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Commentary

Fire Risk Rating Assessment for Wood Specimens Coated with Flame Retardant

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Abstract

Chung's equations-II, -III, and -IV were applied to evaluate the fire risk and fire risk ratings of flame retardants. As an example, a wood specimen coated with a flame retardant was selected and tested using a cone calorimeter according to the ISO 5660-1 standard. The external heat flux was fixed to 50 kW/m^2. Fire performance index-III used three variables to evaluate the initial fire risk: the time to ignition, first peak heat release rate, and first peak smoke release rate. Fire growth index-III was calculated using the first peak heat release rate, peak smoke production rate, and time to reach the first peak smoke production rate. This index is a standardized fire hazard category with poly(methyl methacrylate) as the reference material. The fire risk rating index, fire risk index-IV, is expressed as the value obtained by dividing the fire growth index-III by fire performance index-III. In this study, the methodology for fire risk rating evaluation is discussed.

Keywords: Chung's equation-IV, Fire performance index-III, Fire risk rating assessment, Titanium(IV) oxide

Introduction

Wood is a renewable combustible and relatively environmentally friendly material with excellent overall performance. It is used widely as an interior and exterior material for residential and commercial buildings [1]. Nevertheless, wood must be treated with a flame retardant to compensate for these disadvantages. Various flame retardant technologies, such as coprecipitation, hydrothermal treatment, thermal solvation, and sol-gel chemistry, have attracted attention [2]. Among them, the sol-gel method has a distinctive advantage in producing a solid material from a chemically uniform precursor. The sol-gel method has been studied widely as an effective method for surface modification and has traditionally been used to develop organic-inorganic composite polymer networks [3-6]. Some studies reported that the flame retardant efficiency could be improved by incorporating several flame retardants into a single flame retardant system, such as phosphorus/nitrogen [7-9], phosphorus/boron [10,11] and boron/nitrogen [12]. The presence of silica, phosphorus and nitrogen in a single system increases the thermal oxidation stability and flame retardancy of fabrics [13].

The fire risk of combustibles can be assessed effectively by the following: the combustion performance of combustibles when exposed to fire conditions, and key factors, such as ignition, heat release rate, flame propagation, and the harmfulness of smoke and toxic gases. The heat release rate is very important because it indicates the potential hazard of the target material in case of fire. Many techniques have been developed to measure heat release rate, and the cone calorimeter is one of them [14]. This method most closely simulates the real fire phenomenon and is based on the oxygen consumption principle that approximately 13.1 MJ of heat is released when most organic materials consume 1 kg of oxygen during combustion. The external heat flux provides a spectrum of fire scenarios that can vary between 0 and 100 kW/m^2, with heat fluxes of fire growth phases being the most widely used in 35 or 50 kW/m^2.

Smoke generated during a fire is a flow of gas generated by a flame and continuously mixed with air without a further chemical reaction. Smoke is a combustible gas resulting from the thermal decomposition of wood to form polycyclic aromatic hydrocarbons that produce char upon flame combustion. The unburned char escapes as smoke in the flame combustion region due to radiant cooling, where it burns incompletely [15]. The smoke measurement test method using a cone calorimeter is based on Beer-Bouguer-Lambert's law, which generally states that the intensity of transmitted light decreases exponentially with distance [14].

The smoke production rate, total smoke release, specific extinction area, and smoke factor are used to indicate smoke generation [16-18]. Despite this, these parameters are a limited method according to time changes, and there are still many insufficiencies in implementing the risk and quantitative evaluation of smoke generation.

A method of evaluating the fire risk that correlates to two or more variables has been proposed. The aim is to expand the correlation between the fire indices based on the three fire factors used to evaluate the overall fire risk rating. In previous studies, Chung's equations 1, 2, and 3 were established as smoke risk assessment methods [19], and a fire risk evaluation method based on Chung's equations-II, -III, and -IV was newly established [20]. The fire risk evaluation method based on this can be implemented using equations including heat and smoke, and the fire risk can be standardized using Chung's equations-III. A method of evaluating fire risk that correlates two or more variables has been proposed. A measurement index and a quantitative evaluation index can be provided for non-dimensional evaluation and a combustible materials, respectively, and it is possible to evaluate fire risk and fire risk rating by evaluating the priority of fire risk using reference materials [20].

The cone calorimeter test uses polymethylmethacrylate (PMMA) as a reference material because of its excellent repeatability and reproducibility. Therefore, the fire risk rating of each material was evaluated using PMMA.

This commentary uses the fire risk assessment method of wood specimens coated with TiO_2 flame retardant as an example to explain the methodology for fire risk rating evaluations for combustible materials.

Fire Risk Rating Assessment Method [20]

Fire performance index-II (FPI-II) and fire growth index-II (FGI-II)

The fire performance index-II and the fire growth index-II were calculated using the measured data. They can be viewed as a comprehensive evaluation for identifying the fire risk of materials in the cone calorimeter experiment.

The method for calculating the fire performance index-II (FPI-II) is expressed in equation (1).

$$FPI-II = \frac{TTI\ (s)}{SPR_{peak}\ (m^2/s)\ \cdot\ PHRR\ (kW/m^2)} \tag{1}$$

This equation considered three variables, time to ignition, peak smoke production rate, and peak heat release rate, to evaluate the fire performance index-II. FPI-II is defined as the time to ignition (TTI) divided by the product of the peak smoke production rate (SPR_{peak}) and peak heat release rate (PHRR, HRR_{peak}). The fire risk can be judged comprehensively using three variables. TTI is an essential factor that can explain the fire vulnerability of combustible materials, and a faster time to ignition indicates a more combustible. For the peak smoke production rate (SPR_{peak}), SPR_{1st_peak} was used to evaluate the initial fire risk. For the peak heat release rate (PHRR), HRR_{1st_peak} was used to evaluate the initial fire risk. These parameters characterize the fire risk of the material. The maximum value was used to determine the fire risk, the most dangerous state in the growing fire at the experimental condition of external heat flux of 50 kW/m^2. The smoke safety decreases because there is a correlation between the fire spread of wood and the flashover time [21], just as fire safety decreases as fire spread increases [22].

Therefore, the fire risk decreases as the FPI-II increases.

The method for obtaining the fire growth index-II (FGI-II) is expressed as equation (2).

$$FGI-II = \frac{SPR_{peak}\ (m^2/s)\ \cdot\ PHRR\ (kW/m^2)}{Time\ to\ SPR_{peak}\ (s)} \tag{2}$$

This equation considered three variables to evaluate FGI-II; the peak smoke production rate, the peak heat release rate, and the time to reach the peak smoke production rate. FGI-II is defined as the product of the peak smoke production rate and the peak heat release rate divided by the time to reach the peak smoke production rate. Using three variables, fire risk can be judged comprehensively. For the peak smoke production rate (SPR_{peak}), SPR_{1st_peak} was used to evaluate the initial fire risk. The peak heat release rate (PHRR), HRR_{1st_peak} was used to evaluate the initial fire risk. A faster the time to reach the first peak smoke production rate ($TSPR_{1st\_peak}$) indicated a higher fire risk, so a higher FGI-II means a higher fire risk.

Fire performance index-III (FPI-III) and fire growth index-III (FGI-III)

The fire performance index-III (FPI-III) is expressed as equation (3).

$$FPI-III = \frac{\left[\frac{TTI\ (s)}{SPR_{peak}(m^2/s)\cdot PHRR(kW/m^2)}\right]_{combustible\ materials}}{\left[\frac{TTI\ (s)}{SPR_{peak}\ (m^2/s)\cdot PHRR\ (kW/m^2)}\right]_{PMMA}} \tag{3}$$

FPI-III is defined as the value obtained by dividing FPI-II by the standard value of $FPI\text{-}II_{[PMMA]}$ (based on PMMA).

This expression is dimensionless. The peak smoke production rate and heat release rate used the SPR_{1st_peak} and HRR_{1st_peak} values considering the importance of the initial fire. The higher the FPI-III, the lower fire risk.

The fire growth index-III (FGI-III) is expressed as equation (4).

$$FGI - III = \frac{\left[\frac{SPR_{peak}(m^2/s) \cdot PHRR\ (kW/m^2)}{Time\ to\ SPR_{peak}(s)}\right]_{combustible\ materials}}{\left[\frac{SPR_{peak}\ (m^2/s)\ \cdot PHRR\ (kW/m^2)}{Time\ to\ SPR_{peak}\ (m^2/s)}\right]_{PMMA}} \qquad (4)$$

FGI-III is defined as FGI-II divided by the standard value of $FGI\text{-}II_{[PMMA]}$ (based on PMMA). This expression is dimensionless. The peak smoke production rate and peak heat release rate used the SPR_{1st_peak} and HRR_{1st_peak} values, and the time to reach SPR_{peak} was applied to the time to reach SPR_{1st_peak} value. The first peak values were applied, considering the importance of the initial fire. A higher FGI-III indicated a higher fire risk.

Fire risk index-IV (FRI-IV)

The fire risk index-IV (FRI-IV) equation is expressed as equation (5).

$$FRI - IV = \frac{FGI - III}{FPI - III} \qquad (5)$$

FRI-IV is defined as FGI-III divided by FPI-III. This is equivalent to a decrease in fire stability as the fire spread increases. Therefore, a higher FRI-IV value means a higher fire risk, and vice versa [21].

Application of fire risk rating assessment methods

As shown in **Table 1**, the fire performance index-II of the wood specimens coated with flame retardant increased by 3.2 to 11.9 times compared to the uncoated specimens. This suggests that the fire risk of wood specimens coated with flame retardant was lowered. A high fire performance index-II means a decreased fire risk.

The fire risk by fire performance-II increased in the following order.

SS < TSS < TiO_2(R)SS < TiO_2(A)TSS < TiO_2(R)TSS ≈ TiO_2(A)SS < Uncoated < PMMA

In the case of SS, the time to ignition increased and the first peak heat release rate decreased. TiO_2(R)SS was more stable at higher temperatures and penetrated better into wood specimens compared to TiO_2(A)SS. The formed ceramic protective layer and the high decomposition temperature of the material influence the time to ignition and peak heat release rate. PMMA had the highest SPR_{1st_peak} and PHRR values among all specimens, resulting in a high fire risk.

As shown in **Table 1**, the FGI-II of the wood specimens coated with the flame retardants was 2.9-36.4 times lower than the uncoated specimens. A high fire growth index-II indicates an increased fire risk.

The fire risk by fire growth index-II increased in the following order:

TSS < SS < TiO_2(R)TSS < TiO_2(A)TSS < TiO_2(R)SS < TiO_2(A)SS < PMMA < Uncoated

TSS has the lowest risk of fire growth among the flame retardants tested because it decreases the HRR_{1st_peak} (first peak heat release rate) and prolongs $TSPR_{1st\_peak}$ (the time to reach the first peak smoke production rate). The HRR_{1st_peak} of TiO_2(R)TSS is the lowest because adding talc decreases the production of combustible gases. Therefore, it decreased the fire risk. Among all specimens, uncoated had a high SPR_{1st_peak} and a high time to reach SPR_{1st_peak}, resulting in a high fire risk.

As shown in **Table 1**, the FPI-III value of the uncoated specimen was the lowest. The FPI-III of wood specimens coated with flame retardant was 3.2-12.0 fold greater than the uncoated specimen. The wood specimens coated with these flame retardants had a lower fire risk [20].

Fire risk by fire performance index-III based on PMMA increased in the following order:

SS < TSS < TiO_2(R)SS <. TiO_2(A)TSS < TiO_2(R)TSS ≈ TiO_2(A)SS < Uncoated < PMMA

SS flame retardants were the lowest, and rutile titanium (IV) oxide had high thermal stability and a long time to ignition. Hence, the value was lower than anatase titanium (IV) oxide. PMMA had the highest SPR_{1st_peak} and PHRR values among all specimens, resulting in a high fire risk.

As shown in **Table 1**, the FGI-III of the wood specimens coated with the flame retardant exhibited values 2.9-36.4 times lower than those of the uncoated specimens. TSS had the lowest fire growth index III and TiO_2(A)SS had the highest.

Fire risk by fire growth index-III based on PMMA increased in the following order:

TSS < SS < TiO_2(R)TSS < TiO_2(A)TSS < TiO_2(R)SS < TiO_2(A)SS < PMMA < Uncoated

TSS decreased the fire growth index-III because of a low heat release rate and a low smoke production rate. The fire risk assessment of FGI-II and FGI-III reveled, TSS to be the lowest fire risk material. Among the wood specimens coated with TiO_2, TiO_2(R)TSS had the lowest fire risk, and rutile-TiO_2 had a lower fire risk than anatase-TiO_2. Among all specimens, uncoated had a high SPR_{1st_peak} and a high time to reach SPR_{1st_peak}, resulting in a high fire risk. A higher FGI-III value of a wood specimen means a higher fire risk. FPI-III and FGI-III values were

Table 1. Fire indices-II, III, and fire risk index-IV of the wood specimens coated with flame retardant.

Materials (Cypress)	[a]FPI-II (s^2/kW)	FPI-III	[b]FGI-II (kW/s^2)	FGI-III	[c]FRI-IV
Uncoated	1.3080	4.4031	0.3572	2.4005	0.5452
SS	15.5712	52.6748	0.0201	0.1351	0.0026
TSS	11.0332	37.0570	0.0098	0.0659	0.0018
TiO_2(R)SS	6.0128	20.2656	0.0855	0.5746	0.0284
TiO_2(A)SS	4.2446	14.3060	0.1225	0.8233	0.0575
TiO_2(R)TSS	4.3869	14.7856	0.0285	0.1915	0.0130
TiO_2(A)TSS	5.2543	17.7091	0.0508	0.3414	0.0193
PMMA	0.2967	1	0.1488	1	1

[a]Fire Performance Index; [b]Fire Growth Index; [c]Fire Risk Index.

calculated from the measurement data. They were applied as a comprehensive evaluation to determine the fire hazard of materials in a cone calorimeter experiments [20].

As shown in **Table 1**, the FRI-IV of wood specimens coated with flame retardants has a 9.5-302.9 fold lower value than the uncoated specimens. The fire risk rated by FRI-IV, was the highest in TiO_2(A)SS. The fire risk rating was obtained by FRI-IV using PMMA as reference material.

Fire risk rating by fire risk index-IV increased in the following order:

TSS < SS < TiO_2(R)TSS < TiO_2(A)TSS < TiO_2(R)SS < TiO_2(A)SS < Uncoated < PMMA.

In particular, TSS and SS had the lowest FRI-IV. Rutile-type TiO_2 had a lower fire hazard rating than anatase-type TiO_2 because of the thermal stability of rutile-type materials. Rutile-type TiO_2 is superior to anatase-type TiO_2 as a char foaming aid [23], and as a result, rutile-type TiO_2 was consistently more effective in improving the thermal stability. All specimens showed a lower fire risk than PMMA, which has the FRI-IV reference value of 1. FRI-IV is a combination of FPI-III and FGI-III, so the order of FPI-III and FGI-III may be different. The fire risk increases as the fire risk index- IV value increases. Therefore, the fire risk of the material can be predicted comprehensively because the fire risk ranking can be determined by calculating the fire risk rating from the experimental data.

All specimens were more flame retardant than uncoated wood, with reduced smoke and heat hazards because of fire resistance. Therefore, they may be more suitable for use in building and interior material applications than the original wood.

The addition of flame retardants on the wood surfaces reduced the fire risk for fire performance indices-II and -III, fire growth indices-II and -III, and fire risk index-IV [20].

Conclusions

Chung's equations-II, -III, and -IV were applied to evaluate the fire risk and fire risk ratings of flame retardants. As an example, a wood specimen coated with a flame retardant was selected and tested as performed using a cone calorimeter according to the ISO 5660-1 standard. The external heat flux was fixed to 50 kW/m^2. The initial fire risk was evaluated from the fire performance index-III using three variables: time to ignition, first peak heat release rate, and first peak smoke production rate. Fire growth index-III was calculated using the first peak heat release rate, the peak smoke production rate, and the time to reach the first peak smoke production rate. This index is a standardized fire hazard index with PMMA as the reference material. The fire risk rating index, fire risk index-IV, is expressed as the value obtained by dividing the fire growth index-III by fire performance index-III. This study discussed the methodology for fire risk rating evaluations.

The titanium (IV) oxide mixtures decreased the heat and smoke risks of the cypress in the initial fire. The fire risk rating assessment by FRI-IV showed that TSS and SS were the lowest fire risk materials. Anatase-type TiO_2 had a higher fire risk rating than rutile-type TiO_2. Incorporating TiO_2 into the commercial sodium silicate improved the combustion inhibition of the uncoated wood.

Conflicts of Interest

The authors have no conflicts of interest to disclose.

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