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Toxicity of smoke from upholstery materials in under-ventilated fires

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Abstract

Toxicity of smoke is an important parameter when evaluating the hazards associated with upholstery materials to be used in buildings and transportation vehicles. Fires in enclosed spaces with limited ventilation such as rooms, carriages and fuselages cause smoke accumulation and increased exposure of occupants to its toxic components. The paper focuses on experimental measurements of smoke toxicity in under-ventilated fires and presents data for various ventilation conditions. The results indicate the influence of ventilation on fire heat output, the composition and amount of produced smoke. The data can be used in fire modelling, fire investigation and evaluation of fire toxicity hazards in a particular field of application.

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1. Introduction

Toxicity of fire effluents is one of the main hazards to people inside buildings, transportation vehicles and other enclosures. An UK study (Stec, 2017) indicates that over the years, there has been a shift from burn-related injuries and deaths toward smoke-related ones. This may be associated with the decrease in the cellulosic component (mainly wood) of the fuel load and an increase in the synthetic component (mainly plastics, upholstery materials, etc.).

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The composition and rate of production of fire effluents varies greatly with the fuel type, chemical composition and configuration, enclosure (room, vehicle, fuselage...) geometry and ventilation conditions. In almost every type of building and vehicle, upholstered furniture and furnishings are present. These contain some type of textile covering and foam filling; very often polyurethane (PUR) foam is the main component. Apart from CO₂ and CO, nitrogen-containing chemical compounds are found in fire effluents due to the presence of nitrogen in the structure of polyurethane. Among others, hydrogen cyanide (HCN – potent toxicant) and ammonia (NH₃ – irritant) are significant contributors to the overall toxicity of the effluents (Stec and Hull, 2010).

There are various standardized tests available to establish the toxicity of fire effluents for construction and furnishing materials. For example a combination of EN ISO 5659-2:2017 Plastics – Smoke generation – Part 2: Determination of optical density by a single-chamber test and EN 17084:2018/AC:2020 Railway applications – Fire protection on railway vehicles – Toxicity test of materials and components is used for determination of toxicity of materials to be used in railway vehicles. Further test methods include bench scale methods such as the cone calorimeter (ISO 5660-1 and 2), radiant furnace (ASTM E 1678) and various tube furnaces in which the samples are burned in controlled conditions. The produced effluents are then sampled and analyzed by an appropriate method, often FTIR spectrometry. In these tests, the samples are rather small and in configurations not necessarily representing their true shape in final use. Nonetheless these tests offer good reproducibility and reference for comparison and classification.

On large scale, the materials are used in their real size, shape and mass and can be burned inside a test enclosure, such as the room corner test (ISO 9705) or single burning test enclosure (EN 13823) or in an open calorimetry configuration (ISO 24473). The produced fire effluents are collected in a hood and extracted through an exhaust duct, from which the samples are taken and delivered to an analyzing apparatus, usually a FTIR spectrometer.

As regards fire scenarios, used for the determination of smoke effluents production, the open calorimetry test represents well-ventilated conditions. The ventilation regime is more dependent on the size of the fuel item tested in the room corner test and single burning item test. Nonetheless under-ventilated fires are of greater importance, because greater yields of products of incomplete combustion are present. This was confirmed by Pitts (1995), showed that for fuel-rich flames, the typical CO yield can be as high as 0,20 g per g of fuel burned.

Purser (2000) also states that vitiated (under-ventilated) fires producing high yields of smoke and toxic products were observed in full-scale apartment and house fire tests. These products included CO in general and HCN when upholstered furniture was present. Such conditions were observed for cases when the test rooms had open and closed doors, which were 600 – 750 mm wide. It appears that such configuration is not capable of providing sufficient air/oxygen entrainment to the combustion zone.

2. Methods and materials

The experiments were aimed at combustion in an oxygen depleted environment, which is representative of under-ventilated fires. This type of fire commonly occurs inside enclosures such as rooms, carriages, and fuselages. To simulate these conditions, all experiments were conducted in a reduced-scale enclosure “Smokebox”. The gases escaping from the smokebox were collected in the Room corner test extraction hood. There are two sampling lines from the extraction duct – one feeding in to the Room corner test analyzer and the other in to the FTIR analyzer. The schematic view of the experimental setup and sample experiment is shown in Fig. 1.



Fig. 1. Schematic view of the experimental setup (left), Smokebox test with 33 % of ceiling open (center), interior thermocouple location (left).

This enclosure is a simple cube with internal dimensions of $1\text{ m} \times 1\text{ m} \times 1\text{ m}$. The walls, floor and ceiling are made from cement fiber board (Fermacell Powerpanel H₂O) which resists well repetitive thermal stress. The ceiling consists of two equally-sized parts. Air entrainment and gas exchange can be controlled by adjusting these parts of ceiling. Ventilation conditions were set as follows:

- 20 % of the ceiling opened = $0,20\text{ m}^2$ of free ventilation area (20% open in figure legends);
- 33 % of the ceiling opened = $0,33\text{ m}^2$ of free ventilation area (33% open in figure legends);
- 50 % of the ceiling opened = $0,50\text{ m}^2$ of free ventilation area (50% open in figure legends).

Four K-type sheathed thermocouples with a diameter of 3 mm were placed in all four corners 100 mm below the ceiling and 100 mm away from the walls as shown in Fig. 1. A further thermocouple was placed in the center point 100 mm above the ceiling opening to measure the temperature of fire plume. The smokebox was placed on a laboratory scale to measure the mass loss and its rate during the experiment.

Gas analysis was conducted in the room corner test and FTIR analyzers. The room corner test has three nondispersive infrared (NDIR) sensors which measure concentrations of CO₂, CO and O₂. Their lower detection limit is 0,01 % and have a resolution of 0,01 %. The concentration of the gases is also used to calculate the heat output – heat release rate – of the fire. This is done through oxygen-depletion calorimetry. The room corner test terminal also records temperatures from the thermocouples and the weight. The interval of data recording was set to 3 seconds.

The FTIR analyzer is Antaris™ IGS Gas Analyzer with a 2 meter gas cell which allows the simultaneous analysis of more than 100 gas species. The Fourier-transform infrared (FTIR) spectroscopy uses the absorption of infrared light at various lengths to identify the molecular structure and composition for the analyzed sample. The samples for the FTIR analyzer are drawn from the extraction ductwork via a heated sampling line at a rate of $6\text{ l}\cdot\text{min}^{-1}$. The temperature of the sampled gas was kept at $165\text{ }^\circ\text{C}$. The spectral resolution was set to $0,5\text{ cm}^{-1}$ and 4 scans were averaged per data point, resulting in approx. four data points per minute.

Material used in samples was a standard flexible polyurethane (PUR) foam with a density of $27\text{ kg}\cdot\text{m}^{-3}$. The polyurethane foam mattress had original dimensions of $0,9\text{ m} \times 2\text{ m} \times 0,1\text{ m}$ and a weight of 5 kg. The foam was in a cover from synthetic textiles – 100% polyester. In order to fit the sample into the smokebox it was cut into two equally sized parts which were then stacked on top of each other. A 50 mm-sided cube from mineral wool soaked in 50 ml of isopropanol was used as the ignition source. The cube was placed in the center of the sample on its surface.

Smoke extraction rate was set to as low as possible to maintain safe conditions in the laboratory and avoid over dilution of the fire effluents collected from the smokebox. The average smoke extraction rate was around $750\text{ l}\cdot\text{s}^{-1}$. To compensate for the fluctuations in the smoke extraction rate, the measured results (ppm) were further normalized to ppm per $100\text{ l}\cdot\text{s}^{-1}$ of extraction rate as shown in the graphs in section 3.

3. Results and discussion

The first measured quantity is heat release rate under various ventilation conditions. The development of heat release rate is shown in Fig. 2 (left). As expected, the rate of heat release is proportional to the size of ventilation opening. The heat release rate increases with the increasing size of the ventilation opening. Given the fixed amount of fuel the duration of burning becomes shorter. The temperatures inside smokebox (average of these four thermocouples), as shown in Fig. 2 (right) follow a similar trend, however, there is a smaller difference between the 50 % and 33 % ventilation. This may be explained by greater gas exchange between the smokebox and the exterior, which leads to greater heat loss by convection at the 50 % ventilation. This increased gas exchange leads also to a more complete combustion, which is reflected in the yields of toxic species, as shown and discussed below.

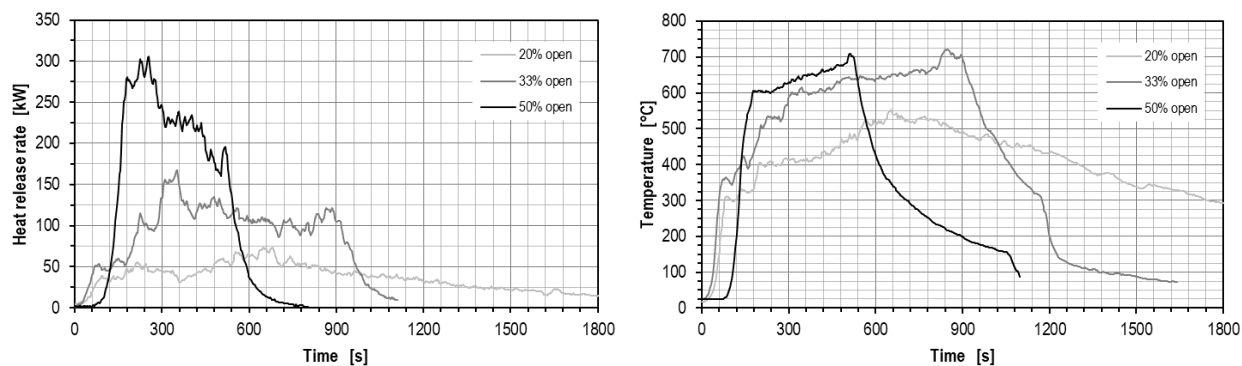


Fig. 2. Heat release rate (left) and average temperature development inside smokebox – 4 thermocouples (right) of burning mattresses at various levels of ventilation (% of ceiling open).

Apart from water vapor, which is not analyzed, the most significant (by volume) fire effluent component is CO_2 . The evolution of CO_2 production for the various level of ventilation is shown in Fig. 3. It may be seen that the concentrations of CO_2 closely follow the heat release rate of the fire. These concentrations are not affected by oxygen-lean conditions noticeably. This is because, in comparison with the amounts of CO_2 produced, only a relatively small proportion of the fuel reacts into the products of incomplete combustion, such as CO, HCN, hydrocarbons, etc.

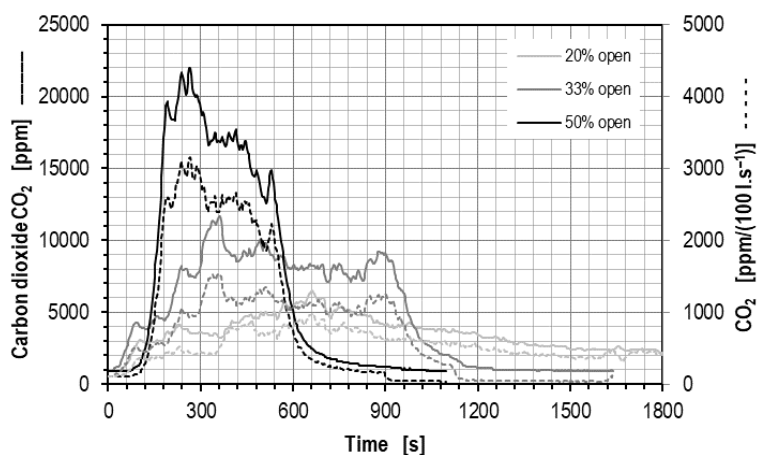


Fig. 3. CO_2 production during combustion of mattresses at various levels of ventilation (% of ceiling open).

The production of CO, show in Fig. 4, appears to be significantly affected by ventilation. Although underventilation is understood to be one of the main contributing factors to the production of CO, the highest concentrations are not observed at the lowest ventilation (20 %). Instead, they were observed at the 33 % ventilation which allows for greater gas exchange. Hence, it appears, that the optimal conditions for CO production require a balance between restricted ventilation and heat release rate. The influx of oxygen (fresh air) must be sufficient to support combustion at a high-enough rate, yet not as much to allow more complete combustion. The concentrations produced at the 33 % ventilation indicate, that significant amounts of CO can be produced for prolonged periods. The duration of the period with production of CO above 50 ppm is about 1,5-times longer for the 30 % ventilation that for ventilation at 50 %.

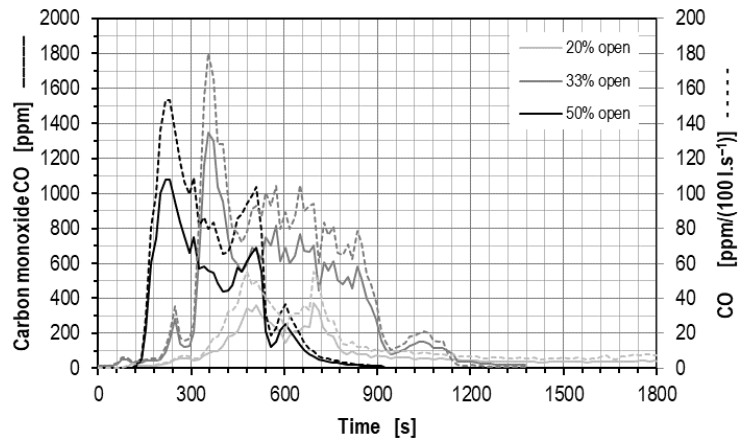


Fig. 4. CO production during combustion of mattresses at various levels of ventilation (% of ceiling open).

A different trend is observable with the results for HCN production shown in Fig. 5. Although the concentrations of HCN remain relatively low at the 20 % ventilation, at the 33 % and 50 % ventilation levels, the concentrations are comparable. It may be seen that the concentrations peak at nearly identical values and have similar development trends above 20 ppm. At the 33 % ventilation, the growth (before 300 s) and decay (after 600 s) phases are longer, which corresponds to the heat release rate. Also, the decay in HCN production precedes the overall decay in heat release rate, which is similar to the results observed at the 50 % ventilation.

In both instances (33 % and 50 % ventilation) the concentration peaks occur concurrently with the heat release rate peaks and then begin decreasing rapidly almost immediately, despite the fact that the heat release rates are decreasing at much slower rate. This could potentially be associated with the temperatures reached at these points – around 600°C. The temperature is then further increasing to the maximums of around 700 °C. This observation is similar to the trend shown in Figure 1 of Alarie, (2002), which may indicate that the increased temperatures (above 600 °C) lead to HCN decomposition. A similar behavior was observed by Levin, (1985) in bench-scale experiments, however, at a higher temperature ~650 °C. The production of HCN at different temperatures appears to be significantly dependent on the mode of combustion and stoichiometric ratio, as McKenna and Hull (2016) note.

The peak absolute concentrations are sufficient for incapacitation after 5 minutes according to Table 63.28 of Hurley et al. (2016), although with accumulation in enclosed spaces more severe effects are expected.

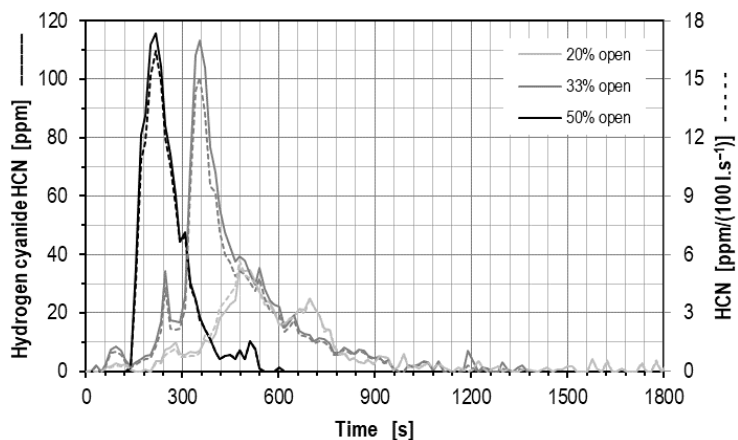


Fig. 5. HCN production during combustion of mattresses at various levels of ventilation (% of ceiling open).

The growth of NH_3 production, shown in Fig. 6, is very similar to that of CO. The decrease phase is, however, without a second peak, which is present for CO. The observed concentrations would be sufficient for slight to moderate sensory irritation (National Research Council, 2000) even without accumulation, which is expected to occur in enclosed spaces.

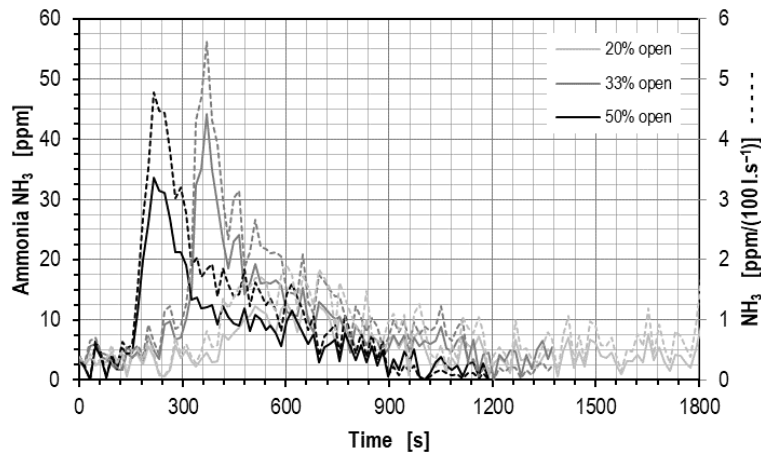


Fig. 6. NH_3 production during combustion of mattresses at various levels of ventilation (% of ceiling open).

4. Conclusion

This paper examines the production of toxic fire effluent components from 5kg PUR-foam mattresses in various under-ventilated conditions. The samples were burned in a 1 m^3 cubic enclosure – Smokebox – and ventilation was controlled by the size (area) of opening in the lid. The following levels of ventilation were examined: 20 % = $0,2 \text{ m}^2$; 33 % = $0,33 \text{ m}^2$; 50 % = $0,5 \text{ m}^2$.

The experiments indicate that the level of ventilation significantly affects both the heat release rate, as well as the concentrations of produced toxic and irritant components of smoke. The heat release rate is directly proportional to the level ventilation and increases with it.

Although the under-ventilated fire conditions were expected to lead to a higher production of toxic and irritant components of fire effluents, the dependence is not so direct. At the most under-ventilated conditions (20% ventilation) the low temperatures and likely lower rate of pyrolysis lead to reduced overall production of fire effluents. Nonetheless this is, by no means, an indication of less hazardous mode of combustion. Under-ventilated conditions indicate limited gas exchange, hence, there may be significant accumulation of the irritant and toxic species, leading to potentially severe exposures even at lower production rates of these species.

If the enclosure (e.g. room, carriage or fuselage) has sufficient volume, the initial fire growth phases may produce significant amount of heat, toxic and irritant species, until the oxygen in the air is depleted. Subsequently there would likely follow a decay phase caused by insufficient oxygen. In such conditions the enclosure would very rapidly fill with the fire effluents and cause untenable conditions. Such development could be associated with the experimental results observed at the 33 % and 50 % ventilation. In both cases, rapid production of heat, toxic and irritant fire effluents was observed at the times of 4 and 6 minutes respectively.

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References

- Alarie, Y., 2002. Toxicity of Fire Smoke. *Critical Reviews in Toxicology* 32, 259–289. <https://doi.org/10.1080/20024091064246>
- ASTM E1678:2021 Standard Test Method for Measuring Smoke Toxicity for Use in Fire Hazard Analysis
- EN 17084:2018/AC:2020 Railway applications – Fire protection on railway vehicles – Toxicity test of materials and components
- EN ISO 5659-2:2017 Plastics – Smoke generation – Part 2: Determination of optical density by a single-chamber test
- Hurley, M.J., Gottuk, D.T., Hall, J.R., Harada, K., Kuligowski, E.D., Puchovsky, M., Torero, J.L., Watts, J.M., Wieczorek, C.J. (Eds.), 2016. *SFPE Handbook of Fire Protection Engineering*, 5th ed. Springer New York, New York, NY.
- ISO 5660-1:2015 Reaction-to-fire tests – Heat release, smoke production and mass loss rate – Part 1: Heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement)
- ISO 5660-2:2002 Reaction-to-fire tests – Heat release, smoke production and mass loss rate – Part 2: Smoke production rate (dynamic measurement)
- ISO 9705-1:2016 Reaction to fire tests – Room corner test for wall and ceiling lining products – Part 1: Test method for a small room configuration
- ISO 24473:2008 Fire tests – Open calorimetry – Measurement of the rate of production of heat and combustion products for fires of up to 40 MW
- Levin, B.C., Paabo, M., Fultz, M.L., Bailey, C.S., 1985. Generation of hydrogen cyanide from flexible polyurethane foam decomposed under different combustion conditions. *Fire Mater.* 9, 125–134. <https://doi.org/10.1002/fam.810090305>
- McKenna, S.T., Hull, T.R., 2016. The fire toxicity of polyurethane foams. *Fire Sci Rev* 5, 3. <https://doi.org/10.1186/s40038-016-0012-3>
- National Research Council, 2000. *Acute exposure guideline levels for selected airborne chemicals*. National Academy Press, Washington, D.C.
- Pitts, W., 1995. The global equivalence ratio concept and the formation mechanisms of carbon monoxide in enclosure fires. *Progress in Energy and Combustion Science* 21, 197–237. [https://doi.org/10.1016/0360-1285\(95\)00004-2](https://doi.org/10.1016/0360-1285(95)00004-2)
- Purser, D.A., 2000. Toxic product yields and hazard assessment for fully enclosed design fires. *Polym. Int.* 49, 1232–1255. [https://doi.org/10.1002/1097-0126\(200010\)49:10<1232::AID-PI543>3.0.CO;2-T](https://doi.org/10.1002/1097-0126(200010)49:10<1232::AID-PI543>3.0.CO;2-T)
- Stec, A., Hull, R. (Eds.), 2010. *Fire toxicity, Woodhead Publishing in materials*. Woodhead Publishing, Oxford.
- Stec, A.A., 2017. Fire toxicity – The elephant in the room? *Fire Safety Journal* 91, 79–90. <https://doi.org/10.1016/j.firesaf.2017.05.003>