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Fire toxicity – The elephant in the room?

Anna A. Stec

Centre for Fire and Hazards Sciences, School of Physical Sciences & Computing, University of Central Lancashire, Preston, Lancashire PR1 2HE, UK

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ABSTRACT

Fire toxicity is the largest cause of death and injury from unwanted fires, yet it is the least well studied area of fire science and engineering. Fire toxicity increases by factors up to 50, as the fire becomes under-ventilated. This has proved difficult, but not impossible, to replicate in a controlled way on a bench-scale. Clear correlations have been observed between the stoichiometric equivalence ratio, and the yields of the major asphyxiants, carbon monoxide and hydrogen cyanide. In addition, irritant components of fire effluents, which have an instantaneous effect, can incapacitate fire victims, trapping them in a fire. However, the longer term toxicants present in fire effluents, such as the carcinogenic polycyclic aromatic hydrocarbons, and the microscopic particulates which result from their agglomeration are probably responsible for hundreds or thousands more deaths than the acute asphyxiants and irritants.

1. Introduction

The toxicity of fire effluents is known to be the biggest cause of death injury from unwanted fires [1]. Compared with natural materials (wood, wool, cotton, leather, etc.), widely used synthetic polymers (derived from oil) burn more quickly; they also generate more smoke and toxic effluents, particularly when compounded with halogenated flame retardants [2,3]. Although the overall number of fire deaths in the UK has decreased [4], there has been a progressive shift in cause of death from 'burns' to 'overcome by toxic gas or smoke' ("Smoke") from 1955 to 2015 (Fig. 1). The rise in the fire toxicity injuries is even more dramatic. In many parts of Europe fire deaths and injuries are still rising; for example, recent Polish fire deaths and injuries show twice the UK's number of fatalities per head of population (Fig.2) while Latvia, Estonia and Lithuania have a factor of 10 more fire deaths [5–7].

The overwhelming majority of fire deaths 80% [1] occur in people's homes, which are less regulated than public buildings or transport. Findings from a number of dwelling fire death cases over the period 2003–2011 in Mazowieckie region (Poland) showed the majority of fire deaths were in the room of origin, of whom around half were found close to burned upholstered furniture. By far the majority of victims had inhaled sufficient smoke, carbon monoxide (CO) and other gases to cause incapacitation and 80% were reported as having soot in their airways. Approximately 60% had inhaled sufficient CO, smoke and other gases to have contributed to or been the main cause of death [8].

The asphyxiants carbon monoxide (CO) and hydrogen cyanide (HCN), are known to cause the death of most fire victims in the short

term. CO and HCN yields are much higher in under-ventilated flaming, which is more difficult to replicate on a bench scale. The recent findings that firefighters have twice the rate of cancer deaths of the civilian population highlights the significance of carcinogens as longer-term fire toxicants. There is currently no requirement to quantify carcinogens from burning materials for products, and no restriction on products emitting lethal quantities of carcinogens during a fire.

Further, it is becoming increasingly clear that airborne particulates are resulting in a very large loss of human lives. In 2014, 367,000 European lives were lost from inhalation of airborne particulates [9]. These deaths are currently being blamed almost exclusively on diesel vehicles. However, a pioneering report from Sweden in 1998 [10] demonstrated that unwanted fires (as distinct from power stations, urban incinerators and engines etc., and also *excluding* wildland fires) were responsible for a disproportionately large amount of the emissions of polycyclic aromatic hydrocarbons (PAH) and atmospheric particulates; the emission of particulates and unburnt hydrocarbons from one tonne of fuel from an unwanted fire is equivalent to that from burning almost 200 t of solid fuel in a power station; they estimated that in Sweden 1000 t of particulates were emitted by fires, 4000 t by power stations and 9000 t by road transport. In their follow-up study they quantified the emissions of PAH in Sweden from unwanted fires as 7 ± 5 t [11]. Alongside these two reports of PAH/particulate emissions from actual or reproduced unwanted fires, recent evidence shows that wood burning stoves, which are much closer to unwanted fires than burning coal, oil, diesel, petrol or gas, emit far more PAH and the most dangerous PM_{2.5} particulates [12,13]. The heterogeneity of unwanted fires and their high burning rates and low combustion efficiency are

E-mail address: aastec@uclan.ac.uk.

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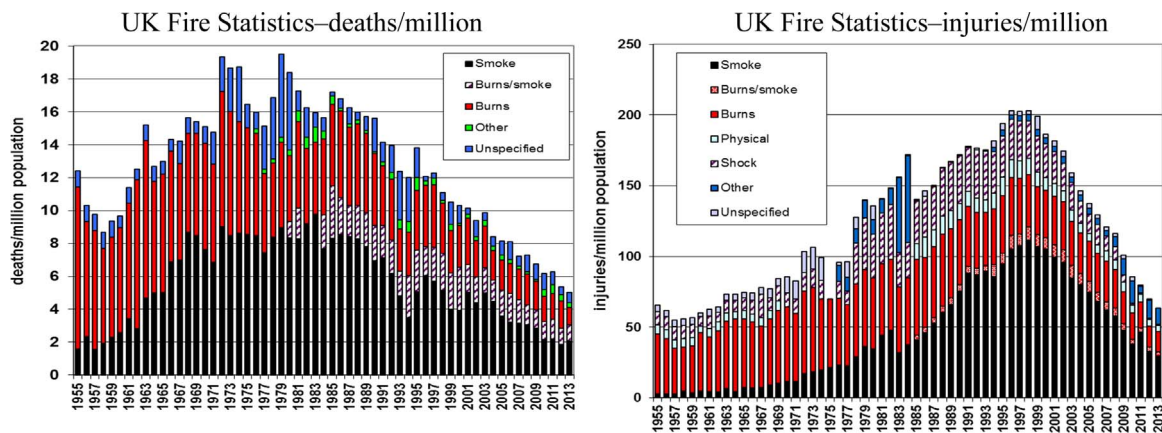


Fig. 1. Fire deaths and injuries in the UK (1955–2013).

therefore highly likely to produce particles of widely different, and potentially much greater toxicity than those from diesels or other combustion.

Recently there has been a resurgence of interest in fire toxicity. This has been driven by three factors:

- The progressive replacement of prescriptive codes by performance based design approaches to ensuring fire safety.
- The development of tools to make meaningful assessments of fire toxicity.
- The gradual recognition that the problem of fire toxicity had not been addressed by the emphasis on heat release in fire safety engineering.

2. Fire scenarios

The factors affecting fire gas toxicity [14–16], have been systematically determined in terms of the yields of toxic gases and other combustion products (smoke, particulates) [17,18] as a function of fire condition for a wide range of polymers. This requires painstaking analytical investigation to correlate the concentrations of individual toxicants in fire gases, obtained by interpretation of gas phase FTIR spectra, with those from complementary analyses (HPIC, spectrophotometry, chemiluminescence, NDIR, GC-MS, and wet chemical analysis) [19,20]. Indeed, the generation, sampling and quantification of fire effluents is in itself highly challenging work [21]. For many common materials carbon monoxide is not the only significant toxicant in fire gas (hydrogen cyanide from burning nylon [15], or hydrogen chloride from burning PVC are both produced in yields of greater toxicological significance) [22].

The steady state tube furnace has been developed from a little-used

British Standard (BS 7990) into the first international standard (ISO TS 19700) for bench-scale measurement of fire toxicity [23], specifically as a tool for fire safety engineering. Its repeatability and reproducibility, have been quantified [24,25], relating its yields to other national and international standards (the smoke chamber, ISO 5659 modified for toxicity measurements as ISO draft DIS 21489, the French railway test NF X 70–100, the US Fire Propagation Apparatus ASTM E2058, and DIN 53436) [26] and finally to comparable data from the limited data available from large scale tests [27,28]. This work showed, for the first time, that under controlled conditions, robust quantification of fire toxicity was achievable.

Material composition, temperature and oxygen concentration are normally the most important [29]. The generalised development of a fire has been recognised, and used to classify fire growth into a number of stages, from smouldering combustion and early well-ventilated flaming, through to fully-developed under-ventilated flaming [30]. Although on some occasions smouldering (oxidative pyrolysis) can generate toxicologically significant quantities of effluent (for example smouldering cotton, or polyurethane foam), the rate of reaction, and hence the amount of toxic species generated will be small, so unlikely to affect anyone outside the immediate vicinity. Similarly, well-ventilated fires are generally small, so extinguishment or escape is still feasible, while the fire effluent moves across the ceiling above head height. However, as they grow, fires become ventilation controlled, and fires in enclosures such as buildings rapidly change from well-ventilated to under-ventilated (or vitiated). These fires are larger, and therefore produce greater volumes of effluent, affecting occupants over a much wider part of any building. While well-ventilated fire scenarios are routinely used for assessment of flammability, because the object is to stop the fire growing to the out of control stage, where fire toxicity is concerned, the important fire stages are under-ventilated. There are two reasons for this:

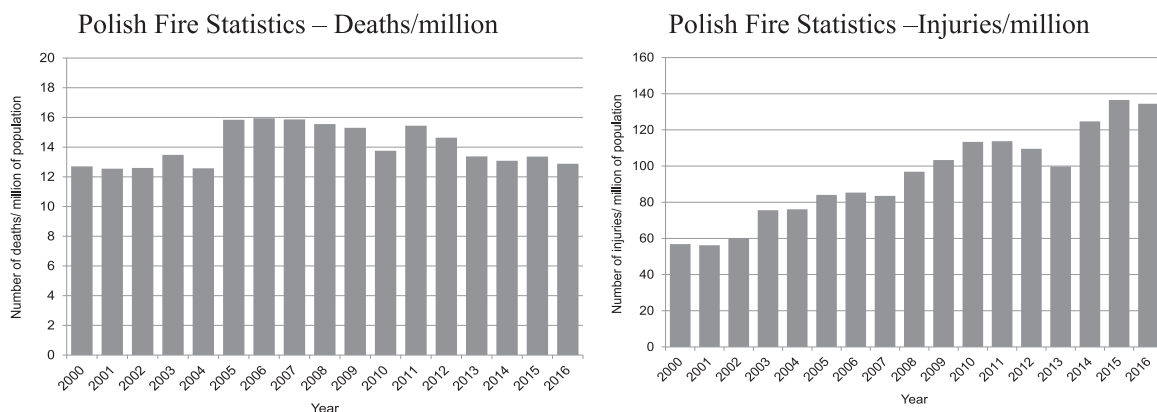


Fig. 2. Fire deaths and injuries in Poland (2000–2016) [8].

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