Flame Projectors for Show Effects – Investigations of Thermal Radiation for Assessing Safety Distances

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Abstract: The use of flames as part of shows is state of the art. Besides pyrotechnic flame projectors, the use of projectors that produce flames by burning various gases, liquids and dusts is significantly increasing. In this study infrared radiation in the wavelength range from 7.5 to 14 microns was measured for several systems (flame projectors) and set in relation to known human pain threshold levels. From this relation safety distances been determined for a static scenario (audience watching show) and compared with those of approved pyrotechnic articles.

Introduction

When flames are assessed with regards to the setting of safety distances at stage and music shows usually only visual dimensions of the flames in combination with a safety margin are taken as the basis for the determination of the corresponding safety distances. This refers to pyrotechnic article effects as well as for flames generated by the combustions of flammable gases, fluids and non-explosive solids (dusts, e.g. Lycopodium or cork dust).

The generation of flames is associated with the emission of thermal radiation, which is the predominant key factor in the hazard analysis for spectators and actors on stage, as well.

The thermal radiation of the projectors was measured and set in relation to the processes known from the human pain threshold levels. From these relations safe distances for a static scenario were finally confirmed by a test person.

Background

The hazard of thermal radiation has been treated in various studies regarding labor safety and accident simulations. However, different values of human pain threshold levels are reported. The thermal radiation dose, i.e. consideration of the exposure time as well, is more suitable for an assessment of hazards to persons by the consideration of flame projectors. In this study, the thermal radiation dose and the pain threshold or the limit for the time-independent thermal radiation from ref. 1 are considered as a reference.

From the different critical irradiances for humans, documented in the literature, the following were used as a reference:

Maximum irradiation (independent of time) $q = 1.7$ kW m[2] [ref. 1]

Pain threshold for a contact time of 3 sec $q = 12.6$ kW m[2] [ref. 2]

The draft standard prEN 16263-3: 2012 (other pyrotechnic articles according to 2007/23/EC and 2013/29/EU)[3] gives a limit on the thermal radiation for the assignment of articles to the category P1 of $D \leq 125$ [(kW/m^2)$^{4/3}$ * s] at reference time ≤120 s or $q_m \leq 1,0$ kW m^{-2} at a reference time >120 s (where q_m is the thermal radiation at the safety distance and D is the thermal radiation dose).

The calculation of the thermal radiation dose was performed according to ref. 3 according to the following formula:

Thermal radiation dose $D = q^{4/3} * t$ (1)

Where D = thermal radiation dose (kW s m^{-2})

q = thermal radiation (kW m^{-2})

t = duration (s)

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Measurements

The measurements to determine the thermal radiation were carried out by using an infrared camera (VarioCam®HD, company InfraTec) with the following technical specification:

- Spectral range: : 7.5–14 µm
- Infrared frame rate 30–240 Hz
- Temperature range −40 to 2000 °C
- Thermal resolution: 0.05 K
- Measurement certainty:
    - ± 1.5 K (0–100)°C;
    - 1.5 % (<0 and >100)°C

The experiments were performed in an indoor venue of sufficient dimensions to realize air interchange but also minimize any influence of weather conditions.

The study included several pyrotechnic flame projectors (pyrotechnic articles for stage use with a national German approval) and the following non-pyrotechnic projectors which use different media to produce flames:

- Gas – propane (flashpoint 97 °C); Figure 1
- Liquid – Isoparaffin (flashpoint 62 °C min.), Figure 2
- Solid – lycopodium (particle size range of about 35 microns, bulk density 300g dm^{-3}, tetrahedral shape), Figure 3.

For all flame projectors the lifetime and heights of the flames were measured during investigations depending of the performance spectrum of the flame projectors.

In the case of gas systems, the number of simultaneously used nozzles (projectors and corresponding flames side by side) was varied up to four.

***Figure 1**. Flame projector (gases, propane).*

***Figure 2**. Flame projector (liquid, Isoparaffin).*

***Figure 3**. Flame projector (solid/dust, lycopodium).*

For the evaluation or comparison of the thermal radiation values, the maximum values (hot spot) and the data related to the whole radiation area values were determined for each measurement. For the assessment of the hazards, the maximum value (hot spot) of thermal radiation was the focus of this study.

For further interpretation of the generated values the emission factor plays a key role and must be determined for each material that is investigated. A material-related assignment of an emission factor to any flame is difficult and often not sufficiently precise. For this study, an emission factor of 0.90 was used as an average and basis due to the lack of further analysis of the flame compositions.

***Table 1**. Radiation data from flame projectors at 15 m distance*

Flame projector type	Max. thermal radiation q_{max} (kW m^{-2})	Max. thermal radiation dose D_{max} (kW s m^{-2})
Propane	0.8–1.2	0.87–3.66 (4.19 for 4 parallel flames)
Isoparaffin	0.9–1.3	0.95–2.24
Lycopodium	1.2–1.4	1.67–2.65
Pyrotechnic flame projector no. 1	0.9	0.50
Pyrotechnic flame projector no. 2	0.8	1.85
Pyrotechnic flame projector no. 3	1.4	3.20
Pyrotechnic flame projector no. 4	0.9	0.34
Pyrotechnic flame projector without any approval	1.1	0.56

Results of thermal radiation measurements

Table 1 summarizes the results measured at 15 m distance to the single flames regarding the thermal radiation and the calculated thermal radiation doses (radiation multiplied by its exposure time). For propane, the results are given separately with four parallel flames.

Table 1 reveals that the range of the maximum thermal radiations for projectors with gas and isoparaffin are comparable. Considering the thermal radiation dose the influence of system parameters is seen more clearly.

For the propane flame projector the differences between the thermal radiation dose of the single flame and the four parallel flames are quite small. This is due to the fact that the thermal spheres of the flames overlap only minimally. The resulting differences in the safety distance are shown in Table 3.

Human exposure limits to thermal radiation

Two fundamental approaches to determining the stress or pain thresholds regarding thermal radiation can be found in the corresponding literature: The limits of thermal radiation (irradiance/thermal flux) were determined by thermal radiation dose. The data from ref. 2 are used as examples for further considerations and are partly summarized in Table 2.

***Table 2**. Pain thresholds taken from ref. 2*

Radiation intensity q (kW m^{-2})	Temperature pain threshold (°C)	Exposure time t until pain threshold (s)
4.2	45.1	13
5.2	45.3	10
6.3	46.5	8
8.4	47.1	5.5
12.6	48.3	3

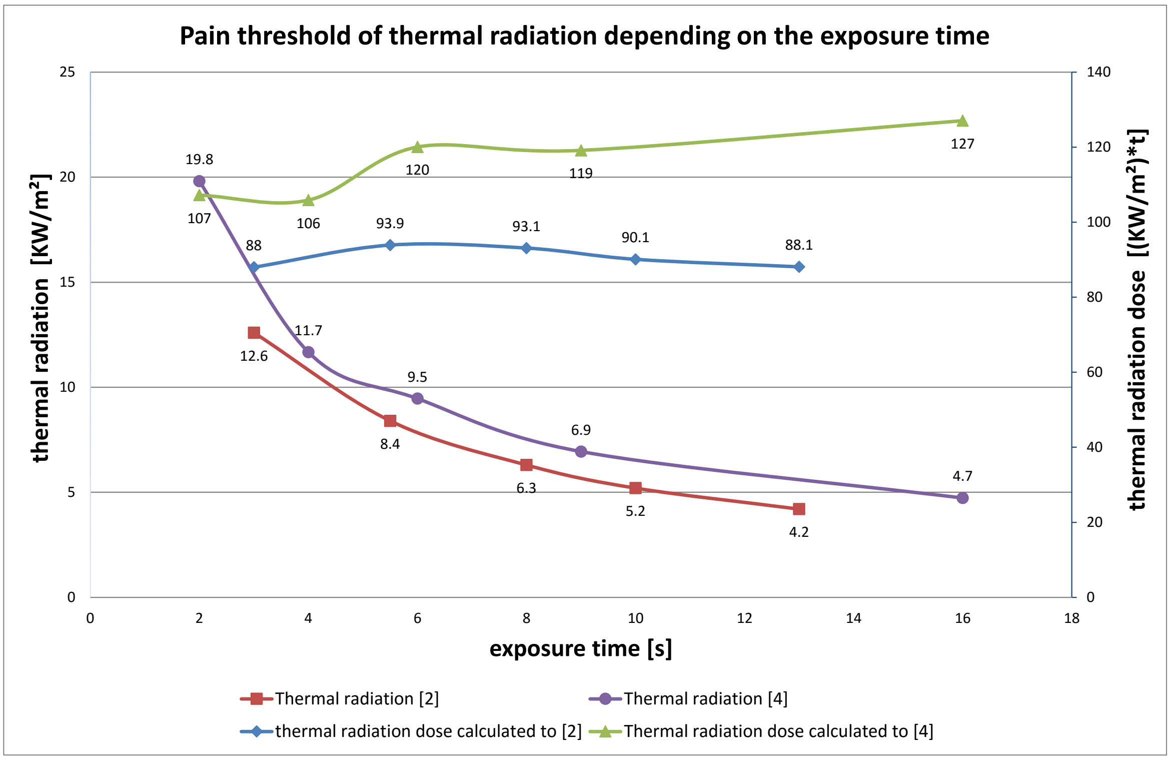
Figure 4 shows the relationship of the pain threshold for thermal radiation and exposure time of the flame (red curve). The blue curve represents the thermal radiation dose, which has been calculated from the thermal radiation values and the exposure times from ref. 2. The purple curve represents the thermal radiation from ref. 4. The green curve represents the thermal radiation dose, calculated from ref. 4.

It can be seen that the approach is sufficiently accurate, since the results in this graph (blue curve) can be seen as an approximately straight line (regardless of the exposure). The advantage of using the thermal radiation dose is that a fixed limit value can be set.

Assessment of safety distances

The pain thresholds were defined on the basis of thermal radiation limits given in ref. 1 with 1.7 kW m^{-2} and according to ref. 2 with 12.6 kW m^{-2}. The reference value of 12.6 kW m^{-2} with a contact time of 3 s (ref. 2) was chosen

***Figure 4**. Calculated thermal radiation (doses) from the literature (ref. 2 and 4)*



because the duration of the flame columns mostly lied between 0.5 and 4.0 seconds. Thus, a reasonable comparison is given.

For the determination of the safety distances on the basis of the thermal radiation dose taken from ref. 2, the average value of 91 kW s m^{-2} was used (see blue curve in Figure 4). This approach is conservative in terms of thermal radiation doses. Using the limits prescribed in ref. 3 or 4, the commitment averaged limits for the thermal radiation dose were calculated to be 125 kW s m^{-2} and respectively 117 kW s m^{-2}.

Starting from the assumption that the radiation decreases with the square of the distance, the safety distance may be calculated using the following formula:

$$r = \sqrt{\left(\frac{D}{D_G}\right) \times R^2} \qquad (2)$$

Where r = safety distance (m)

D = thermal radiation dose (kW s m^{-2})

D_G = pain threshold based on thermal radiation dose (kW s m^{-2})

R = measuring distance (m)

If using the approach according to ref. 1 with 1.7 kW m^{-2} (without regard to the exposure time) the safety distance r[a] of 12.5 m has been calculated.

According to the approach of ref. 2 with 12.6 kW m^{-2} and an exposure time of 3 s a safety distance r[b] of 5.0 m has been calculated for propane.

Substituting the linearized pain threshold of the thermal radiation dose of 91 kW s m^{-2} according to ref. 2 and the real lifetime of the flames, the result of real safety distance r[c].

A summary of the safety distances is shown in Table 3. These safety distances are based on the maximum thermal radiation or thermal radiation dose.

It should also be mentioned that the given maximum value of thermal radiation (hot-spot) has been adopted for the entire lifetime of the flame. As this is not the case in real terms, the calculated safety distances follow a conservative assessment.

On the base of thermal radiation dose, the influences of flame projector parameters on the safety distance are clearly recognizable.

Assessment of the calculated safety distances based on studies with a test person

The calculated safety distances based on the measured thermal radiation and ref. 1 and 2 were demonstrated with tests with a human test person.

***Table 3**. Summary of the calculated safety distances/maximum values with (2) (1 – only one measurement; 2 – four burner with maximum flame size and lifetime)*

Flame projectors	Safety distances			
	$r^{[a]}$ (m)	$r^{[b]}$ (m)	$r^{[c]}$ (m)	Safety distance according to old BAM approval
Propane	12.5	5.0	3.0 3.5[2]	
Isoparaffin	13.0	5.0	2.5	
Lycopodium	13.0	5.0	3.0	
Pyrotechnic flame projector no. 1	11.0	4.0	1.5	radial 2 m effect direction 3 m
Pyrotechnic flame projector no. 2	10.5	4.0	2.5	radial 2.5 m effect direction 3 m
Pyrotechnic flame projector no. 3	14.0	5.5	3.0	radial 3 m effect direction 5 m
Pyrotechnic flame projector no. 4	11.0	4.0	1.0[1]	radial 8 m effect direction 40 m
Pyrotechnic flame projector without any approval	12.0	4.5	1.5	–

The thermal imaging camera was used to record the change in the skin temperature of the subject and the heat radiation of flame projectors. In addition to the detection of the surface temperature of the skin, the subjective feelings from the subjects were also documented.

All experiments were carried out with the uncovered torso of the test person.

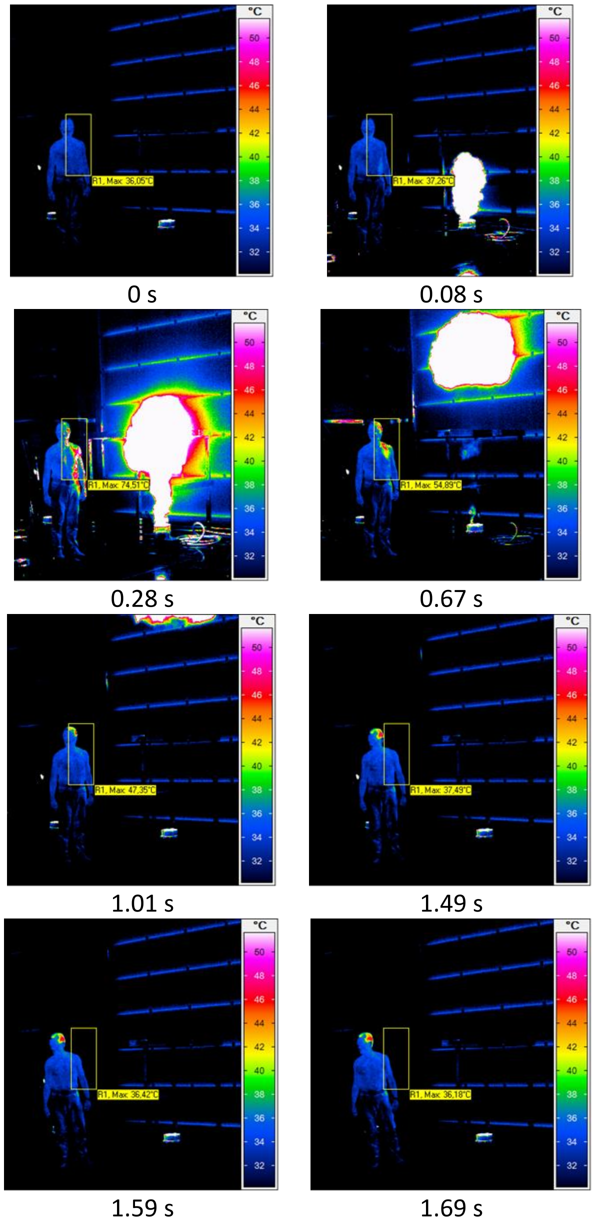
Under identical parameters, the flame projectors (propane, Isoparaffin and Lycopodium) and the distances between the flame and the subject were varied. As distances 5 m, 3 m, 2 m and 1 m have been selected. For each distance (with the exception that described next series) at least three experiments were carried out.

For illustration the following sequence of IR images from a series of tests with a propane flame and a distance between the test person and the flame of 1 m are used (Figure 5).

The thermal radiation dose of the flame was 1.3 kW s m^{-2} in this experiment. This would lead to a safety distance $r^{[c]}$ = 1.7 m. The calculated safety distance was much higher than the distance in this experiment, which was reflected by the feelings of the test person. The thermal radiation at this distance was perceived by the tester as clearly painful (permanent damage to the skin, however, was not observed thereafter). For this reason, the series was stopped after two attempts.

The listed maximum temperatures of the measuring field on the body in these frames show mainly the reflected thermal radiant from the skin. To assess the actual (deep) heating, the difference between the initial skin temperature and skin temperature must disappear after the flame exposure. After the disappearance of the flames an increase in temperature of 0.13 K was observed. The prolonged heating of the hair on the head of the test person to recognize the color detachment

***Figure 5**. Sequence of IR images at a distance of 1 m flame (propane flame)*



(green–yellow–red), indicates a significantly better absorption of thermal radiation by hair/scalp/air. A stronger deterioration of this area has not been detected by the test person in the subjective perception. A slightly longer-lasting feeling of heat was observed by the tester.

By increasing the distance between the test person and the flame the thermal perception of the tester was significantly reduced.

To determine the effect of the number of flames on the acceptable pain feelings also a comparative study series has been carried out with one and four flames.

The thermal feeling when being exposed to four gas flames was only slightly more pronounced than with one flame. This perception was also reflected in the barely measurable difference in skin temperature immediately after extinguishing the flame.

The differences in the emitted thermal radiation doses between propane, Isoparaffin and lycopodium, as indicated in Table 1, also correspond to the subjective feelings of the test person. The propane gas flame is more easily perceived as "warmer".

Conclusions

Infrared radiation in the wavelength range from 7.5 to 14 microns of various systems (flame projectors) was measured and set in relation to known threshold levels of pain for persons from the literature. From this relation safety distances have been determined for a static scenario (audience watching show).

The results of this study show that the thermal radiation dose should be the basis for the determination of safety distances. The exposure time has an indisputable impact on the hazards. In this respect the specific limit of 91 kW s m^{-2} (ref. 2) is proposed as the basis for the calculation. The use of pain thresholds/limits based on thermal radiation values unrelated to the exposure time as described in ref. 1 are not suitable for the determination of real safety distances to flame projectors.

The effectiveness of the developed method for calculating the safety distance *r*[c] has been verified by studies with a test person. The safety distances thereafter determined reflect the subjective feelings of the test person. The method can be regarded as a useful means for calculating safety distances with regard to the effect of thermal radiation from flame projectors on persons.

Notes and references

The author himself was the human subject. The aim of the investigation was the development of national regulation in view of the heat radiation when flame projectors be used. All other national regulations were be fulfilled.

1 UBA Bericht “Ermittlung und Berechnung von Störfallablaufszenarien nach Maßgabe der 3. Störfallverwaltungsvorschrift“; Forschungs- und Entwicklungsvorhaben 297 48 428, Band 2, S. 194, Umweltbundesamt, Februar 2000.

2 I. Hymes, W. Boydell and B. Prescott, Thermal Radiation: Physiological and Pathological Effects, Institution of Chemical Engineers, Health and Safety Executive 1996.

3 DIN Deutsches Institut für Normung e.V. (2005). Pyrotechnische Gegenstände; Sonstige pyrotechnische Gegenstände E DIN EN 16263- Teil 3 (prEN 16263_3): Kategorien und Typen, Beuth Verlag GmbH Berlin.

4 American Institute of Chemical Engineers, Center for Chemical Process Safety. Guideline for evaluation the characteristics of vapor cloud explosions, flash fires, and BLEVES, 1994.