

## TIME TO FLASHOVER OF A VINYL BASED LINING MATERIAL: CONE CALORIMETER EXPERIMENTS

by

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*Fire behaviour of a vinyl based lining material with and without anti-corrosion painting has been evaluated through 35 and 50 kW/m<sup>2</sup> cone calorimeter tests. The minimum heat flux required for surface ignition was estimated. The data were compared by those provided by a revised Kokkala-Thomas's classification index prediction model, the Östman-Tsantaridis empirical linear regression model, and the Hansen-Hovde multiple discriminant function analysis. All results collected allowed to predict the material flashover time and to classify the lining material. The results illustrate some differences in the classification of the material due to different approaches of the models used.*

*Key words: fire behaviour, lining material, cone calorimeter, flashover time prediction*

### Introduction

Vinyl products are widely encountered in home and industrial applications as cover materials, pipes and fitting, household and automotive electrical applications, as well. Therefore, the fire performance of vinyl materials is of primary importance due to their important contribution to the life maintaining environment.

Fire is a complex phenomenon and the behaviour of materials under such conditions is primary importance considering potential applications in construction, flooring or lining. There are no unified fire codes [1]. The fire behaviour of a certain material depends on its chemical composition of the subject material. A number of factors must be taken into account in assessing the contribution of any one material to a fire situation; especially it is used in room lining for cabin in aircraft, marine or train applications. In a detailed assessment of the overall fire-performance of a material many factors must be taken in account. These factors are ignitability, flammability, heat release, and spread of flame, smoke emission, toxic gas emissions, and corrosion hazard. When the lining material is used in restricted room space, its fire behavior leading to flashover should be considered as a key reference for fire protection design.

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Large scale test fires in ISO room allow classifying lining materials according to its flashover time but it is costly to perform. Because of that bench scale cone tests a frequently used to evaluate the fire behaviors of materials with small samples [1-4]. Commonly, the cone tests provide data allowing to find a complex models [5-7] and to classify the materials to ISO room classification [8, 9]. In this context, the cone calorimeter data at  $50 \text{ kW/m}^2$  irradiance can be used to predict the time to flashover under ISO test fires either under the room [10] or the room corner [11] test conditions.

Hansen *et al.* [12] have applied a multiple discriminant analysis (MDA) to cone test data to predict the flashover (FO-category) under room corner test conditions. This analysis allowed to evaluate some deficiencies of the Östman-Tsantaridis' model [11] which over-predicts the time to flashover when it exceeds 10 minutes. Both models were verified by Xu *et al.* [13] with glass-reinforced polyester (GRP) fire behaviour by cone and ISO room tests. Some other empirical methods such as those of Babrauskas [14], McCaffrey *et al.* [15], and the method of Thomas [16] have been developed to define the minimum heat release required for a flashover. All of them address compartment fires, ventilation factor, effective heat transfer coefficient, fire spread rate, and the heat release of the lining materials tested.

The present work employs the above mentioned models in evaluation and classification of the fire behaviour of lining materials using cone calorimeter data.

### Experimental: Test procedure

The tests were performed with the cone calorimeter in Henan Province Key Laboratory of Coal Mine Methane and Fire Prevention, Henan Polytechnic University, China. This calorimeter is based on "the oxygen consumption method", and meets all existing standards including ISO5660 and ASTM E1354.

Twelve samples of vinyl lining materials of average density  $1152 \text{ kg/m}^3$  ( $100 \times 100 \text{ mm}$  and  $2 \text{ mm}$  thickness) provided commercially by Nanjing Huagong Plastic Company, China, were tested in a horizontal orientation under two levels of the heat flux,  $35 \text{ kW/m}^2$  and  $50 \text{ kW/m}^2$  (tab. 1). Six of them, first samples, labelled with a prefix F (*i. e.* F-1-35, *etc.*) were native samples while second samples with a prefix S (tab. 2) were covered by an anti-corrosion painting. All samples were bonded to steel plates of the same size by epoxy resin. Then, each sample was positioned on a sample plate with edge and bottom was covered by an aluminum foil to avoid the edge effect. The effective test surface area of each sample was about  $0.008836 \text{ m}^2$ . The nominal exhaust system flow rate for all tests was about  $0.24 \text{ m}^3/\text{s}$ . Before testing all materials were conditioned under room temperature ( $23 \pm 2 \text{ }^\circ\text{C}$ ) and a relative humidity of  $50 \pm 5\%$  for 1 week.

**Table 1. The first samples' parameters and results of cone calorimeter tests**

Sample	F-1-35	F-2-35	F-3-35	F-4-50	F-5-50	F-6-50
Irradiance, [ $\text{kWm}^{-2}$ ]	35	35	35	50	50	50
Ignition time, [s]	29	31	31	19	17	19
Maximum <i>HRR</i> , [ $\text{kWm}^{-2}$ ]	153.6	165.3	164.1	165.3	160.5	161.9
Time of maximum <i>HRR</i> , [s]	39	39	41	29	26	25
Average effective heat combustion ( <i>EHC</i> ), [ $\text{MJkg}^{-1}$ ]	3.4	3.7	3.3	8.9	8.5	9.5
<i>THR</i> <sub>300</sub> [ $\text{MJ}\cdot\text{m}^{-2}$ ]	29.6	33.9	32.2	35.2	36.5	38.7
$\ln(\text{FIGRAcc})$	–	–	–	1.74	1.82	1.87
$t_{fo}$ [s]	–	–	–	288.4	271.9	261.9

## Results

### Heat release rates

Heat release rate (*HRR*) curves for some covered and uncovered samples under two irradiance heat fluxes are shown in fig. 1. The samples with anti-corrosion painting (S-1-35, S-21-35, S-3-35) tested under 35 kW/m<sup>2</sup> exhibit multiple peaks in the *HRR* curves. Under the same irradiance conditions (35 kW/m<sup>2</sup>) the uncovered samples (see the F-1-35 curve in fig. 1) decreases monotonically after a sharp peak at about 50-60 seconds after the irradiation onset. In contrast, the *HRR* curve of the covered samples S-1-35 exhibits two peaks: a rapid decay, after first peak, lasting about 20 seconds, then followed by a growth to a second peak. This behaviour was attributed to the charring of the anti-corrosion painting, which, in fact, delayed the surface pyrolysis of the lining material.

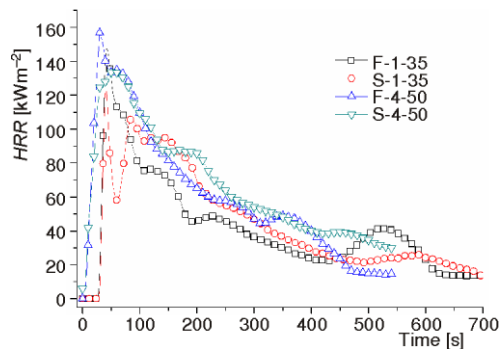


Figure 1. Typical *HRR* in cone tests

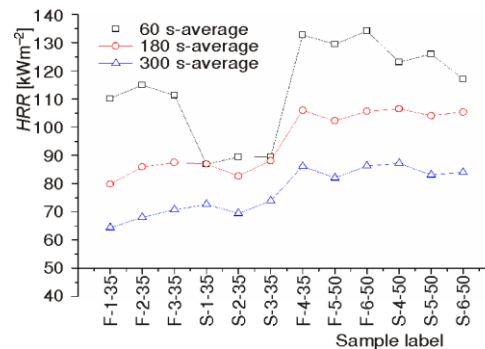


Figure 2. Average of *HRR* in cone tests

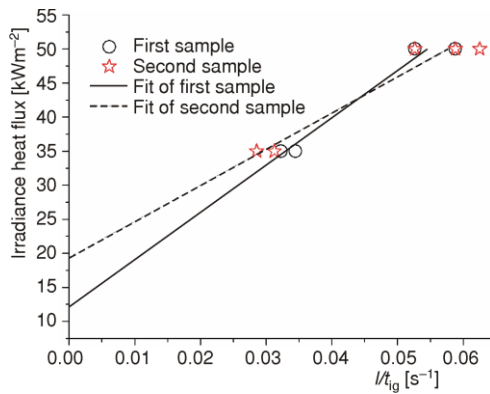
The average *HRR* for all samples at three (60, 180, and 300 seconds) average times are shown in fig. 2. There above-mentioned charring of the painting and the delay in the surface ignition after first peak in *HRR*, result in almost equal performance of the covered samples (S-1-35 to S-3-35): the 60 second average and 180 seconds average *HRR* are almost equal. In general, covered surfaces are more sensitive at lower irradiation fluxes as it can be inferred from 60 second average curve, but at long period the effect is negligible. All the test data are summarized in tab. 1 and tab. 2.

Table 2. The second samples' parameters and results of cone calorimeter tests

Sample	S-1-35	S-2-35	S-3-35	S-4-50	S-5-50	S-6-50
Irradiance, [kWm <sup>-2</sup> ]	35	35	35	50	50	50
Ignition time, [s]	35	35	32	17	19	16
Maximum ( <i>HRR</i> ), [kWm <sup>-2</sup> ]	119.8	124.1	121.3	138.3	156.9	155.7
Time of maximum <i>HRR</i> , [s]	41	40	41	47	57	58
Average effective heat combustion ( <i>EHC</i> ), [MJkg <sup>-1</sup> ]	3.6	3.1	3.7	8.9	8.5	8.6
<i>THR</i> <sub>300</sub> , [MJm <sup>-2</sup> ]	32.6	32.1	35.7	39.5	37.9	37.1
ln( <i>FIGRAcc</i> )	–	–	–	1.08	1.01	0.99
<i>t</i> <sub>f0</sub> [s]	–	–	–	257.2	274.0	270.7

### Surface ignition

Material ignition properties were derived by the method of Janssens [17] by plotting the irradiance heat flux against the reciprocal ignition time (fig. 3). The tests reveal that the minimum heat fluxes required for ignition are about 12.08 kW/m<sup>2</sup> and 19.40 kW/m<sup>2</sup>, for the first and second sample, respectively. The exhibited difference indicates that the samples are thermally thin in accordance with the Janssens' model [17].



**Figure 3.** Effect of incident heat flux on the time to ignition ( $t_{ig}$ )

### Analysis of fire behaviour by different models

#### Classification index prediction

The classification indices developed by Kokkala *et al.* [10] are derived through a dimensional analysis of the fire growth (to the ISO room fire test) and use input data from cone calorimeter test at 50 kW/m<sup>2</sup> irradiance. These indices allow the materials at issue to be classified in several groups depending on the predicted time to flashover lasting 2, 10, 12, and 20 minutes.

The classification procedure involves several steps, among them:

- (1) cone calorimeter tests of samples at 50 kW/m<sup>2</sup> irradiance.
- (2) calculation of the ignition times  $t_{ig}$  defined by the points as which the heat release rate reaches 50 kW/m<sup>2</sup>, and
- (3) calculation of the ignition index ( $I_{IG}$ )

The *HRR* integral of the sample is:

$$I_Q = \int_{t_{ig}}^{t_{fo}} \frac{q''(t)}{(t - t_{ig})^m} dt \quad (1a)$$

The values of  $I_Q$  were determined for two values of the exponent  $m$ : 0.34 and 0.93. The use of two exponents in eq. (1a) is based on empirically based criteria of the time to flashover, namely:

- (a)  $m = 0.34$  m when the flashover is either  $t_f \leq 10$  minutes or  $t_f \leq 20$  minutes, and
- (b)  $m = 0.93$  m when the flashover is either  $t_f \leq 2$  minutes or  $t_f \leq 12$  minutes.

This initial classification enables the tested materials to be divided into four groups, namely:

- (1) time to flashover shorter than 2 minutes,
- (2) time to flashover from 2 to 10 minutes,
- (3) time to flashover from 10 to 12 minutes, and
- (4) materials that do not go to flashover (even in the range from 2 to 2 minutes and from 10 to 20 minutes, as well after the fire onset).

Based on these criteria, the limits are:

$$I_Q = 6800 - 540 I_{IG}, \text{ when } t_f \leq 10 \text{ minutes or } t_f \leq 20 \text{ minutes} \quad (1b)$$

$$I_Q = 1650 - 165 I_{IG}, \text{ when } t_f \leq 12 \text{ minutes and} \quad (1c)$$

$$I_Q = 2475 - 165 I_{IG}, \text{ when } t_f \leq 2 \text{ minutes} \quad (1d)$$

Hence, with the above defined values of the exponent  $m$ , we have:

$I_{Q(m=0.34)} > 6800 - 540 I_{IG}$ , when the expected flashover is:  $t_f \leq 10$  minutes or  $t_f \leq 20$  minutes

$I_{Q(m=0.93)} > 1650 - 165 I_{IG}$ , when the expected flashover is : 10 minutes  $\leq t_f \leq 12$

$I_{Q(m=0.93)} = 2475 - 165 I_{IG}$ , when the expected flashover is :  $t_f \leq 2$  minutes.

Otherwise flashover is not expected according to this classification.

Delichatsios [18] has developed a simplified model to do the calculation, in which a top hat profile of maximum heat release rate  $\dot{q}_{max}''$  and duration  $t_B$ , are used:

$$I_Q = \frac{\dot{q}_{max}'' t_B^{0.07}}{0.07} \text{ for } m = 0.93 \quad (2)$$

$$I_Q = \frac{\dot{q}_{max}'' t_B^{0.66}}{0.66} \text{ for } m = 0.34 \quad (3)$$

The present study employs the definition of the burnout time  $t_B$  developed by Cleary *et al.* [19]. In accordance with this approach, the heat release rate is approximated by a square wave with amplitude equal to 90% of the peak. The wave starts at  $t_{ig}$  and encloses an area equivalent to the area under the curve. Following this approximation, the effective burnout time  $t_B$  matches the width of the enclosing box. When, the burning duration is longer than 300 seconds after apparent time to ignition, the following transformations of eqs. (2) and (3) are suggested under the framework of the present study, namely:

$$I_Q = \frac{\dot{q}_{av-300}'' (300)^{0.07}}{0.07} \text{ for } m = 0.93 \quad (4)$$

$$I_Q = \frac{\dot{q}_{av-300}'' 300^{0.66}}{0.66} \text{ for } m = 0.34 \quad (5)$$

The subscript av-300 denotes the average heat release rate during 300 seconds after the apparent time to ignition, *i. e.*, the burnout time is fixed to 300 seconds.

For the two vinyl-based lining materials tested, the classification results calculated by eqs. (2) and (3) and eqs. (4) and (5) are summarised in tab. 3.

**Table 3. Results of classification index prediction model**

Sample label	Results of eqs. (2) and (3)	Results of eq. (4) and (5)
F-4-50	$t_{fo} < 2$ minutes	2 min. $< t_{fo} < 10$ minutes
F-5-50	$t_{fo} < 2$ minutes	2 min. $< t_{fo} < 10$ minutes
F-6-50	$t_{fo} < 2$ minutes	2 min. $< t_{fo} < 10$ minutes
S-4-50	$t_{fo} < 2$ minutes	2 min. $< t_{fo} < 10$ minutes
S-5-50	$t_{fo} < 2$ minutes	2 min. $< t_{fo} < 10$ minutes
S-6-50	$t_{fo} < 2$ minutes	2 min. $< t_{fo} < 10$ minutes

### Flash over category

The approach of Östman *et al.* [11] uses a simple empirical linear regression for prediction of time to flashover (FO) requiring information about the mean density of the tested material, namely:

$$t_{FO} = 0.07 \frac{t_{ig}^{0.25} \rho^{1.7}}{THR_{300}^{1.3}} + 60 \quad (6)$$

The model was applied to test data taken from the cone calorimeter but the time to ignition was replaced by the apparent time to ignition  $t_{ig(ap)}$  [11] based on the model of Kokkala *et al.* [10]. Then the value of  $THR_{300}$  is calculated as the total heat release ( $THR$ ) during 300 s after the apparent time to ignition.

The components of eq. (6), *i. e.*  $THR_{300}$ ,  $t_{ig}$ , and the calculated  $t_{FO}$  are listed in tabs. 1 and 2 for both samples tested. It is evident, that for both of them, irrespective of the cover (with and without painting), the apparent ignition times under 50 kW/m<sup>2</sup> irradiance are about 10 seconds shorter than those under 35 kW/m<sup>2</sup> heat flux.

The determination of the FO-category of a certain material permit to predict the time to flashover based on ISO room tests [12], namely:

- FO-category 1: products not reaching flashover during 1200 seconds of testing time,
- FO-category 2: 600 seconds  $\leq t_{FO} < 1200$  seconds,
- FO-category 3: 120 seconds  $\leq t_{FO} < 600$  seconds, and
- FO-category 4:  $t_{FO} < 120$  seconds.

With eq. (6) the calculated  $t_{FO}$  values for the tested materials span the range from 257 seconds to 288.4 seconds. Hence, the vinyl-based lining materials at issue belong to FO-category 3.

In the context of FO-category determination, we refer to the statistical information taken from cone calorimeter test treated by the so-called multivariate statistical method of Hansen *et al.* [12]. By using the Fisher's linear discriminant function for classification of cases, the outcome of this analysis is a set of four linear functions corresponding to the FO-categories defiend, namely:

$$F_{FO1} = 0.01789z_1 - 0.06057z_2 + 0.971z_3 - 7.910 \quad (7a)$$

$$F_{FO2} = 0.01492z_1 + 0.03354z_2 + 1.877z_3 - 7.418 \quad (7b)$$

$$F_{FO3} = 0.008589z_1 + 0.409z_2 + 2.721z_3 - 13.406 \quad (7c)$$

$$F_{FO4} = 0.0000256z_1 + 0.347z_2 + 3.621z_3 - 9.215 \quad (7d)$$

The selected parameters are:

$z_1 = \rho_{mean}$ ,  $z_2 = THR_{300}$  [MJm<sup>-2</sup>],  $z_3 = \ln(FIGRAcc)$  and  $FIGRAcc = \max.(HRR/t_{HRR})$ . The logarithms of  $FIGRAcc$  are listed in tab. 1 and tab. 2. The results developed through this approach are summarized and listed in tab. 4.

For the six samples in tab. 4, all  $F_{FO3}$  (in bold) correspond to the largest values of the Fisher's linear discriminant functions. Therefore, the vinyl-based lining material belong to the 3<sup>rd</sup> FO-category meaning times to flashover in ISO room are from 120 to 600 seconds. In this context, these results match those obtained by the method of empirical linear regression model of Östman *et al.* [11]. Hence, both models could be used simultaneously in evaluation procedures that will improve the reliability of the predicted time to flashover and the categorization of the tested materials.

**Table 4. Results for some samples developed through the multivariate statistical method of Hansen and Hovde [12]**

	F-4-50	F-5-50	F-6-50	S-4-50	S-5-50	S-6-50
$F_{FO1}$	12.2568	12.2557	12.1710	12.0889	12.1179	12.1469
$F_{FO2}$	14.2164	14.4102	14.5778	13.7336	13.5485	13.4841
$F_{FO3}$	<b>15.6199</b>	<b>16.3692</b>	<b>17.4051</b>	<b>15.9349</b>	<b>15.0900</b>	<b>14.7084</b>
$F_{FO4}$	9.3294	10.0702	11.0147	8.4327	7.6241	7.2740

## Conclusions

Cone calorimeter data were used to predict the time to flashover and to classify vinyl-based lining materials, with and without anti-corrosion painting, in accordance with the ISO9705 room corner tests procedure. The main outcomes of the cone test and the data analyses can be outlines as:

- The materials belong to the 3<sup>rd</sup> FO-category.
- The outcomes of both the Hansen-Hovde multivariate discriminant analysis and the Östman-Tsantaridis' empirical linear regression model are practically the same; the same results are provided by the method of Delichatsios (see tab. 3 and the FO-category definitions).
- The anti-corrosion painting affects the minimum heat flux required for the surface ignition, but, in fact, has not effect on the fire behaviour classification irrespective of the methods used for that.

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## Nomenclature

$FIGRA_{acc}$	– maximum value of the ratio between $HRR$ and time when $HRR$ was measured ( $=\max. (HRR/t_{HRR})$ , [ $\text{kWm}^{-2}\text{s}^{-1}$ ])	$t_{fo}$	– time to flashover, [s]
$I_Q$	– heat release rate integral, [ $\text{Wm}^{-2}$ ]	$t_{ig}$	– time to ignition time in the cone calorimeter at $50 \text{ kW/m}^2$ , [s]
$I_{IG}$	– ignition index	$THR_{300}$	– total heat release during 300 seconds after ignition at $50 \text{ kW/m}^2$ , [ $\text{MJm}^{-2}$ ]
$m$	– empirical exponent determined, [-]	<i>Greek simbol</i>	
$q''$	– rate of heat release per unit area, [ $\text{Wm}^{-2}$ ]	$\rho$	– mean density of tested samples, [ $\text{kgm}^{-3}$ ]
$q''_{max.}$	– maximum in the heat release per unit area, [ $\text{Wm}^{-2}$ ]	<i>Acronym</i>	
$t$	– time, [s]	$HRR$	– heat release rate
$t_B$	– burnout time, [s]		
$t_{FO}$	– the time to flashover in the room corner test, [s]		

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