Infrared Radiation Measurement at Failure of Mobile Gas Vessels

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1 Introduction

The project CoFi-ABV (Complex Fires: Consequences of Accidental Failure of Gas Tanks) of the German federal institute "Bundesanstalt für Materialforschung und –prüfung" (BAM) has the aim to increase the safety in case of accidents involving gas vessels, especially relating to vehicles with alternative fuels like CNG (compressed natural gas), LPG (liquefied petroleum gas) and hydrogen.

When gas vessels containing flammable gases are exposed to a fire, and safety devices like pressure relief valves fail, after a short time the failure of the vessel with a subsequent explosion of the gas air mixture involving blast, fragments, hot gases and intensive infrared radiation may occur [1, 2, 3]. Infrared radiation can cause damages to skin and retina of humans in the surrounding [4]. Because of the short duration of the radiation pulse (0.3 s to 2 s), there is actually no time to escape in contrast to the case of a continuous fire. Extensive investigations are already available about radiation during LPG fires and explosions [5, 6, 7, 8].

The presented bonfire tests of 15 identical gas vessels (commercial, off-the-shelf cylinder filled with 11 kg of liquid propane) deliver a stable basis for studying the resulting infrared radiation. Three different types of fire for the heat transfer into the cylinders were used (wood fire, gasoline pool fire, propane gas fire). All tested cylinders failed within a time period of 70 s to 152 s and fragmented into up to seven major parts (average: four objects) covering distances of up to 260 m.

This paper presents measurements of the infrared radiation of the explosion in the aftermath of the vessel failure using two different types of bolometers. The recorded data is compared with an estimation of the radiation using an approach based on video data and an extended version of the Stefan-Boltzmann law. It is demonstrated, that both methods are in good compliance, and that bolometers are in general also capable to measure radiation pulses of short duration. The presented abstract contains only one kind of fire type affecting the vessel. The three fire methods differ in the intensity of the heat transfer into the vessel, their susceptibility to weather effects and the magnitude of the potential secondary thermal radiation caused by the fuel in case of the explosion. The wood fire comprises the maximum intensity (with regard to the fully developed fire) and negligible secondary effects of the fuel on the recorded overall radiation.

The dataset gained within this project can help to estimate potential damages to persons, infrastructure and the environment. They can also be used to increase the safety of firefighters and other forces responding to fires involving gas cylinders. The currently available standard tactics, the recommended safety distances and the properties of the personal protective equipment can be adjusted with regard to this analysis.

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2 Experimental set-up and measurement equipment

The tests were carried out on the test site of the BAM (TTS) south of Berlin. The large blasting area has a diameter of 400 m, surrounded by a sand-wall of about 3 m height. In the middle, a U-shaped sand-wall system for the blasting and fire tests with a free area of about 15 m x 15 m is located.

The measurement equipment used during the test series and the instrumentation of the cylinder is depicted in Fig. 1. Next to the equipment used for the measurement of the thermal radiation, several cameras in the near- and far-field were used to monitor the bonfire and the failure process. In order to observe the status of the bonfire and the status of the vessel, several thermocouples (TIR 101 to TIR 108) were used to measure the flame temperature, the casing temperature, the temperature of the liquid phase inside the cylinder and the gas temperature near the pressure sensor, which monitored the pressure inside the cylinder.

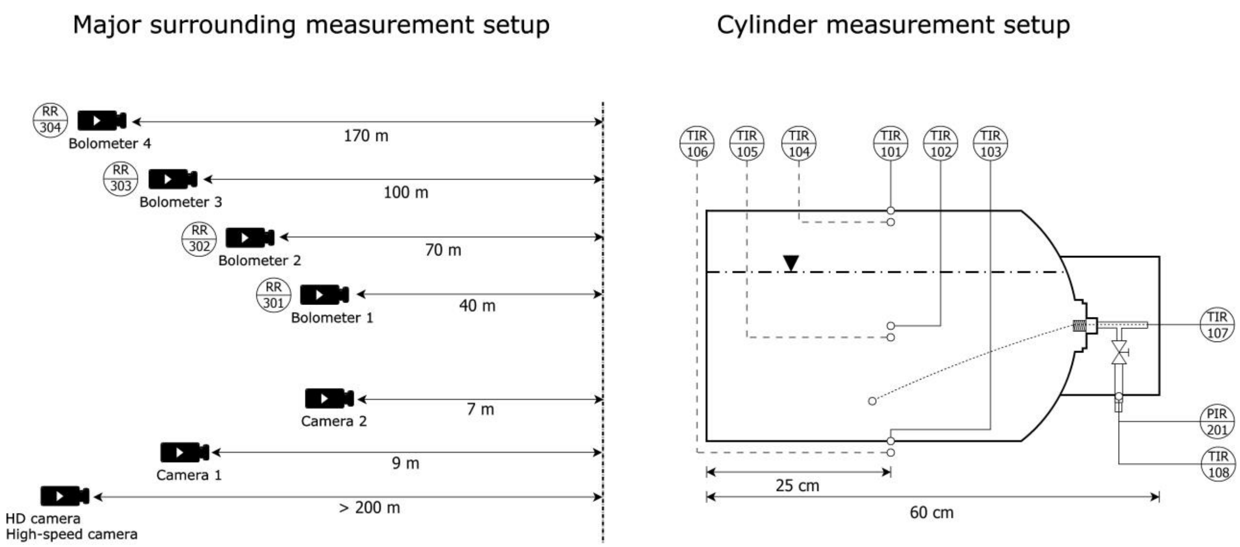

Fig. 1: Schematic diagram of the experimental and measurement set-up and the instrumentation for the bonfire tests of the propane cylinders

The resulting infrared radiation was measured by a mixed set of slow and fast sensors, capable of recording the radiation up to a wave length of 10 µm (consistent with the temperature of the flames which is between 1000°C and 1800°C), providing a measuring range of 2 kW/m^2 (RR 301 and 302) and 10 kW/m^2 (RR 303 and 304), and a voltage output of 10 mV. The slow, but very rugged and stable in time, infrared bolometers for continuous fire measurements (Type Medtherm 64-0.2-14, time constant of 250 ms, RR 301 and 302) were combined with faster sensors (Nikkohm LP111S, currently in internal test phase, sensors not before tested under hard environmental conditions, time constant of 45 ms, RR 303 and 304). The distance of the bolometers to the origin of the explosion was set to 40 m / 70 m (RR 301 and 302, slow sensors) and 100 m / 170 m (RR 303 and 304, fast sensors), respectively. The sensors were calibrated using a black radiator SW11 (max. temperature 1000°C).

The measurement of the infrared radiation consists of two steps, the measurement itself and the subsequent data processing and analysis.

The first step includes the positioning of the sensors. On the basis of experiences gained within former test series, the optimal distance between the site of the fire and the explosion and the location of the sensors has to be estimated. The lower limit is fixed by the maximum load of the sensors (for instance 2 kW/m^2). Already a short overload may damage the sensors. Also the viewing angle (reduction of sensitivity by cosine law and mechanical cut by aperture of the window) has to be taken into account. The upper limit of the distance is determined by the reduction of the signal to noise ratio (S/N). In order to reach a sufficient measurement uncertainty, a S/N ratio with the magnitude of 10^3 is recommendable. Several influences, like time varying backscattered radiation from ground, electrical disturbances and a temperature shift, reduce the S/N ratio.

Because of the long distances and the small output of the sensors, three converters NI 9211(National Instruments) with a low cutoff-frequency (strongly reducing disturbances at 50 Hz) made for temperature measurements were used in the raw mode. Measurements with sample rate of 2 1/s can be made. In this case, three identical modules were used, which were synchronized by a common time scale and triggered with a time shift of 160 ms, so that an average of 6 measurements per second was possible.

In the second step, the files are processed and analyzed with the aim to calculate the unsteady radiation. Corrections are carried out regarding the temperature shift, the backscattering radiation from the ground and the attenuation by air. The backscattered intensity is measured by an additional sensor in perpendicular direction to the fire and antiparallel to the sun and afterwards subtracted from the main signal.

3 Example of infrared radiation caused by a gas explosion after vessel failure

In all cases, after a maximum period of 152 s after the onset of the heat impact, the vessel ruptured and the liquid propane was released, vaporized and mixed with the surrounding atmosphere. After ignition of this gas cloud, a fireball arose. Figure 3 depicts the process of the gas cloud explosion after the vessel failure recorded with a HD camera (optical spectrum, cf. Fig. 1).

In the first picture of Fig. 2 (A), approximately 0.5 s after rupture of the vessel, a hot fireball (camera is overloaded) with a spherical shape can be seen. Due to buoyancy force, in the next picture (B), the fireball has the typical fungus form. In picture 3 and 4 (C and D), the visible radiating area already decreased rapidly. Comparing with Fig. 3a, where the measured intensity (especially of the first two bolometers RR 301 and 302) declines much slower, it has to be taken in to account that the resulting hot gases also emit in the infrared spectrum, and that the higher time constants of the first two sensors cause a general broadening of the peak and delay of the decay of the measured intensity (integration over a specific time period).

In Fig. 3a, the unsteady intensity of the infrared radiation recorded by the four bolometers is presented. The slower systems with higher time constants (RR 301 and RR 302) cause a shifting of the maximum and a broadening of the pulse. It can be seen, that the slow sensors (distances of 40 m and 70 m, RR 301 and RR 302) have only one maximum each, the sensors with the lower time constant (distances of 100 m and 170 m, RR 303 and RR 304) show two maximums, or, to be more precise, one maximum and an adjacent saddle point. Thus, the real structure of the fireball can be rendered superiorly with the faster sensors.

Due to the higher time constants, a significant underestimation of the maximum value has to be expected for the first two sensors. This is confirmed by the second approach to depict the infrared radiation presented in Fig. 3b, where the recorded values for RR 301 and 302 can be found considerably below the curve gained using the Stefan-Boltzman law.

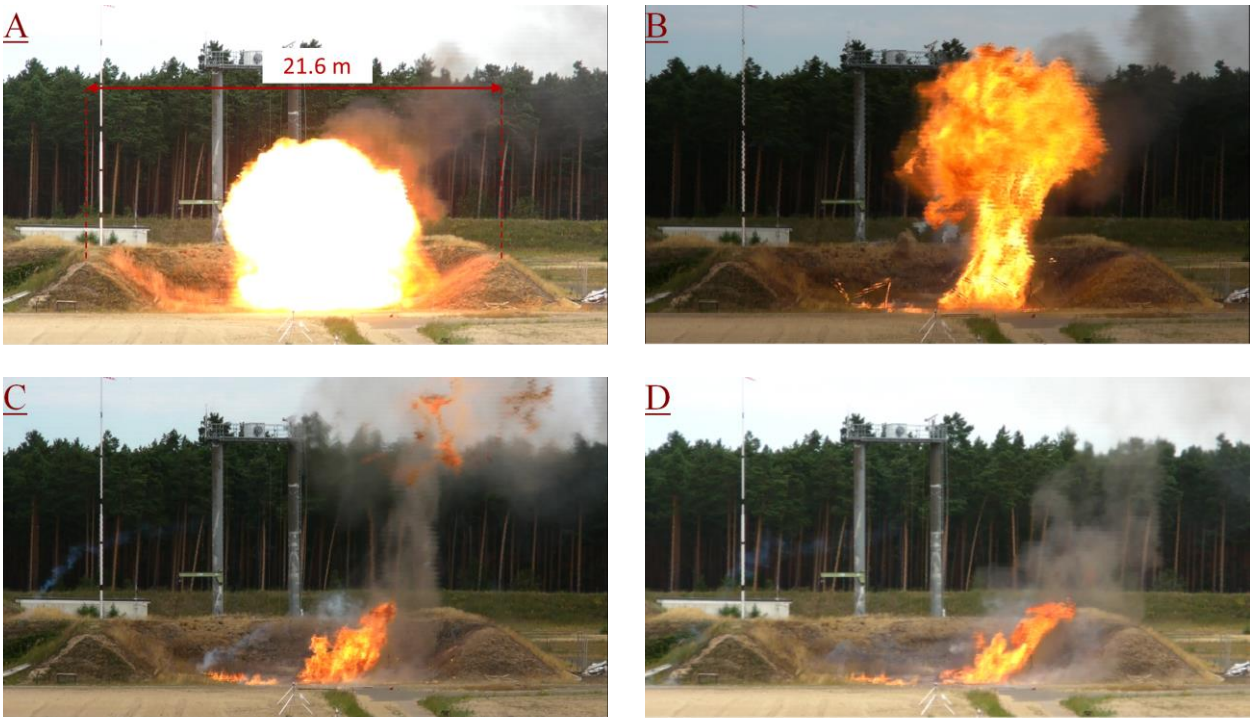

Fig. 2: Sequence of failure of a propane cylinder and the subsequent explosion of the gas cloud; approximately 0.5 s (A) / 1.5 s (B) / 2.5 s (C) / 3.5 s (D) after the rupture of the vessel (cf. Fig. 3a), wood fire, test pc-02

Figure 3b presents the maximum values of the infrared radiation on the basis of two independent methods. The first approach is based on the direct measurement using the prementioned bolometers (points RR 301 to 304) in four discrete distances to the gas cylinder. The second method uses a calculation of the radiation on the basis of the Stefan-Boltzmann law (cf. Eq. 1). The required flame temperature T_f was estimated using similar experiments and a pyrometer (COMET 1000) and an assumed mean emission coefficient of $\varepsilon_f = 0.8$. The pyrometer itself has an accuracy of +/- 1 K, but due to the uncertainty of the emission coefficient and the temporal and spatial variation of the reaction an overall accuracy of +/- 100 K for the flame temperature has to be assumed. The transmission factor τ_{air} represents the damping of the radiation for carbon dioxide and water vapor in the surrounding air. Fundamental for this approach is the determination of the purely geometrical value ρ called view factor as a function of the flame dimensions and the distance between the fire and the sensor (cf. [9]). This view factor, in detail presented in Eq. 2, describes the approximated solution of the surface integral for transmitting radiation between two geometric surfaces (radiator and absorber) without considering temperature effects and other factors. The parameter s represents the length of the straight line connecting two differential area elements, while β_1 and β_2 are the polar angles between the normal line of these differential elements and the connecting line. The maximum dimension of the fireball, gained from the video data of the experiments, was approximated using a coextensive trapezoid.

$$I = \rho\sigma\varepsilon_f\tau_{air}\left(T_f^4 - T_{ambient}^4\right) \qquad \text{Eq. 1}$$

$$\rho = \frac{1}{\pi A_1} \int_{A_1} \int_{A_2} \frac{\cos\beta_1 \cos\beta_2}{s^2} dA_1 dA_2 \qquad \text{Eq. 2}$$

Next to that, a model to predict the thermal radiation of a BLEVE based on the work of Roberts et al (cf. [10]) is presented. In the far field, the consistency of the empirical model with the measurements (bolometers and evaluation of the video data using the Stefan-Boltzmann law) is much better than in the near in a distance of d < 20 m to the vessel, where the calculation using the Stefan-Boltzmann law overestimates the radiation considerably. Furthermore, it has to be taken in to account, that the model according to Roberts was gained using data of ideal BLEVE events with a filling mass of m > 279 kg of liquid propane. The dimension of the fireball calculated using the prementioned model, yielding d = 13 m, is in good conformity with the actual results (cf. Fig. 2).

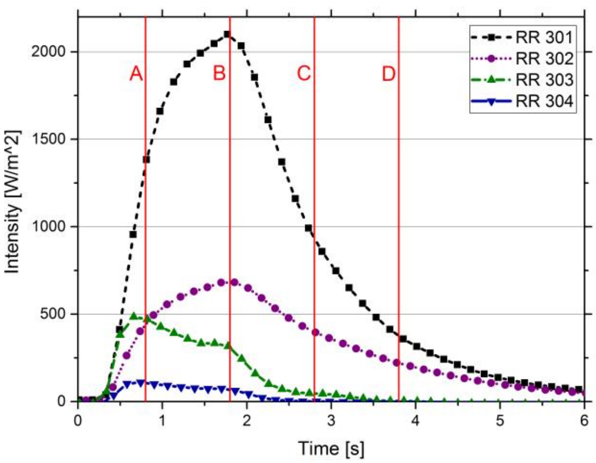

Fig. 3a: Intensity of the infrared radiation recorded by the bolometers (in distances of 40 m and 70 m to the vessel using slow bolometers RR 301 and RR 302, in distances of 100 m and 170 m using fast bolometers RR 303 and RR 304), wood fire, test pc-02, cf. Fig. 2 regarding points A to D

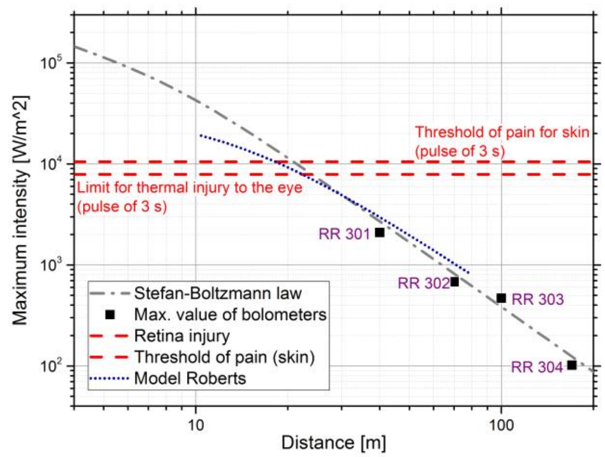

Fig. 3b: Maximum intensity of the infrared radiation, comparison between the maximum heat flux calculated using the Stefan-Boltzmann law applied to the video data of the fireball, the measurements using the bolometers (RR 301 to 304, cf. Fig. 1) and BLEVE model according to Roberts (cf. [10]), wood fire, test pc-02

The susceptibility of the eye, especially the retina, to infrared radiation is higher than the susceptibility of the skin. For instance, for a pulse of 3 s, the acceptable limit to prevent thermal injury to the eye is about 7.9 kW/m^2 [4], the pain level regarding the skin is reached for approximately 10.5 kW/m^2 [11]. These limits, which are also included in the exemplary Fig. 3b, are exceeded in a distance of approximately 21 m (skin) or 24 m (retina), respectively. Thus, measurements of the infrared radiation are a crucial component of the assessment of the consequences of failure of gas cylinders and the subsequent gas explosion.

4 Resume and future work

The consequences of failure of small, commercial, off-the-shelf propane cylinder filled with a mass of 11 kg of liquid propane were examined in a comprehensive test series. A series of 15 identical cylinders was exposed to a fire until failure using three different types of fire (wood, gasoline, propane) without any pressure relief device. One of the potential, severe consequences of vessel failure is the intensive pulse of thermal radiation caused by the subsequent explosion of the gas cloud consisting of a mixture of vaporized propane and the ambient air.

With the help of specially selected infrared sensors, it is possible to measure the dynamic thermal radiation in different distances of reactions of very short duration and high unsteadiness. Next to bolometers, also an evaluation of video data in connection with the Stefan-Boltzmann law and a so-called "view" factor is presented yielding a good estimation of the maximum of the thermal radiation. An assessment of the potential impact of the infrared radiation to humans and a validation of empirical models (e. g. BLEVE models) is possible using the comprehensive dataset gained within this project.

The availability of new A/D converters with sampling rates of $50 \cdot 10^3$ 1/s and a resolution of 24 bit at voltage levels of 100 mV opens the possibility of enhanced measurements. Also sensors with smaller time constants than 45 ms are available now. Next to that, a system of three IR cameras, integrated into one pyrometer, is currently under construction in order to record the highly dynamic temperature of the fireball and the emission ratio in future test series with a sufficient temporal and spatial resolution. Three small wavelength windows, suitable for hydrocarbon air flames, in the range of 2 μm, will be chosen.

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