Analysis of Thermal Load of Pressure Cylinders with Flammable Gases in Fire

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The submitted paper analyses the thermal load of pressure cylinders with LPG and acetylene in case of fire. In the fire condition, pressure cylinders with flammable gases pose an increased risk to their surroundings. Due to the thermal load, the temperature and consequently the pressure inside the cylinder increases, which ultimately leads to a loss of compactness of the shell and its rupture. As a part of the experimental measurements, the LPG and acetylene cylinders were exposed to the effects of fire. The fire was simulated using a pre-validated woodpile. The results show the range of thermal load on the surface of pressure cylinders when they are exposed to a defined heat source. During the burning of the bonfire, there was a progressive increase in temperature and a gradual decrease in the weight of the fuel. Experimental measurements served as an opportunity to examine in detail the thermal load on a defined type of pressure cylinders used for filling LPG and acetylene. At the same time, it was possible to verify the actual ability of the prepared woodpile for the possibility of fire simulation. Based on the experimentally determined temperature values, it is possible to estimate the time resistance of the cylinders in the fire condition.

1. Introduction

Pressure cylinders are used in many activities, for example, welding, inertisation, recovery, heating, and cooling. They are also used as breathing apparatuses or fire extinguishers and as containers for storing extinguishing media in stable extinguishing systems. From a practical point of view, the purpose of the pressure cylinders is to keep the required gas in as small of a volume as possible. On the other hand, there is a risk of the pressure cylinder physically bursting. This phenomenon occurs in the event of rupture of the cylinder envelope, valve failure, or excessive increase of pressure due to high temperatures (also due to the effects of fire).

Pressure cylinders are classified according to several criteria: the kind of gas used, the material used, the bottle construction, the filling pressure, or the cylinder kits. Pressure gas cylinders are used for gases that do not condense at normal temperatures under pressure, such as oxygen, nitrogen or argon. Dissolved gas cylinders are used for gases that cannot be pressurized to high pressure because they will decompose and explode, for example, acetylene (Leite, 1996). Cylinders for liquefied gases under high pressure are used for gas in a liquid state for which a critical temperature can be exceeded during operation, thus the liquid is changed to gas, such as carbon dioxide and nitrous oxide. Cylinders for low pressure liquefied gases are used for gasses having a low vapour pressure, for example LPG and propane (Price, 2005).

Acetylene pressure cylinders are usually made with a water volume between 3 and 60 litres; a cylinder with a water capacity of 50 litres, for example, contains 10 kg of acetylene. In the Czech Republic, seamless steel acetylene pressure cylinders are used for which the ISO 4705 (ISO 4705, 1983) standard is applicable. The bottles are completely filled with a porous material that is soaked with a solvent. Most often, the acetylene is dissolved in acetone, but it can also be dissolved in dimethylformamide (DMF). In accordance with ISO 3807 (ISO 3807, 2008), acetylene pressure cylinders are filled with regard to the selected solvent, its weight, and the weight of the acetylene at a filling pressure of 17.25 bar.

An external heat source causes the cylinder and therefore the content itself, the porous mass and the solvent, to heat up. Increasing the temperature also induces an increase in the acetylene temperature and the pressure inside the pressure cylinder. When the temperature and pressure inside the cylinder exceed critical values,

conditions inside the bottle allow for the further increase of pressure and temperature, even when the external heat source is removed. This is due to the fact that inside the cylinder there exist the ideal conditions for the reactions to continue simply due to the sufficient energy inside the bottle, until the cylinder ruptures (Ferrero, 2012).

In the case of LPG, the situation is similar except that LPG is a liquefied gas in a pressure cylinder and has different critical values of temperature and pressure. The pressure inside the cylinder depends on the temperature of the bottle. At 0 °C, the cylinder is under a pressure of 1.5 bar, while at 70 °C the pressure inside the cylinder is 24.8 bar. Since the pressure inside is significantly dependent on the temperature, gradual warming continues to increase the pressure, which may, under specific conditions, cause a physical explosion of the cylinder (Tschirschwitz et al., 2017).

2. Experiments

The preparation of the tests consisted mainly in determining an appropriate repeatable heat source, for which the woodpile was chosen. Due to the repeatability of the experiments, a specific woodpile defined in the standard for performance requirements for Class A fire extinguishers was chosen. Given the need for weight loss measurement of the bonfire, the woodpile was placed on the measuring scale. K-type thermocouples were used to measure the bonfire temperatures. At the same time, thermal radiation from the bonfire was measured, and weather conditions were monitored. The remote control ignition initiated the disposal of 14 litres of n-heptane on the water surface of the metal tubs. The tests were carried out in the open air at atmospheric conditions (BAM Research Report, 2009).

For the sake of measurement repeatability, a combination of woodpiles derived from the EN 3-7+A1 (EN 3-7+A1, 2007) standard was used. With respect to uniform loading of the cylinder, two 5A woodpiles were combined with two 13A woodpiles. Experimental woodpiles were assembled from 39 × 39 mm (± 2 mm) wood prisms made of pine wood (Pinus silvestris).

The average wet basis moisture content of the wood prisms was 11.5 %. The experimental 5A woodpile has a square plan of 500 × 500 mm and is made up of 14 layers of prisms, each layer rotated 90° over the previous one. Square dimensions of the 13A woodpile are 1,300 x 500 mm; consecutive layers are constructed from longitudinal and transverse prisms. The axis distance between the prisms is 100 mm. Figure 1 shows a visualization of the described woodpiles (Mynarz et al., 2019).
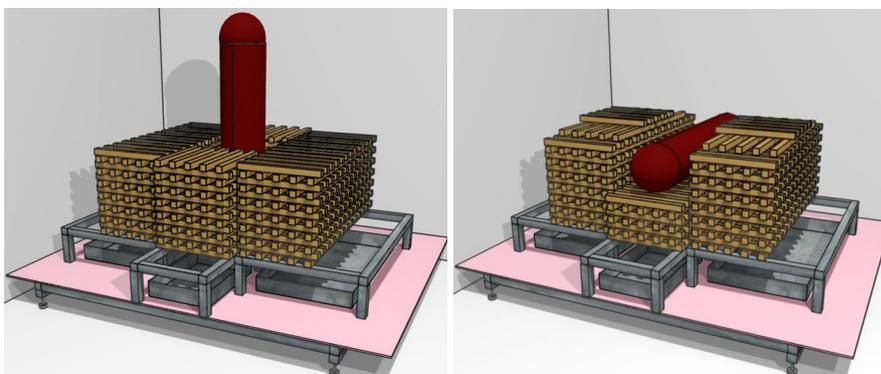
Figure 1: Composition of woodpiles (left: vertical position and right: horizontal position)

The 13A woodpile was placed on a base with dimensions of 800 × 1,300 × 250 mm; the base 700 × 500 × 250 mm was used for the 5A woodpile. The bases were made from square hollow structural steel sections. To protect the steel elements, water was poured into the hollow sections. Under the bases, tubs were placed with dimensions that exceeded the dimensions of the plan woodpiles by 100 mm (Półka et al., 2012).

To determine and verify the characteristic values of pine wood, a measurement was performed on a cone calorimeter. Before measuring with the cone calorimeter, the specimens were placed in the climatic chamber where they were stored for 5 weeks. The climatic chamber was set to a temperature of 22.5 °C and relative humidity of 50 %.

Table 1: Average values during flame burning

Experiment no.	HRR [kW.m^{-2}]	MLR [g.s^{-1}]	EHC [MJ.kg^{-1}]	THR [MJ.m^{-2}]
1	66.367	0.049	11.881	100.316
2	79.216	0.052	13.336	110.116
3	82.761	0.056	12.961	115.886
4	76.527	0.061	12.189	83.136
Average value:	76.218	0.055	12.592	102.364

The specimen was subjected to heat radiation of 35 kW·m^{-2} during the test, which represented the temperature of the conical emitter 942.5 K. Measurements were made on four specimens. A specimen area of 88.4 cm^2 was exposed to heat exposure of the emitter. The following Table 1 presents measured values of heat rate release, mass loss rate, effective heat of combustion, and total heat release from all measurements.

Thermocouples were positioned circumferentially every 90° at certain height levels, depending on the type of pressure cylinder. For the acetylene cylinder, thermocouples were placed at five levels at distances of 180 mm, 480 mm, 780 mm, 1,080 mm, and 1,380 mm from the bottom of the cylinder. The heat flux from the woodpile was measured at different heights using SBG01 heat flux meters in 50 kW·m^{-2} and 100 kW·m^{-2} versions.

3. Results

3.1 Acetylene pressure cylinder in horizontal position

When measuring the bonfire acetylene pressure cylinder in horizontal position (H1), n-heptane burned out after 143 s. At this time, the flame was fully expanded throughout the bonfire. Burn-out and collapse of the bonfire occurred at 14 min 27 s. By the time of the fall/breakdown of the bonfire, the weight had decreased by a total of 303.5 kg. This weight includes the burning of n-heptane, the evaporation of water from the tubs and structures, and the burning of a defined amount of wood. The heat flux emitted from the bonfire was monitored from the northeast and southeast by heat flux meters located 2 m from the vertical axis of the bonfire, 350 mm and 650 mm from the bottom edge of the bonfire. Along with the percentage weight of the bonfire, measured values are presented in Figure 2. The fluctuation in measured values can be explained by the atmospheric conditions at the test site, where conditions corresponded to the open air, often varying in wind speed and direction.
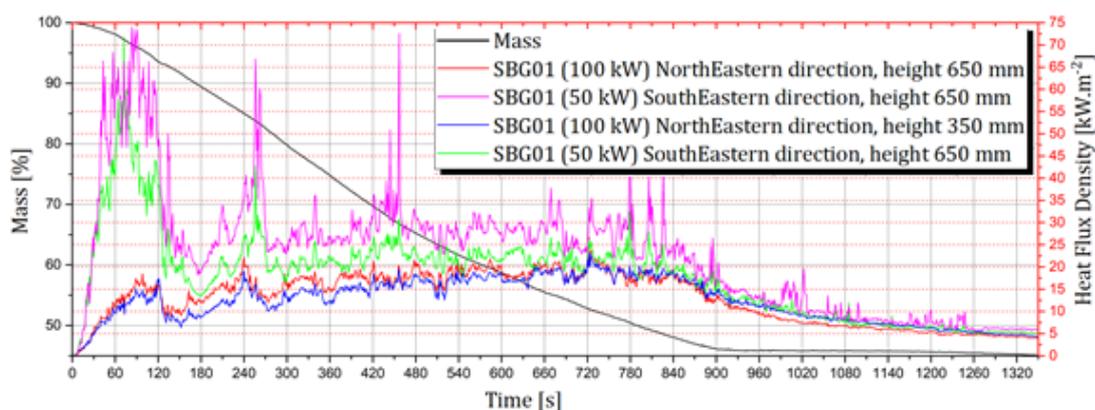
Figure 2: Time dependence on relative weight of the bonfire and heat flux density - H1

The temperature growth in the first minutes is not very fast, as seen in Figure 3. At the time of the most intense burning, the flames reached a height of about 6.0 m. After combustion of n-heptane, the burning stabilized and was dependent only on pyrolysis and the amount of air present during the burning. Approximately after 5 min, the burning was stable and the temperature remained about the same until the bonfire burned out at 867 s. From the time that the bonfire burned out, there were collapses of the individual elements of the bonfire and hence a reduction in the intensity of the thermal action.
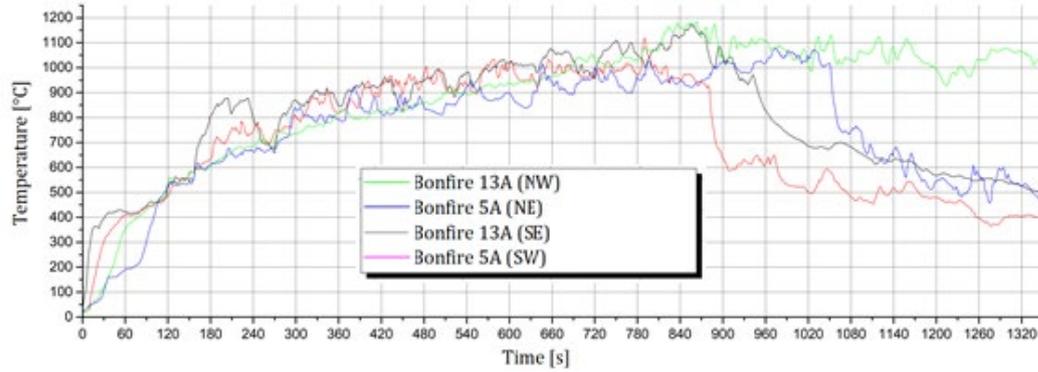
Figure 3: Time dependence of partial bonfire temperatures - H1

Figure 4 describes the thermal loading of the pressure cylinder. The temperatures of the thermocouples are demonstrated on the thermal map of the unrolled cylinder. The thermal maps present the times at 5 min and 10 min from the moment the fire was ignited. Temperatures fluctuated at about the same time as heat flux fluctuations occurred. At the time of 867 s, when the bonfire collapsed, it is possible to see (in Figure 3) a decrease in temperatures within the 5A (SW) bonfire. It was caused by the cylinder falling over the burnt-out bonfire and completely deflecting the thermocouple from its original position. Gradually the cylinder fell lower over the burnt bonfire and so the other two partial bonfires were destroyed.
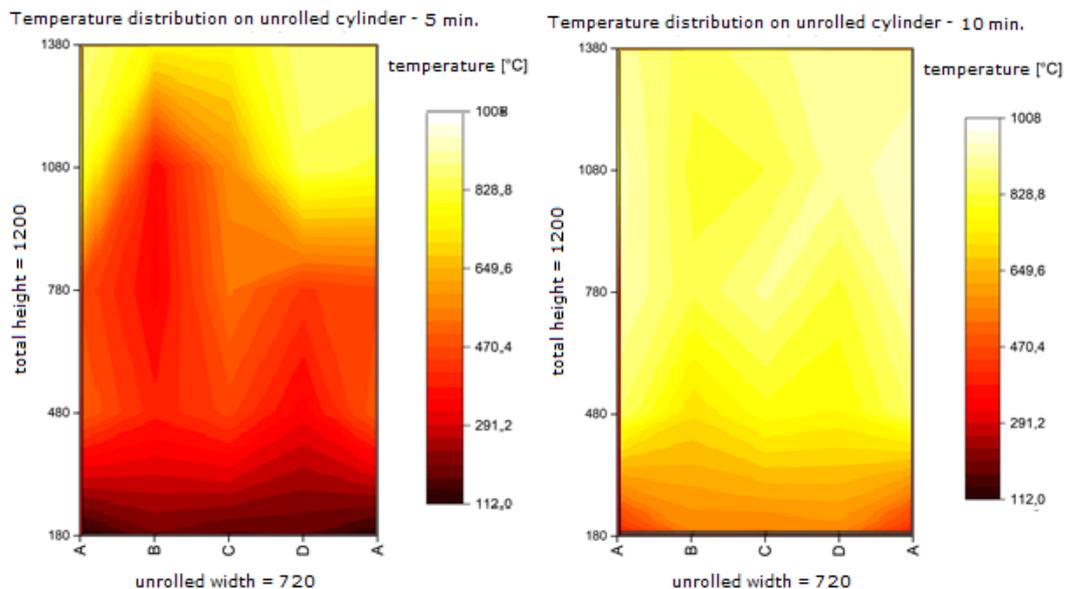
Figure 4: Thermal maps of unrolled cylinder at defined times - H1

3.2 LPG pressure cylinder in vertical position

During measuring the bonfire LPG pressure cylinder in vertical position (V1), n-heptane burned out after 127 s. At this time, the flame was fully expanded throughout the bonfire. Burn-out and collapse of the bonfire occurred at 14 min 6 s. By the time of the fall/breakdown of the bonfire, the weight had decreased by a total of 271.9 kg.

Values of heat flux and time-dependent relative weight are illustrated in Figure 5. Radiated heat flux after n-heptane burn-out was between 10 kW·m^{-2} and 40 kW·m^{-2}. A visible decrease in the intensity of heat flux can be seen after the burning of n-heptane and also after the fall of the bonfire in the time of 846 s. In the period from 15 min to 17 min there was a relative weight loss of 50 %.
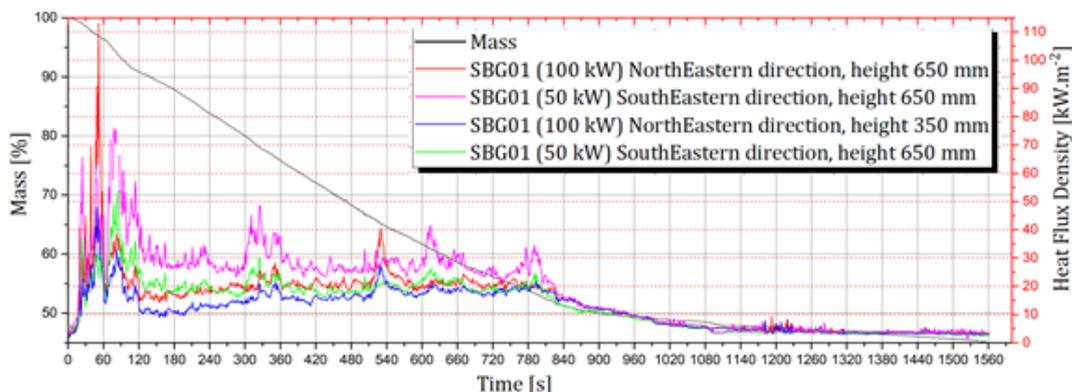
Figure 5: Time dependence on relative weight of the bonfire and heat flux density - V1

Figure 6 shows nearly incremental growth on all thermocouples in the first minute. This was caused due to the burning of the fired n-heptane when maximum burning intensity was reached within a few seconds. After combustion of n-heptane, the burning stabilized and was dependent only on pyrolysis and the amount of air present during the burning. Approximately after 6 min, the burning was stable and the temperature remained about the same until the bonfire burned out at 825 s. Since the burning out of the bonfire there have been collapses of the individual elements of the bonfire and hence the reduction of the intensity of the thermal action.
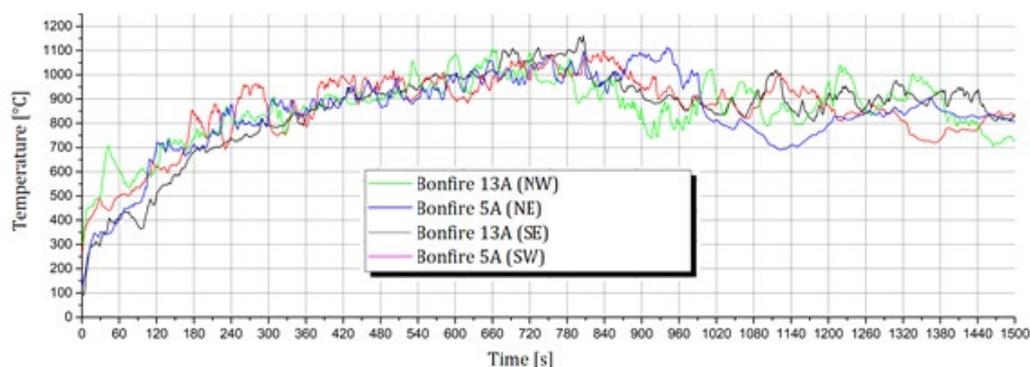
Figure 6: Time dependence of partial bonfire temperatures - V1
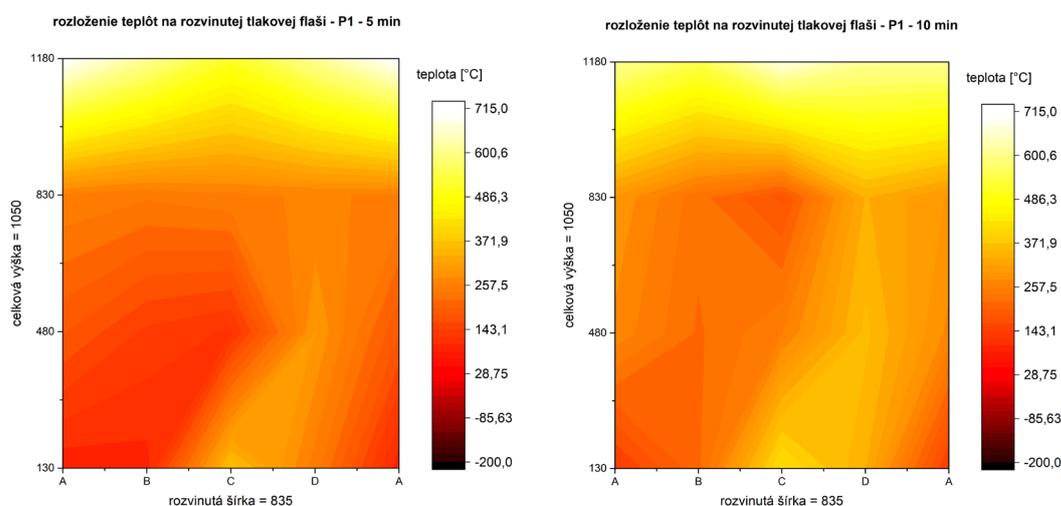
Figure 7: Thermal maps of the unrolled cylinder at defined times - V1

Figure 7 demonstrates the thermal loading of the pressure cylinder. The thermocouple temperatures are presented on the thermal map of the unrolled cylinder at 5 min and 10 min from the moment the fire was ignited. The most loaded was the height level of 1,180 mm, while the temperature of the cylinder shell reached approximately 680 °C for 9 minutes.

4. Conclusions

The measurements described in this paper were taken at the woodpile as the heat source. This source proved to be relatively appropriate, since it shows approximately the same characteristics in each test, either in terms of weight loss, heat flux density, or bonfire temperatures. The source can be considered safe, available, and easily modified in the case of eventual changes. The disadvantage of the woodpile is its slow assemblage, the necessity to provide adequate storage space, and the expense. The advantage of the woodpile is that its course approximately follows the standard time-temperature curve. This brings it closer to the conditions of a real fire, so the woodpile was chosen as the heat source. A relatively stable alternative source of heat appears to be a burning liquid, n-heptane, as it shows more uniform expressions. The advantages of using n-heptane would be easier preparation, transportation, shelf life, and handling. The disadvantage is its high price. Besides the woodpile, fire burners burning propane-butane can be used as another heat source for heating the pressure cylinder.

The horizontal position of the acetylene cylinder was included in the test variants, although it is not stored or transported in this position. The variant was included because the cylinder may move to this position due to external factors. In this variant, a uniform thermal loading of the pressure bottle was observed, when the lower part of the pressure bottle was intensively cooled by wind in the fifth minute and the surface temperatures did not exceed 210 °C. At the same time, the top of the cylinder was heated to an average temperature in excess of 650 °C. The LPG bottle tested in the vertical position reached an average surface temperature of 230 °C in the 5th min and the upper part reached an average value of more than 620 °C.

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