ASSESSING BURNING BEHAVIOUR OF COMMON BUILDING MATERIALS BY A CONE CALORIMETER

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(Received 14 January 2005; Accepted 28 February 2005)

ABSTRACT

Fire behaviour of selected building materials commonly used in the market were assessed. Four wood samples of beech, oak, pine and maple; and three plastic materials samples of polyvinyl chloride (PVC), polycarbonate (PC) and poly(methyl methacrylate) (PMMA) were selected. Both thermal aspects and smoke toxicity in burning those samples were tested in a cone calorimeter. Thermal radiative heat fluxes encountered in flashover of 20 kWm^{-2} (at floor level) and 50 kWm^{-2} (at ceiling) were applied.

It was found that under 20 kWm^{-2}, all wood species and PMMA were ignited, but PVC and PC were not ignited. Therefore, the thermal effects of burning PC and PVC by an accidental fire would not be so bad. However, when the heat flux was increased to 50 kWm^{-2}, all samples were ignited.

Combustion product liberated from 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. The smoke generated would give problems upon ignition of the materials.

1. INTRODUCTION

Combustible materials such as wood species, polyvinyl chloride (PVC), polycarbonate (PC), and poly(methyl methacrylate) (PMMA) 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 fires from accident or on purpose appears to be increasing.

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. 4]. Testing the samples under high heat fluxes would be useful in fire hazard assessment. For example [5], 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. 6,7].

As proposed earlier [8,9], the fire behaviour of plastic materials for consumer products should be assessed at least by a cone calorimeter. In this paper, burning behaviour of seven samples of materials were studied by a cone calorimeter [e.g. 10] in assessing thermal aspects and smoke emission. Four samples of wood on beech, oak, pine and maple; and three samples of plastics on PVC, PC and PMMA were selected. Samples were tested under heat fluxes of 20 kWm^{-2} and 50 kWm^{-2}.

2. CONE CALORIMETER TESTS

Seven samples on combustible materials of wood species on beach, oak, pine and maple; PVC, PC 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} and higher heat flux of 50 kWm^{-2} as encountered in the ceiling of a flashover fire.

The seven samples were cut into a 10 cm by 10 cm square as shown in Fig. 1.

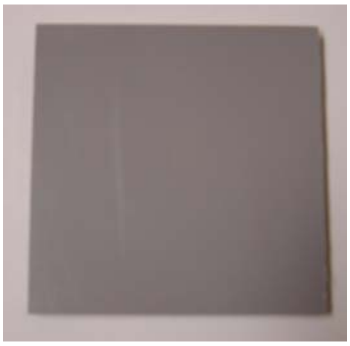
The transient heat release rate per unit area $Q_{cone}(t)$ (in kWm^{-2}), oxygen concentration $[O_2]$ (in %), CO concentration [CO] (in ppm of dry air), CO_2 concentration $[CO_2]$ (in % of dry air), mass lost and smoke release rate S_R (in s^{-1}) curves for the two tests were measured.

(a) Wood sample: beach

(b) Wood sample : oak

(c) Wood sample: pine

(d) Wood sample: maple



(e) PVC sample

(f) PC sample

(g) PMMA sample

Fig. 1: Samples tested

Key thermal parameters can be deduced [10] from the transient curves of $Q_{cone}(t)$, [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, pkHRR (in kWm^{-2})
- Time to pkHRR after ignition, t_{fp} (in s)
- Average heat release rate in 60 s after ignition, $\overline{Q}_{60}$ (in kWm^{-2}), given by:

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

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

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

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

$$THR = \int_0^t Q_{cone}(t)dt \tag{3}$$

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

Smoke parameters are:

- 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:

$$TSR = \int_0^{t_B} S_R dt \tag{4}$$

- 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.
- 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) [11], a lower limit of FED can be estimated [6,12] from the peak concentration of CO denoted by pk[CO] :

$$FED = \frac{pk[CO]}{5000} \tag{6}$$

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

Effective values of LC_{50} for the combustion products can be calculated as in ISO 13344 [13], in terms of FED (with appropriate units) in a space volume V and the mass lost Δm of the fuel as:

$$LC_{50} = \frac{\Delta m}{FED \times V} \tag{7}$$

The values of FED in a real fire and those measured in a bench-scale test such as by a cone calorimeter are very different, say 0.1 and 6.7 respectively for a sample tested by Babrauskas [7]. But the values of LC_{50} 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 LC_{50} from bench-scale fire tests, full-scale burning tests and real-scale fire scenarios will be studied further and reported afterward.

3. RESULTS

Results of $Q_{cone}(t)$, [CO] and S_R curves are shown in Figs. 2 to 4. A summary of the key parameters are listed in Table 1.

Three parameters, the flashover propensity x (in $kWm^{-2}s^{-1}$), y on THR (in MJm^{-2}) and z on smoke toxicity were proposed for studying the contribution of the materials to flashover [14], thermal contribution and smoke:

$$x = \frac{pkHRR}{TTI} \tag{8}$$

$$y = THR \tag{9}$$

$$z = LC_{50} \tag{10}$$

The results on x, y and z for the tests of the samples timber, PVC, PC and PMMA samples tested by the cone calorimeter were calculated (with a correction factor of 4000 explained earlier [3]) and are shown in Table 1.

Table 1: Summary of testing results

Parameters	50 kWm^{-2}							20 kWm^{-2}						
	Beech Wood	Oak Wood	Pine Wood	Maple Wood	PVC	PC	PMMA	Beech Wood	Oak Wood	Pine Wood	Maple Wood	PVC	PC	PMMA
Initial mass / g	83.2	79.0	62.9	96.8	140	114	31.3	84.3	79.0	61.3	95.5	141	114	31.0
Mass of residues / g	0.6	0.7	0.1	0.8	16.4	12.0	0	2.5	2.2	0.2	4.0	92.6	113	0.1
Mass loss / %	99.3	99.1	99.8	99.2	95.4	89.5	100	97.0	97.2	99.7	95.8	34.3	0.9	99.7
TTI / s	30	24	6	36	21	68	10	519	684	65	743	-	-	60
pkHRR / kWm^{-2}	351	255	194	325	152	447	908	300	232	169	314	-	-	581
t_{fp} / s	33	36	24	42	96	67	95	33	174	32	268	-	-	144
THR / MJm^{-2}	134	121	106	155	132	233	82	109	94	104	119	-	-	79
EHC / $MJkg^{-1}$	16.2	15.5	16.9	16.1	10	22.8	26.2	13.3	12.2	17.0	13.0	-	-	25.6
x / $kWm^{-2}s^{-1}$ Classification	12 HRF	11 HRF	33 HRF	9 IRF	7 IRF	7 IRF	91 HRF	0.6 LRF	0.3 LRF	3 IRF	0.4 LRF	0 LRF	0 LRF	9 IRF
y / MJm^{-2} Classification	134 HRH	121 HRH	106 HRH	155 HRH	132 HRH	233 HRH	82 IRH	109 HRH	94 IRH	104 HRH	119 HRH	0 VLRH	0 VLRH	79 IRH
TSR / -	715	59	1326	843	12580	9730	621	2612	1184	1173	2350	4815	378	677
pk[CO] / ppm	86	111	83	109	349	593	191	155	194	263	250	6	0	118
FED	39	48	32	53	136	170	6	34	44	65	53	-	-	5
LC_{50} / gm^{-3}	212	164	196	183	103	67	498	250	180	95	180	-	-	631

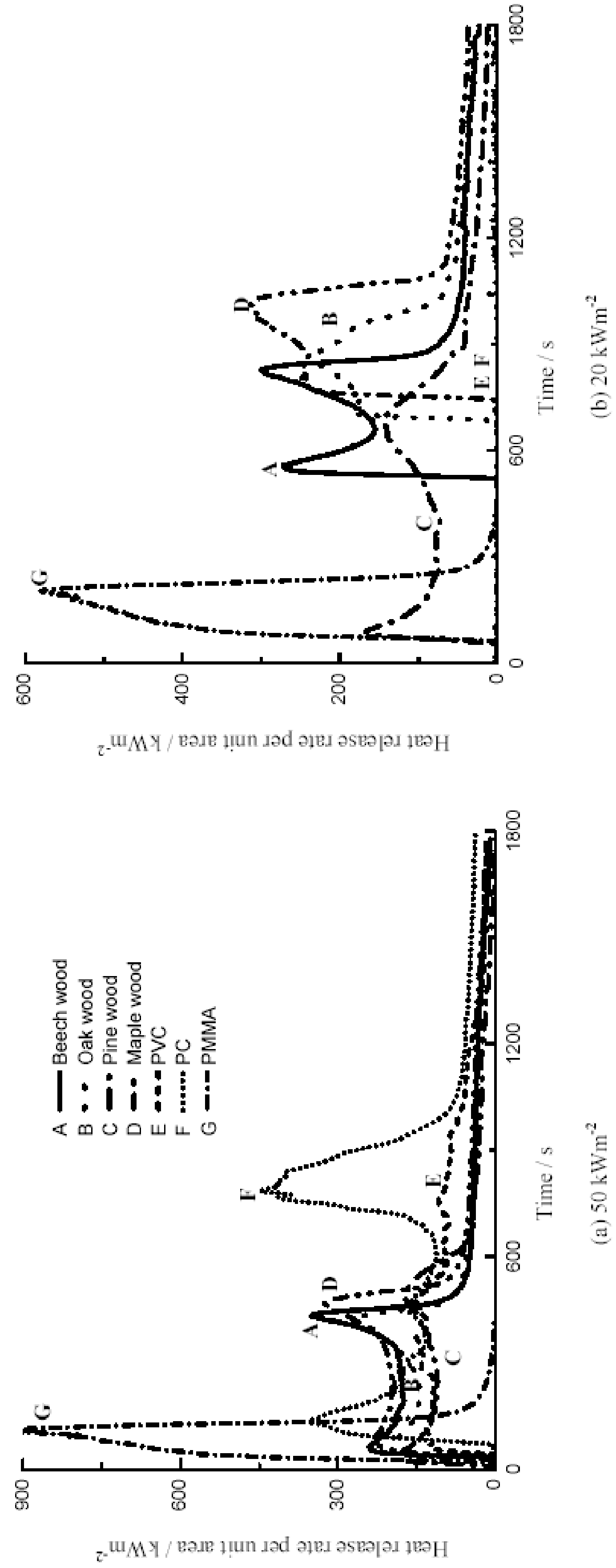


Fig. 2: Heat release rate per unit area

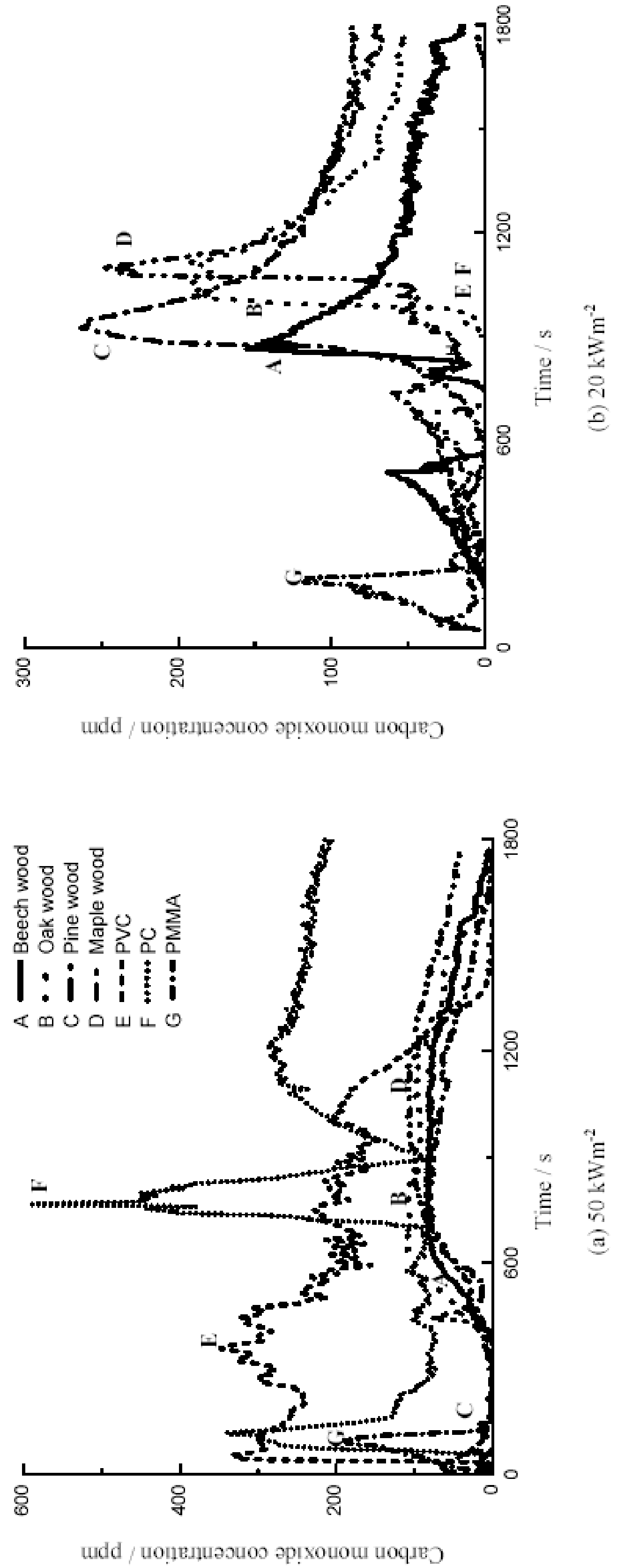


Fig. 3: Carbon monoxide concentration

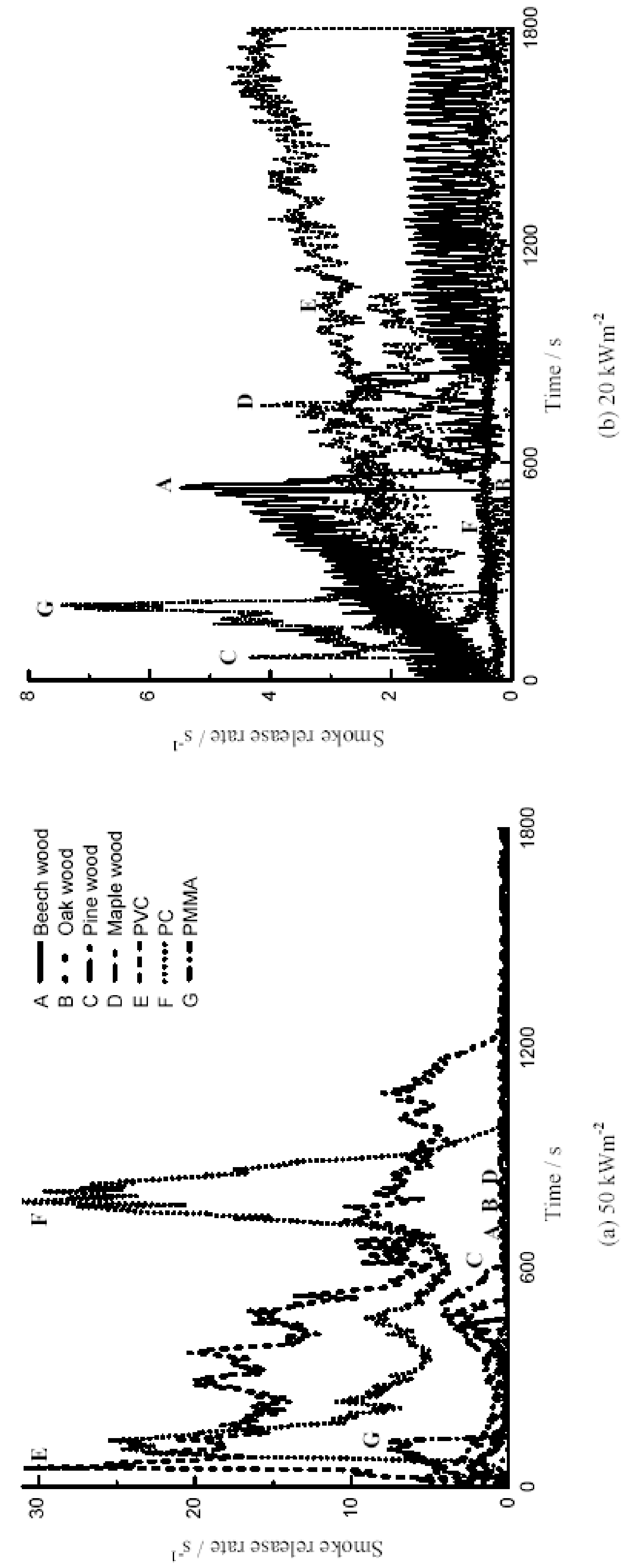


Fig. 4: Smoke release rate

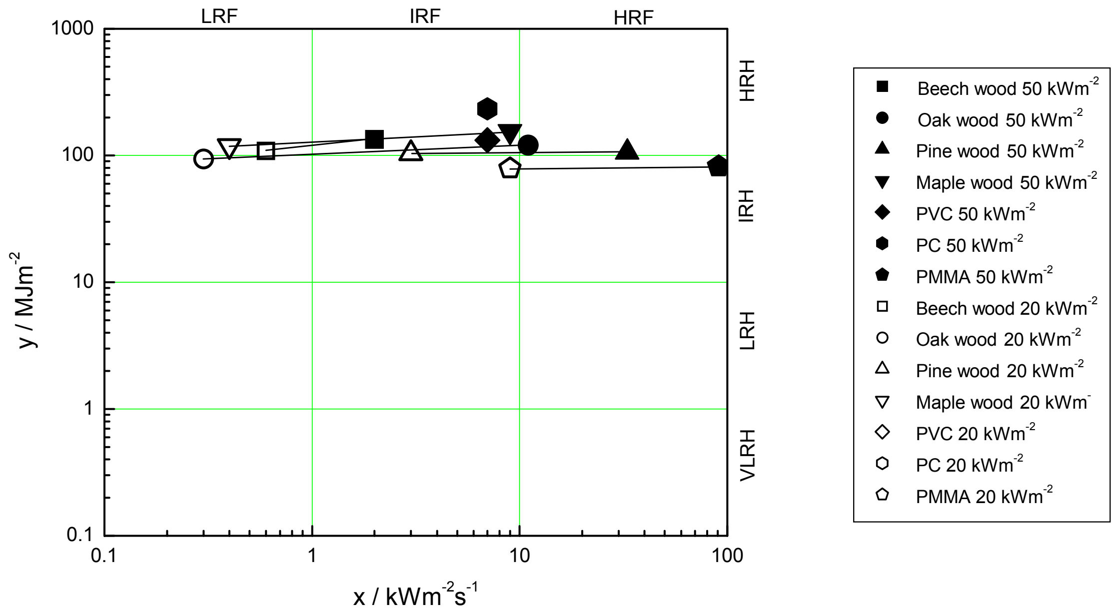
Arbitrary scales suggested [14] for x are:

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

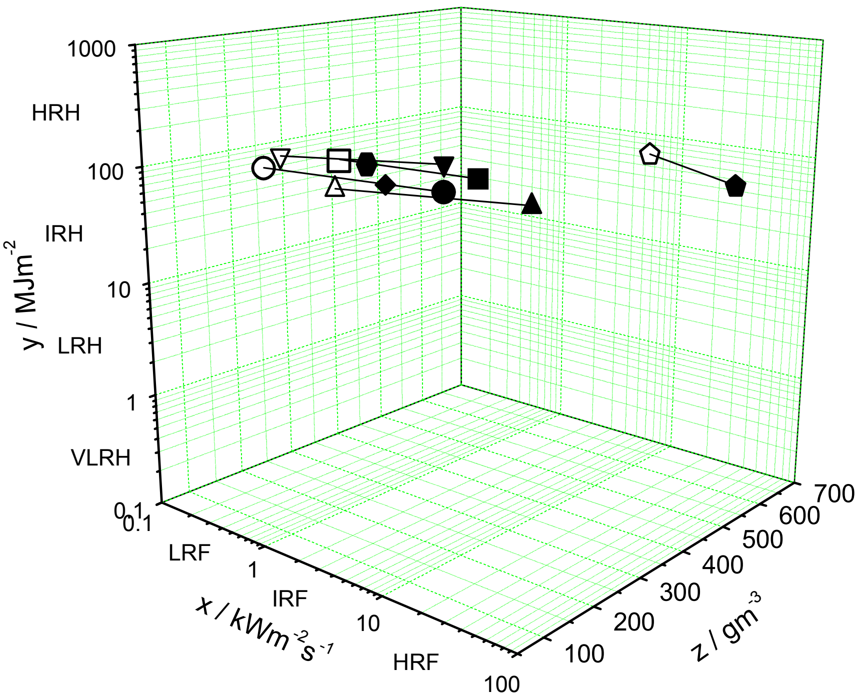
Similarly, arbitrary scales [14] for y are:

Very low risk	: 0.1 to 1.0
Low risk	: 1.0 to 10
Intermediate risk	: 10 to 100
High risk	: 100 to 1000

LC_{50} is well-known and useful in applying fire models for hazard assessment. A risk diagram on x, y and z is plotted in Fig. 5.



(a) x-y plane: thermal only



(b) x-y-z in 3-D: thermal and smoke

Fig. 5: Risk diagram

4. DISCUSSIONS

As the wood samples were not treated with fire retardant, all were ignited under both heat fluxes. Over 95% of the initial mass was lost with smoke coming out.

The PVC sample was not ignited to burn when exposed under a heat flux of 20 kWm^{-2}. The material appears to be safe in thermal aspect under heat flux up to this value, explaining why it is widely used, say as electric cables. Gasified fuel vapours liberated with 34.3% of the initial mass lost. Smoke liberated out gave a TSR of 4815, a value even higher than from PMMA. While exposed under a higher radiative heat flux of 50 kWm^{-2} on simulating the behaviour for ceiling mounted materials in a flashover fire, the PVC sample was ignited at 21 s. The pkHRR would go up to 152 kWm^{-2}. Large quantity of smoke liberated with a TSR of 12580, being the highest among all the seven samples. Exposing PVC to high heat fluxes [5,9] should be watched carefully.

PC was not ignited at 20 kWm^{-2}, with very little loss in mass of 0.9%. Very little smoke came out with a TSR of 378 only. It was ignited when exposed under 50 kWm^{-2} at 68 s, giving a pkHHR of 447 kWm^{-2}. TSR is quite high at 9730, and pk[CO] went up to 593 ppm, being the highest among all the seven samples.

PMMA appears to be dangerous as it was ignited easily within 60 s even under 20 kWm^{-2}. The whole sample was almost completely consumed with 99.7% of the initial mass lost. The pkHHR was high of 581 kWm^{-2}, giving a high value of flashover propensity x. When exposed under 50 kWm^{-2}, TTI was shortened to 10 s, with pkHHR increased to 908 kWm^{-2}. However, not much smoke was generated, giving TSR of 677 and 621 respectively for heat fluxes of 20 kWm^{-2} and 50 kWm^{-2}. Values of pk[CO] were low at 118 ppm and 191 ppm respectively.

It is observed that the selected PVC and PC samples are of low fire risk under 20 kWm^{-2}, confirming those plastic materials 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 them in places where flashover is likely to occur. Note that the minimum heat release rate required for flashover [15] 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 are recommended. Therefore, testing only the ignitability of the plastic samples is not adequate.

5. CONCLUSION

In this paper, the fire aspects of four samples of wood and typical combustible plastic materials including PMMA, PC and PVC were assessed by a cone calorimeter [10]. No doubt, unprotected wood samples can be ignited easily with smoke liberated. The samples should be treated with fire retardants.

It is observed that exposing the plastic materials to high heat fluxes would be very dangerous. PVC samples would be ignited within 21 s under a heat flux of 50 kWm^{-2}; giving a TSR of 12580. A high peak heat release rate up to 581 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}. PVC got the highest TSR under both heat fluxes, but PC got the highest pk[CO] when burnt under 50 kWm^{-2}.

Care must be taken in designing fire safety provisions for scenarios with post-flashover fires, rather than for accidental fires. The arson fire in an underground train vehicle in early 2004 [16] is a good demonstration that a low heat release rate would be sufficient for flashover to occur due to the ‘sealed’ structure. Total flooding gas protection system or water mist fire suppression systems should be considered to ‘suppress’ or even ‘extinguish’ the fire.

Parameters deduced from the cone calorimeter are useful for the Authority to supplement the current assessments [e.g. 17] on the fire behaviour of materials. Arbitrary scales proposed by Petrella [14] on the propensity to flashover and total heat release rate would be a good starting point to supplement the fire codes by assessing both the thermal behaviour and smoke emission in burning the materials. That was proposed earlier on assessing furniture materials [e.g. 8]. The information on smoke aspects is useful for designing fire detection systems and assessing smoke toxicity of building materials [18].

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. Applying the convolution theorem [e.g. 5,19] using the heat release rate per unit area curves measured from a cone calorimeter might be useful in studying furniture fires. However, burning areas deduced from the furniture calorimeter have to be assumed. Smoke measurement and gas analysis would give both information for designing fire detection systems and estimating the smoke toxicity in real fires [e.g. 6,7]. With advanced instruments such as Fourier Transform Infrared Spectrometer (FTIR), toxic species in smoke can be measured and quantified upon burning the materials.

REFERENCES

1. C.L. Chow, "Importance of smoke toxicity in fire hazard assessment", Proceedings of Advanced Fire Research and Necessity on Modelling Fire and Smoke Management as part of the National 973 Project "Fire Dynamics and Fundamentals of Fire Safety", 5 September 2003, Tsinghua University, Beijing, China, pp. 43-46 (2003).
2. C.L. Chow, N.K. Fong and W.K. Chow, "Assessment of materials by toxic potency data: A preliminary study", Proceedings of the International Symposium on Fire Science and Fire-protection Engineering (2003 ISFSFE), 12-15 October 2003, Beijing, China, pp. 270-275 (2003).
3. C.L. Chow, W.K. Chow and Z.A. Lu, "Assessment of smoke toxicity of building materials", 6th Asia-Oceania Symposium on Fire Science & Technology, 17-20 March 2004, Daegu, Korea, (2004).
4. W.K. Chow, G.W. Zou, H. Dong and Y. Gao, "Necessity of carrying out full-scale burning tests for post-flashover retail shop fires", International Journal on Engineering Performance-Based Fire Codes, Vol. 5, No. 1, pp. 20-27 (2003).
5. G.J. Duggan, "Usage of ISO 5660 data in UK railway standards and fire safety cases", A One-Day Conference on Fire Hazards, Testing, Materials and Products, Paper 3, Rapra Technology Limited, UK, pp. 1-8 (1997).
6. V. Babrauskas, R.H. Harris, Jr. E. Braun, B.C. Levin, M. Paabo and R.G. Gann, "The role of bench-scale tests data in assessing real-scale fire toxicity", NIST Technical Note 1284, Center for Fire Research, National Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, Maryland, USA (1991).
7. V. Babrauskas, "Fire safety improvements in the combustion toxicity area: is there a role for LC_{50} tests?", Fire and Materials, Vol. 24, No. 2, pp. 113-119 (2000).
8. W.K. Chow, "Assessment on heat release rate of furniture foam arrangement by a cone calorimeter", Journal of Fire Sciences, Vol. 20, No. 4, pp. 319-328 (2002).
9. W.K. Chow and S.S. Han, "Studies on fire behaviour of video compact disc (VCD) materials with a cone calorimeter", Polymer Testing, Vol. 23, No. 6, pp. 685-694 (2004).
10. ISO 5660-1, Reaction-to-fire tests - Heat release, smoke production and mass loss rate - Part 1: Heat release rate (cone calorimeter method), 2nd edition, International Organization for Standardization (2002).
11. V. Babrauskas, "Sandwich panel performance in full-scale and bench-scale fire tests", Fire and Materials, Vol. 21, No. 1, pp. 53-65 (1997).
12. R.A. Ogle and J.L. Schumacher, "Fire patterns on upholstered furniture: Smoldering versus flaming combustion", Fire Technology, Vol. 34, No. 3, pp. 247-265 (1998).
13. ISO 13344, Determination of the lethal toxic potency of fire effluents, International Organization for Standardization (1996).
14. R.V. Petrella, "The assessment of full-scale fire hazards from cone calorimeter data", Journal of Fire Sciences, Vol. 12, No. 1, pp. 14-43 (1994).
15. P.H. Thomas, "Testing products and materials for their contribution to flashover in rooms", Fire and Materials, Vol. 5, pp. 103-111 (1981).
16. South China Morning Post, "14 injured in peak-hour MTR arson attack", Editorial, pp. A1, SCMP, Hong Kong, 6 January (2004).
17. FSD circular letter 1/2000, "Flammability standards for polyurethane (PU) foam filled mattresses and upholstered furniture in licensed premises and public areas", Fire Services Department, Hong Kong (2000).
18. C.L. Chow, "Smoke toxicity of materials in a building fire", MSc Dissertation in Fire and Safety Engineering, The Hong Kong Polytechnic University (2004).
19. "Fire safety of upholstered furniture", Final Report on the CBUF Research Programme, Edited by B. Sundström, Interscience Communication Ltd, London, UK (1995).