# Cone Calorimeter with Simulated Compartment for Air Starved Fire Toxicity and Heat Release Rate Studies

**Ismaila, A\*[1], Andrews, G. E[2], Abdullahi, I[3] and Idris M.C[3]**

[1]*Physics Department Ahmadu Bello University, P.M.B 1044, Zaria, Nigeria*
[2]*Energy Resources Research Institute, University of Leeds, Leeds, LS2 9JT, UK*
[3]*Physics Department Ahmadu Bello University School of Basic & Remedial Studies, Funtua*

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## ABSTRACT

*This experiment involves the burning of a given mass of 100% folded cotton bath sized towels at a fixed ventilation rate of 5 and 10 air change per hour in a small steel chamber of $0.03762m^3$ attached to a conical shaped heater of the Cone Calorimeter. The ignition of the cotton was investigated at $25KW/m^2$. A Temet FTIR was used for the toxic gas measurement for raw and diluted tests. Comparison of the two set of data have shown that cone calorimeter with simulated enclosure is a good method for the evaluation of toxicity from materials under air starved fires, but is unrepresentative of CO yields at very low ventialtion rate (5ACH) due to the non repeatabilty of the measured HRR beteween raw and diluted test but repeatable at 10ACH  The cotton fires was also observed to exhibited both flaming and slow smouldering combustion with the low yield of acrolein and formaldehyde in the peak heat release rate region, but very high in the smouldering combustion phase. Carbon monoxide and benzene yields were high in the peak fire heat release, but low in the smouldering phase. Analysis of the results using the standard toxicity limits (COSHH and LC50) have shown a good agreement between these toxic limits interms of time to location of the peak toxicity. COSHH 15 minutes toxicity assessment method gave acrolein as the dominant toxic gas for both intense and smouldering fires, while $LC_{50}$ put CO as the dominant gas. Acrolein, formaldehyde, CO and benzene were found to be the most dominant gases in this experiment.*

**Keywords:** Acrolein, Cone Calorimeter, Cotton Fires, FTIR, Toxicity.

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## INTRODUCTION

 "As a process, fire can take many forms all of which involve chemical reaction between combustible species and oxygen from the air. Properly harnessed, it provides great benefits as a source of power and heat to meet our industrial and domestic need, but unchecked, it can cause untold material damage and human suffering" (Drysdale, 1999). Complete control of fires and its

effects in buildings is not possible since we cannot eliminate with full certainty the fire triangle (Oxygen, heat, and fuel) from building as long as there is human occupation.

It has been observed that most fire deaths are due not to direct fire burns, but to exposure to toxic smoke products, limited oxygen in the compartment and other effects collectively called "smoke inhalation" (Purser, 2010 and Pylaktou, 2009). Statistical information for casualties in fires for private dwellings produced by the department of the environment, UK have shown that in the period from 1955-1971, there has been a fourfold increase in fire deaths in dwellings due to most likely increase in toxic emissions from synthetic material use in furnishings which replaces the natural materials e.g. wood, cotton, wool and leather (Bowes, 1974). Another study on the effect of burns versus smoke inhalation in fires was carried out in USA between the periods of 1979-1985, also confirmed that fire deaths due to smoke inhalation outnumbered those due to burns by roughly 2.5 to 1 in 1985 (Harwood et al , 1989). In the Maryland study of 463 fire deaths (1972-77) base on 50% carboxyhemoglobin (COHb) in the blood as an indicator of CO poisoning, 48% of the victims had lethal COHb levels, 26% had COHb levels 30-50% and other conditions (e.g. Exposure to cyanide) which is sufficient to cause death, 18% had lethal injuries, with COHb levels below 30% and death of 8% of this deaths are caused by other miscellaneous (Andrews, 2005). Another fire statistics carried out in Great Britain between the period 1955-2007 have shown that about 64% of the total fire deaths are caused by smoke and toxic gases, direct burns from fires and others account for 36% of the total deaths. The analyses showed that two thirds and three quarters of total fire deaths are due to smoke inhalation, with majority of these deaths due to CO poisoning. This shows that in building fires, the most common hazard to human is from smoke and toxic gases rather than the victim having severe burns or injury (Andrews et al, 2005). Considering the fact that most building-related fire deaths are directly related to the product of combustion, there has been considerable research in the recent years to determine how toxic effluents and smoke affects human escape in dwellings fires particularly in a starved air condition and this is the aim of this research. It has been observed that there are very high yields of toxic products including smoke, carbon monoxide, hydrogen cyanide and irritants in vitiated flaming fires (the temperatures not particularly high). In the UK and Europe, most fire deaths (55% in 2002 in the UK) result from small fires when the victim is in the room of fire origin.

Andrews et al. (2007) investigated the toxicity from CHO Materials (wood and cotton) for 1-40 air changes per hour, and the results show that for a cotton textile which is the main fire load of this work, there is generation of high acidic toxic gases at low ventilation than wood, but for high ventilation the wood fires were more toxic. It is believed that the toxic gases generated by the textiles at low ventilation level are the type of gases that are likely to have been released in the Rose Park Nursing home that killed 14 people. Both wood and cotton fires exhibit smouldering combustion phase at low ventilation rates and high toxic emissions throughout the fire period. Oxygenated toxic products (formaldehyde and acrolein) and CO were the highest toxic species in both fire loads. It was also observed that toxicity from CHO wood and cotton was significantly high than hydrocarbon pool fires and CO were of low proportion when compared with the other two gases (Andrews et al, 2007). In both pool and wood fires loads, the toxic gases acrolein and formaldehyde are of more importance than CO in terms of the overall toxicity.

This research is aimed to consider the effects of smoke and toxic fire products in a small scale enclosure using cone calorimeter and compare it with large scale fires under starved air condition. In the work, 100% cotton towel (fire load) was burnt in $0.03762m^3$ enclosure at 5 and 10ACH (ventilation rates) and toxic emissions were determined. The work also investigated the effect that change in ventilation rate may have on the smoke production and particulate emission yield of toxic products from cotton textiles and quantify toxic emissions against recognised

toxicity limits usually based on the $LC_{50}$ and COSHH 15 minutes assessment. The former determines toxicity in terms of 50% die after 30 minutes of exposure and the latter determines the no-harm condition, which enables escape to be achieved with no acidic or irritant gases to impede the escape.

## MATERIALS AND METHODS

### 2.1. Instruments and materials
A cone calorimeter with the simulated compartment was used to determine the toxic gas emission from a folded bath size cotton towel. The instrument was calibrated as per the instructions in the manual. The cone measurement is based on the oxygen depletion calorimetry which relies on the precisely known air flow through the system. In the process the fuel mass loss rate is converted to energy. The heat release data are readily computed by the cone and appeared in an excel spread sheet given in $KW/m^2$. The area here is that of the specimen sample. Directly measured by the cone are the heat release rate, time to ignition, effective heat of combustion, specific extinction area, exhaust flow rate, mass loss rate, final sample mass, time to sustained ignition, smoke release rate, rates of release of toxic gas release (e.g. CO2) and other parameters associated with the burning properties of the samples. Samples of 100% cotton bath size towel with the elemental compostion shown in table 1.0 and and calorific value of 16.1 were burnt on the cone calorimeter at 25Kw/m2 heat flux.

**Table 1.0: Elemental Composition by mass of the Fire Load (cotton)**

| Element | MW | % Mass | Vol. For Unit Mass-Mol | Rel. Vol. or Mol. Ratio |
|---------|-----|--------|------------------------|-------------------------|
| C | 12 | 43.5 | 0.435/12 = 0.03625 | 1 |
| O | 16 | 48.9 | 0.489/16 = 0.0305625 | 0.84 |
| H | 1 | 7.6 | 0.076/1 = 0.076 | 2.10 |

A Temet FTIR was used for the toxic gas analysis. The machine had a multi-pass cell with gold-coated mirrors with a 2m path length and volume of 0.22l. This had an 8 $cm^{-1}$ wavelength resolution and a 900 – 4250 $cm^{-1}$ scanning range. This low resolution was used as this has a much better signal to noise ratio for complex multi-component gas analysis. Liquid nitrogen cooled MCT detector was used that scans 10 spectra per second and several scans are used to produce a time-averaged spectrum. The response time of the instrument is 2s to reliably measure 51 gas species. The Temet FTIR has 2ppm resolution with an accuracy of 2% and a precision that is 0.01% of the measurement range. The FTIR has been calibrated for all the significant species that are present in the gas sample from fires. The only calibration necessary prior to the test was to zero the instrument on nitrogen. The calibration was checked for some gases, CO, $CO_2$, benzene and methane using certified span gases and the agreement was satisfactory.

### 2.2. Sample Collection and Preparation
A 100% cotton bath sized towel was purchased from Morrison supermarket at Leeds city centre. The samples of varying size and thickness summarized in table 2.0 below were arranged in a rectangular shape that fitted into a specimen holder of 0.16m (w) x 0.12m (l) x 0.09m (h). This arrangement will represent the condition of textiles storage. The specimen is ignited by a 10 KV spark generator and a flux of $25KW/m^2$ is set from conical heater.

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**Table 2.0: Varying mass and thickness of the cotton samples**

| Specimen mass (g) | Test type | Thickness (mm) | Flux (KW/m2) | Ventilation rate (air change/hr) | Set flow (L/minutes) | Air flow (g/s) |
|---|---|---|---|---|---|---|
| 61 | Enclosed Raw | 27.2mm | 25 | 10 | 6.2 | 0.12 |
| 50 | Diluted | 27 | 25 | 10 | 6.2 | 0.12 |
| 65 | Enclosed Raw | 26 | 25 | 5 | 3.08 | 0.06 |
| 39 | Diluted | 27 | 25 | 5 | 3.08 | 0.06 |

## 2.3. Procedure

A folded cotton bath sized towels of varying thickness shown in table 2.0 were burnt in a small steel chamber of $0.03762m^3$ (i.e. 0.38 m deep x 0.30 m wide x 0.33 m high) attached to a conical shaped heater of the Cone Calorimeter for a fixed ventilation rate of 5 and 10 air change per hour. The apparatus is designed to simulate heat release rate and smoke production measured in the cone calorimeter and used it to predict the results of the larger scale toxicity tests under starved air condition as against open test measurement with the cone. The box had an entrained air inlet at a floor level directly connected to the truncated shape of the cone heater.

The conical shaped heater irradiates uniform heat to a square specimen in a sample holder of 0.12m deep x 0.16m wide x 0.09 m height. The heat flux of $25KW/m^2$ ($625^O$ C) was set from the heat flux meter and the heated specimen was ignited by 10 kV spark generator fitted with a safety cut-out device. As the specimen is placed on a weigh cell, its mass is constantly measures throughout the test. Oxygen concentration is constantly measured by the paramagnetic oxygen analyzer which has a range of 0-25% and air flow are all constantly measured by the flow meter. Temperature control is achieved using 3-type K thermocouples and a 3-term (PID) temperature controller. The entrained air will be control by using compressed air system and opening the values to sufficient degree to obtain the required flow rate. Enclosed raw and diluted test exposed to same condition of air flow and heat flux were conducted for different samples. Throughout the test, the fire products are drawn away through a calibrated exhaust hood for analysis using heated Temet FTIR to measure concentration of acidic and irritant toxic gases for cotton towels. Carbon dioxide and carbon monoxide are measured by Non-Dispersive infra-Red (NDIR) gas analyzer all of them attached to a Cone Calorimeter. Smoke obscuration is measured in the flow system by means of a laser photometer system.

With the help of cone calorimeter windows Software data for each parameter is collected during the test and computer processed to provide complete test results in form of excel spread files. Two sets of data were computed, one on raw tests and other on diluted tests all exposed to same condition of heat flux and air flow rate.

## RESULTS AND DISCUSSION

### 3.1. Mass Loss and Heat Release Rate on the Cone Calorimeter

Figures 1 show the fuel mass loss as a function of time for 5 and 10 ACH raw and diluted tests. The four fire conditions observed to have similar initial fire development with the raw tests observing to have a faster burning rate. The pyrolysis weight loss was high as the combustion efficiency was high in the raw than in the diluted tests. Mass loss rate was observed to be rapid in the early flaming combustion due to available oxygen in the box but decreases slowly in the char burning cotton. The bigger masses are observed to smolder for longer period of time and this is ideal for partial oxidation of the fire load and the generation of toxic acidic gases. It was noted that the char burning stage produces high toxic acidic yields (formaldehydes, acrolein, and

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benzene) but high CO is produced in the intense burning condition few minutes after ignition. The negative value mass for 5 raw appeared in the graph comes due to none zeroing of the load cell before the start of experiment.
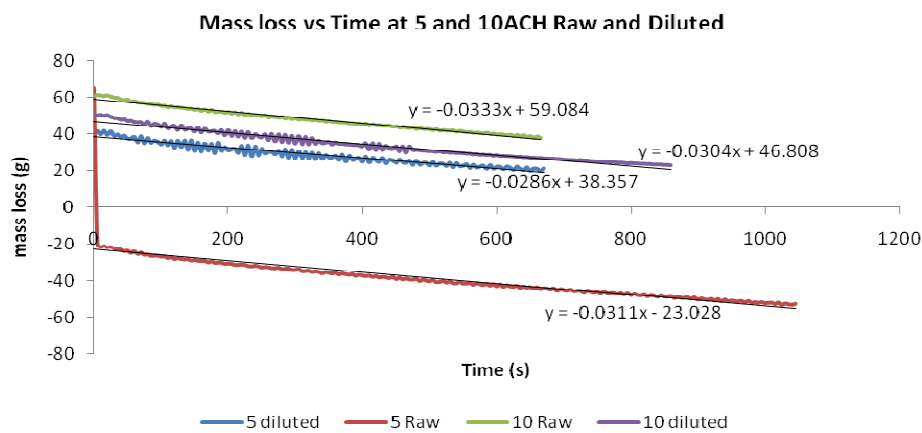


**Figure 1.0: Fuel mass loss rate**

### 3.2. Heat Release Rate

Heat Release Rate (HRR) is an important parameter required to assess the fire hazard of a particular materials and products as it easily quantifies fire size, rate of fire growth and consequently the release of associated smoke and fire toxic gases.

**(a)**                                                                                    **(b)**
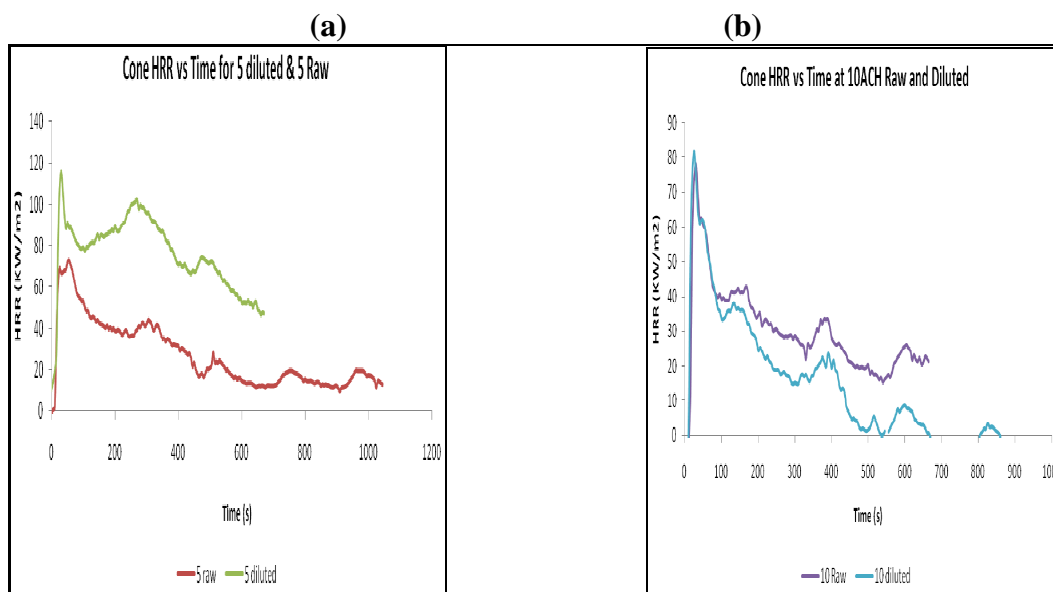


**Figure 2a: HRR by oxygen consumption calorimetry for 10ACH Raw and Diluted (Repeatable tests)**
**Figure 2b: HRR by oxygen consumption calorimetry for 5ACH Raw and Diluted (Non-repeatable tests)**

Figure 2.0 (a) and (b) shows the heat release graphs for 5 and 10ACH. The heat release rate increased rapidly at the early flaming stages of the fire for all the air changes and for both raw and diluted tests followed by a longer slower heat release rate in the smouldering phase. The peak heat release rate corresponds to the minimum oxygen figure 3.0. It was observed that heat release rate is high in the 5 diluted tests but not repeatable for the 5ACH, and is repeatable (there is good agreement between the two tests on the time to location of the maximum and minimum heat release rate) between raw and diluted tests at 10ACH. This has to do with the difference in

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the combustion efficiency as it was low in the 5ACH and high in the 10ACH. As the combustion efficiency for the 5ACH raw and diluted is not same, the two tests will not have the same CO yields.

During the phase of combustion the compartment temperature was less than 130$^o$C most of the time and there was peak heat release rate at the flaming stage of 115 KW/m2 and 81KW/m2 for 5 and 10 air change hour diluted. Heat release of 72 KW/m$^2$ and 78 KW/m$^2$ was recorded for 5 and 10 air change hour raw. In all the cases, the diluted tests observed to have high heat release rate due to enough oxygen which produces high combustion intensity, and increasing the ventilation rates decreases the corresponding heat release rate. This is strange as the heat release should increase. All measured heat released rates are observed to follow t-square fire graph which is always accelerating in the initial fire growth.

### 3.3. Fuel Oxygen Depletion

The rate of burning, the combustion efficiency and the yields of specific toxic products depends on percentage oxygen in the surrounding atmosphere and the rate at which depleted oxygen is replenished (Steck and Hull, 2010).  Figure 3.0 below shows the oxygen depletion for raw and diluted tests at 5 ACH and 10ACH respectively. It can be seen that the fire has two stages: flaming and smoldering stage. In the initial flaming there were rapid heat release rate (Figure 2a and 2b above) and minimum oxygen concentration which decreases to about 6% at 100s and 200s for 5 ACH and 10ACH raw respectively. The oxygen concentration increases at lower and longer smoldering phase for the two raw tests. The fire growth and mode of oxygen consumption can be seen to be the same for 5 and 10 raw and for 5 and 10 diluted with a slight difference since 10 raw has the lowest O2 (5%) as against 6% in 5 raw and 10 diluted has the lowest O2 value of 21.14%.
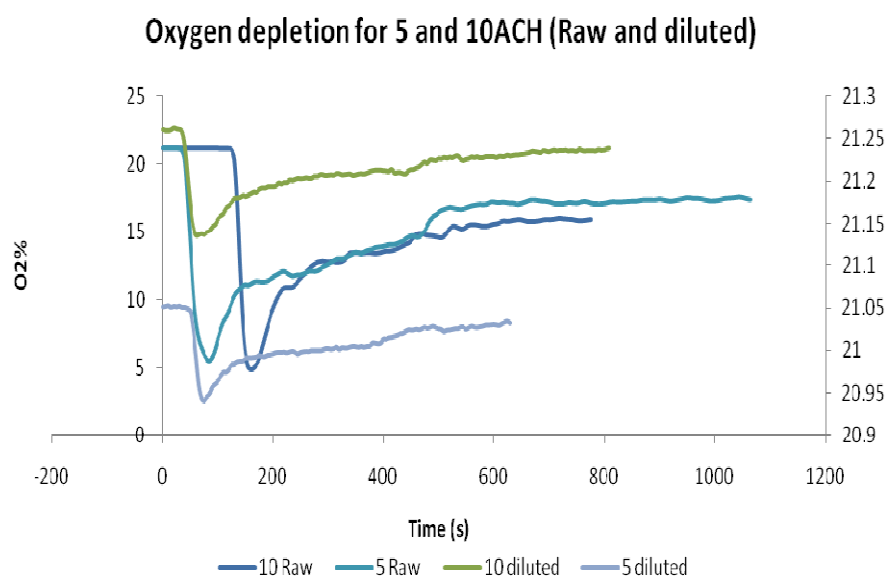


**Figure 3.0: Oxygen depletion vs. Time at 5 and 10ACH Raw and Diluted**

### 3.4. Fire peak CO, HC and CO2 concentration (FTIR)

Figure 4.0 presents the CO level for all tests. The CO concentrations were high at maximum heat release rate of fire due to very rich combustion for 10ACH but relatively low for the 5 ACH as the combustion intensity was overall lean. The peak is about 96,000 ppm at 125sec for 10ACH and is 68,000 ppm at almost same time for the 5ACH. These observed concentrations are quite high than stated CO level required by COSHH (200 ppm) or LC50 assessment (3000 ppm).

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However, in the diluted tests the CO levels are quite lower than observed in the raw data with the maximum peak of 480 ppm at 10 ACH. Also in this case the high ventilation rate (10ACH) produces high CO levels. The air dilution of the fire products in the diluted tests makes the concentration of the toxic species much lower than have been measured from the raw using the same FTIR. The peak CO levels at peak heat release rate is from equilibrium CO and is always very large in the rich mixtures and much lower, but still significant in the lean mixture.

The $CO_2$ level in figure 5.0 increases as the oxygen decreases. It was about 33% in the first 30s of fire for 5 raw and 32% for the 10 ACH raw at 115s. The concentration dropped to about 4% in the char cotton burning stage. This corresponds to the time the oxygen concentration starts to increases in the char burning cotton, figure 3.0. In all these fire conditions CO concentration were observed to be reciprocal of oxygen depletion.
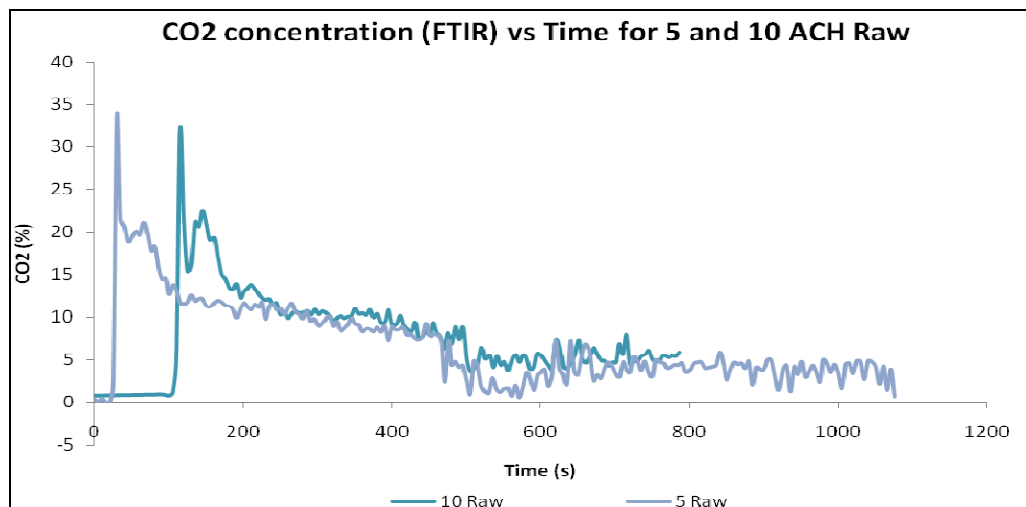


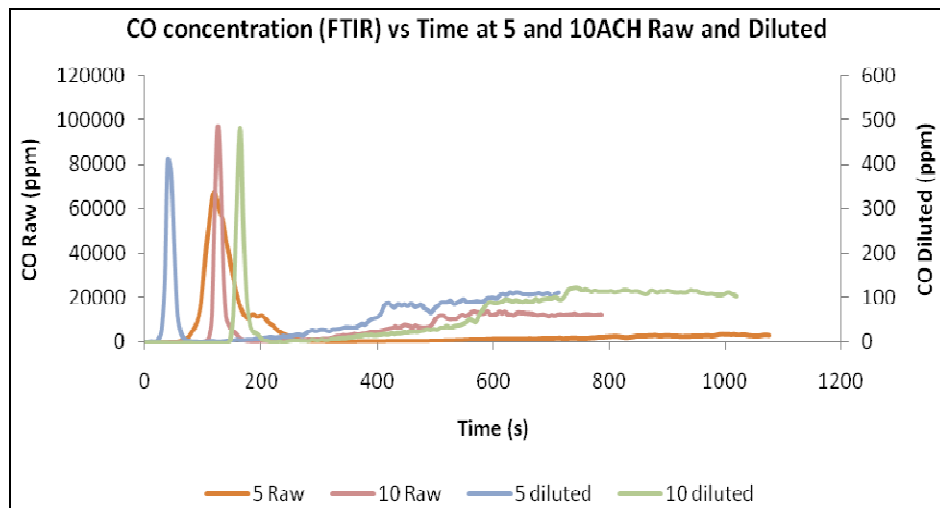**Figure 4.0: CO concentration vs. Time (FTIR)**



**Figure 5.0: CO2 concentration vs. Time (FTIR)**

### 3.5. Total Hydrocarbon (HC)
The unburnt hydrocarbons are produced in cotton fire and are measured by the FTIR machine connected to cone calorimeter. The measurement of total hydrocarbon with FTIR is done by adding the concentration of all measured hydrocarbons observed during the test (53 species). It can be seen from figure 6.0 that the unburnt hydrocarbons had their peaks in the maximum heat

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release rates region (figure 2.0) for all air changes.  For the 5 and 10 ACH raw the hydrocarbon release is mainly quickly alongside benzene and CO yields and then burnt out at a very low concentration in the later stage of fire. The peak HC emission in the flaming stage is due to the high CO emission in the equilibrium mixture which is very large in the rich mixture and also significant in the lean mixture.

The cotton fires in the maximum heat release region had CO and HC emissions that increased as the ventilation increased, due to the fire global equivalence ratio becoming richer and toxic emission of carbon monoxide and other acidic gases is high at this stage. The HC emission decreases at about 200s and increase in the char burning cotton for the raw tests. The high heat release rate and maximum temperature from the cone heater gives rise to these high concentrations of the unburnt hydrocarbons.

Hydrocarbon concentration in the diluted tests is very small when compared with that of raw data. The concentrations of the dominant gases (acrolein, formaldehyde, benzene and formic acid) are so small and carbon monoxide do oxidized throughout the tests.

Andrews et al. (2007) have shown that for the pine crib fires, CO and HC increased with the ventilation due to peak fire intensity occurring in the richer mixtures but CO and unburnt HC decreased with the increase in ventilation for cotton fires at 1.1 and 2.7ACH. In this experiment we observed that CO and unburnt HC increased with the increase in ventilation rate for the raw and diluted tests. The peak value for the 10ACH unburnt HC concentration is 32,000 ppm while for the 5ACH is 18000 ppm figure 6.0 below.
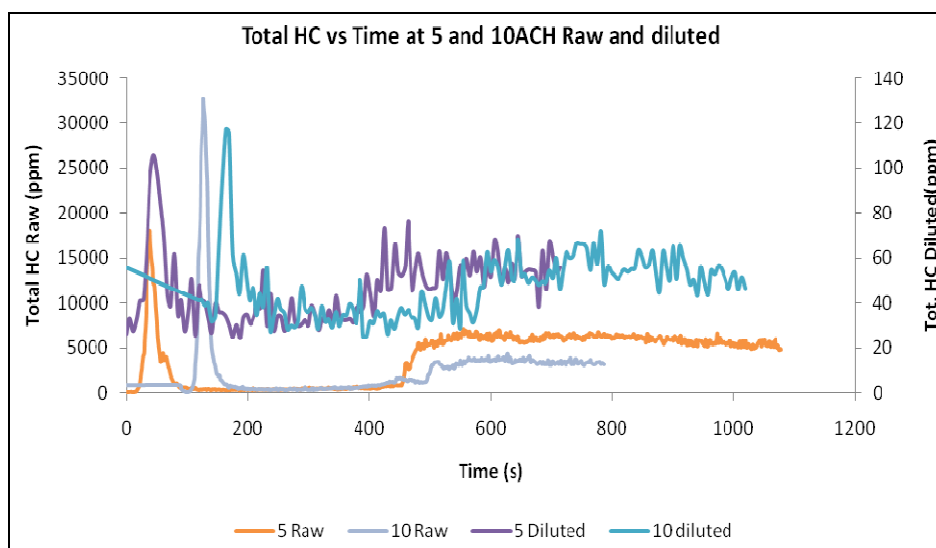


**Figure 6.0: Unburnt hydrocarbons (FTIR) vs. Time for all air change**

## 3.6. FTIR Analysis of the Main Toxic Gases (Toxic Yields)
### 3.6.1. Formaldehyde and Acrolein
Formaldehyde is one of the most prominent gases produced in the cotton combustion. For the cotton fires at 10ACH the emissions were highest in the low oxygen phase of the fire, where the CO also peaks. Acrolein and formaldehyde were low in the peak heat release region, but very high in the smoldering combustion phase for all air changes, figure 7(a) and 7(b) respectively. The yields of acrolein and formaldehyde had their peaks at almost the same time as can be seen from the figures below and correspond to the smoldering phase condition as the gases are produced in the low temperature. At each given temperature species (acrolein and formaldehyde)

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yields and rate of decomposition increases with the increase in ventilation condition (increases from 5-10ACH).

**(a)**                                                    **(b)**
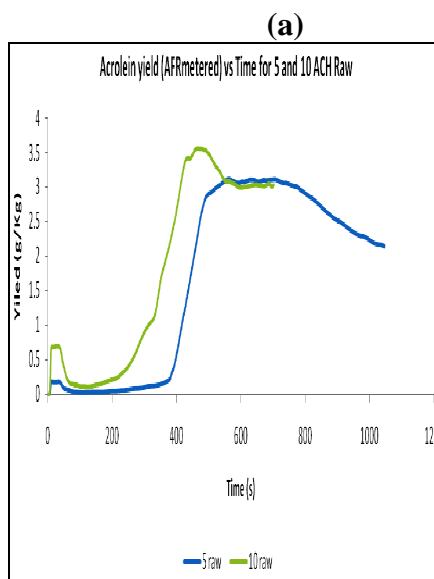


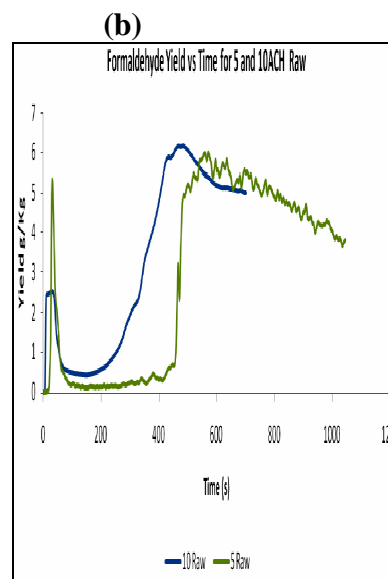**Figure 7(a): Acrolein Yield vs. Time (Raw)**      **Figure 7(b): Formaldehyde yield vs. Time (Raw tests)**

### 3.6.2. Benzene Yield

Similar trend was observed in the yield of benzene. Benzene is observed to have peak value in the early flaming stage for all air changes with the 10ACH produced the highest yield figure 8.0 below:
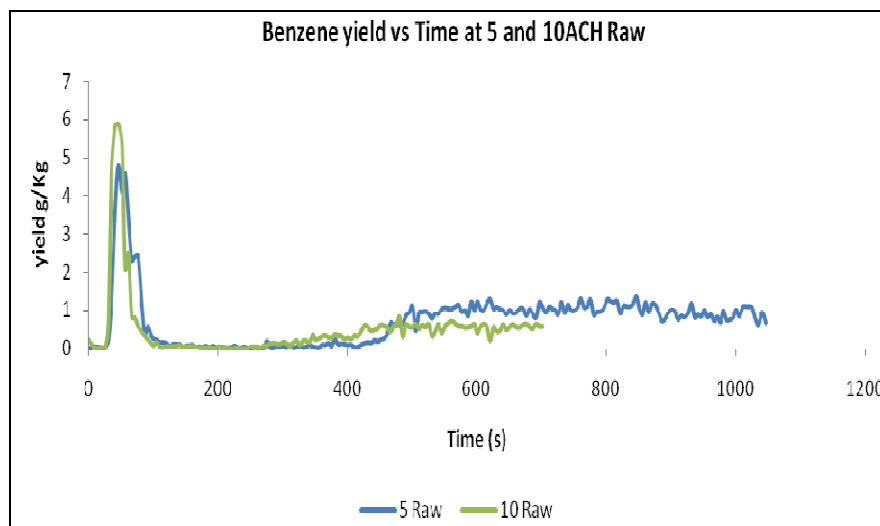


**Figure 8.0: Benzene yield vs. Time for 5 and 10ACH raw tests**

### 3.7. Relative Toxicity:

Table 3.0 shows a range of methods for expressing gas toxicity for gases that are found in fire effluents, all of which are measured using FTIR in this work. They are based on occupational exposure legislation for comparison with $LC_{50}$ data. Although the relative toxicity for CO and HCN are similar for $LC_{50}$ and occupational exposure data (COSHH15 minutes), comparison with other gases show major disagreements in the irritant and acidic gases areas of acetaldehyde, acrolein and acetic acid.

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**Table 3.0: Toxic Gas Concentration Limits ppm (OSHA, COSHH, EU)**

| Toxic Gas | | 15 Min Exposure Limit COSHH [22] | Threshold Limit Value TLV | Short Term Exposure Limit STEL | Immediately Dangerous to Life And Health IDLH | 5 Min Tenability Limit DD240 | $LC_{50}$ 30 min (23, 24) | COSHH Ratio to CO Limit | LC50 Ratio to CO Limit |
|---|---|---|---|---|---|---|---|---|---|
| Carbon Monoxide | CO | 200 | 20 | 100 | 1200 | 10,000 | 3,000 | 1 | 1 |
| Nitric Oxide | NO | 35 | 25 | | 100 | | 2,500 | | |
| Nitrogen Dioxide | $NO_2$ | 5 | 0.2 | 5 | 20 | 80 | 500 | 40 | 6 |
| Hydrogen Cyanide | HCN | 10 | | 4.7 | 50 | 100 | 135 | 20 | 22 |
| 1,3 Butadiene | $C_4H_6$ | | 2 | 1000 | 2000 | | | | |
| Benzene | $C_6H_6$ | 3 | | | | | | 67 | |
| Toluene | $C_7H_8$ | 150 | | | | | | | |
| Xylenes | $C_8H_{10}$ | 150 | | | 100 (EU) | | | | |
| Trimethylbenzenes | $C_9H_{12}$ | 25 | | | | | | | |
| Napthalenes | $C_{10}H_8$ | 15 | | | | | | | |
| Methanol | $CH_3OH$ | 250 | | | | | | | |
| Ethanol | $C_2H_5OH$ | 1000 | | | | | | | |
| Acetaldehyde | $C_2H_4O$ | 50 | | 25 | 200 | | 20,000 | | |
| Formaldehyde | $CH_2O$ | 2 | | | | | 250 | 100 | 12 |
| Acrolein | $C_3H_5O$ | 0.3 | 0.1 | 0.3, 0.05(EU) | 2 | 2 | 300 | 667 | 10 |
| Acetic Acid | $C_2H_4O_2$ | 15 | 10 | 15 | 50 | | 11,000 | | |
| Formic Acid | $CH_2O_2$ | 5 | | | | | | 40 | |
| SO2 | $SO_2$ | 5 | | | | 30 | 500 | 40 | 6 |
| HCl | HCl | 5 | | | | 200 | 3,700 | 40 | 0.8 |
| HF | HF | 3 | | | | 120 | 2,000 | | |
| HBr | HBr | 3 | | | | 200 | 3,000 | | |

Figure 9.0 below compare the relative toxicities (N) recorded for the burning of cotton textiles. The value of N was calculated by using the ratio, n, to the COSHH 15 minute limit for the mixture of gases in table 3.0 and then adding the individual toxic gas ratios together to produce an overall toxic ratio, N. It can be seen that there was high toxic emission at maximum fire intensity and increasing the ventilation rate from 5ACH to 10ACH caused the corresponding decreased for the value of N for both toxicity assessment. Andrews et al (2007) have observed similar trend for folded cotton between 1-40ACH that as the combustion intensity was lower, the toxicity was highest for the lower ventilations and toxicity decreased as ventilation increased for both methods of toxicity assessment. At higher ventilation the combustion intensity and air supply ensured more complete combustion and reduced toxic emission of acrolein, formaldehyde, benzene, xylene and other acidic gases.

For the COSHH limits the value of N reaches 2000 at peak flaming stage and peaks to about 3000 at 600s which is the smoldering phase for the 5ACH. The peak value of N for the LC50 measurement was 27 at the first 100s, dropped to 2 at 150s and N peaks to 18 at 600s. At peak fire intensity the N value reaches 2000 and 40 for the 10ACH COSHH and 10ACH LC50 respectively. In the char burning phase the N value peaks to 1800 at 600s for the COSHH and was 10 for the LC50. During the smoldering phase of fire there was also high value of N due to the fact that some of the dominant gas species (Formaldehyde and acrolein) are mostly produced in a low temperature condition or in the smoldering stage.

The differences in toxicity assessment would not matter as the toxic assessment in fires depends on which toxicity limit data is chosen. For example COSHH 15 minutes limits placed much emphasis on acrolein and LC50 place more emphasis on CO, see table 3.0 for these limits (Andrews et al, 2007 and Aljumaiyah et al, 2010. In all the case, there is good agreement between LC50 and COSHH 15 minute on the time to location of the peak toxicity.

It can be seen by comparison of the two toxic limits that toxic gases need to be diluted with the fresh air by factor of about 3000 for the 5 raw COSHH data and to be diluted by a factor 27 for the 5 raw LC50 relative toxicity. For the 10ACH the COSHH dilution factor is about 2000 and was 40 for the LC50 measurement. These dilution ratios can be incorporated into fire CFD models so as to predict toxic smoke leakage and the required dilution before they do no harm to occupants.
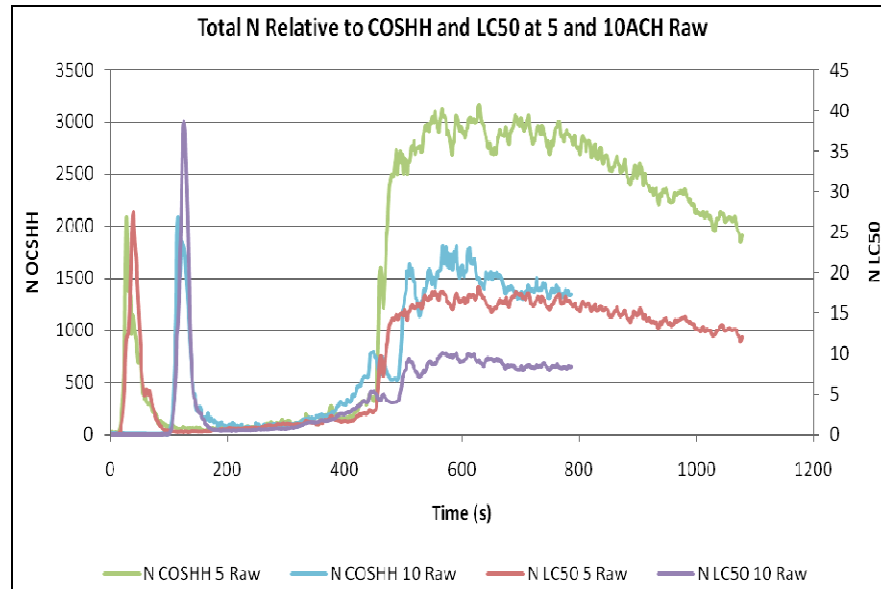


**Figure 9.0: Total N relative to COSHH and LC50 (Raw) vs. Time for all air change hour**

Cone calorimeter cannot provide sensible results for the measured concentration of acrolein, formaldehyde, benzene, and some dominant species for the diluted tests. However it is found good in measuring CO concentration in the diluted tests.
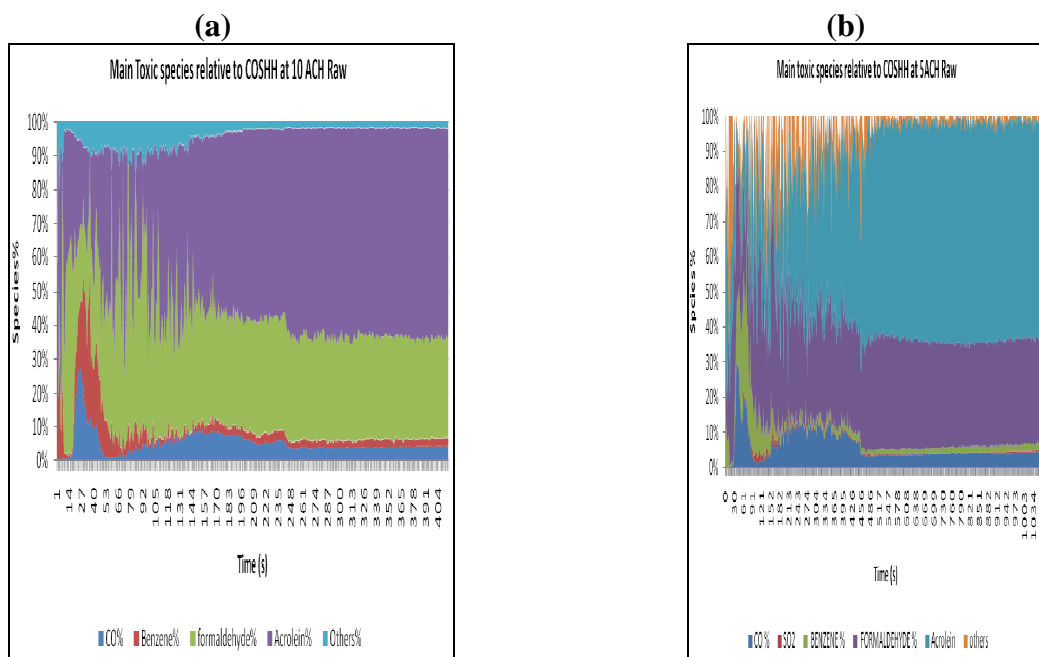
**(a)**                                  **(b)**



**Figure 10a: Proportion of dominant gases at 10ACH (COSHH 15 minutes)**
**Figure 10b: Proportion of dominant gases at 5 ACH (COSHH 15 minutes)**

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### 3.8. Total N Relative to COSHH and LC50 in Percentage

The trend of the proportion of each dominant gases contribution over the fire duration was shown in figure 10(a) and 10(b) respectively. The figures have shown that at the minimum oxygen condition that the COSHH method gave the most important toxic gas to be acrolein then formaldehyde, CO and benzene for 5 and 10ACH. However, CO and benzene were low contributors and about 85%+ of the toxicity was from acrolein and formaldehyde. In contrast, figure 11(c) and 11(d) shows that using the $LC_{50}$ method, the minimum oxygen fires were dominated by CO, then formaldehyde, acrolein and hydrogen cyanide at all ventilation rates. In both assessments formaldehyde was the second toxic gas and acrolein was the third most significant toxic gas. These high toxic emissions were believed to be prominent in the smoldering combustion phase of the fires at about six minutes (360s) after the fire start. It was also observed to be the time after which the cotton specimen in the box starts to smolder. Similar results were obtained by Cox (2005), Andrews et al. (2007) and Aljumaiyah et al. (2010).
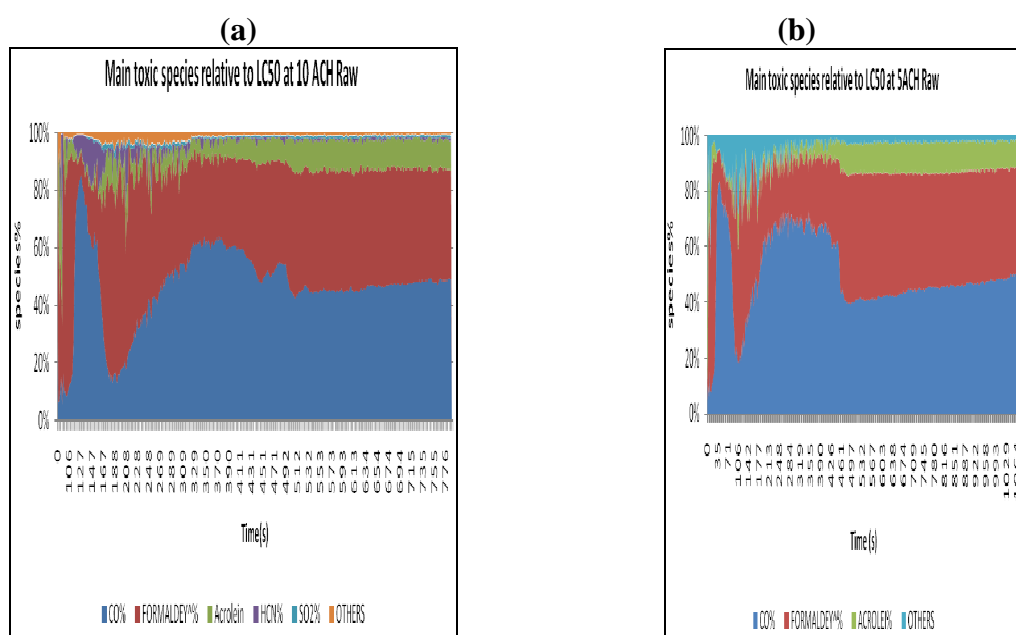


**Figure 11c: Proportion of dominant gases at 10ACH (LC50)**
**Figure 11d: Proportion of dominant gases at 5 ACH Raw (LC50 30 minutes)**

### CONCLUSION

The cone calorimeter with simulated compartment is a good method for the evaluation of toxicity from materials in starved fires, but in some situation CO yields is unrealistic as the raw and diluted are not having the same yield under same test condition. The observed fire escalation during the test is an indication that there is oxidation process taken place in the chimney and therefore accurate CO measurement is not possible. This is very similar to compartment fire, heat is vented out and toxic concentration reduces.

The cotton fire was observed to exhibit two burning phase with the peak heat release rate at the flaming stage of 115 KW/m2 and 81KW/m2 for 5 and 10 air change hour diluted. Heat release of 72 KW/m$^2$ and 78 KW/m$^2$ was recorded for 5 and 10 air change hour raw. Heat release rate were found to be non repeatable between raw and diluted tests in the 5ACH but repeatable for the 10ACH. Raw results measurement appeared to be more accurate than diluted as the air dilution of the fire products in the test encourages oxidation of products in the mixing area. The relative

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high dilution of fire gases in the hood and duct may lead to difficulties in measuring the actual toxic concentration of the fire products.

It was confirmed in this work that there is high toxic emission at very low fire ventilation rate and low temperature condition. The relative toxicity assessment for combustion of cotton is dominated by acrolein, formaldehyde, CO, HCN and Benzene with the acrolein being the most important gas according to COSHH 15min and CO was dominant according to the $LC_{50}$. For both assessment methods formaldehyde was the second most toxic gas. The toxic gases acrolein and formaldehyde are of more significant effects than CO in terms of overall toxicity.

## Acknowledgement

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