Chapter 2
Health Risk Assessment of Combustion Products from Simulated Residential Fire

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Abstract The chapter concentrates on the health risk assessment of selected pollutants derived from residential fire simulated in fire container. The key interest is dedicated to Polycyclic Aromatic Hydrocarbons (PAHs) and their toxicity and harmful effects on the health of firefighters, whose protection by breathing apparatus is insufficient. The final evaluation suggests measurements regarding the issue of the protection of people dealing with fire.

Keywords Fire · Combustion products · Polycyclic aromatic hydrocarbons · Toxic effects · Health risks

2.1 Introduction

Currently, fires belong among the most significant risk events because of high number of injuries and deaths caused by fires. In 2014, there were 114 dead and 1179 injured people at all fires in the Czech Republic. The most of fires with tragic consequences begins at family houses and residential houses, where 63 persons died and 694 persons were injured. The residential fires add up to 20% from the total number of firefighting events (Vonásek and Lukeš 2015).

The health consequences from fires are mostly caused by burns, injuries derived from mechanical damages, high heat or lower oxygen content, then by burning products intoxication and finally by psychosocial impacts on residents and members of rescue units. The combustion products intoxication has absolute major contribution to the total number of deaths caused by fires. It was estimated that up to 30% of burned persons were also intoxicated by products of combustion (Brown 1990). Toxic combustion products represent higher risk than other causes of injuries and

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Š. Hošková-Mayerová et al., *Mathematical-Statistical Models and Qualitative Theories for Economic and Social Sciences*, Studies in Systems, Decision and Control 104,
DOI 10.1007/978-3-319-54819-7_2

deaths of people occurred in vicinity of fire. The monitoring of combustion products during simulated fires at the Flashover fire container or other special spaces enables to acquire important information about their chemical make-up and their toxicity, which helps to predict health risks of fire participants.

2.2 Analysis of the Current State

The amount, chemical properties and toxicity of combustion products arisen from fires depend on the type of burning material and other factors resulting from dynamical nature of the given fire. The toxicity of combustion products from concrete materials is significantly influenced by the amount of oxygen present in the fire environment. It is known that the combustion products become more toxic with the decreasing concentration of oxygen. These conditions occur mainly in closed areas, in which more significant toxic substances emerge more probably than in open areas. Nowadays, the interiors of residents and flats are equipped with synthetic materials, which may highly contribute to the emerging of toxic substances during fires.

Therefore, the experiments with simulation of residential fire are carried out in order to gather comprehensive information about qualitative and quantitative combustion products composition. The attention is given to low molecular chemical compounds such as CO_2, CO, HBr, HCl, HCN, NOx and volatile organic compounds (VOC) such as benzen and styrene and mainly to polycyclic aromatic hydrocarbons (PAHs), polychlorinated and polybrominated dibenzo-p-dioxins/furans (PCDD/F, PBDD/F) and fragments of brominated flame retardants (BFRs) e.g. from tetrabromobisphenol A (TBBPA) or dekabromodiphenyl ether (deka-BDE) and, last but not least, particulate matters (PM). Despite the fact that CO_2 and HCN mostly contribute to intoxication of persons, the attention is especially given to obtain data about organic substances.

Particulate matters are known for their mutagenic, carcinogenic and genotoxic effects. The inhalation and effect of PM on human organism are directly influenced by their size. Only such PM smaller than 10 micrometers in diameter reach deeply respiratory tract. Increased PM deposition in lungs may lead to acute cardiovascular events (Donaldson and Borm 2007). Increased morbidity and mortality due to cardiovascular and respiratory system illnesses belong among health effects of the short-term exposure to PM. The long-term exposition may result in augmented incidence of respiratory tract cancer and in shortened life expectancy as a consequence of cardiovascular, pulmonary and oncological diseases (Lippman 2010).

The majority of PAHs belongs to indirectly acting genotoxic substances. Diarrhea, nausea, lack of appetite and vomiting may be considered as short-term effects of PAHs. The mostly emphasized member of PAHs is benzo(a)pyrene (BaP). The typical rout of entry for BaP and other PAHs is by inhalation or skin absorption. The exposure to BaP potentially leads to fetal development disorders, irritation and burning of skin and disease cancer risk. Repeated exposure causes reduced and chapped skin. International Agency for Research on Cancer (IARC) classifies BaP as carcinogenic to human into Group 1, then naphthalene, chrysene and benzo(b) fluoranthene as possibly carcinogenic to humans into Group 2B (International Agency on Research of Cancer 2015).

PCB are those substances which may cause cancer diseases and also may induce other harmful effects on human health, e.g. effects on immune, reproductive, nerve and endocrine system of individual organism.

Harmful health effects of PCDD/F are connected with chloracne development, which may occurs during several days up to months after the exposure (International Programme on Chemical Safety 1989). Further impacts on human health after the acute exposure to dioxins are mostly hepatotoxic and neurotoxic effects and hypertension. Research studies involving animals indicate dioxins as harmful substances for reproductive system and as teratogenic agent. IARC classifies 2, 3, 7, 8-TCDD as carcinogenic to human (Group 1). TBDD/F are considered as toxic to reproduction of animals. Bromide compounds are potentially toxic to human skin, liver and gastrointestinal tract.

2.3 Applied Methods and Devices

Combustion products derived from fire container were picked up by passive samplers filled with porous polymer Tenax TA (with specific surface area of 35 $m^2\ g^{-1}$) and by samplers with coal sorbent Carbopack (12 $m^2\ g^{-1}$) and by the portable concentrator (Ministry of the Environment of the Czech Republic 2005). Passive samplers were clipped on the garment of firefighters training in fire container. The average exposure duration of passive samplers to combustion product lasts about 20 min, combustion products have been captured by the portable concentrator for 3 min.

After the exposure, the adsorbent from passive samplers was extracted by mixture of hexan-dichloromethane in closed vial and the extract was examined by gas chromatography and mass spectrometry (GC-MS) with the help of devices Agilent GC7890-A and MS 5775C Agilent. Analysis were especially oriented on the identification of PAHs. The sample of combustion products captured by the portable concentrator was also examined by the GC-MS method.

From the aspect of possible assessment of health risks, the data from residential fire simulations presented at specialized literature (Večeřa et al. 2010) were applied. The issue was primarily discussed with the author of research study investigating residential fire simulation named Per Blomqvist from Swedish National Testing and Research Institute. After the personal consultation (Blomqvist et al. 2004), the study data was carefully compiled and the exposure scenario for the health risk assessment was created.

At the health risk assessment, the methodical directive prepared by the Ministry of the Environment of the Czech Republic (MoE) called “The Risk Analysis of the Contaminated Area” was applied. Following equations were used for the estimation of health risks of carcinogenic substances (Ministry of the Environment of the Czech Republic 2005):

$$ILCR = LADD \cdot ICPF. \tag{2.1}$$

where *ILCR (Individual Lifetime Cancer Risk)* indicates increasing probability of cancer diseases number over the general average, *LADD (Lifetime Average Daily Dose)* means average lifelong daily exposure [mg kg^{-1} den^{-1}] and *ICPF (Inhalation Cancer Potency)* represents inhalation slope factor [mg kg^{-1} den^{-1}].

In the case of inhalation, the following equation for calculation of *LADD* is used:

$$LADD = CA \cdot IR \cdot ET \cdot EF \cdot BW^{-1} \cdot AT^{-1}. \tag{2.2}$$

where *CA* (*Average Concentration*) is concentration of the pollutant in the air [mg m^{-3}], *IR* (*Intake Rate*) represents the volume of inhaled air [m^{-3} h^{-1}], *ET* (*Exposure Time*) [h day^{-1}], *EF* (*Exposure Frequency*) [den $year^{-1}$], *ED* (*Exposure Dose*) [year], *BW* (*Body Weight*) [kg] a *AT* (*Average Time*) [day].

The value 10^{-6} is regarded as acceptable rate of risk. This value represents increase of the individual lifelong carcinogenic risk about one case per million exposed persons.

2.4 Results and Discussion

2.4.1 Fire Container

Selected chromatogram of determined combustion products originated from wood materials burned in the fire container, which were captured in passive samplers filled with various sorbents and picked up by portable concentrator is introduced at the Fig. 2.1. The comparison of capture efficiency with respect of determined compounds is also demonstrated. Chemical compounds assigned to particular peaks are introduced at the Table 2.1. With the respect of NIST database, other peaks have probability lower than 10%. Therefore, the identification is not possible. The origin of the intense peak of mono(2-ethylhexyl)phthalate is obviously caused by decomposition of plastic remnants of pallet packaging. By passive sampler usage, peaks of organic compounds emerge at chromatograms with retention time corresponding to identified compounds given earlier. Concentrations were extremely low thus their identification was complicated and unreliable.

Naphthalene was identified in examined samples taken by the portable concentrator. This compound is categorized by United States Environmental Protection Agency (US EPA) into category C and by IARC into Group 2B for its possible carcinogenic effects. Naphthalene acts as neurotoxic compound, may cause serious chronical diseases of the respiratory tract and lungs, asthmatic bronchitis, serious chronical skin and eyes diseases. Naphthalene was also identified at samples taken

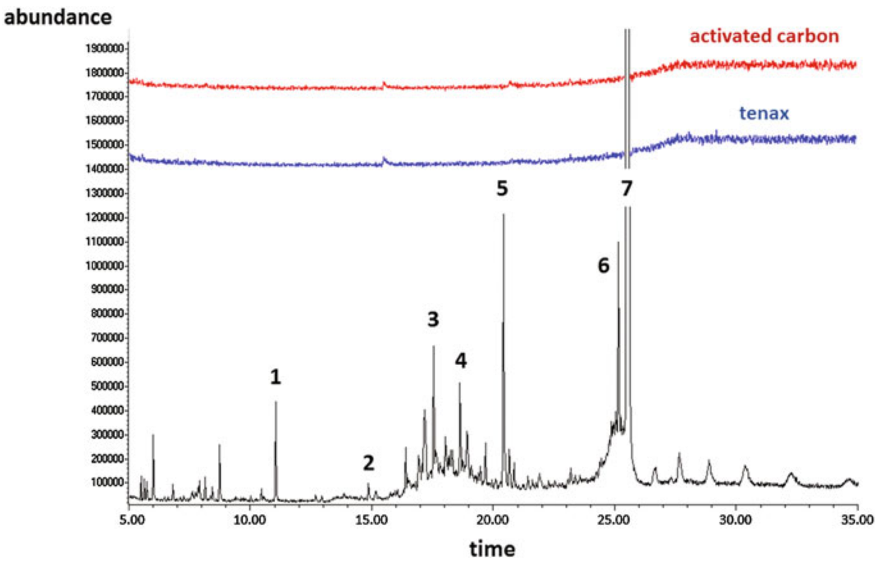

Fig. 2.1 Chromatogram of sample taken by passive samplers and portable concentrator

Table 2.1 Chemical compounds assigned to particular peaks

Peak	Assigned compound	Probability
Peak 1	Naphthalene	Identical RT standard
Peak 2	Acenaphthylene	Identical RT standard
Peak 3	Heptadecane	18.8%
Peak 4	Phenanthrene	Identical RT standard
Peak 5	Di-n-butyl phthalate	33.1%
Peak 6	Diisooctyl phthalate	32.1%
Peak 7	Mono(2-ethylhexyl) phthalate	37.1%

from cotton face piece, which firefighters wear during the training. Therefore it is obvious, that given substances are captured in these firefighter gadgets and garment and such substances are in direct contact with their skin on face area. Instructors of the training program are repeatedly exposed to such substances and they may suffer from listed chronical effects of naphthalene and other PAHs.

US EPA classifies acenaphthylene and phenanthrene into Group D as Not Classifiable as to Human Carcinogenicity. Heptadecane is indicated as substance hazardous for human. Dibutyl phthalate is substance with relatively low acute and chronical toxicity and in according to US EPA, it is categorized as substance which cannot be classified. Diisooctyl phthalate is applied as softening agent in plastic used predominantly at households. It is extensively used in processing polyvinyl chloride and ethylcellulose resins to produce cable wearer, imitation leather and electric wire. There is no sufficient data for classifying diisooctyl as carcinogenic substance and there is no evidence of its acute or chronic effects on humans.

2.4.2 Simulated Room Fire Scenario and Health Risk Assessment

Results arisen from the experimental study on the simulation of room fire carried out at Swedish National Testing and Research Institute are used as the ground for health risks calculation. The room fire simulation was conducted by the study author (Blomqvist et al. 2004) at rooms with floor area of 4 × 4 m^2 and the height to the ceiling was 2.4 m. Rooms were equipped with 303 kg of typical domestic furniture including sofa, armchair, books, carpet, shelving etc. Rooms were equipped with identical furniture except various types of televisions (TV set). The experiment EX1 employed a TV set with non-fire retarder enclosure material produced at European Union (EU) and the experiment EX2 employed a TV set containing brominated flame retardants produced at USA. The fire was initiated by a lighted candle. The combustion gases were determined with the help of infrared spectroscopy Fourier transformation method (FTIR). The Table 2.2 contains comprehensive results of combustion gases mass.

The particular combustion products and their mass are listed at the research project final report (Navrátil et al. 2013). On basis of results from conducted experiments EX1 and EX2, benzene contributes to the total mass of detected VOCs with 21%, resp. 38% and naphthalene with 16%, resp. 18%. Benzene acts as precursor of PAHs and soot particle. According to IARC, benzene is classified as

Table 2.2 Mass of the detected combustion products from the simulated room fires (Blomqvist et al. 2004)

Detected products	Experiment 1—EX1	Experiment 2—EX2
	Total g	
Inorganic gases	4.490E+05	4.740E+05
VOC	4.100E+02	1.420E+03
PAH	3.329E+02	8.670E+02
PCDD/PCDF	4.200E-06/3.280E-06	13.972E-06/6.350E-06
PBDF	8.100E-06	2.400E-06

Legend *VOC*—volatile organic compounds, *PAH*—polycyclic aromatic hydrocarbons, *PCDD*—polychlorinated dibenzo-p-dioxins, *PCDF*—polychlorinated dibenzofurans, *PBDD*—polybrominated dibeznodioxins, *PBDF*—polybrominated dibenzofurans carcinogenic to human (Group 1) causing especially leukemia and lung cancer. Toluene, phenol and styrene rank among the next volatile compounds determined during the experiment. Their characteristics contribute to their toxicity and irritant effects of produced smoke during a room fire. Naphthalene had the most contribution to the PAHs detected at the experiment (EX1–43.9%; EX2–43.5%). Phenanthrene, acenaphthylene, fluoranthene and pyrene were also detected in considerable quantity.

The calculation of health risks was accomplished with help of results derived from chemical analysis connected with mentioned study on simulated room fire. At the suggested scenario, it was assumed that a room fire conditions are identical as the simulated fire conditions. It was also assumed that the fire is conducted at modular home (prefab house), where approximately 10% of combustion gases volume leaks out to staircase ($20 \times 5 \times 10$ m^3). There is an expectation, that smoke enter the staircase area during the fire, where persons without breathing apparatus spend no more than 5 min (Kukleta 2014, personal communication). The exposure scenario was focused on the health risk assessment of benzene and benzo (a)pyrene. It was also expected that rescuers will arrive at the scene of fire with 30 min delay caused by late fire notification, which means that the majority of furnishing have burned down.

Benzene and benzo(a)pyrene were selected on basis of examined combustion products from simulated room fire due to their carcinogenic effects on humans proven by IARC.

The health risk assessment of benzene and benzo(a)pyrene was proceeded according to the methodical directive created by MoE. The LADD was calculated with the following values: $IR = 0.83$ m^{-3} h^{-1}, $ET = 0.083$ h day^{-1}, $EF = 0.130$ den $year^{-1}$, $ED = 30$ years, $BW = 85$ kg and $AT = 3900$ days.

The risk rate ILCR was obtained with help of calculated LADD and ICPF values listed in particular documents published by the Office of Environmental Health Hazard Assessment (OEHHA) in 2009: $ICPF_B = 1, 00E–0.1$ and $ICPF_{BaP} = 3.90E +0.1$ (California Environmental Protection Agency, Office of Environmental Health Hazard Assessment 2001). The Table 2.3 contains the assessment of ILCR for benzene and benzo(a)pyrene.

According to the Table 2.3, the value of ILCR for both substances are greater at the experiment EX2 (TV USA) than at the experiment EX1 (TV EU). The carcinogenic risk of benzene at experiment EX1 is balancing the acceptable rate of risk. The acceptable rate of risk was exceeded 4.4 times in case of benzene

Table 2.3 The calculation of LADD and ILCR for benzene and benzo(a)pyrene (Navrátil et al. 2013)

Pollutant	Experiment	C mg m^{-3}	LADD mg kg^{-1} day^{-1}	ILCR
Benzene	EX 1 (TV EU)	8.610E+00	0.698E-05	0.698E-06
	EX 2 (TV USA)	5.396E+01	4.373E-05	4.373E-06
Benzo(a)pyrene	EX 1 (TV EU)	5.162E-01	4.183E-07	1.631E-06
	EX 2 (TV USA)	1.301E+00	1.055E-06	4.112E-06

determined at the experiment EX2. The ILCR values for benzo(a)pyrene exceeded the acceptable rate of risk at both experiments EX1 and EX2: 1.6 times, resp. 4.1 times. The probability of cancer development resulted from inhalation exposure to bezno(a)pyrene is highly significant. Therefore those rescuers operating in vicinity of fire without breathing apparatus are exposed to combustion products with carcinogenic effects. With respect to the ILCR values, it is necessary to accept certain measures for those rescuers who do not wear breathing apparatus and operate in vicinity of fire or in area which is secondary filled with smoke.

2.4.3 The Analysis of Health Risk Uncertainties

During the health risk assessment, range variety of uncertainties appears and it is required to respect them at the final result interpretation. Passive samplers chosen inappropriately and incorrect sample collecting may rank among main causes of those uncertainties. The choice of chromatographic column may be connected with the uncertainty of the concentration determination during the analysis conducted on the standard operation procedures (Navrátil 2017; Hošková-Mayerová 2017).

Scenarios related to the health risk assessment have suggested the full burning down of the room and no fire progress to other housing units. The combustion gases concentration were not constant for whole duration of fire. During the clearance operations, combustion gases concentration was lowered by dilution with surrounding air.

Synergetic effects of benzene, benzo(a)pyrene and other substances were not included at the cancer risk calculation. The inhalation exposure was the only one reflected route of entry. The results may be overestimated due to inaccurate calculation of LADD values. Other combustion products which may emerge during fire were not included in the assessment.

2.5 Conclusion

Beside the heat radiation, the combustion product toxicity ranks among obvious fire danger, which may threaten people afflicted with fire and rescuers without breathing apparatus operating indirectly and repeatedly at fire environment.

High toxicity of combustion products is often influenced by application of new synthetic materials used in house building and for furnishing production. Mutual combination of material decomposition products from fire may result in formation of products with considerable toxicity in high concentration. It is required to accept the preliminary precaution principal and to implement useful measures in order to eliminate health risks consequent upon exposure to combustion products from fire primarily at operational management (during fire) and secondary at organization management (after transfer of firefighter gear to fire station). Rescuers are exposed to long-term effects of harmful combustion products and exhalations. Therefore, it is desirable to observe those rescuers repeatedly with respect to their state of health and irrespective to their duty description. The monitoring of PAHs as combustion products is also determining factor for selection of effective decontamination process of personal protective equipment.

The experiment conducted in order to take samples at fire container pointed out the necessity of further study on combustion products from residential fires. Further period of study is going to focus on colleting samples from rescuers gear and the inner part of the fire container or room after a fire.

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Mathematical-Statistical Models and Qualitative
Theories for Economic and Social Sciences
Hošková-Mayerová, Š.; Maturo, F.; Kacprzyk, J. (Eds.)
2017, XVII, 437 p. 104 illus., 79 illus. in color.,
Hardcover
ISBN: 978-3-319-54818-0