A study on the appropriateness of the performance criteria of a smoke control system among the local fire safety standard for underground spaces

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Abstract

This study is intended to evaluate the characteristics of smoke spreading and the appropriateness of evacuation time extended by the operation of a smoke control system during a fire within the underground space of the building. The building is structured in compliance with the smoke control system performance criteria from the local fire safety standard, which has been recently applied to all buildings in Korea. As a preceding review, the heat release of the combustibles was identified and based on the outcome thereof; the type and specification of the combustibles existing at the possible fire location were examined, estimating the heat releases. In a bid to validate the estimated values, modeling of a single underground shopping mall was carried out, and the combustibles examined during the preceding review were placed inside the building for a real scale fire test, the results of which were then reviewed and compared with a numerical analysis result. Using the heat release per unit weight of the combustibles, a numerical analysis both in case of the smoke control system in operation and the system not in operation was carried out at several different shopping malls. From the viewpoint of securing the evacuation time, the results were compared in an attempt to assess the appropriateness of the fire safety criteria.
Keywords: underground market, smoke control, evacuation.

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1 Introduction

Underground spaces have been increasingly developed and their use has been diversified, such as for stores, car parking and resting and cultural facilities. In line with such tendencies, the number of users has also been on the rise [5]. However, the criteria for smoke control systems under the fire safety standard has yet to demonstrate separate rules for underground spaces from those above ground level; the same rule has been applied irrespective of the level

Underground structures, in contrast to those at ground level, are highly enclosed resulting in poor circulation of air between the inside of the building and the outside, which requires assurance that the current fire safety rules specify sufficient evacuation time for the people when a fire occurs, as well as the appropriateness of the standards.

Prior to commencing the study, the examination to identify the fixed combustibles and movable combustibles occupying the internal space of the building was carried out, along with the measurement of heat release /unit weight of the raw material of those combustibles. To estimate the total heat release of the whole shopping mall area, a preliminary site survey to identify the entire structure of the shopping mall, location of each store, type of business, area and ceiling height was carried out and furthermore, the survey included the type, size, weight and raw material of the fixed combustible material such as office supplies, showcase and interior furniture. Also, the examination for movable combustibles was conducted to check the type, quantity, weight and raw material. Using the information on heat release per unit weight of the raw material, the heat release of combustible material available at the site was calculated. To prove the estimated heat releases of their own, modeling of a store randomly selected was carried out and the total heat release of the store based on the values of combustibles at the store was calculated on assumption of certain combustibles available by the store at all times.

Simulating the situation with the modeling stores, a fire test was conducted, along with the numerical analysis under the same condition and the outcome thereof was compared with the estimated heat release of the store.

In an effort to evaluate the appropriateness of the performance criteria of a smoke control system under the domestic fire safety standard currently effective, a numerical analysis at 16 different shopping malls under the management of current fire safety rules was carried out on the assumption that the fire occurs while a smoke control system is in operation. The location and category of store subject to numerical analysis were arranged based on data obtained during site survey, and the fire load by type of business was estimated, referring to the information on combustibles, and the heat releases of the combustibles calculated based on values of raw material [1]. A fire was assumed to have occurred near the center of the shopping mall, which was further expanded with the smoke spreading to the emergency exit [2]. Smoke spreading was analyzed based on two different scenarios; the first scenario was the case when a smoke control system was not operable so that the smoke was discharged through the exit only, and the second scenario was the case when a smoke control system was in operation, allowing the smoke to go out through both the exit and exhaust duct. The comparison was performed from the viewpoint of securing the evacuation time required [3].

2 Research

2.1 Selection of shopping malls and examination of the combustibles

The survey was carried out initially at 60 underground shopping malls in an operation in six metropolitan cities, of which results were categorized by type and in the 2nd stage, the shopping malls were grouped into the linear type and plaza type before finally selecting 16 large shopping malls to make it more comprehensive. The site survey was conducted at these 16 locations having 2,740 stores in total with 32 different types of business.

At the site survey, the total heat release of the stores was set as the value representing the combustion characteristics, and 1 to 3 stores were selected for sampling, making a total of 70 samples, and the survey to check the combustibles available within the store was carried out. The survey classified the combustibles into the fixed ones and movable ones. The fixed combustibles included interior decoration, showcase and office supplies, while movable combustibles included the goods displayed for sale. As a result, a total 953 combustibles were identified. The survey was aimed at identifying the type, raw material and weight of the combustible stuff, which served the basic data for estimating the heat release of each combustible.

2.2 Measuring the heat release per unit weight of the raw material (KJ/Kg)

A total of 953 kinds of combustibles checked as a result of site survey for measuring the heat release of the raw material were classified by type of raw material and consequently, a total of 49 types of raw material were determined, which are in detail 8 kinds of wooden material, 3 papers, 9 textiles, 12 synthetic resins, 13 inorganic material and 4 composite materials. The heat releases per unit weight of those materials were measured in accordance with ISO 5660-1.

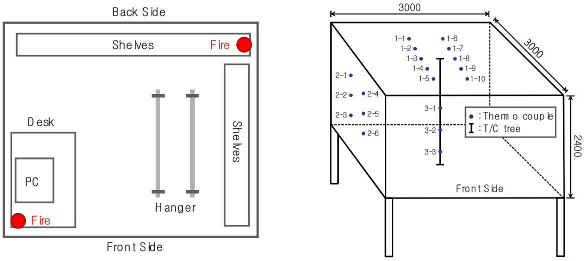
2.3 Estimate of total heat release of the combustibles (KJ)

To estimate the unique heat release of the combustibles identified in the wake of site survey, the heat release of the raw material measured was used. The unique heat release of each combustible was calculated in a way of multiplying the value of raw material by total weight.

2.4 A real scale fire test

Modeling of randomly selected clothing stores was carried out for a real scale fire test and numerical analysis as indicated in Fig 1. A fire-rated gypsum board sized, 3,000×3,000×2,400 mm was used, and the front side of the store was left fully open. K-type thermocouples, 6 inside the left wall, 10 inside the ceiling and

3 at internal space were arranged for monitoring the temperature. The fire initially occurred at 2 locations on the floor, one around the internal corner on the right side and another on the opposite side diagonally. A small amount of lamp oil soaked in cotton wool was used to set the fire. Total heat release based on estimated value of the combustibles was assumed to be about 2,500GJ and in the space, 2 large wooden showcases, 2 steel coat hangers, wooden desk and the computer made of plastic material were set up, and as the goods usually displayed, some clothes were put on a shelf, some on hangers and on the wall.

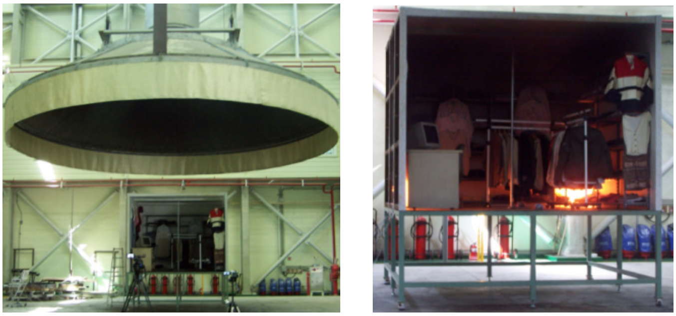


a. Top view b. T/C position

Figure 1: A real scale fire test model and thermocouples.

Table 1: Estimated heat release of the combustibles.

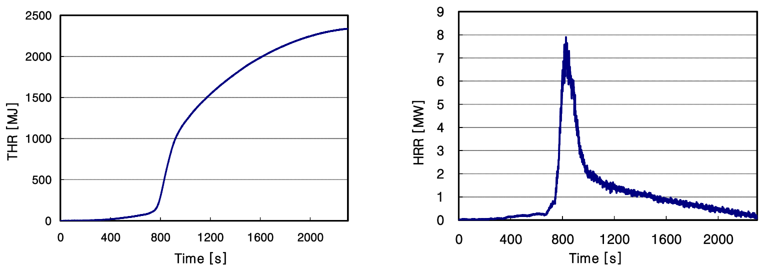
	Material	Heat release (MJ/kg)	Weight (kg)	Total HR (MJ)
Table	Wood 1	10.9	10.5	114.45
Showcase1	Wood 2	13.9	31.3	435.38
Showcase2	Wood 2	13.9	31.3	435.38
Computer	plastic	18.1	7	126.35
Casual wear	cotton	22.4	63	1,411.20
Estimated heat release of the store				2,522.77



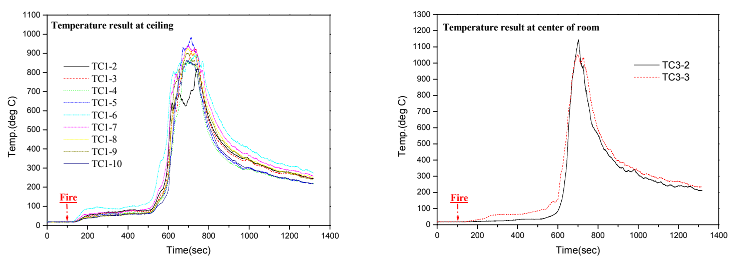
a. Store model b. fire setting

Figure 2: A real scale fire test.

A fire continued for about 40 minutes and Fig 3.a indicates the total heat releases. Fig 3.b indicates hourly discharged heat release. A fire gradually developed eventually reaching to a flashover state in 7 minutes, growing significantly, and in 10 minutes it reached its peak, indicating the max heat discharge before falling into the declining state. Total heat released was measured as 2,330 MJ with max hourly rate of 7,896 kW. The temperature at the time on the ceiling, internal sides and space were all monitored to have reached slightly more than 1,000ºC (Fig 3.c,d).



a. Total heat release b. Heat release rate



c. Ceiling temperature d. Internal temperature

Figure 3: Results of real scale fire test.

2.5 Numerical analysis

A numerical analysis of the single store was conducted with a real scale model sized, 3,000×3,000×2,400 mm comprising with grids, 100×100×100. The heat release of raw material, the wall, showcase, table, computer and the clothes were arranged to simulate the real store, and the fire was set at the two same locations as the real scale test. The positions for measuring the temperature were arranged as the real scale test, 10 on ceiling, 6 on left side wall and 3 in internal space. Fig 4 shows the model before and after numerical analysis.

A numeric operation was done in an abnormal course and the analysis equivalent to 1,600-second simulation was carried out. As a result, the maximum heat release rate appeared in 7.5–8MW section at 700–900 seconds, based on 800 seconds, and then a constant value with an average of 2MW was sustained at 900–1,300 seconds. Fig 5.a indicates the total heat release from a single store, while Fig 5.b represents heat release rate. When it comes to the total heat release, it appeared to have reached up to 2,300MJ at 1,300 seconds.

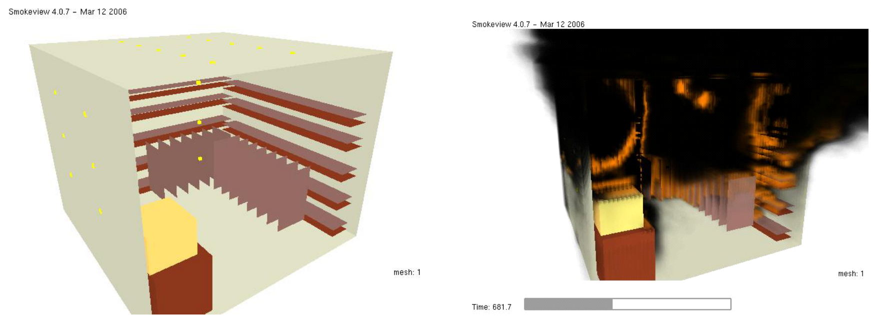
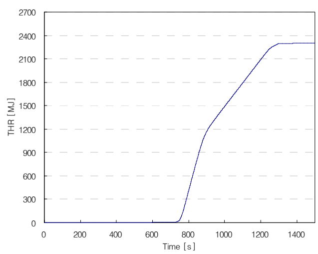
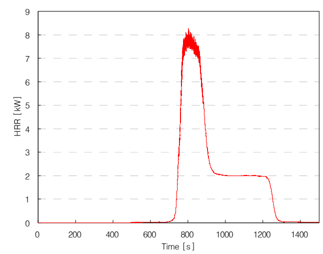


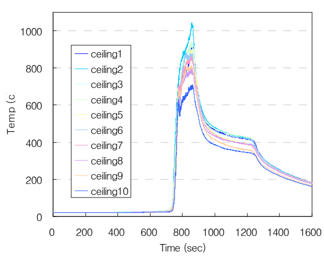
Figure 4: Numerical analysis model and combustion analysis.



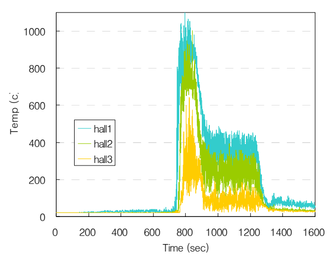
a. Total heat release



b. Heat release rate



c. Ceiling temperature



d. Internal temperature

Figure 5: Results of numerical analysis.

The heat is usually concentrated on the ceiling surface in line with the growing flame inside the building and it indicated a higher temperature than other parts. The temperature mostly rose up to 700–800ºC, and in case of #2, it reached to 1,100ºC. The temperature on the left wall and inside the building indicated the broad range of 400–1,000ºC (Fig 5.c,d).

When comparing with a real scale test of a single store, total heat release, heat release rate and temperature rising tendency appeared to be qualitatively consistent, and when comparing with the total heat release estimated before the test, the error was within a 8% range.

2.6 Estimate of fire load by category of business (kW/m^2)

Given the investigation of all combustibles at the stores totaled as many as 2,740 is practically unachievable, 2,740 stores were grouped into 32 categories, and one to three stores per category were randomly selected, making the sample stores 70, and the site investigation of these stores was carried out to identify the quantity, size and weight of fixed and movable combustibles. Using heat release per unit weight of the raw material, total heat release and fire load of each store were calculated. 70 stores were grouped into 32 categories to figure out the average fire load of sample store of each category, and the value calculated was considered as the fire load representing the category which it belongs to.

2.7 Performance criteria of smoke control system

The performance criteria of smoke control system for underground structure is not differentiated from those for the structure at ground level by domestic fire safety standards, and thus smoke-exhausting and air-supplying performance shall be in accordance with the common smoke control system. The air supply system may be either mechanical or a natural system, which has been generally adopted, and when it comes to exhaust system, relevant regulation requires using the mechanical system. Thus the shopping mall area was divided into a number of smoke control zones and the capacity required was determined based on each zone.

Table 2: Exhaust capacity and numerical grids of underground shopping malls.

Shopping mall No	Area (m^2)	No of store	No of zone	Exhaust (m^3/hr)	Total HR (x10^6 kJ)	No of grid for analysis
SM 1	977.2	32	1	50,000	903.61	347,760
SM 2	2,310.7	100	4	160,000	628.60	771,722
SM 3	2,975.4	97	3	130,000	2,096.77	996,604
SM 4	3,141.9	64	2	100,000	1,554.10	1,119,552
SM 5	3,676.3	82	3	150,000	1,774.98	1,213,632
SM 6	4,242.7	59	3	150,000	1,353.78	2,225,664
SM 7	4,566.8	105	6	280,000	1,713.88	1,549,464
SM 8	4,704.2	113	5	230,000	2,177.31	1,713,908
SM 9	7,080.3	230	5	230,000	4,316.65	2,455,600
SM 10	7,151.3	218	6	295,000	6,206.83	1,532,720
SM 11	7,640.1	286	7	345,000	7,751.77	3,007,648
SM 12	8,315.2	162	6	300,000	2,352.32	2,387,308
SM 13	8,830.7	224	6	300,000	3,021.31	3,248,546
SM 14	11,512.4	192	6	350,000	2,633.69	3,843,434
SM 15	12,234.5	481	13	510,000	6,585.25	6,095,096
SM 16	13,402.4	295	10	500,000	13,346.14	4,958,450

Table 2 indicates the smoke control zones at 16 shopping malls, which were determined according to the domestic fire safety standard, and the exhaust capacity required was estimated depending on each zone.

2.8 Numerical analysis at the underground shopping malls

To carry out the numerical analysis of 16 shopping malls, the modeling of each shopping mall in a real scale, providing the same number of stores and area, was conducted. Fig 6 is one of the models for numerical analysis, among 16 shopping malls. The combustibles based on fire load of each category were brought to each store, and the outlet of smoke control system was provided in the ceiling. The fire source was arranged at the center of the underground shopping mall so as to allow the flame and combustion gas to spread in a radial shape. The evacuation route was determined, calculating the short-cut to all exits. At 1m intervals along the evacuation route smoke detectors were allocated to calculate the time of spreading combustion gas and they were placed at 1.6m above the floor so as to monitor the time taken till the evacuation route is closed due to combustion gas coming down from the ceiling (Fig. 7).

The number of grids used for modeling is indicated in Table 2 and the grids were arranged in a form of rectangle multi-block, which were calculated by parallel process using multi-processor.

A numerical analysis was conducted based on two cases which were firstly, when the smoke control system was not operable so that fresh air comes and combustion gas goes out naturally through the exits only, and secondly, when the smoke control system was in operation so that the natural circulation of both the air and combustion gas could be made, while mechanical exhaust of combustion gas could also be made through the outlet in ceiling.

Figure 6: A real scale modeling.

Figure 7: Outlet and detection sensor for combustion gas.

3 Result and discussion

In the wake of monitoring the variation of heat release rate in both cases, as indicated in Fig 8, it appeared to have been significantly increased at all of 16 underground shopping malls due to a smoke control system in operation, which was attributable to more fresh air coming from the outside and mechanical exhaust of combustion gas that activated the combustion. Fig 9 is the example indicating the variation of spread speed of combustion gas at the shopping mall

#8. In getting closer to the fire source the difference tended to be getting smaller, indicating that the effect of the smoke control system appeared to be decreased as it gets closer to the fire source. As a result of monitoring the spread speed of combustion gas, no significant character was found, but when they were grouped to 5 categories as shown in Table 3, the tendency in common by group was monitored. No effect of smoke control system appeared in Group 1, which means no evacuation time could be provided at all, while the effect to some extent could be expected in Groups 2 and 3, but at the location within a certain distance, no sufficient time for evacuation could be expected. Hence, a redesign of smoke control systems to enhance the effect will be needed for the shopping malls belonging to Groups 1, 2 and 3. However, no performance design is required for Group 5 as the current smoke control system provides sufficient evacuation time.

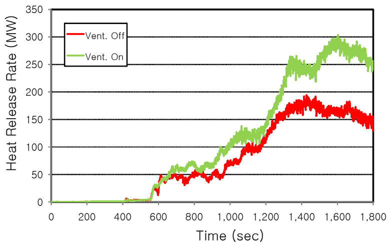


Figure 8: Variation of hourly rate of heat discharged.

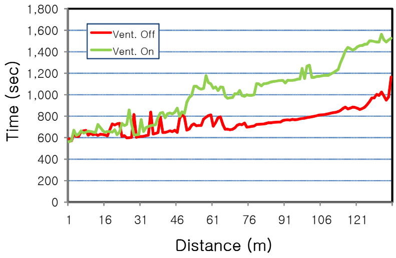


Figure 9: Variation of combustion gas detection time.

Table 3: Effect of smoke control system.

Group	Effect to prevent combustion gas from spreading	Shopping mall #	Number of stores
Group 1	None	1, 2, 6, 15	4
Group 2	0 second ~ 100 seconds	3, 4, 5, 7, 9, 12, 14	7
Group 3	100 seconds ~ 200 seconds	11, 13, 16	3
Group 4	200 seconds ~ 300 seconds		0
Group 5	300 seconds	8, 10	2

4 Conclusion

A numerical analysis was carried out using Fire Dynamics Simulator for the case when the smoke control system was in operation, and the system was not in operation during the fire and the outcomes were compared from the standpoint of evacuation safety.

As indicated in the outcome, as a result of applying the same standard, without consideration of spatial characteristics of underground structure and the fire load of combustibles stored in the space, the effect of the smoke control system designed to prevent the combustion gas from spreading at some shopping malls appeared not to have satisfied the certain level. This clearly implies that the system may not be able to provide the sufficient time required for safe evacuation for the people when the fire occurs at the underground structure which has been controlled according to the current fire safety standard uniformly applied to all structures.

Thus, to be able to provide the time required for safe evacuation for the people in the underground building when a fire occurs, the appropriate capacity of smoke control system shall be calculated, taking into account the structural characteristics of the building and fire load and combustion characteristics of the combustibles stored, which shall be eventually incorporated into the design using a performance design approach to finally determine the capacity to be provided.

Following this study, measuring the heat release per unit weight of various raw materials shall be carried out to produce more specific estimate of total heat release of the combustibles, and through the fire tests of diverse stores, the efforts to enhance the reliability of the values shall continue. Furthermore, the performance criteria of smoke control systems shall be established based on a performance design approach, thereby identifying whether or not the time for safe evacuation could be provided.

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