the temperature to be approximately 100°C or below, or the sprinkler have very limited influence on the temperature. As noted above, it is also clear that pressure has an influence on the ability to form a water film. Therefore, it is of relevance to investigate the number of the 28 measuring location that are protected by a water film (i.e. has a temperature below 100°C) as a function of pressure. This is presented in figure 4.

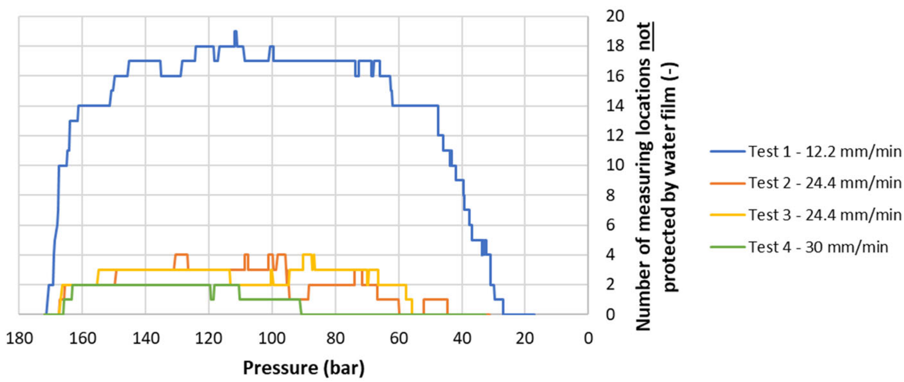


Fig. 4. Number of measuring locations (of 28) not protected by water film, as a function of pressure. Note the difference in sprinkler head location for test 1.

As can be seen from figure 4, more locations are being protected at the higher water densities and lower pressures since both these factors contribute to undisturbed water film formation.

DISCUSSION

In this section, discussions on the usefulness of the approach and limitations of the study are provided.

The influence of sprinklers on the thermal impact

The results show that a sprinkler system will provide some cooling of the tank, but locally the temperature can still increase 600-800K even for the rather small jet used in the current study. It is difficult to compare this value to bonfire tests performed according to ECE R134 since only the gas temperature are measured in that test and the flames are (more or less) engulfing the tank. However, since gas temperatures are higher compared to the tank temperature, a local failure of a Type-IV-tank can probably be expected in less than 10 minutes when comparing to the results obtained in Makarov et al. [13]. Even if this is substantially longer than can be expected from the approximately 1300K increase in the unprotected tank, it is not likely to be acceptable in most designs. It could, however, possibly be used in combination with an emergency blowdown valve to increase the time allowed for blowdown. This has, however, not been studied in the current paper.

For a steel tank, a better performance can be expected since the sprinkler will provide a general cooling of the tanks and thereby reduce the risk of the internal pressure increase. The tank will, however, still be exposed to a hot spot. Adopting a similar scheme as Makarov et al. [13] where a 44% reduction in tensile strength is accepted due to that the requirement of a burst pressure of at least 2.25 times the working pressure, a local temperature of approximately 870K can be accepted for a steel tank [14]. This is below 900-1100K temperatures measured for the different densities. However, the difference between the simulated tank and a regular steel tank needs to be acknowledged. Firstly, in an actual steel tank, heat will be lost to the gas inside and redistributed, while, in the simulated tank, the inside was insulated with 25 mm ceramic wool. Secondly, the material in an actual steel tank is substantially thicker compared to the 1.5 mm steel that was used in the experiment allowing the locally high temperature to diffuse across the tank material. Because of this, it is possible that a rupture of a steel tank could be prevented by sprinkler cooling. However, more experiments are needed with, for example, different sizes of jet flames, different distances, and different sprinkler locations to confirm this.

Repeatability

In figure 5, a comparison between the results in the first and second test at 24.4 mm/min can be found. The comparison is for maximum temperature as well as the temperature at 150, 100 and 50 bar at all 28 locations resulting in 112 pointwise comparisons. The results from the two tests are generally in good agreement except for one substantial deviation and that is for location A-1 and 100 bar. This deviation is due to the fact that a water film was present at this location in test 2 and not in test 3. The physics of water film formation and breaking up is complex and sensitive to small perturbations in the initial conditions, and therefore, this was not unexpected. A deviation is also found at a few other locations (especially C-3 at 100 bar), but most other points, and all maximum values, showed a good agreement.

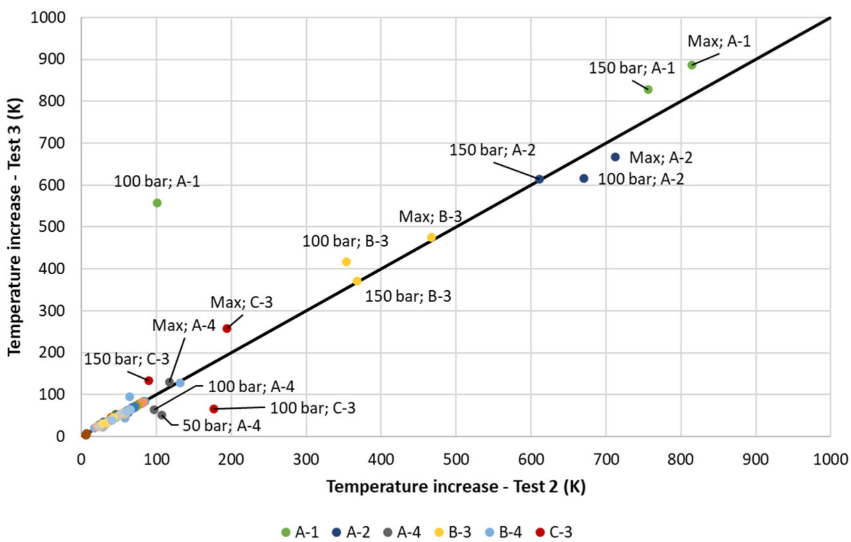


Fig. 5. Repeatability-diagram for the two repeats at 24.4 mm/min for maximum temperature and temperature at 150 bar, 100 bar and 50 bar for all 28 locations. Data series with all points below 100°C has been removed from legend to improve readability.

Limitations

This current study is intended as a first test of the ability to use sprinklers to prevent tank rupture and is subject to several limitations.

One limitation is that measuring location was only placed in one direction from the point of jet impingement, this was due to an expectation of symmetry. However, since the water droplets came from one direction, the results were actually not exactly symmetric, which can be seen in figure 6 where a notable mark on the tank was visible slightly left of the A-1 measuring location. It is likely that the temperature at this location was higher which is also supported by observations presented in table 2. However, since the conclusion was that the design was generally not acceptable for type-IV-tanks and requiring more studies for type-I-tanks, the possibilities of a higher temperature at this location will not affect the conclusion.

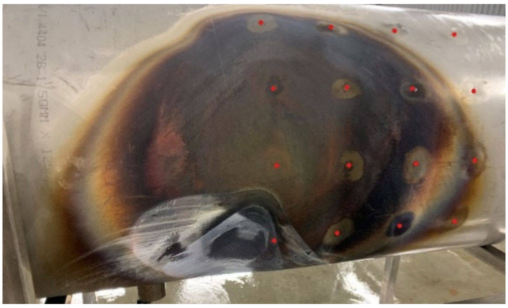


Fig. 6. Colour shift in the tank after the last test with sprinkler (test 4). Measuring locations highlighted with red.

Another potential source of error was that the tank was deformed so that it buckled in approximately 1 cm near the point of jet impingement due to the expansion of the material when heated. However, this happened already during the first test, and no additional deformations were noted during the rest of the tests, so even if the deformation will lead to that the tank was not exactly cylindrical, it will still allow comparison between the different tests.

CONCLUSIONS

When using a sprinkler system to protect a tank from a hydrogen jet fire, the primary protection mechanism is to create a water film on the tank. In the performed experimental study, the circumstances of the formation of such a film were investigated depending on the pressure of the release and the water density from the sprinkler system. In the experiments, the water film was found to cover most of the tank during the experiments, but could not form close to the point of jet impingement until the pressure of the release had been significantly reduced. This is likely due to the momentum of the jet pushing the water film. A higher water density was found to be linked to water film formation at slightly higher pressures.

The results show that, albeit a sprinkler system can slightly increase the time to failure for a type-IV-tank, it is still expected to be below 10 minutes for a typical tank even with high sprinkler densities (30.5 mm/min), making it not a viable option in most designs. It could potentially be used in tandem with an emergency blowdown valve to increase the allowable blowdown time, but this needs to be further investigated.

For type-I-tanks, sprinklers are expected be more beneficial since they will limit the pressure increase, but more studies are needed to investigate both the effect of jet flame size and if local temperature increases might induce a rupture due to reduction in tensile strength of the material.

Although not within the main scope of the current paper, it can be noted that there appears to be an increase in flame visibility with increasing water density. This might be due to impurities in the sprinkler water.

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REFERENCES

[1] V. Molkov, S. Kashkarov, Blast wave from a high-pressure gas tank rupture in a fire: Stand-alone and under-vehicle hydrogen tanks, Int. J. Hydrogen Energy. 40 (2015) 12581–12603. https://doi.org/10.1016/j.ijhydene.2015.07.001.

[2] NFPA, NFPA 55: Compressed Gases and Cryogenic Fluids Code, 2020 Edition, National Fire Protection Association, 2020.

[3] NFPA, NFPA 13: Standard for the Installation of Sprinkler Systems, 2022 Edition, National Fire Protection Association, 2022.

[4] V. Molkov, J.B. Saffers, Hydrogen jet flames, Int. J. Hydrogen Energy. 38 (2013) 8141–8158. https://doi.org/10.1016/j.ijhydene.2012.08.106.

[5] D.B. Willoughby, M. Royle, The Interaction of Hydrogen Jet Releases with Walls and Barriers, in: 3rd Int. Conf. Hydrog. Saf., 2009.

[6] T. Evanger, B. Grimsmo, V. B.E., C. Sesseng, R. Wighus, B.F. Magnussen, Large Scale Experimental and Computational Study of Fire Mitigating Effects of Water Droplet Spray Systems, in: Proc. Seventh Int. Semin. Fire Explos. Hazards, 2013.

[7] CEN, EN 1363-1:2020 Fire resistance tests - part 1: General requirements, 2020, (2020).

[8] ISO, ISO 834-1:1999 Fire-resistance tests - Elements of building construction - Part 1: General requirements, (1999).

[9] U. Wickström, A proposal regarding temperature measurments in fire resistance furnaces, SP Report 1986:17, Borås, Sweden, 1986.

[10] H. Ingason, U. Wickström, Measuring incident heat flux using the plate thermometer, Fire Saf. J. 42 (2007) 161–166.

[11] U. Wickström, R. Jansson, H. Tuovinen, Validation fire tests on using the adiabatic surface temperature for predicting heat transfer, SP Report 2009:19, Borås, Sweden, 2010.

[12] U. Wickström, Methods for Predicting Temperatures in Fire-Exposed Structures, in: M. Hurley, D. Gottuk, J.R. Hall Jr., K. Harada, E.D. Kuligowski, M. Puchovsky, J. Toreo, J.M. Watts, C. Wieczorek (Eds.), SFPE Handb. Fire Prot. Eng., Fifth, Society of Fire Protection Engineers, 2016.

[13] D. Makarov, Y. Kim, S. Kashkarov, V. Molkov, Thermal Protection and Fire Resistance of High-Pressure Hydrogen Storage, in: Proc. Eighth Int. Semin. Fire Explos. Hazards, 2016.

[14] The Engineering Toolbox, The influence of temperature on the strength of metals., (n.d.). https://www.engineeringtoolbox.com/metal-temperature-strength-d_1353.html (accessed January 27, 2022).