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STUDY OF SMOKE EFFECT ON HUMAN BEINGS USING TOXIC POTENCY DATA

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ABSTRACT

As reported in past fire records, most people died in burning fires due to toxic effects of smoke not heat. In most cases, fire deaths occurred after flashover, involving victims located in adjacent room other than the room or area where the fire originated. As toxic gases in smoke are harmful to human beings, tests were developed to determine the toxic potency data for different materials. This research project will first review the past test methods of smoke toxicity and the effects of toxic components of smoke to human beings. A series of tests will then be carried out to determine the toxic potency data of selected building materials. The tests will follow NFPA269 'Standard Test Method for Developing Toxic Potency Data for Use in Fire Hazard Modeling' and ASTM E 1678 'Standard Test Method for Measuring Smoke Toxicity for Use in Fire Hazard Analysis', with some modifications to satisfy local requirements. The results should be useful for selecting materials and will be demonstrated at the end.

1. INTRODUCTION

In a fire hazard, harm may be caused by falls, heat, suffocation or smoke inhalation. But people believed that smoke is the major cause of harm. Fire deaths in Maryland was analyzed by Berl and Halpin in 1970s [1] and it was found that 48 % of victims had lethal carboxyhaemoglobin levels and 26 % of victims had carboxyhemoglobin level of 30 to 50 % and other conditions like cyanide exposure or preexisting heart diseases which deemed sufficient in combination with the sub-lethal carboxyhemoglobin levels to cause death. Smoke inhalation accounted for roughly three-quarters of all fire deaths. The effects on human included incapacitating the victims, i.e. affecting the victims' own escape and reducing their egress speed, or the victims have chosen a longer egress path due to eye and lung irritation, visual obscuration and decreased mental acuity. These effects were brought by the toxicants inside the smoke. In the past 30 years, different test methods were developed to determine the toxic potency of smoke that different materials released during combustions. The toxic potency data were measured by parameters EC_{50}, LC_{50}, IC_{50} or sometimes LT_{50} and IT_{50} defined as follows:

- EC_{50} is the effect concentration which is used for any observed response of the animal.
- LC_{50} is used to denote the concentration of materials or fire effluent that produces death in 50 % of the animals for a specified exposure time.
- IC_{50} is the concentration necessary to incapacitate 50 % of the animals for a specified exposure time.
- LT_{50} is the mean time-to-death.
- IT_{50} is the time-to-incapacitation, where concentration is fixed [2].

2. FIRE TYPES

The amount of toxic gas released from burning materials not only depends on the chemical structure of the materials, but also on the fire type. The oxygen concentration and the relative concentrations of carbon dioxide and carbon monoxide (CO_2/CO) can be used to characterize the fire types. This is because the concentrations of carbon monoxide and carbon dioxide depend on the oxygen concentration. High oxygen concentrations would favor complete combustion to give more carbon dioxide; and limited supply of oxygen would give rise to carbon monoxide.

Table 1: General classification of fire types [2]

Fire type	Oxygen concentration (%)	CO_2/CO ratio
Smouldering (self-sustained)	21	N/A
Non-flaming decomposition (oxidative)	5-21	N/A
Non-flaming decomposition (pyrolytic)	< 5	N/A
Developing fire (flaming)	10-15	100-200
Fully developed (flaming) with low ventilation	1-5	< 10
Fully developed (flaming) with high ventilation	5-10	< 100

3. SMOKE TOXICANTS

Smoke toxicants can be divided into two types: asphyxiants or narcosis-producing toxicants; and irritants [3].

- Asphyxiants can cause central nervous system depression, loss of consciousness or ultimately death. The effects depend upon the accumulated dose. They should be tested by using toxic gas model which requires as input the concentration-time profile of each asphyxiant gas present along with an effective concentration-time value expected to cause incapacitation or 'mass lost model', which requires to input the rate of mass loss of materials or products in the fire along with the effective concentration-time value expected to cause incapacitation due to smoke produced from those materials or products [3]. Major asphyxiants include carbon monoxide (CO), hydrogen cyanide (HCN) and carbon dioxide (CO_2).

- Carbon monoxide (CO) is mainly formed from smoldering and flaming combustion, with insufficient oxygen supply. The toxicity is due to the formation of blood carboxyhemoglobin which will compete with oxygen for heme-binging sites of hemoglobin. Inadequate supply of oxygen will be resulted as the affinity of hemoglobin for carbon monoxide is 200 times greater than oxygen and the carboxyhemoglobin is much more tightly held than oxyhaemoglobin.

- Hydrogen cyanide (HCN) would cause rapidly fatal asphyxiant poison and is 25 times more toxic than CO. Cyanide ion formed by hydrolsis in the blood would be distributed throughout the body water and make direct contact with the cells of tissues and organs. The cyanide ion will then react with enzyme cytochrome oxidase to form a cytochrome oxidase-CN complex and also with methemoglobin to form cyanomethemoglobin. They will prevent the utilization of oxygen by the cells, the heart and the brain are particularly susceptible to this inhibition of cellular respiration, with bradycardia, cardiac arrhythmia, and EEG brain wave activity indicative of central nervous system depression.

- Carbon dioxide (CO_2) will stimulate the rate and depth of breathing, therefore increase the respiratory minute volume (RMV). RMV would be increased by 50 % with 2 % change in CO_2. Moreover, inhalation of toxicants will be resulted due to respiratory stimulation.

- There are two kinds of irritation, sensory irritation and pulmonary irritation caused by irritants. Sensory irritation mainly refers to the irritation of eyes and the upper respiratory tract. For eyes, the nerve endings in the cornea are stimulated, causing pain, reflex blinking, and tearing. Victims may shut their eyes, and this action may impair their escape from a fire. Airborne irritants enter the upper respiratory tract, causing burning sensations in the nose, mouth, and throat, along with the secretion of mucus. The effects of pulmonary irritation are coughing, bron-choconstriction, and increased pulmonary flow resistance. The effects of pulmonary irritation are dependent both on the concentration of the irritant and the duration of the exposure. Some common irritants include haloden acids, nitrogen oxide, organic irritants, sulfur dioxide (SO_2) and isocyanates.

- Hydrogen chloride (HCl) is the most important halogen acid which is formed from the decomposition of polyvinyl chloride (PVC). HCl is both a potent sensory irritant and also a strong pulmonary irritant. Fire-retardant based on chlorine or bromine is also a source of halogen acids, fluoropolymers being the major source of HF.

- Nitrogrn oxide (NO_X) including nitrogen dioxide (NO_2) and nitric oxide (NO) is a strong pulmonary irritant capable of causing immediate death as well as delayed injury. Acrolein is an example of organic irritants, only a few parts per million are extremely irritating to the eyes and upper respiratory tract. Sulfur dioxide (SO_2) is a strong irritant intolerable well below lethal concentrations and isocyanates are a potent respiratory irritant, believed to be the major irritants in smoke of isocyanate-based urethanes.

4. REVIEW OF TEST METHODS

The study of combustion toxicity in 1970s and early 1980s involved a number of bench-scale apparatus designed to obtain quantitative data on the toxic potency of the smoke and the chemicals that might be the source of harm. Those testing materials were focused on commercial products but the interactive effects of multiple products involved in a single fire were not addressed [1]. The study in this field by that time also focused on issues such as the probability of "super toxicants" whether or not to assess incapacitation, the validity of data obtained from tests using rodents in assessing toxicity to humans, the precision and accuracy of smoke toxicity data, the relevance of laboratory-scale tests to real fires and how much data should be used [3]. Super toxicants means the formation of a neurotoxin from the thermal decomposition of noncommercial rigid polyurethane foam and the unusual toxic potency exhibited by polytetrafluoroethylene in some laboratory tests which would appear to be largely an aircraft of the test method. The research at that time also indicated that mass loss rate or other measures of the quantity of toxic gas released per unit time, which would be a factor in the dose received by any exposed people; the flame spread rate; time to ignition or other measures of how quickly a product becomes involved in fire which would be also a factor in the quantity of toxic gas released, are the elements potentially important in the overall fire hazard.

Several standard testing methods were developed [2,3] from 1980 to 2000: the DIN Method, the US-National Bureau of Standards (NBS) test, the U-PITT methodology (US-University of Pittsburgh) (1983), ASTM E1678/NPFA 269 (1991) and ISO 13344 (1995).

- DIN Method was fully developed in the Federal Republic of Germany in 1981. This is used to assess the relative toxicities of combustion products of a material under different temperatures or to compare the relative toxicities of combustion atmospheres produced by different materials. Toxicity is expressed in terms of mortality as the ratio of the number of dead animals to the number of animals exposed. The mortality values were related to the total air flow and to either the volume of the specimen heated or to the mass or mass loss of the specimen. Dose-response relationship and LC_{50} was determined for each material by varying the volume of diluting air in order to vary the concentration of the combustion mixture to which the animals are exposed.

- The US-National Bureau of Standards (NBS) test was fully developed in 1982 and mainly used in 1980s. This is a static system using a cup-type furnace as the combustion device and the concentration-response relationships are determined using rats. The concentration of gas sample is done by controlling the sample mass. The toxic potency data obtained is in LC_{50}.

- The U-PITT methodology (US-University of Pittsburgh) was established in 1983. The testing procedure is to expose mice to fire effluents produced in a dynamic system from programmed heating of a specimen in a box or muffle fur with 30 minutes exposure and 10 minutes postexposure period. Then the concentration-response and time-to-death for lethality and the LC_{50} data in this test method only refer to the weight.

- ASTM E1678/NPFA 269 test method is originally developed by the National Institute of Standards and Technology (NIST) and Southwest Research Institute and standardized in 1991. This test involved exposing the specimen to a radiant heat flux of 50 kWm^{-2} for 15 mins. Then smoke will be collected for 30 mins within a 200 L chamber and the concentrations of CO, CO_2, O_2, HCN, HCl, and HBr are monitored over this 30-minute period. After that, the fractional effective exposure dose (FED) and the LC_{50} can be calculated. Finally, the estimated FED is then tested by using rats.

- ISO 13344 was standardized in 1995. The test specimen is subjected to the combustion conditions of a specific laboratory combustion device, chosen to have demonstrated relevance to one or more of the specific classes or stages of fires. The concentration of the major gaseous toxicants in the smoke atmosphere is monitored over 30 minutes. Then the concentration-time products were determined from the integration of the areas under the respective concentration-time plots. The concentration-time product data with either the mass charge or mass loss of the test specimen during the test are used in FED calculations to predict the 30-minute $LC_{50.}$

- In May 2000, the FPRF and NIST began a major private/public fire research entitled the "International study of the sublethal effects of fire smoke on survival and health (SEFS)". Research tasks of this project include toxicological data, smoke transport data, behavioral data, fire data, risk calculations, product characterization, social analysis, and dissemination [4].

5. PROPOSED EXPERIMENTAL METHODOLOGY

In the past two decades, the NIST has studied thoroughly the toxic potency of smoke. A concept known as the N-Gas Model was developed. This method is used as standard by the National Fire Protection Association (NFPA) and the American Society for Testing and Materials (ASTM), i.e. NFPA269 'Standard Test Method for Developing Toxic Potency Data for Use in Fire Hazard Modeling' and ASTM E 1678 'Standard Test

Method for Measuring Smoke Toxicity for Use in Fire Hazard Analysis'.

The objective of NFPA269/ ASTM E 1678 test is to determine the toxic potency of materials in a post-flashover fire. The measured quantity of toxic potency is LC_{50} (in gm^{-3}). The resulted toxicity data is useful for fire hazard analysis and materials selection.

In this project, a modified setup of N Gas-Model will be used to conduct the experiment. This is proposed because some of the experiment setups are far too expensive to purchase at this preliminary stage, also some parts might not be necessary under local condition. Therefore, modification will be carried out in this project.

The experiment will be divided into two parts, the first part will be the estimation of LC_{50} and the second part will be the checking of the estimated LC_{50}. The second part of experiment will involve studying the activities of animals upon exposure to smoke.

6. A MODIFIED TEST RIG

The main difference between the test rig of NFPA269/ ASTM E 1678 test and the test rig used in this project is the structure of the combustion cell. For NFPA269/ ASTM E 1678 test, the combustion cell is constructed of a circular quartz tube and the test specimen is ignited by four quartz lamps. The radiant heater of the test rig is outside the combustion cell. For the test rig of this project, the combustion cell is a 127 × 127 × 320 mm rectangular stainless steel box; the heater will be electrical heating wires put into the combustion cell directly.

There are three parts in the proposed test rig: an animal exposure chamber (1220 × 370 × 450 mm polymethylmethacry), a chimney (30 × 300 × 300 mm stainless steel) and a combustion cell (127 × 127 × 320 mm stainless steel) as shown in Fig. 1 and 2.

Smoke movement inside the rig during the experiment was observed as in Fig. 3.

Fig. 1: The animal exposure chamber

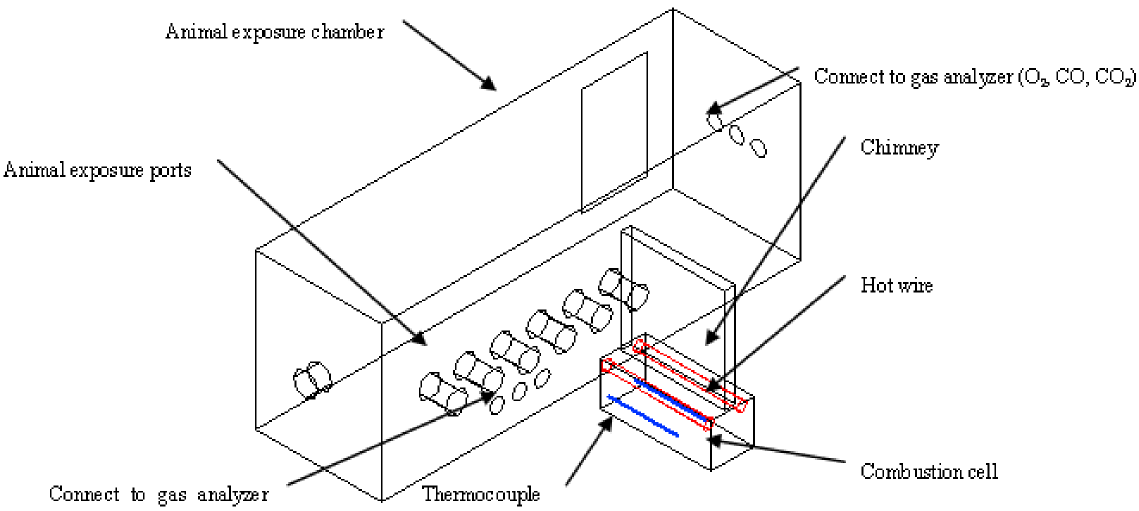

Fig. 2: Test rig

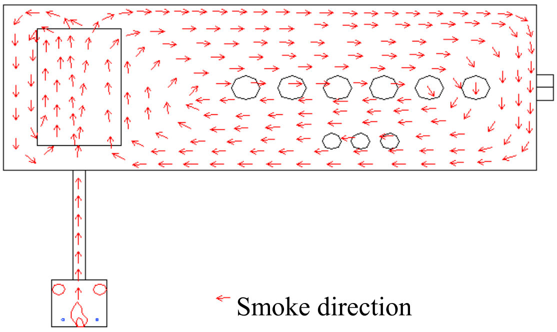

Fig. 3: Observed smoke movement inside the rig

Apparatus used for gas analysis and temperature control inside combustion cell are:

- Model IQ 1000 Portable multi-gas detector for detecting HCl (0-200 ppm), HCN (0-200 ppm) and HBr (0-200ppm).
- Series CA-6200 CA-CALC™ Combustion analyzers for detecting O_2 (0-25 %) and CO (0-5000 ppm). The accuracy of the O_2 sensor is ± 0.3 % and the accuracy of CO sensor is ±10 % (for 2000-5000 ppm).
- Thermocouple for temperature control of the combustion cell.
- Two thermocouples and temperature control device will be used for temperature control inside the combustion cell.

7. SAFETY PRECAUTION

For safety reasons, no plastic materials will be tested in this project. The test specimens will be different kinds of wood only. The experiments will be conducted mainly in non-rush hours of the campus as the exhaust of the laboratory is next to the podium of the campus.

8. ESTIMATION OF LC_{50}

The concentrations of O_2, CO_2, CO, HCl, HCN and HBr of the smoke generated from a sample are measured in a fixed volume chamber for plotting a concentration-time curve. The concentration-time product (in ppm/min) is then obtained by the integration of the area under a concentration-time curve. The fractional effective exposure dose (FED) is firstly calculated from the following formula [5-7].

$$FED = \frac{m[CO]}{[CO_2]-b} + \frac{21-[O_2]}{21-LC_{50}O_2} + \frac{[HCN]}{LC_{50}HCN} + \frac{[HCl]}{LC_{50}HCl} + \frac{[HBr]}{LC_{50}HBr}$$

$$= \frac{m[CO]}{[CO_2]-b} + \frac{21-[O_2]}{21-5.4\%} + \frac{[HCN]}{150\,ppm} + \frac{[HCl]}{3700\,ppm} + \frac{[HBr]}{3000\,ppm} \quad (1)$$

*For CO_2 concentration < 5%: m = -18, b = 122000; CO_2 concentration > 5%: m = 23, b = -38600.

LC_{50} can be estimated by:

$$LC_{50} = \frac{\text{specimen mass loss}}{\text{FED} \times \text{chamber volume}} \quad (2)$$

For post-flashover fires, correlation of LC_{50} is needed and to be calculated as follows:

$$LC_{50(corr)} = \frac{1}{[1/LC_{50(raw)}] + 44\times10^{-3} - 5.0\times10^{-5}([CO]/m)} \quad (3)$$

The values of LC_{50} estimated will then be checked by testing with animals.

9. CONCLUSION AND FUTURE PLAN

The results on LC_{50} would be useful as one of the factors for fire hazard assessment. In this way, materials can be selected properly. Note that this is the first time for Department of Building Services Engineering of The Hong Kong Polytechnic University to carry out a study of this kind. Further plan will be on comparing the physical measured data with biological determined parameters, and investigate how this can be applied to more complicated fire models with psychological effects.

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Q & A

Q1: Does the concentration of the smoke inside the box vary? Is the concentration of smoke different in each experiment? Did you try any preliminary test which shows smoke or chemical species concentration curve?

Chow: The smoke generated from the burning objects varied with its concentration. But the measurement was carried out after burning for 15 minutes in order to achieve the equilibrium concentration of the gases in the chamber. It is different in each test too. I did not do the preliminary test and did not get the concentration curve because we do not have a gas analyzer.

Q2: Which one is the most important combustion product of the materials?

Chow: In the equation, it is LC_{50}. The toxic gases are divided into two parts already; one is CO, CN and so on and the other is HBr, HCN and so on. One is irradiant and one is harmful. Six species are identified. Their concentrations would be different when different materials are burnt and different types of burning are used.

Q3: How would your result help to provide fire safety?

Chow: It is helpful to provide information for choosing building materials that are not harmful to the environment.