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An experimental study on the combustibles investigation and fire growth rate for predicting initial fire behavior in building

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Abstract

In this study, combustibles investigation and fire growth rate experiment were performed for predicting initial fire behavior in buildings. Combustibles investigation was performed for residential buildings, which is most frequently affected by fire in Korea. Spatial characteristics and combustibles properties were separately investigated, and occupied area and layout characteristics of combustibles were identified to produce general layout models. Of the layout models, room was selected for fire test of a single compartment. From this test, fire propagation for each combustible was identified, which was delayed compared to the summed heat release rate of a single combustible. Also, comparison with Matsuyama model allowed improvement in the modeling of the process of fire spreading to nearby combustibles, but closer examination of ventilation factors will be required in the future.

Keywords: Fire growth rate; Combustible investigation; Fire safety design; Initial behavior

1. Introduction

Due to frequent occurrence of large-scale fires in Korea such as the recent fire in high-rise complex in Haewoondae-gu, Busan [1], interest in fire safety in buildings has extended nationwide. Also, numbers of large complexes are increasing as buildings are becoming taller, hybridized, and larger due to limitation of available land. Due to this trend, personnel safety is becoming more problematic in case of fire in buildings, and human loss due to fire is expected to continue to increase [2].

Accordingly various legal systems for fire and evacuation safety are in enforcement in 2012 in Korea, including PBD (Performance Based-Design), FIAR (Fire Impact Assessment Regulations; enforced in 2009), and Special Law for Emergency Management in High-rise and underground-connected complexes. To secure fire safety performance, fire behavior inside buildings must be scientifically described and systemized as a theory, thereby allowing application to fire safety design of buildings.

Fire behavior prediction in buildings largely depends on properties of combustibles such as the quantity, material, or exposed surface area of the combustible. Quantity of combustibles depends on the purpose of the space, and exposed surface area of combustibles depends on the type of the combustibles and the form of their storage. Properties of combustibles, which are important factors for design and evaluation of evacuation safety, include fire growth rate (fire spread speed), maximum heating rate of a single combustible, separation distance between combustibles (distribution of combustibles), and expansion of combustion of fixed combustibles such as ceiling and floor. Of these, fire growth rate is generally expressed αt^2 as using α (kW/s^2). This parameter is closely related to the quantity, material, and distribution of combustibles.

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At the same time, existing studies in Korea has focused on researching fire load (kg/m^2) for various purposes in order to introduce performance based design for fire resistance of buildings [3, 4]. However, such PBDs are overall appraisal of fire safety design of buildings and do not provide insight into early fire behavior. In order to identify early fire behavior required for evacuation safety design, prediction of heating rate according to fire growth rate is required. In this case, a reference model is required for the investigation of fire growth rate, exposed surface area, and layout of combustibles for various purposes. Due to time limitation of survey, a simplified investigation method would be required.

Internationally, Harmathy [5] proposed an equation for relationship between the weight of combustible and the exposed surface area, and Aburano [6] proposed a regression equation through survey of the quantity of combustibles and the surface area. Especially, Matsuyama [7] evaluated regression equation of existing combustible studies by surveying combustibles properties. In this study, Matsuyama proposed a method for simplification of survey, verified the method, and established a fire behavior model that can be used for performance based design of fire safety.

Because combustibles properties such as layout characteristics and fire growth rate are different for each country, a study on combustibles survey and prediction of fire growth rate is required for domestic circumstances. Therefore, in this study, a survey of combustibles was performed for residential buildings, which is most frequently affected by fire in Korea, was performed to produce a layout model for residential unit. This model was used to perform a full-scale test (ISO-9705) to examine changes in initial fire behavior. Also, method for predicting fire growth rate by Matsuyama [7] was compared and analyzed, and fundamental data for fire safety design appropriate to circumstances in Korea is provided.

2. Survey of combustibles and layout reference model

2.1. Method for combustibles survey

Fig. 1 shows method for combustibles survey in this study. The survey was divided into spatial characteristics, combustibles properties, and characteristics of openings. Values obtained were used for residential modeling performed to calculate exposed surface area. To calculate values for spatial characteristics, area and ceiling height were measured for rooms for each purpose. Heat of combustion of materials by AIJ [8] was used for fire load of each combustible, total heat release rate [MJ] for heat of combustion of material [MJ/kg], and heat release rate per unit area [MJ/m^2]. 10 residential units were selected for the survey, which corresponds to 66~11.54 m^2 (maximum frequency distribution for each size of residential building: 56.6%) in size [9].

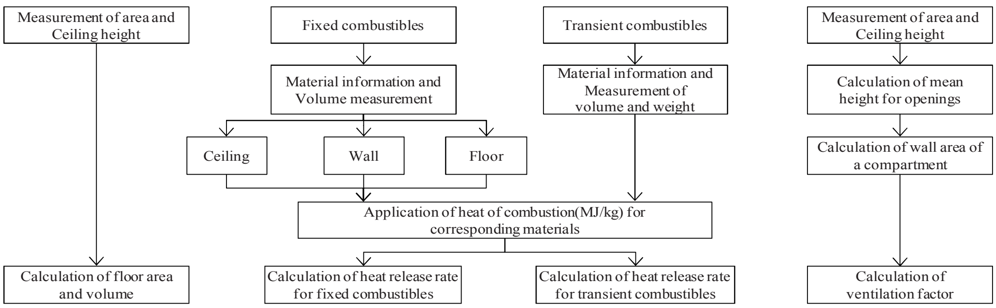


Fig. 1. Method and overview of combustibles survey.

2.2. Method for combustibles survey

Spatial characteristics and combustibles properties were examined in the combustibles survey of buildings. Area of each room and proportion of transient combustibles (%) was calculated, and mean value for the proportion was produced. Table 1 shows area of residential spaces and Table 2 shows proportion of transient combustibles converted into percentage according to volume in a given space.

Based on these results, a reference layout model was produced for each space (Fig. 2). A reference model was constructed from average layout of 10 residential units, and mean proportion of combustible was applied to each room. The established reference layout model can be used to examine exposed surface area and quantity of combustibles. It is also expected to provide data for fire simulation and layout of combustibles required for full-scale fire test. Table 3 is the list of transient combustibles in the reference layout model. Number in each room of the layout corresponds to superscript of combustibles in the table.

Table 1. Area for residential space (m^2)

	A	B	C	D	E	F	G	H	I	J
Room 1	15.59	20.79	14.04	28.56	19.11	19.69	14.63	11.24	11.49	15.62
Room 2	12.40	17.82	10.80	11.76	8.30	18.13	8.70	8.98	7.51	11.23
Room 3	15.49	-	5.76	7.14	9.63	11.33	10.47	8.47	15.70	10.37
Living Room	25.25	20.79	17.31	14.58	26.18	25.67	28.39	11.10	23.36	17.91
Kitchen	5.76	22.08	11.34	10.35	16.78	11.12	12.03	13.67	9.79	18.70
Balcony1	5.76	12.00	9.36	6.00	15.20	2.90	11.35	25.40	4.48	13.06
Balcony2	6.20	-	7.65	-	8.20	-	5.33	-	6.58	4.06
Balcony3	-	-	-	-	3.63	-	4.88	-	4.86	4.38
Balcony4	-	-	-	-	-	-	6.67	-	4.73	5.21
Entrance	2.34	1.80	1.35	3.30	1.91	4.05	3.27	2.01	3.43	2.46
Dressing room	2.18	-	-	-	-	-	2.16	-	2.17	3.39
Total Area	90.98	95.28	77.61	81.69	108.93	92.88	107.88	80.87	94.10	106.39

Table 2. Proportion of combustible in a given space (%)

	A	B	C	D	E	F	G	H	I	J
Room 1	23%	16%	22%	10%	17%	9%	19%	28%	19%	23%
Room 2	24%	7%	13%	24%	18%	4%	7%	20%	34%	24%
Room 3	19%	-	6%	14%	34%	13%	19%	51%	55%	29%
Living Room	6%	6%	5%	24%	6%	4%	3%	9%	12%	15%
Kitchen	23%	5%	10%	11%	18%	4%	21%	21%	30%	11%
Balcony1	8%	2%	18%	0%	0%	25%	8%	0%	13%	9%
Balcony2	7%	-	12%	-	18%	-	5%	-	1%	14%
Balcony3	-	-	-	-	9%	-	13%	-	4%	13%
Balcony4	-	-	-	-	-	-	12%	-	12%	20%
Entrance	19%	13%	24%	5%	21%	14%	15%	18%	15%	20%
Dressing room	35%	-	-	-	-	-	48%	-	5%	39%
Total Area	18%	8%	14%	13%	16%	10%	15%	21%	18%	20%

Table 3. List of combustibles

Name	List of transient combustibles
Room 1	Bed[1], mattress[2], closet[3], TV[4], drawer[5], cabinet[6]
Room 2	Bed[1], mattress[2], wardrobe[3], desk[4], chair[5], PC[6], bookshelf[7]
Room 3	Bed[1], mattress[2], closet[3], wardrobe[4], drawer[5], chair[6]
Living room	Sofa[1], TV[2], TV cabinet[3], table[4], cabinet[5], PC[6], computer desk[7], air conditioner[8]
Kitchen	Sink[1], shelf[2], dining table[3], chair[4], refrigerator[5], rice cooker[6], microwave[7], cabinet[8]
Balcony 1	Drying rack[1], cleaner[2], cabinet[3], built-in cabinet[4]
Balcony 2	Washer[1], Kim-Chi refrigerator[2], cabinet[3]
Entrance	Shoe rack[1], shelf[2]

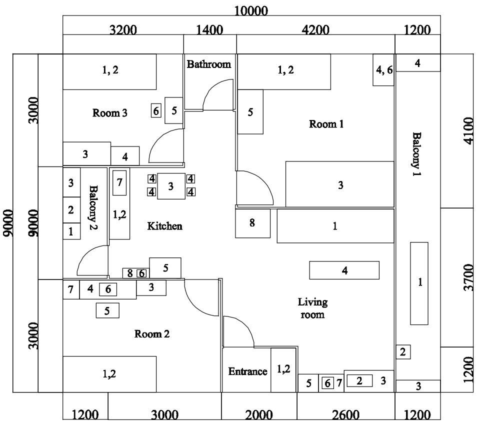


Fig. 2. Layout reference model of transient combustibles.

3. Fire test of a single compartment

3.1. Method for combustibles survey

Based on combustible layout model in Section 2, layout and quantity of combustibles was determined for Room 2. Fig. 3 shows positions of combustibles. List of combustibles used for the test is given in Table 5, which shows the size (W*D*H), exposed surface area, and weight of the combustibles. For measurement, K-type thermocouples were placed at G1~ G5 as in Fig. 4, and three CCTVs were set up to observe fire propagation in the room. Heating rate measurement was performed twice using a large calorimeter at Korea Institute of Construction Technology. Thermocouple placement and state of test specimen are shown in Fig. 4 and 12.5 mm fire-resistant gypsum board (KS F 3504, KS F 3504 specifications) was used for walls [10]. To examine fire behavior for each ignition source, 50ml heptanes was placed in the wastebasket or TV shelf for each experimental case as in Table 4.

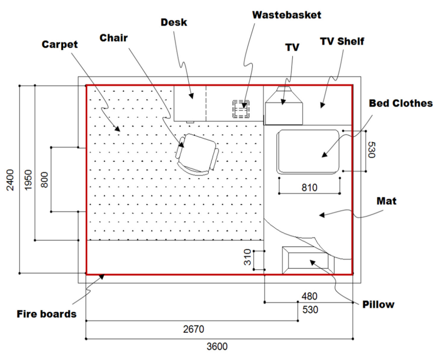


Fig. 3. Layout and types of combustibles in a single-compartment fire test.

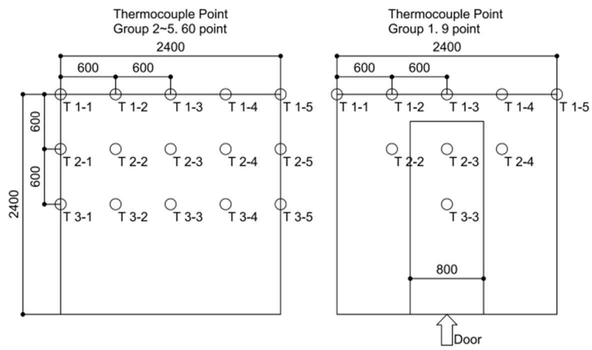


Fig. 4. Measurement location of K-type thermocouples (mm).

Table 4. Experimental conditions

Experiment Case	Ignition source	Quantity and layout of combustibles	Fire source
Exp. 1	Wastebasket	Constant	Heptane 50 ml
Exp. 2	TV Shelf		

Table 5. List of combustibles

Name	Size(W×D×H) [m]	Exposed surface area [m^2]	Weight of combustibles [kg]
TV	0.50×0.45×0.47	1118.0	3.53
TV Shelf	1.20×0.50×0.40	828.8	23.35
Carpet	1.95×2.67×0.01	410.3	3.15
Desk	1.20×0.45×0.67	1659.1	33.15
Chair	0.54×0.57×0.77	1434.8	9.4
Mat	1.19×2.00×0.02	223.1	2.75
Bedclothes	0.81×0.53×0.03	429.4	1.7
Pillow	0.48×0.31×0.07	148.9	0.4
Wastebasket	0.22×0.22×0.41	0.4	0.75

3.2. Experimental results

Figure 5 shows heating rate over time. Due to delay of heat in reaching measurement sensor of the large calorimeter, heating rate [kW] was measured as 69 kW at 467 seconds and as 499 kW at 469 seconds. Maximum heating rates were 2572 kW (Experiment 1) and 2876 kW (Experiment 2). Fire growth rate α was deduced from the relationship between maximum heating rate Q_{peak} and time to reach the maximum heat release rate t_{grow}.

$$Q(t) = (Q_{peak} / t_{grow}^2) t^2 \tag{1}$$

Expressed in terms of fire growth rate α,

$$\alpha = Q_{peak} / t_{grow}^2 \tag{2}$$

Although fire growth rate can vary with time, stable fire growth rate can be deduced when relationship with maximum heating rate is used. Deduced fire growth rate was 0.1 for Experiment 1 and 0.0048 for Experiment 2. Fire propagation of combustibles from CCTV and thermocouple measurement is as in Fig. 6(a) and Fig. 6(b). In summary, ignition from the wastebasket spread directly to the desk in Experiment 1, and ignition from TV shelf spread to TV in Experiment 2.

In Experiment 1, initial fire growth rate is thought to have increased when fire has propagated from the wastebasket to the desk, which has large exposed surface area. Fire behavior is thought to have changed as fire spread to the chair, which is made of plastic. However, fire propagation is thought to have been delayed as fire spread to a combustible with relatively small exposed surface area. Especially, materials of ignition sources were synthetic polymer in Experiment 1 and wood in Experiment 2, which may have resulted in difference in fire growth rates.

Table 6. Fire propagation over time

	Fire propagation of combustibles
Exp. 1	Wastebasket(1) → Desk(2) → TV(3) → Mat(4) → Etc.
Exp. 2	TV Shelf(1) → TV(2) → Bedclothes(3) → Chair(4) → Etc.

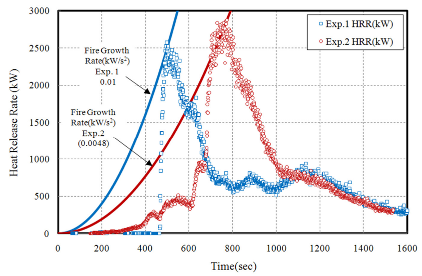
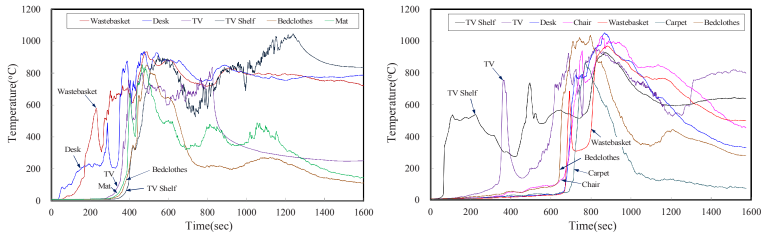


Fig. 5. Experimental result (heat release rate and fire growth rate).



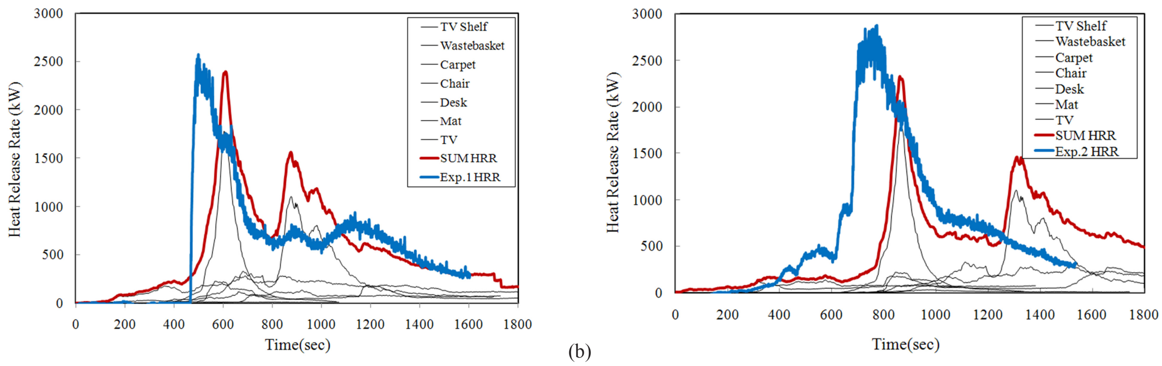
(a) Experiment 1 (b) Experiment 2

Fig. 6. Order of fire propagation according to temperature distribution of thermocouple.

4. Analysis of heat release rate of a single combustible and comparison with previous prediction model [7]

4.1. Analysis of heat release rate of a single combustible

Heating rates of combustibles used for single-compartment fire test have been measured in a furniture calorimeter [11]. Referring to heating rate measurement of each combustible in Table 6, ignition time was delayed according to the order of fire propagation. Time delay was determined by observing the instantaneous time at which temperature of the thermocouple rises above 100 ^{o}C and defining that time as the start of combustion of a single combustible. The result is shown in Fig. 7. Experimental heating rates of both Experiment 1 and 2 were different from respective summed heating rates. This difference is thought to be caused by determination of ignition onset time using thermocouple temperature, which may result in difference in conduction of radiative heat to nearby combustibles. From the result, experimental results are concluded to be insufficient for ignition time of nearby combustibles and quantitative analysis such as model for ignition to nearby combustibles is required.



(a) (b)

Fig. 7. Comparison of summed and experimental heating rates. (Exp. 1, Exp. 2)

4.2. Comparison with a theoretical model of fire growth rate

A theoretical fire growth rate prediction model proposed by Matsuyama [7] was compared to our results. A survey of combustibles in office buildings was conducted for standardization of fire growth rate for each value from survey of combustibles in office buildings. Relationships for combustible density [kg/m^2] and fire growth rate [kW/s^2] were deduced, and calculation was conducted every 10 interval of combustible density [kg/m^2] for the result to be applicable to design. From these calculations, a relationship between combustible density and fire growth rate was deduced as in Eq. (3).

$$\alpha \propto w^{8/3} \tag{3}$$

Based on this model, fire source model for a single combustible was established as follows. In NFPA 72 [12], fire growth rate of a combustible is classified as slow ($\alpha \le 0.0066$), medium ($0.0066 < \alpha \le 0.0469$), fast ($0.0469 < \alpha \le 0.1876$), and ultra-fast ($0.1876 < \alpha$). Ignition properties of combustibles generally stored inside a building are not significantly higher than those of wood, and fire growth rate can be assumed to be medium. Then heating rate of a combustible Q_f can be expressed as Eq. (4).

$$Q_f = 0.0469t^2 \tag{4}$$

Here, coefficient of 0.0469 is expressed by fire growth rate of a single combustible α_s [kW/s^2].

Also, the maximum heating rate of a combustible Q_{peak} [kW] can be calculated from surface area of combustible [m^2] and heating rate per unit area [kW/m^2]. From experiment, the maximum heating rate was measured to be 2,572 [kW]. Using Eq. (5), the maximum rate was assumed to be 3,000 [kW]. Here, W [kg] is the weight of the combustible.

$$Q_{peak} = 90W^{2/3} \tag{5}$$

A model for ignition heating rate of a single combustible is as in Fig. 8. Initial growth expresses mean growth rate of combustibles using fire source of t^2 and the maximum heating rate is expressed by relationship with combustible weight.

Also, ignition process is required for spread of fire. For ignition of radiation from fire, the radiation is assumed to be constantly emitted at 4π solid angle without orientation. Incident heat flux q'' [kW/m^2] for different separation distances is as in Eq. (6).

$$q'' = (1/4\pi X_{step}^2)(Q_f/3) \tag{6}$$

Here, q'' is incident heat flux, Q_f is heating rate of a combustible [kW], and X_{step} [m] is mean separation distance between combustibles. As loss from radiative heat is generally in the range of 0.15~0.6 [12], a coefficient of 1/3 was used. Also, inflammability limit for wood has been reported to be as in Eq. (7).

$$\int I^2 dt = 1000 \sim 4000\ [\mathrm{kW/m^2}]^2 \mathrm{min} \tag{7}$$

Fig. 8. Model for ignition heat release rate of a combustible.

In this study, consideration of safety factor has led to use of Eq. (8).

$$\int I^2 dt = 1000 [\mathrm{kW/m^2}]^2 \mathrm{min} \tag{8}$$

Also, for separation distance of combustibles, when combustible density is w [kg/m^2], combustible with weight of W [kg] represents a combustible with floor area of W/w [m^2]. Because weight of each combustible (e.g. a furniture) has characteristic magnitude, it was assumed to be spatially uniform. Then mean separation distance of combustibles can be expressed by Eq. (9).

$$X_{step} = \sqrt{W/w} \tag{9}$$

Here, length of a single side of a combustible l can be used to deduce Eq. (10), and subsequent separation distance is as in Eq. (11).

$$l = \sqrt[3]{W/\rho} \tag{10}$$

$$X_{step} = X_{ave} - l \tag{11}$$

Table 7 shows the above values obtained from experiments, and fire growth rate was calculated to be $0.0144\,t^2$.

Table 7. Input parameters used for calculation of fire growth rate

Floor area of the calculated range [m^2]	8.64
Fire load [kg/m^2]	9.04
Total weight of combustibles [kg]	78.18
Number of analysis regions	9
Combustible weight per analysis region [kg/region]	8.69
Number of combustibles in the analysis region [unit]	36
Combustible weight [kg]	19.55
Distance between combustibles [m]	0.545
Fire growth rate [kW/s^2]	0.0144

4.3. Comparison of experimental results and prediction model

Figure 9 shows comparison of fire growth rates from experiments and prediction model. As mentioned earlier, fire growth rate for Experiment 1 was 0.01 and for Experiment 2 was 0.0048, which are significantly different from the theoretically predicted values. Matsuyama's model [7] excludes ventilation factors in prediction of initial fire behavior. Ventilation factor is generally expressed by $A\sqrt{H}$ [m$^{5/2}$] and it is related to the size of openings [12]. Although initial fire behavior is not significantly affected by ventilation factor, the observed difference between experimental and theoretical results prompts for a closer examination of the effect of ventilation factors for designs that accounts for fire load.

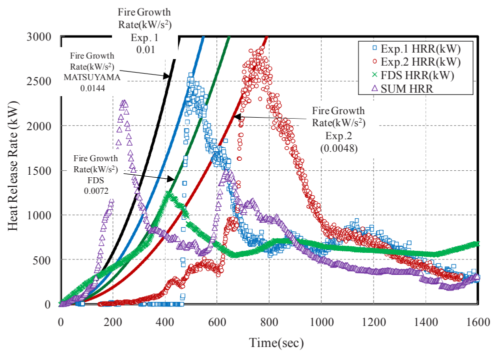


Fig. 9. Comparison of fire growth rates from experiments and prediction model.

5. Conclusions

Initial fire behavior was experimentally investigated for performance-based fire safety design of buildings. From the results, following conclusions were made.

(1) Spatial characteristics of combustibles and respective occupied spaces according to layout of transient combustibles were obtained to produce a layout reference model for layout of combustibles. The obtained layout reference model may serve as a reference for fire safety design of buildings, and is expected to become a standard alternative to full-scale modeling and fire modeling.

(2) Experiment in a single compartment showed that small exposed surface area of ignited combustible and material differences led to delay in fire propagation time. Also, there was a difference between summed heating rate and experimental heating rate in Experiment 1 and 2. This was attributed to determining ignition onset time using thermocouple temperature. Accordingly, experimental results for ignition of nearby combustibles were determined to be insufficient, and qualitative analysis such as a model for ignition of nearby combustibles will be required.

(3) Comparison with theoretical model showed that fire growth rate was $0.0144\,t^2$, with $0.1\,t^2$ for Experiment 1 and $0.0048\,t^2$ for Experiment 2. Although fire growth rates were different, maximum heating rates from experiments were compared to the model. In the future, research on ventilation factor and correction factor for experimental values will be required.

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