

ASSESSING FIRE BEHAVIOUR OF COMMON BUILDING MATERIALS WITH A CONE CALORIMETER

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ABSTRACT

Fire behaviour of selected samples of building materials including wood and plastic materials such as polyvinyl chloride (PVC) and poly(methyl methacrylate) (PMMA) commonly used in the market were assessed. Both thermal aspects and smoke toxicity were studied by testing the samples of wood, PVC and PMMA in a cone calorimeter. PVC was found to be very toxic as it has the smallest value of smoke potency. Not much smoke was given out in testing wood with a cone calorimeter. PMMA has a higher value of smoke potency, appeared to be not so toxic.

A flashover heat flux at floor level of 20 kWm^{-2} was applied. It was found that under such heat flux, both wood and PMMA were ignited, but PVC was very difficult to ignite. Therefore, the thermal effects of burning PVC by an accidental fire would not be so bad. However, when the heat flux was increased to 50 kWm^{-2} , smoke would give problems upon ignition of the materials.

1. INTRODUCTION

Combustible materials such as polyvinyl chloride (PVC), Poly(methyl methacrylate) (PMMA) and wood are widely used as building materials and consumer products. The fire behaviour of burning those materials should be watched. Although PVC materials are much more difficult to burn, earlier studies on smoke toxicity of those samples [1-3] indicated that burning PVC will give a very low value of toxic potency, denoted by LC_{50} . On the other hand, though PMMA is easier to burn, it has a higher value of LC_{50} and appeared to be not so toxic. Not much smoke was given out in testing wood with a cone calorimeter. This point should be considered carefully as the number of arson fires appears to be increasing. Obviously, full-scale burning tests [e.g. 4,5] are good for understanding the actual fires. However, huge resources are required for studying so many fire scenarios.

Another alternative is to study the fire behaviour of the samples by a cone calorimeter [e.g. 6,7]. Both thermal aspects and smoke emission can be assessed. The results of the heat release rate per unit area of the component materials can be used to deduce the heat release rate of the actual arrangement, say in a retail shop, using the theory available in the literature. Convolution theorem

[e.g. 8,9] can be applied in studying furniture fires from the heat release rate per unit area curves measured from a cone calorimeter with some assessed burning areas deduced from the furniture calorimeter. Smoke measurement and gas analysis would give both information for designing fire detection systems [e.g. 10] and estimating the smoke toxicity in real fires [e.g. 11,12]. With advanced instruments such as Fourier Transform Infrared Spectrometer (FTIR) [e.g. 13], toxic species in smoke can be measured and quantified upon burning the materials.

It is observed in some past fires that the burning of those combustibles under a post-flashover fire would be very different from that before flashover [e.g. 14]. There are interests in assessing the fire behaviour of those materials. Testing the samples under high heat fluxes might give a very different picture and such tests would be useful in fire hazard assessment. For example [9], the floor materials of a room might be exposed to a heat flux of 20 kWm^{-2} , the vertical wall material to 35 kWm^{-2} and the ceiling mounted material to 50 kWm^{-2} . In addition, the results from smoke measurement should also be useful in assessing toxicity [e.g. 11,12]. In fact, the fire behaviour of plastic materials for consumer products should be studied at least by a cone calorimeter as proposed earlier [15,16].

2. CONE CALORIMETER TESTS

Combustion materials of wood, PVC and PMMA widely used in the Far East [1-3] were selected for fire hazard assessment with a cone calorimeter. The transient curves of heat release rate per unit area; concentrations of oxygen O_2 , carbon monoxide CO and carbon dioxide CO_2 ; and smoke aspects were measured under an incident radiative heat flux of 20 kWm^{-2} . However, PVC was not ignited under 20 kWm^{-2} . The sample was then tested under a higher heat flux of 50 kWm^{-2} , as encountered in the ceiling.

Three sets of tests on the samples as shown in Fig. 1 were carried out.

- Test 1: PMMA sample of 113.74 g under 20 kWm^{-2}

The sample was not ignited but smoke was emitted. The sample was softened upon heating, expanded and stayed closer to the cone. Some sparks appeared upon touching the electric pilot ignitor. Heat generated was not strong enough to sustain combustion. There was a slight loss in mass of only 0.7 g over the testing time of 1000 s. The sample was hardened after cooling.

- Test 2: Wood sample of 113.48 g under 20 kWm^{-2}

The sample was ignited at 68 s. The sample was consumed almost completely, leaving some ash of mass 12.0 g behind.

- Test 3: PVC sample of 113.34 g under 50 kWm^{-2}

The sample was ignited at 35 s and then burnt out almost completely. The test was stopped at 2015 s and 11.5 g of ash was left.

The transient heat release rate per unit area $Q_{\text{cone}}(t)$ (in kWm^{-2}), oxygen concentration $[O_2]$ (in %), CO concentration $[CO]$ (in ppm of dry air), CO_2 concentration $[CO_2]$ (in % of dry air), mass lost and smoke release rate S_R (in s^{-1}) curves for the three tests are shown in Figs. 2 to 7.

3. KEY THERMAL PARAMETERS DEDUCED

Key thermal parameters can be deduced [6] from the transient curves of $Q_{\text{cone}}(t)$, $[CO]$, $[CO_2]$, S_R and others measured from the three tests for assessing the materials under a fire. Important parameters are:

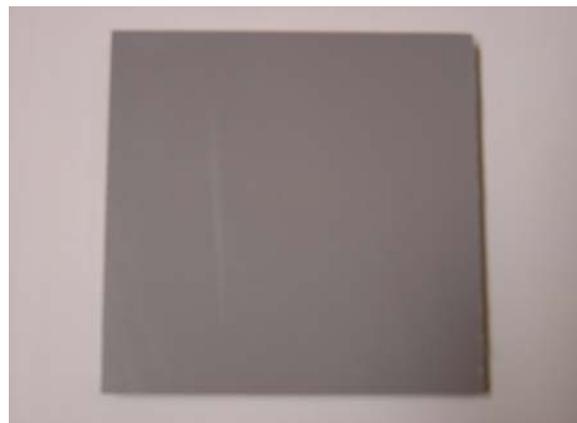
- Time to ignition, TTI (in s)
- Peak heat release rate, pk RHR (in kWm^{-2})
- Time to pk RHR after ignition, t_{fp} (in s)



(a) PMMA sample



(b) Wood sample



(c) PVC sample

Fig. 1: Testing samples

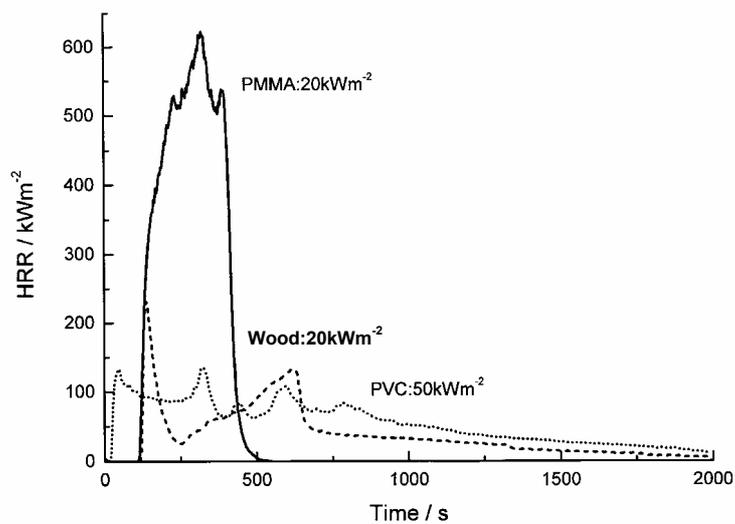


Fig. 2: Heat release rate

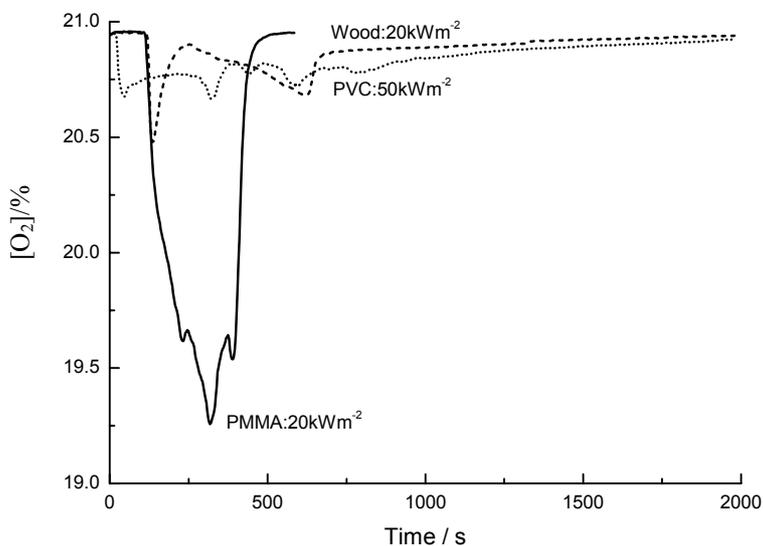


Fig. 3: Oxygen concentration

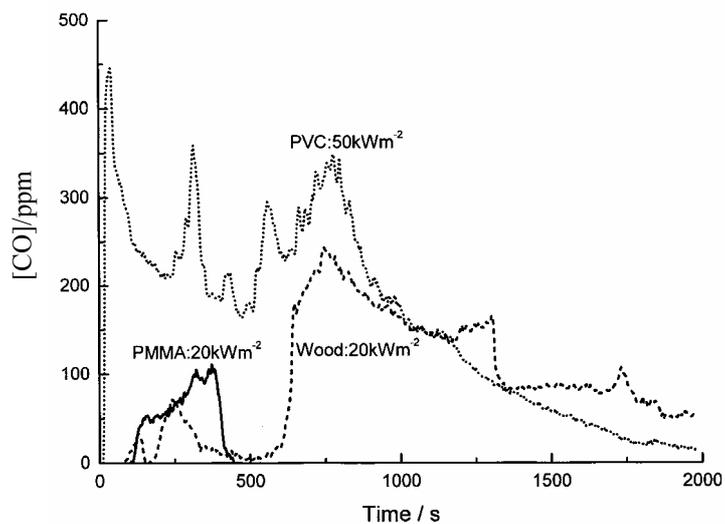


Fig. 4: Carbon monoxide concentration

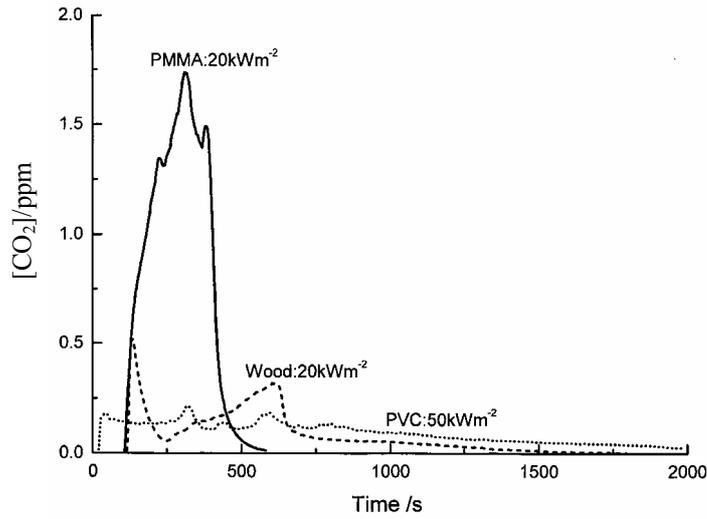


Fig. 5: Carbon dioxide concentration

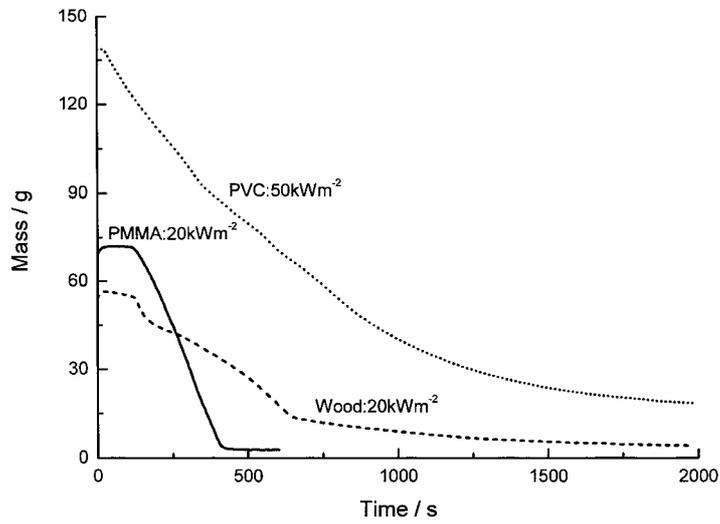


Fig. 6: Mass lost

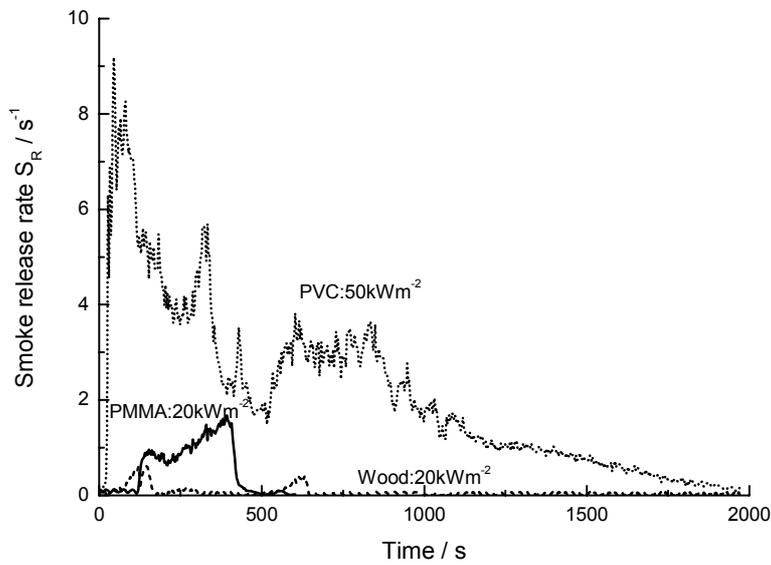


Fig. 7: Smoke release rate

- Average heat release rate in 60 s after ignition, \bar{Q}_{60} (in kWm^{-2}), given by:

$$\bar{Q}_{60} = \frac{1}{60} \int_{TTI}^{TTI+60} Q_{\text{cone}}(t) dt \quad (1)$$

- Average heat release rate in 180 s after ignition, \bar{Q}_{180} (in kWm^{-2}), given by:

$$\bar{Q}_{180} = \frac{1}{180} \int_{TTI}^{TTI+180} Q_{\text{cone}}(t) dt \quad (2)$$

- Total heat released, THR (in MJm^{-2}), calculated from:

$$\text{THR} = \int_0^{\infty} Q_{\text{cone}}(t) dt \quad (3)$$

- Mass loss percentage of sample, m_L (in %)
- Average effective heat of combustion, ΔH_c^{av} (in MJkg^{-1})

4. SMOKE PARAMETERS

Total smoke released TSR (a non-dimensional quantity) at the end of the test can be calculated by integrating the S_R (in s^{-1}) curve over the burning time t_b :

$$\text{TSR} = \int_0^{t_b} S_R dt \quad (4)$$

The concentration LC_{50} of a material or fire effluent that causes death in 50% of the animals for a specified exposure time is the toxic potency, a parameter commonly used for assessing smoke toxicity. LC_{50} means the concentration of a sample causing 50% mortality in a standard toxicity test on the specified species over a specific period of time.

In following ASTM E1678 [17], fractional effective exposure dose (FED) is defined as “the ratio of the concentration and time product for a gaseous toxicant produced in a given test to that product of the toxicant that has been statistically determined from independent experimental data to produce lethality in 50% of test animals within a specified exposure and post-exposure period”.

FED can be expressed mathematically in terms of the concentration c_i of the i^{th} toxic component by summing up all the n species as:

$$\text{FED} = \sum_{i=1}^n \int_{t_0}^t \frac{c_i}{(ct)_i} dt \quad (5)$$

Note that $(ct)_i$ is the specific exposure dose (concentration-time product) of the i^{th} toxic component required to produce the toxicological effect. When FED is equal to 1, the mixture of the gaseous toxicants would be lethal to 50% of the exposed animals. Mathematically, if the exposure time can be cancelled, FED becomes the ratio of the average concentration of a gaseous toxicant to its LC_{50} value for the same exposure time.

The peak FED can be calculated from the measured concentration of toxic gases in a cone calorimeter. Since only CO and CO_2 were measured and the toxic potency LC_{50} for CO_2 is much greater than that for CO (i.e. 5000 ppm) [18], a lower limit of FED can be estimated [11,19] from the peak concentration of CO denoted by $pk[\text{CO}]$:

$$\text{FED} = \frac{pk[\text{CO}]}{5000} \quad (6)$$

The values of TSR, $pk[\text{CO}]$ and FED for the three samples are shown in Table 1.

As discussed by Babrauskas [12], LC_{50} is commonly used in assessing the smoke toxicity of a product. Toxic effect might be calculated from two factors on burning real products:

- Real-scale mass loss rate
- Real-scale LC_{50}

It was found from a developed database that the value of LC_{50} in actual fires would not be deviated much from that determined by bench-scale tests. However, the mass loss rates in a real fire and in a bench-scale test varied significantly. Therefore, the burning rate should be reduced, rather than making the effluent less toxic. Anyway, another point of concern is how the materials will burn, as incomplete combustion of polymer will give higher levels of carbon monoxide.

LC_{50} can be used as a ‘toxic potency’ parameter to account for the combustion product toxicity. It can be viewed as ‘per-gram toxicity’ (in gm^{-3}) not affected by the burning rate of the product nor by the amount of product present. The scale is an ‘inverse’ one as this is the amount of substance dispersed to a unit square volume to cause a 50% probability of lethality. Bench-scale LC_{50} is commonly used. The recent standard ISO 13344 [20] is the first normative international standard on smoke toxicity.

Toxic gases would be dispersed into some specific total air volume V . If there is no design information on the building volume, an arbitrary value of 100 m^3 would be used for full-scale burning tests, and 0.01 m^3 for bench-scale tests.

Table 1 : Summary of testing results on PMMA, wood and PVC samples

Aspects	Parameters	PMMA	Wood	PVC
Thermal behaviour	Radiative heat flux applied / kWm ⁻²	20	20	50
	Mass / g	69.8	54.4	139.4
	Mass lost / %	100	96.3	89.4
	Ignition time / s	113	108	26
	pkHRR / kWm ⁻²	622	231	135
	t _{fp} / s	208	20	186
	THR / MJm ⁻²	146.9	74.3	109.9
	EHC / MJkg ⁻¹	21.0	14.2	8.8
	x / kW ⁻² s ⁻¹ Classification	5.5 Intermediate risk	5.1 Intermediate risk	5.2 Intermediate risk
	y / MJm ⁻² Classification	147 High risk	74 Intermediate risk	110 High risk
Smoke emission	TSR / -	337	126	422
	Peak CO / ppm	111	243	446
	FED	0.022	0.049	0.089
	LC ₅₀ / gm ⁻³	79	27	35

Effective values of LC₅₀ for the combustion products can be calculated as in ISO 13344 [20], in terms of FED (with appropriate units) in a space volume V and the mass lost Δm of the fuel as:

$$LC_{50} = \frac{\Delta m}{FED \times V} \quad (7)$$

The values of FED in a real fire and those measured in a bench-scale test such as by using a cone calorimeter are very different, say 0.1 and 6.7 respectively for a sample tested by Babrauskas [12]. But the values of LC₅₀ should be similar, say 5.8 and 6.4 respectively in the same study. Perhaps, varying the space volume V is the key point in applying the results. This point on estimating LC₅₀ from bench-scale fire tests, full-scale burning tests and real-scale fire scenarios will be studied further and reported afterward.

The values of LC₅₀ on the timber, PMMA and PVC samples tested by the cone calorimeter were calculated (with a correction factor of 4000 explained earlier [3]) and shown in Table 1.

5. DISCUSSIONS

The PVC sample was not ignited to burn when exposed under a heat flux of 20 kWm⁻², only with a

slight loss in mass. The material appears to be safe under heat fluxes up to 20 kWm⁻², explaining why it is widely used, say as electric cables. While exposed under a high radiative heat flux of 50 kWm⁻² on simulating the fire environment for ceiling mounted materials, the PVC sample was ignited at 26 s. Therefore, exposing combustibles to high heat fluxes [9,16] should be watched carefully.

Two parameters, the flashover propensity x (in kWm⁻²s⁻¹) and y on THR (in MJm⁻²) were proposed by Petrella [21] for studying the contribution of the materials to flashover and thermal contribution:

$$x = \frac{pkHRR}{TTI} \quad (8)$$

$$y = THR \quad (9)$$

Arbitrary scales suggested [21] for x are:

Low risk : 0.1 to 1.0
Intermediate risk : 1.0 to 10
High risk : 10 to 100

Similarly, arbitrary scales [21] for y are:

Very low risk : 0.1 to 1.0
Low risk : 1.0 to 10

Intermediate risk : 10 to 100
High risk : 100 to 1000

The results on x and y for the tests of the three samples are shown in Table 1. It is observed that the material is of low fire risk under 20 kWm^{-2} , confirming that PVC sample might be quite safe under small accidental fires. However, there will be much higher risk in exposing the material to higher heat fluxes. Adequate protection must be provided in storing the materials in places where flashover is likely to occur. The minimum heat release rate required for flashover [22] will be very low in small rooms (such as retail shops in public transport terminals or karaoke boxes) with a low ventilation factor. These places should be watched carefully and effective active fire protection systems such as water mist fire suppression system [e.g. 23] are recommended.

6. CONCLUSION

In this paper, the fire aspects of typical combustible materials including PMMA, wood and PVC were assessed by a cone calorimeter [6]. It is observed that exposing the materials to high heat fluxes would be very dangerous. PVC samples would be ignited within 26 s under a heat flux of 50 kWm^{-2} . A high peak heat release rate, say 622 kWm^{-2} would be reached within a short time after ignition as shown in the heat release rate curves in burning PMMA under 20 kWm^{-2} . Care must be taken in designing fire safety provisions for scenarios with post-flashover fires, rather than for accidental fires. The recent arson fire in an underground train vehicle [24] is a good demonstration that a low heat release rate would be sufficient for flashover to occur due to the 'sealed' structure. Water mist fire suppression systems [23] might be required to 'suppress' or even 'extinguish' the fire.

Parameters deduced from the cone calorimeter are useful for the Authority to supplement the current regulations [e.g. 25-30] on assessing the fire behaviour of materials. Arbitrary scales proposed by Petrella [21] on the propensity to flashover and total heat release rate would be a good starting point to supplement the fire codes [25-28] by assessing both the thermal behaviour and smoke emission in burning the materials. That was proposed earlier on assessing furniture materials [e.g. 15]. The information on smoke aspects is useful for designing fire detection systems [e.g. 10] and assessing smoke toxicity of building materials [31].

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