Emissions of Reaction Products and Sound from Outdoor and Indoor Firework Displays

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Abstract: *This work presents results of investigations towards the emission of chemical reaction products and sound pressure during an outdoor and an indoor firework display. Potentially harmful and toxic gases, and aerosols, were measured as well as sound pressures. Aerosols were measured with a Differential Mobility Analyzer (DMA) as well as a Laser Particle Counter. The focus was on particles with diameters between 11 nm and 20 µm. A transportable Fourier Transform Infrared (FTIR) spectroscopy detector registered the concentrations of emitted reaction gases, simultaneously. During the outdoor firework display, peak particle concentrations of >550 000 particles cm^{-3}, equivalent to a mass concentration of approximately 3.95 mg m^{-3}, were detected, revealing a concentration maximum at approximately 175 nm particle diameter. The time-averaged particle mass concentration did not exceed 1.58 mg m^{-3} over 15 minutes. Due to the large distances (110 m) to the firing points, no significant harmful or toxic gas concentrations were measured during the entire firework display. In contrast, concentrations of sulphur dioxide (SO_2) rose after an indoor firework display in a large event hall. On two days, more than 23 000 particles cm^{-3} (which equates to a mass concentration of approximately 0.41 mg m^{-3}) were detected when the hall ventilation was turned off, and more than 11 000 particles cm^{-3} (which equates to a mass concentration of approximately 1.18 mg m^{-3}) when the hall ventilation was activated. Concentration maxima appeared at approximately 300 nm particle diameter. The time-averaged particle concentrations in this case did not exceed 0.56 mg m^{-3} (over 15 minutes).*

Keywords: *pyrotechnic articles, aerosols, combustion gases*

Introduction

Indoor and outdoor firework displays provide possible hazards to man and the environment. High sound pressure impacts can lead to hearing damage (such as acoustic trauma, tinnitus, drum head perforation or acute hearing loss; often irreparable) and fireworks which are not functioning correctly (e.g. "black shells" and "blind stars") directly endanger the audience, and pyrotechnicians as well as third parties. Besides, gaseous and solid reaction products released by the fireworks can be potentially harmful. In recent years, some experimental investigations towards the impact of fireworks on the environment have been described in the literature.

Steinhauser and Klapötke[1] give an overview about possible hazards arising from (consumer) fireworks. These possible hazards comprise the emission of heavy metals, perchlorates, polychlorinated organic compounds, aerosols, and combustion gases. As a result of this work, the authors suggest developing nitrogen rich compounds, and excluding perchlorates and heavy metals from future fireworks. A possible alternative to the conventional oxidiser potassium perchlorate could be the insertion of metal nanoparticles into the pores of nano-metal oxides. Steinhauser *et al.*[2] identified solid reaction products (heavy metals) after New Year's Eve fireworks during snowfall in the Alps. It was found that combustion products are absorbed by snowflakes, and the concentration of barium in the snow increased rapidly. Therefore, the authors stated that an increase in the concentration of barium is a good indicator for the combustion of fireworks. Moreno *et al.*[3]

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measured metalliferous particles from Las Fallas firework displays in Valencia, Spain, and Guy Fawkes celebrations in London, UK. An increase in various metal concentrations was observed (potassium, aluminium, titanium, magnesium, lead, barium, strontium, copper, and antimony). Van der Kamp *et al*.[4] traced a fireworks plume generated by a pyrotechnic display with a lidar ceilometer. Thereby, the vertical height of the plume was measured (~100 m), as well as particulate matter (PM) concentrations of 30–40 μg m^{-3}. Wang *et al*.[5] confirmed the emission of sulphur dioxide (SO_2), nitrogen dioxide (NO_2), and solid particles $PM_{2.5}$ and PM_{10} at a firework display in Beijing, China. In addition, chemical analyses of the particles showed amongst others, the existence of barium, potassium, strontium, lead, and magnesium. The influence of fireworks on the formation of particles was analysed by Vecchi *et al*.[6] at the festivities in Milan, Italy, after the final of the soccer world cup 2006. Significant emissions of metals and metal ions (e.g. strontium, magnesium, potassium, barium, and copper) were measured. Drewnick *et al*.[7] verified the generation of particles consisting of potassium, sulphates, and chlorides after a New Year's Eve firework display in Mainz, Germany. During the millennium fireworks in Leipzig, Germany, a rapid increase of particle and nitrogen monoxide (NO) concentrations was measured by Wehner *et al*.[8] Perry[9] investigated the influence of fireworks on the air quality in the west of Washington State, USA. Large concentrations of strontium, potassium, vanadium, titanium, barium, copper, lead, magnesium, aluminium, sulphur, manganese, and zinc were detected. Smith and Dinh[10] tested the effects of the New Year's Eve fireworks in Honolulu (Hawaii), USA, on the emission of gaseous and solid reaction products. In this pioneering work, an average PM concentration of 2.15 mg m^{-3} was measured (with a maximum value of more than 3.8 mg m^{-3}) during 30 minutes around midnight. This study underlines with its spirometry data that inhalation of reaction products of fireworks can cause a change in human lung function. Hussain and Rees[11] published results for the measurements of gaseous reaction products from burning pyrotechnical substances using Fourier Transform Infrared (FTIR) spectroscopy. The experiments were carried out under different conditions. In an air atmosphere carbon dioxide (CO_2) was identified as the main product, whereas NO_2, NO, and carbon monoxide (CO) were mainly detected in a nitrogen atmosphere. SO_2, however, was mostly determined under an oxygen atmosphere. Dutschke *et al*.[12] reported analysis of reaction gases under isolated conditions in a manometric bomb with FTIR spectroscopy. Thereby, the dependence of the reaction gas composition on the initial masses was determined for black powder, a pyrotechnical light, and a stage fountain. Main reaction products were CO and CO_2. The ratio CO/CO_2 increased with rising pyrotechnic mass, caused by the oxygen limitation in the manometric bomb. Furthermore, high concentrations of hydrogen sulphide (H_2S) and carbonyl sulphide (COS) were observed. The authors also measured particle emissions in a ventilated hall room at different locations during the combustion of single stage fireworks. After the ignition, particle concentrations immediately raised up to <550 000 particles cm^{-3} (which equates a mass concentration of 1.4 mg m^{-3}) and decreased exponentially afterwards. That fact was explained by sedimentation of the particles and room ventilation. Kreyling *et al.*[13] reported the health risks caused by PM. It was stated that the particle size distribution has a major impact on the hazard potential. Particles with a diameter smaller then 100 nm can interfere with the alveolar system.

The objective of this work was to compare two different types of firework displays – indoor and outdoor – with regard to the possible hazards to the audience, pyrotechnicians, other third parties, and the environment. Therefore, continuous measurements of gaseous and solid reaction products, sound pressure levels, surrounding air temperature, pressure, and humidity, as well as wind speed and direction were carried out. The analysed firework displays were the 3rd Pyronale® World Championship of Fireworks (outdoor, September 5th and 6th, 2008, location Maifeld in Berlin, Germany) and the 26th international ADAC-Super-Motocross (opening indoor firework display; November 14th and 15th, 2008, location Martin-Schleyer Hall in Stuttgart, Germany).

Experimental investigations

Figure 1 and Figure 2 illustrate the locations of the festivals as well as the measuring points and

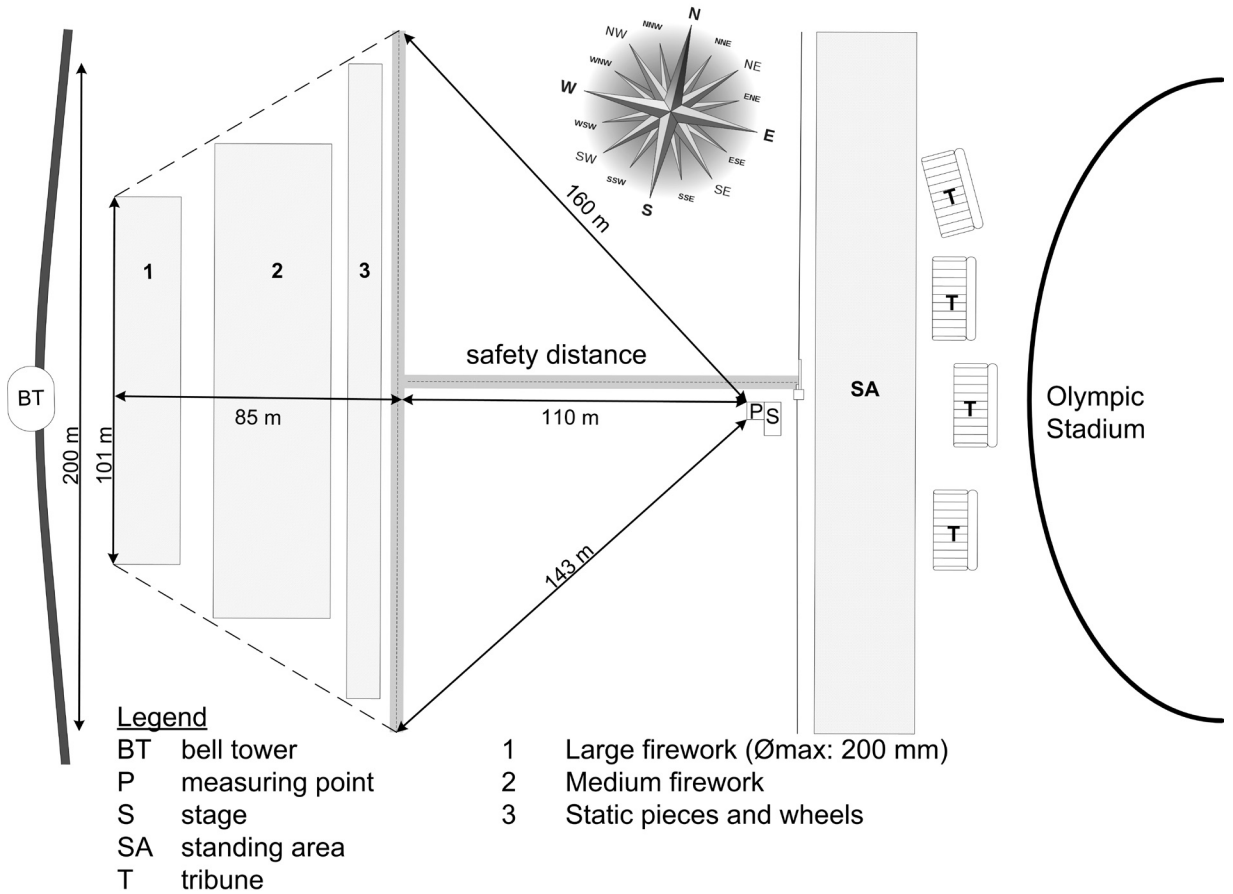

Figure 1. *Map of the Maifeld (outdoor) in Berlin, Germany.*

boundary conditions.

Tribunes and the standing area of the audience were located in front of the Olympic stadium. The standing area and the firework batteries were separated by a safety distance of more than 130 m. The measuring point was set at a horizontal distance to the first firework batteries of approximately 110 m inside the safety distance. It can be seen from Figure 1 that wind coming from west was necessarily needed to measure reaction products liberated by the firework displays. During the Pyronale®, 7 firework displays were performed, 1–3 on the first evening, and 4–7 on the second evening. Each display continued for about 15 minutes.

As illustrated in Figure 2, the ground level, where the indoor motocross show was performed, was surrounded by tribunes for the audience. The measuring point was located at the upper end of the tribunes, next to the ventilation outlet openings.

The ventilation inlet was realized by hall doors. This hall consists of a volume of approximately 200 000 m^3, a ventilation rate of 446 000 m^3 h^{-1}, and a total smoke vent surface of ca. 76 m^2. The hall ventilation was shut down on the first day (November 14th) and activated on the second day (November 15th).

Indoor pyrotechnic articles were placed at ground level in front of the audience (safety distance to the audience approximately minimum 10 m) and partly fixed to the ceiling construction. The indoor pyrotechnic articles contained airbursts, concussions, flash curtains, falling fires, water falls, mortar hits, mines, line rockets, flickering lights, saxons, and gerbs. All in all, 212 indoor pyrotechnic articles, with a net explosive content of 4.2 kg, were burned off on both show days. The overall length of the pyrotechnic show was about 9 minutes on both evenings and started at 20:00.

For continuous and simultaneous combustion gas

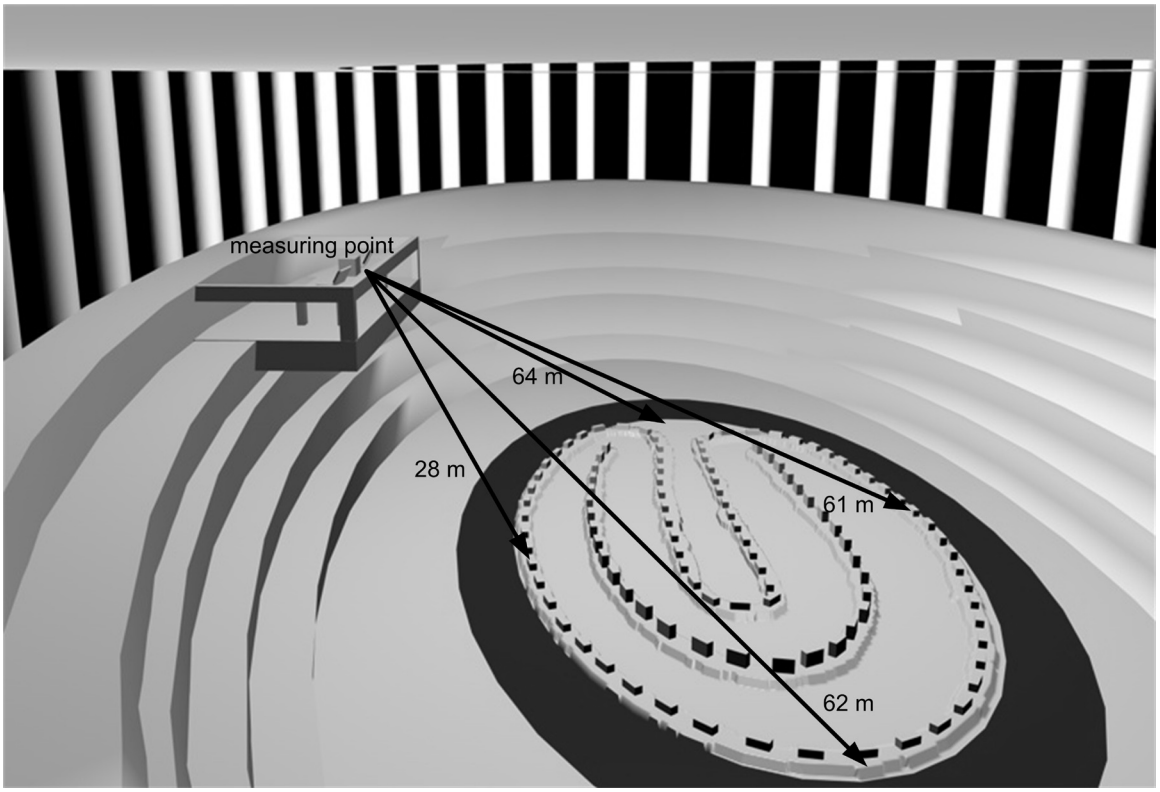

Figure 2. *Map of the Martin-Schleyer Hall (indoor) in Stuttgart, Germany.*

detection, the transportable FTIR spectrometer Gasmet DX-4000N from Ansyco with an optical path range of 5 m was used (detection limit <10 ppm). It offers a wavelength range of 900 cm^{-1} to 6000 cm^{-1}, a resolution of 8 cm^{-1}, a sample volume of 0.5 L, a constant zero gas flow of 2.3 L min^{-1}, and measures at a temperature of 50 °C.

Aerosol measurements were carried out with two different devices with an overlapping particle diameter range:

SMPS (TSI 3936); the measurement range was set between 11 nm and 461 nm (with an aerosol flow rate of 1 L min^{-1} and a scan frequency of 0.5 spectra min^{-1}, and 105 particle size channels), and

a laser particle counter (Grimm 1.108); measurement range between 300 nm and 20 µm, aerosol flow rate of 1 L min^{-1}, and a scan frequency of 10 spectra min^{-1}.

In addition, wind speed and direction were measured continuously at the Pyronale® by an electrical cup anemometer and a weather vane at a height of 2 m. The measuring frequency was set to 1 Hz.

Sound pressure measurements were carried out at the outdoor location with a 2 channel real time analyzer type 830 (company Nortronic) with the following technical data: frequency range 50 Hz to 20 kHz, resolution third octave band width, time weighting impulse, frequency weighting LIN A. A ½″ condenser microphone type MK 221 with a cartridge type 4190 of the company B&K was used (sensitiveness 49.3 mV Pa^{-1}; calibration unit type 4231 of the company B&K).

Results and discussion

3rd Pyronale® World Championship of Fireworks (outdoor)

Table 1 summarizes time-averaged results of the meteorological data such as air temperature, humidity, and pressure during the measurements.

Temperature, ambient pressure, and relative humidity were comparable on both days. The only major difference was the occurrence of continuous

Table 1. *Meteorological data of September 5th and September 6th 2008 at the Maifeld in Berlin, Germany.*

Date	September 5th 2008	September 6th 2008
(Measurement time)	(19:00–22:15)	(20:20–22:35)
Temperature/°C	18 ± 0.5	18 ± 0.5
Air pressure/hPa	1001	1002
Relative humidity (%)	70–75	70–80
Rain ?	No	Rain started after 21:06

rain, which started during the firework display on September 6th, 2008.

Detailed information about the wind conditions on September 5th and 6th, 2008, at the Maifeld in Berlin, Germany, is given in Figure 3 and Figure 4.

The left ordinate of Figure 3 and Figure 4 represents the wind speed at 2 m height; the right ordinate gives the corresponding wind direction with the following definitions:

0/360° = south,
90° = west;
180° = north, and
270° = east.

Figure 3 reveals that due to the wind conditions on Friday September 5th, 2008, measurements of gaseous and solid reaction products liberated by the firework display were not possible. The prevailing wind direction was from the south/east, blowing the fume plume away from the location of instrumentation.

On Saturday September 6th, 2008, wind conditions changed significantly. As can be seen from Figure 4, comparatively low wind speeds (average over the evening < 0.8m s^{-1}) were measured almost during the entire evening. Though, at around 21:15 to 21:30, wind squalls occurred with a maximum speed of 4.5 m s^{-1}, coming from the west and southwest. During that time, firework display 5 was running.

However, even under these conditions, when the

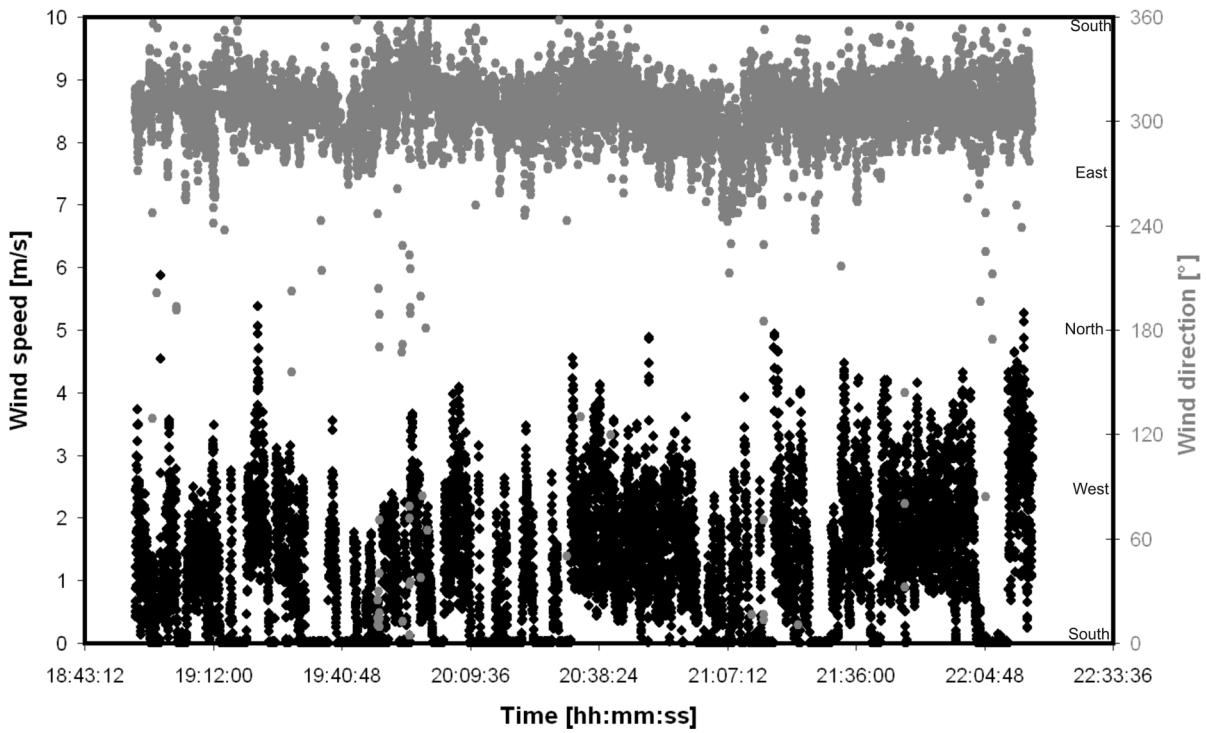

Figure 3. *Wind speed and direction on Friday September 5th, 2008, at the Maifeld in Berlin, Germany.*

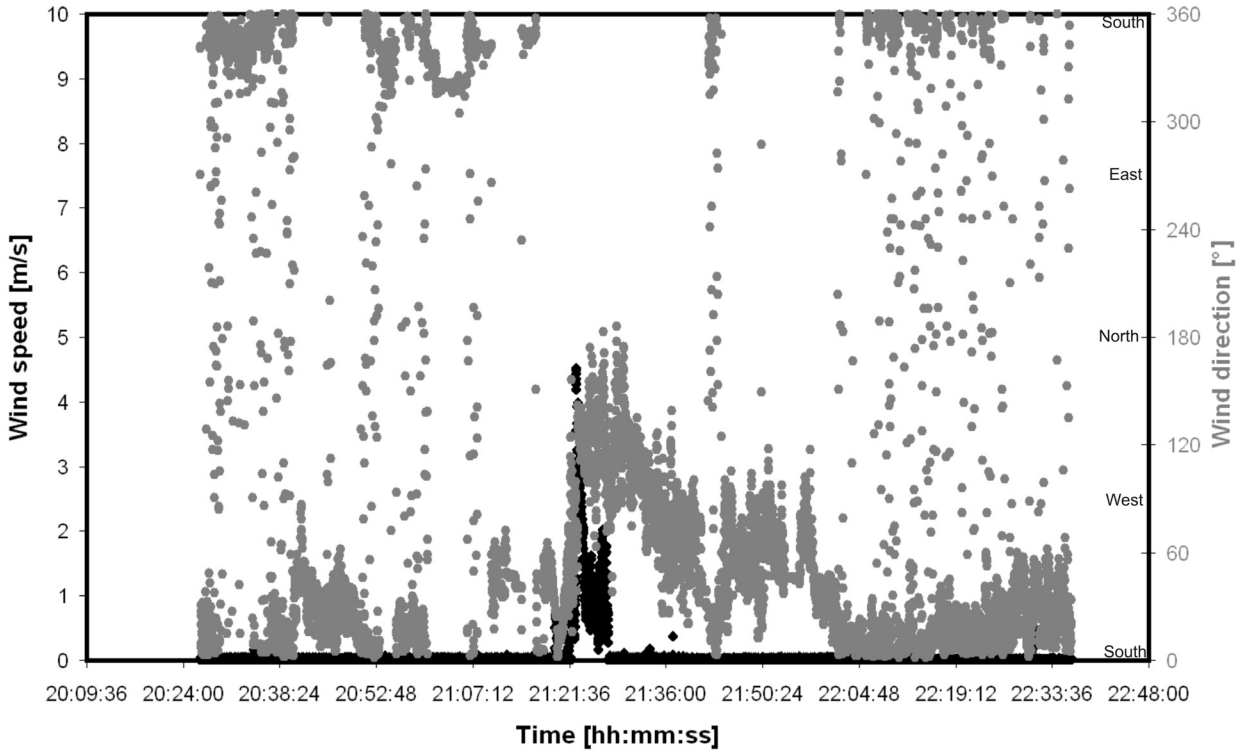

Figure 4. *Wind speed and direction on Saturday September 6th, 2008, at the Maifeld in Berlin, Germany.*

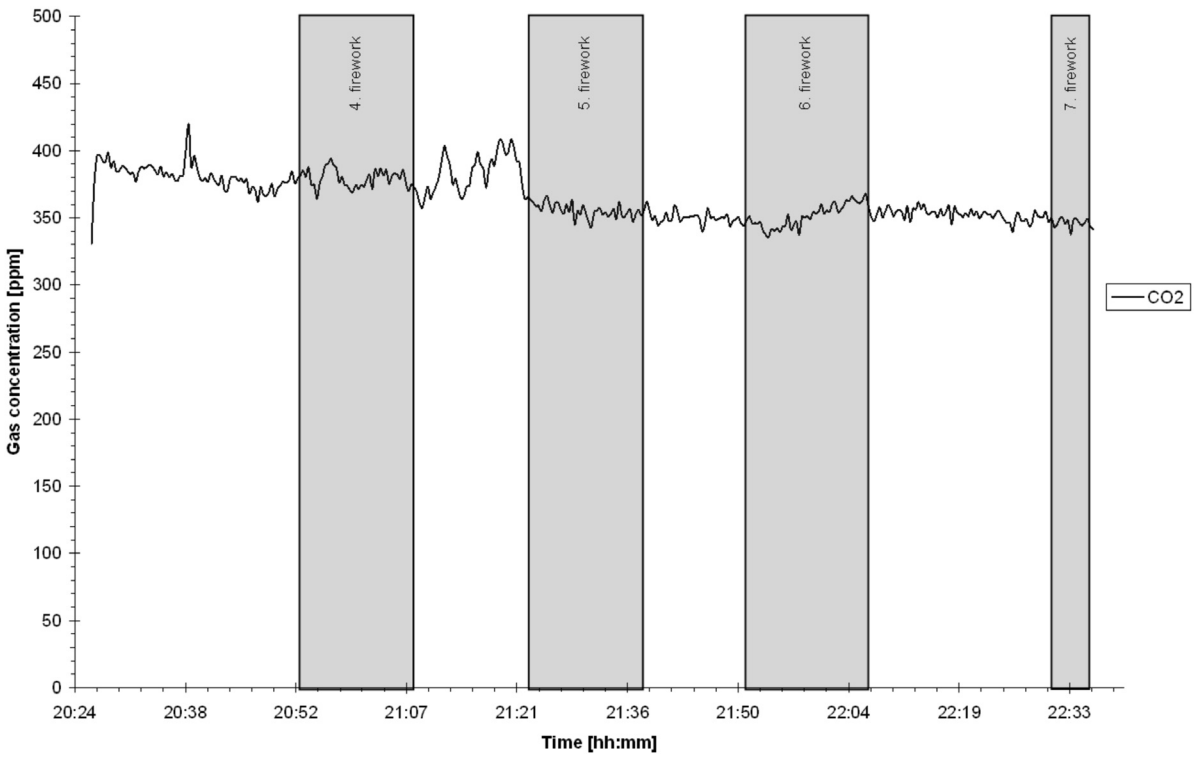

Figure 5. *Gas concentration of CO_2 on Saturday September 6, 2008, at the measurement location at a minimum of 110 m distance from the fireworks setup.*

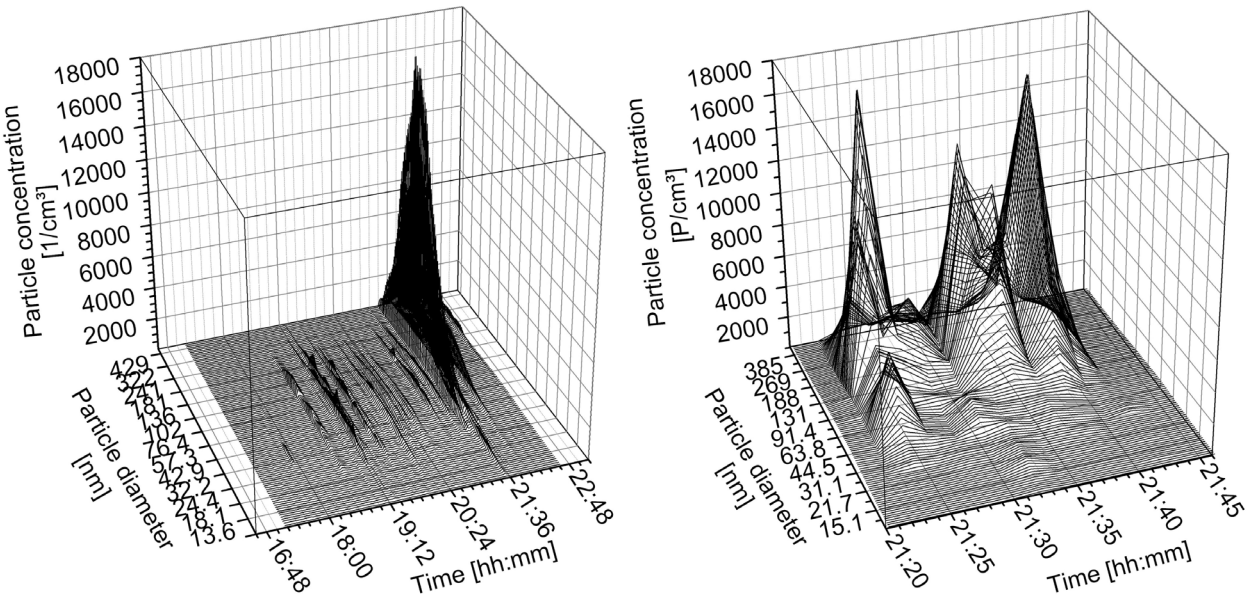

Figure 6. *Time-dependent particle size distribution on Saturday September 6th, 2008; left diagram: full spectrum, right side: scale-up of the time interval from 21:20 to 21:45.*

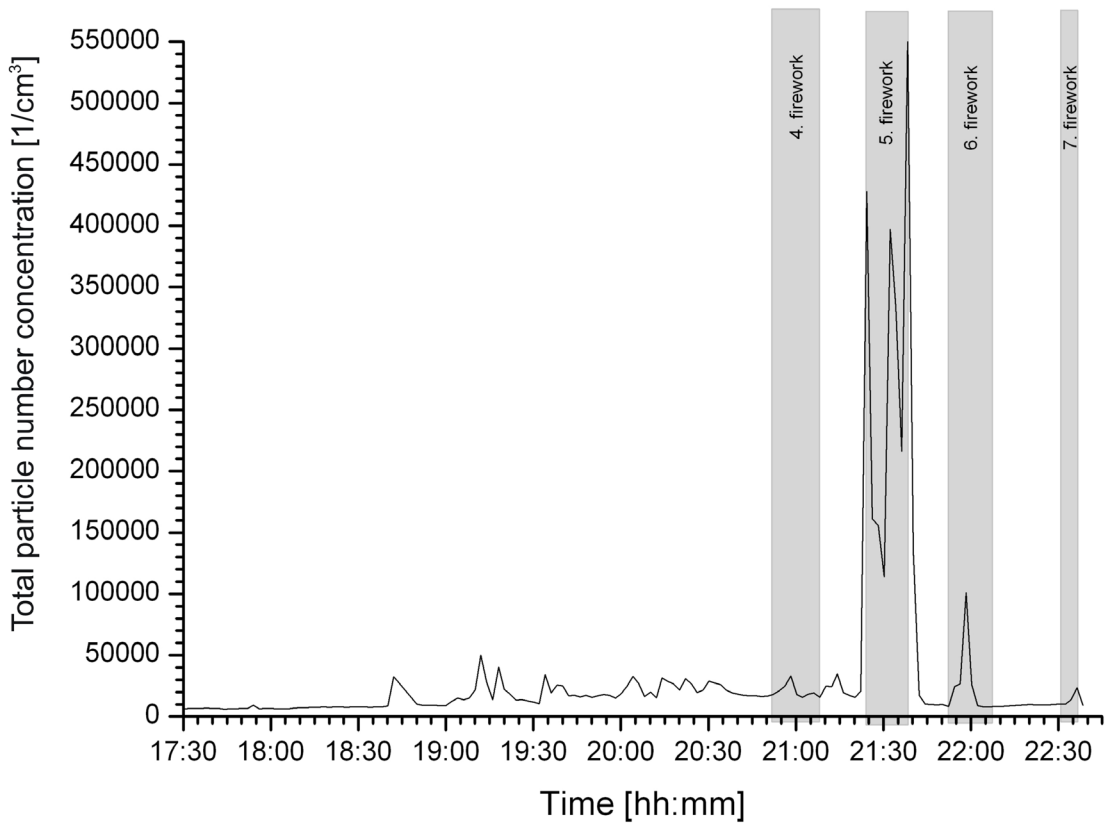

Figure 7. *Time-dependent total particle number concentration (<500 nm) on Saturday September 6th, 2008.*

fireworks emissions were directly transported to the instrumentation, no significant traces of combustion gases were detected by the FTIR spectrometer. This was due to the large distance from the measurement location to the ignition points (>110 m), leading to dilution effects. In addition, hot reaction gases immediately ascended due to buoyancy forces and were partly dissolved by rain drops. Figure 5 illustrates as an example the time-dependent CO_2 concentration during the evening.

In contrast, significant emissions of particles were detected at the measuring point. The results of the particle measurements are illustrated in Figure 6 to Figure 8. Figure 6 gives the time-dependent particle concentrations for all particle size channels below 500 nm diameter.

The time-dependent total particle number concentration is displayed in Figure 7 and Figure 8.

Measurements during firework display no. 5 (wind was transporting the fume plume to the measuring devices) showed that the particle distribution above background was between 40 nm and 400 nm. It is expected that due to homogeneous particle formation processes (i.e. combustion of the fireworks) ultrafine particles are predominately created. Concentration maxima occurred at diameters of approximately 145 nm and 170 nm. The total particle number concentration during firework display number 5 reveals a maximum of > 550 000 particles cm^{-3}.

To evaluate these data, a conversion to a mass based concentration is necessary. Therefore, as a first approximation, all particles were assumed to be ideal spheres with a standard density of 1200 kg m^{-3} (the real composition and physical structure of the particles are unknown).

The calculated maximum of the total mass concentration was 3.95 mg m^{-3} at 21:38. In addition, the following maximum time-averaged values were measured:

1.58 mg m^{-3} over 15 min, and

0.90 mg m^{-3} over 30 min.

Table 2 contrasts the measured data with (legal) limit and reference values in Germany.

The legal background for occupational safety in Germany is the Labour Protection Law

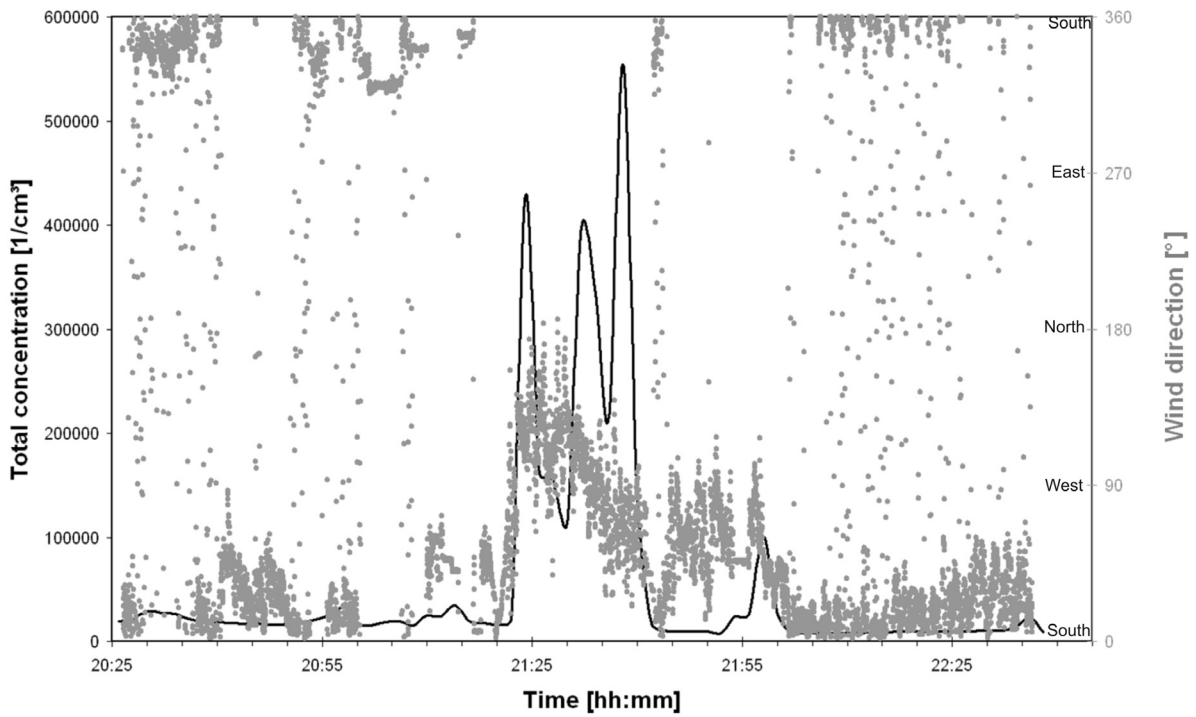

Figure 8. *Time-dependent total particle number concentration and wind direction on Saturday September 6th, 2008.*

Table 2. *Results of particle measurements from Saturday September 6th, 2008, and corresponding (legal) limit and reference values for dusts in Germany.*

Maximum measured particle concentration	550 000 particles $cm^{-3} \approx 3.95$ mg m^{-3}
Maximum time-averaged particle concentration (15 min)	1.58 mg m^{-3}
Maximum time-averaged particle concentration (30 min)	0.90 mg m^{-3}
AGW_a for alveolar dust (8 h/day, 40 h/week)	3 mg m^{-3}
AGW_r for respirable dust (8 h/day, 40 h/week)	10 mg m^{-3}
AGW_{STV} (short time value, over 15 min)	$AGW_{STV} = 2 \times AGW_a = 6$ mg m^{-3}
MI (30 min, respirable)	0.45 mg m^{-3}
MI (30 min, particulate matter)	0.3 mg m^{-3}

(Arbeitsschutzgesetz, ArbSchG)[14] and the ancillary Ordinance on Hazardous Substances (Gefahrstoffverordnung, GefStoffV).[15] For activities at work, which cover the handling, liberation or production of hazardous materials, occupational limit values (Arbeitsplatzgrenzwerte, AGW) are binding according to the ArbSchG. The GefStoffV gives a list of hazardous materials, including respirable and alveolar dusts (defined as particle diameters ≤18 µm). Substance dependent AGW are time-averaged concentrations and refer to a working shift, with a typical exposure time of 8 h a day, 5 days a week for the entire working life. They are listed in the Technical Standard TRGS 900.[16] In addition, short time values exist (AGW_{STV}), which replenish the AGW regarding concentration fluctuations. AGW_{STV} limit the shift mean value in terms of magnitude, frequency, and exposure time. AGW_{STV} are the product of the AGW and the overstepping factor (which is 2 in case of dusts; referred to an exposure time of 15 min). Longer exposure times are allowed, as long as the product of the overstepping factor and overstepping time remains the same. The corresponding AGW for respirable and alveolar dusts are presented in Table 2. As a major limitation of the AGW, these values are not valid for dusts which are mutagenic, carcinogenic, allergenic, toxic, soluble, superfine, and coarse particles.

Furthermore, maximum emission values (MI) are given in the VDI guideline 2309[17] and presented for dusts in Table 2. Here the following definitions are set: respirable dusts with a median particle diameter of 25 µm, and particulate matter with a median particle diameter of 10 µm. The given data are not mandatory and represent a very conservative estimation.

The maximum measured particle concentration of 3.95 mg m^{-3} is in good agreement with the data presented by Smith and Dinh.[10]

As can be seen from Table 2, the maximum time-averaged particle concentration (over 15 min) of 1.58 mg m^{-3} during the firework display was more than 3 times smaller than the corresponding short time value AGW_{STV} = 6 mg m^{-3}, but still of the same magnitude. The same applies for the time-averaged 30 min values. In contrast to this, the measured maximum time-averaged 30 min value of 0.90 mg m^{-3} clearly exceeds the suggested MI value by a factor of 3.

Results towards the emission of sound pressures during the Pyronale® in September 2008 at the Maifeld in Berlin, Germany, are presented in Table 3. An exemplarily unweighted sound pressure versus time history for firework display no. 5 (September 6th, 2009) is illustrated in Figure 9.

Table 3*: Results of the sound pressure measurements (L_{max} = maximal unweighted sound pressure; L_{Imax} = time dependent sound pressure at L_{max}; L_{AImax} = time and A-weighted sound pressure at the L_{max}) for all fireworks during the Pyronale®.*

	1. firework	2. firework	3. firework	4. firework	5. firework	6. firework	7. firework
L_{max} dB	157.6	156.8	153.0	147.4	164.6	159.4	150.5
L_{Imax} dB	121.1	121.6	125.5	120.7	120.1	120.6	125.9
L_{AImax} dB	114.6	113.2	115.5	113.2	111.8	113.0	114.5

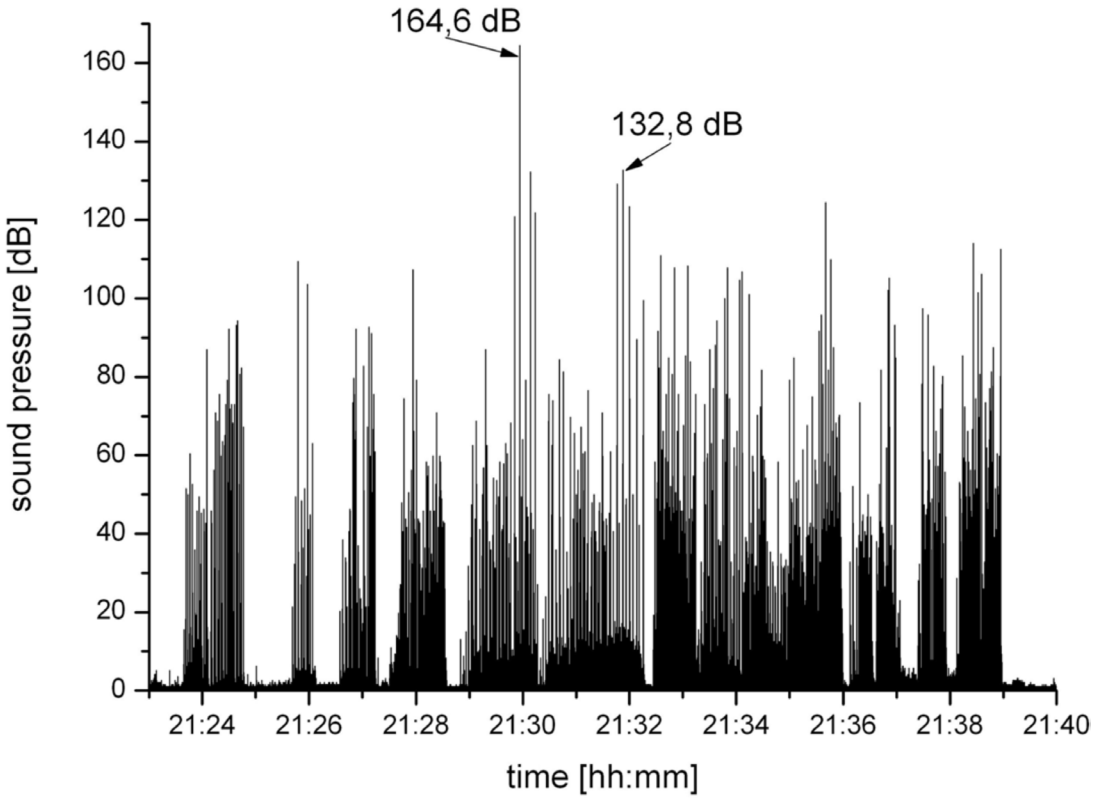

Figure 9. *Unweighted sound pressure versus time for firework no. 5.*

All fireworks provided very low hazards towards sound pressure impacts at the safety distance to the audience. The maximum sound pressure values of all fireworks did not differ much. The highest maximum value of 115.5 dB(AI) was observed during the third firework display. The lowest maximum value of 111.8 dB(AI) was emitted by firework no. 5.

26th international ADAC-Super-Motocross (indoor)

Table 4 gives time-averaged results of the meteorological data and boundary conditions in the Martin-Schleyer Hall in Stuttgart, Germany.

Additionally, all measured gas concentrations are displayed in Table 5. In terms of combustion gases, the results were quite similar on both days, although the ventilation was turned off on November 14th and turned on November 15th.

Even though the functioning of the pyrotechnic articles took place at an indoor site, very low combustion gas concentrations were measured. Nitrogen oxides were just detectable in low quantities, e.g. NO_2 with a maximum concentration of 19 mg m^{-3}. Only dinitrogen monoxide (N_2O) appeared at levels of up to 54.2 mg m^{-3}, likely emitted by the motor cycles. Furthermore, hydrocarbons like methane (CH_4), and propane

Table 4. *Meteorological data of November 14th and November 15th, 2008 inside the Martin-Schleyer Hall in Stuttgart, Germany.*

Date (measuring time)	November 14th, 2008 (20:00–21:00)	November 15th, 2008 (20:00–21:00)
Temperature/°C	18.5 ± 0.5	18.5 ± 0.5
Air pressure/hPa	1003	1002
Relative humidity (%)	34–36	35–38
Ventilation on ?	No	Yes

Table 5. *Measured gas emissions at the motocross show (Martin-Schleyer Hall, Stuttgart, Germany, November 14th and November 15th, 2008).*

	November 14th, 2008			November 15th, 2008		
Gas	Max. concentration/ mg m^{-3}	Max. 10 min average concentration/ mg m^{-3}	Max. 30 min average concentration/ mg m^{-3}	Max. concentration/ mg m^{-3}	Max. 10 min average concentration/ mg m^{-3}	Max. 30 min average concentration/ mg m^{-3}
H_2O	4707	4697	4745	5292	5405	5155
CO_2	1421	1350	1330	1578	1474	1392
CO	37.5	25.9	19.6	29.1	18.5	7.6
NH_3	0.3	0.2	0.1	0.3	0.2	0.1
NO_2	9.3	7.8	7.6	18.9	10.5	8.0
NO	0.0	0.0	0.0	0.0	0.0	0.0
N_2O	42.4	32.4	26.8	54.2	26.8	23.5
SO_2	4.1	1.8	1.3	2.5	1.9	1.1
HCl	3.3	3.4	3.4	3.1	3.8	2.6
HCN	0.8	0.5	0.5	0.8	0.5	0.4
CH_4	1.7	1.6	1.5	1.5	1.3	1.1
C_2H_6	10.9	11.5	10.0	14.1	12.9	9.9
C_3H_8	21.1	16.1	15.4	15.5	17.9	13.9
C_2H_2	5.6	4.0	3.0	7.9	3.2	2.3
C_6H_6	0.0	0.0	0.0	0.0	0.0	0.0

(C_3H_8) with peak concentrations of up to 21 mg m^{-3} were released.

As illustrated in Figure 10 and Figure 11, the SO_2 concentrations increased after the fireworks on both days. To evaluate those concentrations, the WHO AIR Quality Guideline value[18] of 0.5 mg m^{-3} (10 minutes average) is taken into account, since currently no German AGW are published for SO_2.

Whereas on November 14th a maximum SO_2 concentration of 4.1 mg m^{-3} was detected, a significantly lower maximum concentration of about 2.5 mg m^{-3} was observed on November 15th. This effect is explained by the activated hall ventilation on the second day, leading to increased dilution mechanism, as well as possible different compositions of fireworks. In the case of no ventilation, the 10 minute average concentrations constantly exceeded the WHO AIR Quality Guideline value[18] of 0.5 mg m^{-3} more than 30 minutes after the firework display. Due to the effective ventilation on the second day, a substantial exceeding of the guideline threshold was not observed.

Figure 12 presents the results of the CO measurements on November 14th, 2008. During and shortly after the starting indoor firework displays no relevant CO concentrations were observed. The peaks at 20:20 are likely due to the following motocross race.

On both days, only slightly elevated CO_2 concentrations were observed and could not be traced back to the firework displays.

Figure 13 displays the time and diameter dependent particle concentration on November 14th (left image) and November 15th (right image) in the Martin-Schleyer Hall. The zero-point on the time axis refers to the beginning of the firework display at 20:00. The black points represent measured data,

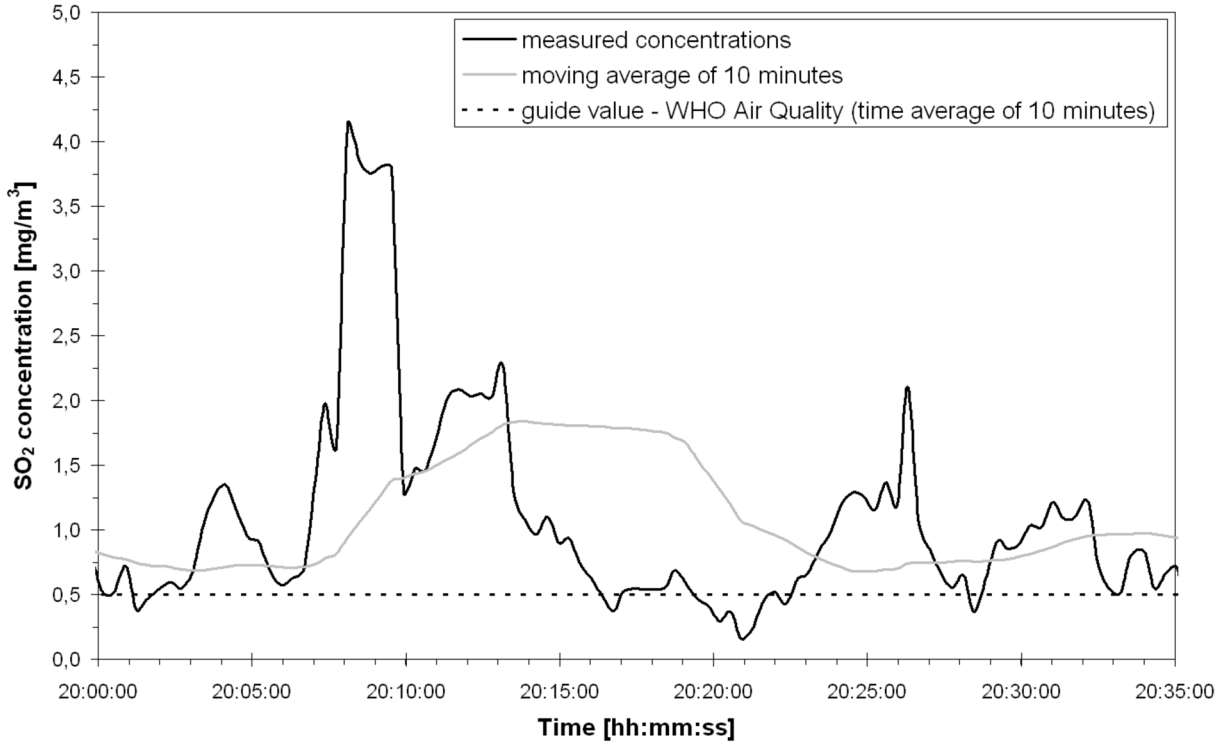

Figure 10. *SO_2 concentration behaviour on November 14th, 2008.*

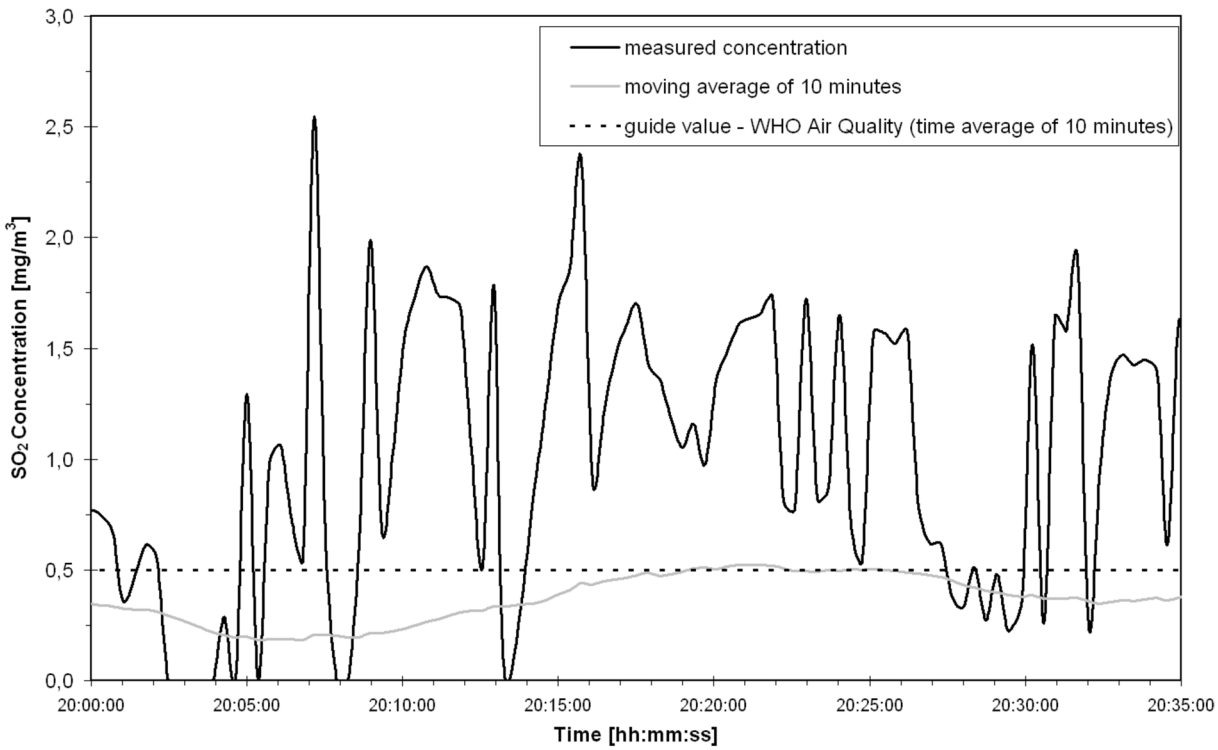

Figure 11. *SO_2 concentration behaviour on November 15th, 2008.*

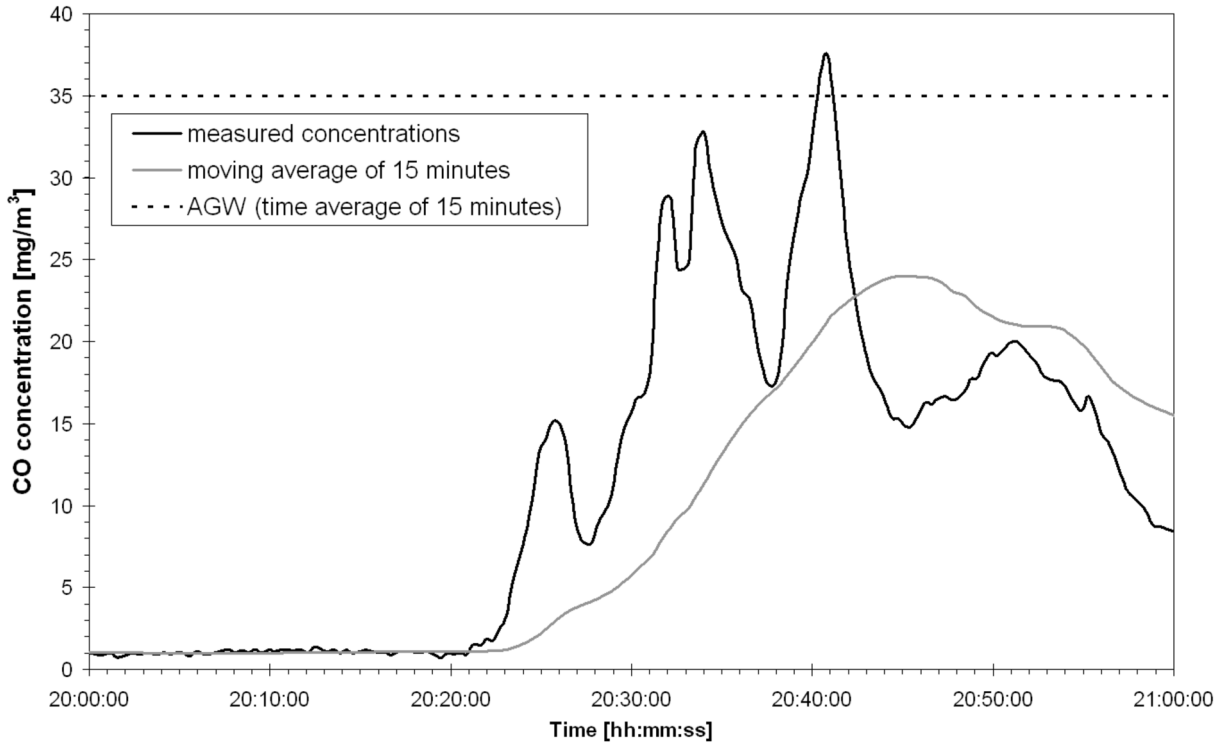

Figure 12. *CO concentration behaviour on November 14th, 2008.*

whereas the gray areas are interpolated trends.

An integration over all particle size diameters leads to the total particle concentration versus time, as displayed in Figure 14.

Subsequent to the start of the fireworks, particle concentrations increased on both days. Especially on the first day, when the ventilation system was turned off, the increase in particle concentration occurred rapidly. After reaching the respective concentration maxima shortly after the fireworks, particle concentrations decreased nearly exponentially. Surprisingly, the base level was reached again after an hour, although the motocross races were running. This indicates that nearly all particles in the range from 300–900 nm

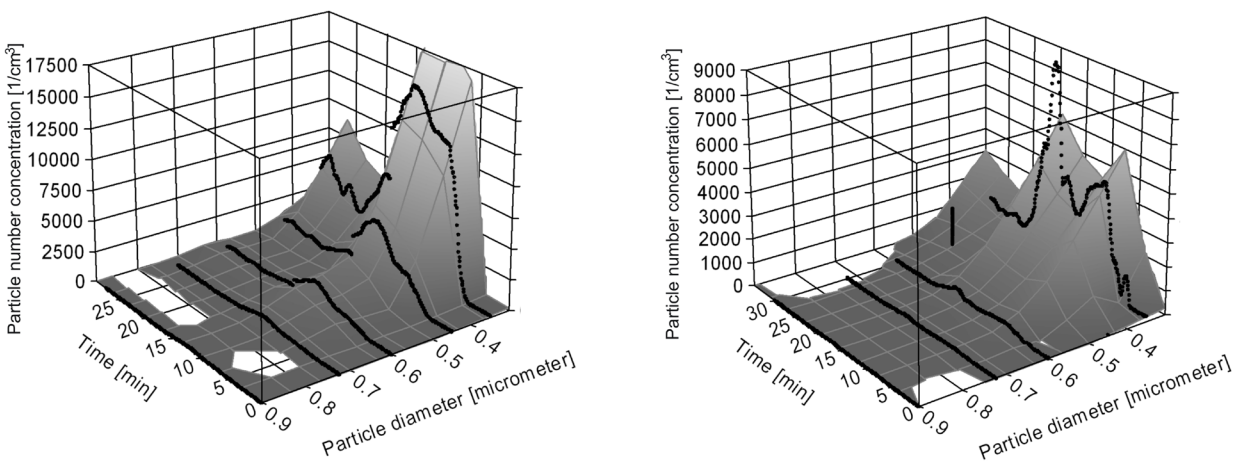

Figure 13. *Time-dependent particle size distribution on November 14th, 2008 (left) and November 15th, 2008 (right).*

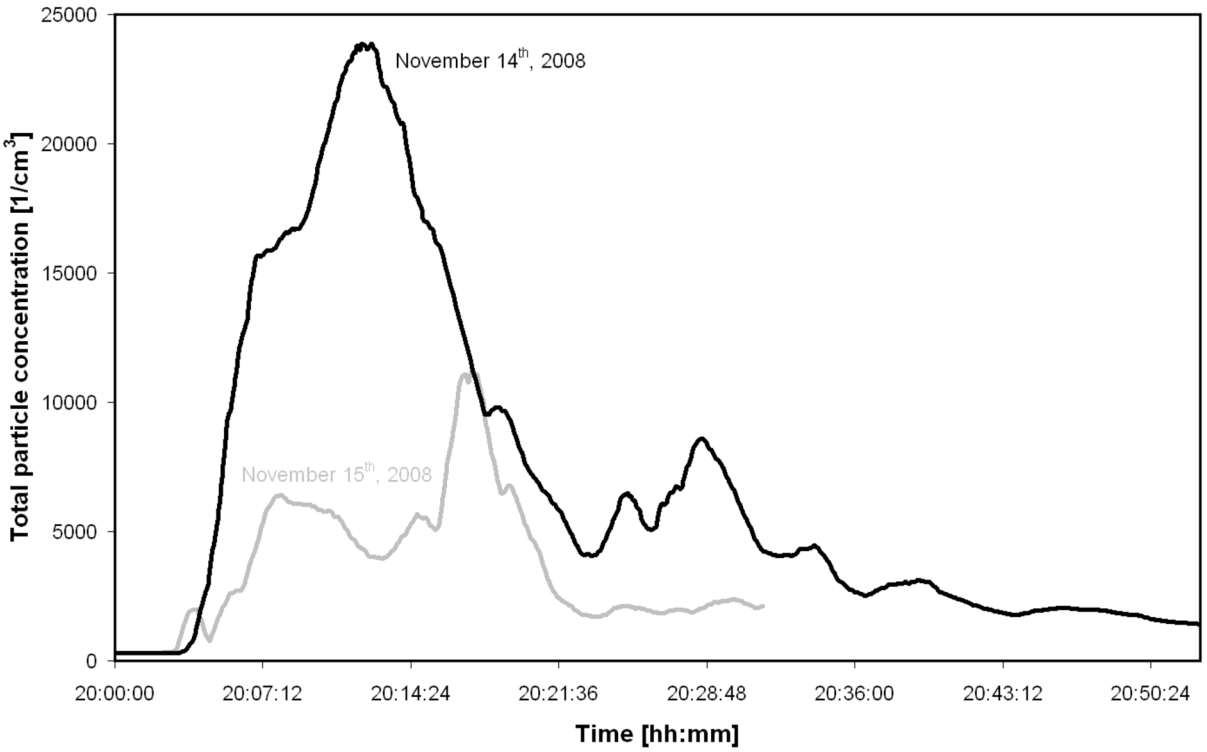

Figure 14. *Time-dependent total particle number concentration on November 14th and 15th, 2008.*

were emitted by the fireworks and a significant rise of the total particle concentration due to the combustion engines of the motocross bikes was not observed.

The main results of the particle measurements are summarized in Table 6.

Even though the maximum total particle number concentration on November 14th exceeded the one

Table 6. *Results of the particle measurements at the opening fireworks of the motocross show on November 14th and 15th and corresponding (legal) limit and reference values for dusts in Germany.*

	Nov. 14th, 2008	Nov. 15th, 2008
Maximum measured particle concentration	>23 000 particle cm^{-3} ≈ 0.41 mg m^{-3}	>11 000 particle cm^{-3} ≈ 1.18 mg m^{-3}
Maximum time-averaged particle concentration (15 min)	0.31 mg m^{-3}	0.56 mg m^{-3}
Maximum time-averaged particle concentration (30 min)	0.19 mg m^{-3}	0.38 mg m^{-3}
AGW_a for alveolar dust (8 h/day, 40 h/week)	3 mg m^{-3}	
AGW_r for respirable dust (8 h/day, 40 h/week)	10 mg m^{-3}	
AGW_{STV} (short time value, over 15 min)	$AGW_{STV} = 2 \times AGW_a = 6$ mg m^{-3}	
MI (30 min, respirable dust)	0.45 mg m^{-3}	
MI (30 min, particulate matter)	0.3 mg m^{-3}	

on November 15th by a factor of 2, the respective maximum mass-concentration on the first day was lower than on the second day. The reason for this is the difference in particle size distributions. On the second day larger particles were detectable over a slightly longer time period. On both days, maximum particle concentrations did not exceed values of 1.18 mg m^{-3}.

It has to be noted that the appearance of particles with diameters of less than 300 nm was very likely, but due to the limitation of the measurement device in this case, only particles with diameters between 300 nm and 20 µm could be observed.

Nevertheless, a substantial hazard to the audience due to aerosol impacts released by the indoor firework displays was not observed during this event.

Summary and conclusions

In this work results of measurements towards the emission of gaseous and solid reaction products, as well as of sound pressure during a large outdoor and indoor firework display are presented.

Depending on the local meteorological conditions, different results were obtained during the two days of the outdoor fireworks. Due to adverse wind conditions, neither gaseous nor solid reaction products (particles) were measured on the first day. The wind direction changed significantly on the second day during one firework show, transporting the plume of reaction products directly towards the measurement technique. Under these conditions massive peak particle concentrations of >550 000 particles cm^{-3} occurred, equivalent to a peak mass concentration of approximately 3.95 mg m^{-3}. The maximum time-averaged particle concentrations (over 15 min and 30 min) during the firework display were more than 3 times lower than the corresponding occupational short time limit values (according to German regulations). However, the measured values were still 3 times higher than the maximum emission values suggested by the VDI guideline 2309, which represent a very conservative estimation.

Even though large increases in particle concentrations were observed during the fireworks, no significant rises in combustion gas concentrations were detected. This is likely due to the long distance from the measurement location to the ignition point (>110 m), leading to dilution effects. In addition, hot reaction gases immediately ascended due to buoyancy forces and were partly dissolved by rain drops.

Furthermore, none of the fireworks during the display ever crossed the sound pressure level of 115.5 dB(AI) at the safety distance to the audience.

Measurements during an indoor firework display led to different results. Sulphur dioxide concentrations rose up to a maximum value of 4.1 mg m^{-3} after the fireworks when the ventilation was turned off, and to a maximum value of 2.5 mg m^{-3} with an activated ventilation system inside the hall.

Peaks in carbon monoxide concentrations were likely due to the following motocross race and could not be traced back to the indoor firework displays. Other combustion gas concentrations (e.g. nitrogen dioxide, dinitrogen oxide) appeared at negligible levels.

Caused by different ventilation settings and particle distributions on both evenings, aerosol concentrations exceeded 23 000 particles cm^{-3} (equivalent to 0.41 mg m^{-3}) when the ventilation in the hall was turned off, and exceeded particle concentrations of 11 000 particles cm^{-3} (equivalent to 1.18 mg m^{-3}) with an activated ventilation system. The highest detected 15 minutes average dust mass concentration of 0.56 mg m^{-3} was nearly 12 times smaller than the corresponding occupational short time limit values (according to German regulations). Due to the used instrumentation at the indoor venue, only particles with diameters between 300 nm and 20 µm could be observed. However, it seems likely that smaller particles were emitted, as well.

Sound pressure measurements were not carried out for the indoor firework show.

In conclusion, possible hazards to the public and the environment arising from large firework displays due to harmful or toxic reaction gases seem unlikely, even when the smoke plume reaches the audience. Moreover, the sound pressure impact can be easily controlled by an adequate safety distance, as well. In contrast to this, particulate matter can be transported over long distances and inhalation may lead to adverse health effects due to the potential toxicity of the inhalable particles.

At indoor events, an effective ventilation system can significantly reduce this hazard. This must be taken into account when developing future firework products or designing firework displays.

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