Full Scale Test of Smoke Leakage from Doors of a Highrise Apartment

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ABSTRACT

Check of smoke leakage of an entrance door,class A fire door, for highrise apartment was carried out in a full scale model using a model fire source which was designed to smolder 1 hour and then to flame. The door openable inward and outward with and without air tight material were used. A total 13 types of experimental conditions was carried out with major variables of door situation (open or close) and of pressure difference between fire room and corridor. Concentrations of smoke, gas, and smoke particles, pressure, temperatures,and weight of fire source were measured. No difference in smoke leakage performance between doors openable inward and outward was obtained. Smoke and combustion gas in corridor were hardly observed when the entrance door was closed, therefore it suggests clearly that the middle corridor is safe enough as an evacuation route when the door was closed.

KEY WORDS; FULL SCALE TEST, SMOKE LEAKAGE FROM DOOR, CLASS A FIRE TIGHT DOOR, SMOKE PARTICLES, FIRE DETECTOR, SMOLDERING

1. Introduction and Objective of this Work

The highrise apartment for this study has a star shape arrangement with middle corridor and veranda as two evacuation routes. There is danger of hot smoky gas filling in the middle corridor as if combustion gas comes out through/around the entrance door. It is very plausible that the residents would take the middle corridor as an evacuation route because they know it well. Therefore, it is necessary and important to keep the middle corridor free from fire products.

The objectives of this experimental study is to check the doors performance against smoke leakage under the conditions of pressure difference given between the fire room and corridor with using an early stage of a fire source which grows from smoldering to flaming. Fire detectors performance is also examined.

2. Fire scenario and Model fire source

The fire statistics shows that about 26% of fires is caused by a cigarette and about 29% of first item of fire development is occupied by a bedding and a sofa. The death rate in midnight is higher than the other period for resident fire. Concern with these situations, the fire scenario to follow is set. A lighted cigarette fell on a sofa and makes smoldering combustion first, then flaming which develops to involve the wallpaper and finally to flashover. The first two stages of the fire, about 1 hour smoldering and 10 min flaming, are adopted for this study as the model of an early development of fire.

(a) mockup cushion

Babrauskas(ref.1) reported that the optical smoke concentration (Cs) of 1/m was generated from a standard chair in 28.3 m^3 volume of fire room. Kawagoe and Mizuno(ref.2) also reported that a cushion gave 1-1.2/m of Cs. A sofa and two loungers, are like a bedding, were adopted as the first item of a fire. The smoke concentration from them is about 4-5 times greater than it from a chair. The volume of fire room is about 42.5 m^3 then the smoke load is expected to be about 200 $m^{-1}\cdot m^3$. Several kinds of mockup cushions fire had been tried in preliminary tests, and its smoke evolution repeatability was especially tested. The fire source adopted finally was consists of 60 cm X 60 cm X 6 cm(T) of polyurethane foam of about 240 g, cotton batting of 160 g, and thick cotton cloth of 270 g. It gave the smoldering duration of about 60 min and Cs V of about 70 $m^{-1}\cdot m^3$. Thus, three cushions were used simultaneously to give the designed smoke load. The average mass loss rate of a chair is about 6-8 g/sec for its first 10 min (ref.1,2) flaming. Therefore, the heat release rate of about 100 Kw for 10 min was planned to give by the alcohol burning.

(b) Full size fire source

A sofa of about 22.7 kg, two loungers of 9.3 and 8.8 kg, a wooden side table of about 8 kg, a wooden magazine rack of 0.5 kg, a 14' TV set with wood frame, carpet of 4 m X 4.5 m, wall- and ceiling paper, and a book stand of 90 cm width and 120 cm height with about 150 kg of books were adopted.

3. Experimental

Monthly average wind velocities in Tokyo area are about 2.9, 3.3, 3.0, and 2,8 m/sec for Jan., May, Aug., and Oct.. Thus 3 m/sec was adopted as an average wind velocity for estimation of the pressure difference between fire room and middle corridor. The corridor is semi-enclosed, therefore, coefficients of upwind and downwind pressures are reduced to half of them, compared with those of ordinary case. About 0.5 mmAq of pressure difference was given between fire room and middle corridor. The plan and vertical views of the facility is shown in Fig. 1. The total ventilating openings was controlled to adjust to the respective value of the real one by sealing off with tapes and putty.

Door 1 was a wooden partition door. Door 2 (inward openable) and door 3 (outward openable) are class A fire door. Leakage characteristics of the door was tested preliminary, and gave the performance of $Q = 0.22\cdot P^{0.76}$ $(0.5 \leq P < 20)$, where Q is ventilation air volume (m^3/h) and P is positive pressure difference (kg/m^2) between inside and outside.

In order to measure the smoke movement and concentration, extinction beams were set in as partly illustrated in Fig. 2. Temperature were measure by K-type thermocouples. The sample gas was introduced about 10 cm below the ceiling and was sent into the analysers. CO, CO2 and O2 gas concentrations were measured. The sample gas was then returned back to the respective section. Two kinds of smoke detectors, ionization (I.S.D.) and scattering type (L.S.D.) which were modified to give analog outputs, and also two kinds of heat detectors, rate of rise heat and fixed temperature type were employed. Simple weighing system was used which consists of load cells with a water jacket and of a bed or a platform. Outputs from many sensors were recorded every 2 min. The smoke filling and movements were also observed and recorded by camera and two sets of video system.

Experimental conditions of door openings, fire source, and pressure difference are shown in Table 1.

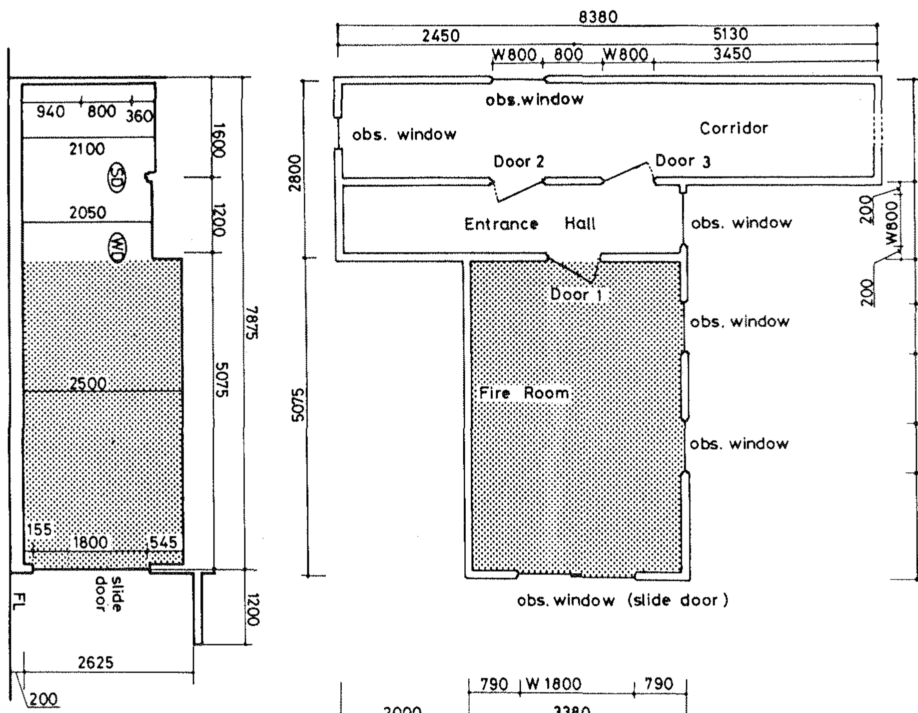

Figure 1 The plan view and vertical view of the facility for this experimental study. The mm unit is adopted for scale.

4. Results and Discussion

(a) Mockup cushions Fire

A pill of METHENAMINE with an electric heater which activated for 10-15 sec was used for ignition method.

The smoldering area on the mockup cushion increased circularly at the rate of about 1 cm/min in radius, and about 30 min after, burning zone developed into the foam. The typical results for weight loss versus time are shown in Fig.3. Each plot shows a remarkable tendency to cluster the curve. This indicates that every fire source gave almost same amounts of smoke, gas, and heat at the almost same release rates. Almost steady state of smoldering combustion at the rate of 15.5 g/min of three cushions was observed for 30-65 min. After 60 min, the alcohol was ignited and gave the heat release rate of about 107 kW for 10 min.

Fire Room

The average smoke filling rate was about 0.3 m/min. After 30 min, the smoke concentration increased rapidly based on the maximum weight loss rate and smoke concentration (Cs) of 4-5/m was observed for 50-60 min. CO and CO2 gas concentration gradually increased to about 0.2% and 1% at around the end of smoldering duration, and O2 decreased to 20.3%. In this period the ratio of CO/CO2 were almost constant of 0.2. At around the end of smoldering duration, average temperature rise in fire room was about 8 K with very flat temperature distribution along the vertical direction. This suggests that the fire detection applying temperature rise, both fixed type and rate of rise heat type, may fail in detection even in fire room for a smoldering fire. After 60 min, hot layer of 1 m thick under the ceiling indicated 70-80 K temperature rise above initial temperature and which drove the smoke and gas away to the entrance hall and gave the decreases in concentrations of smoke and gas. Little

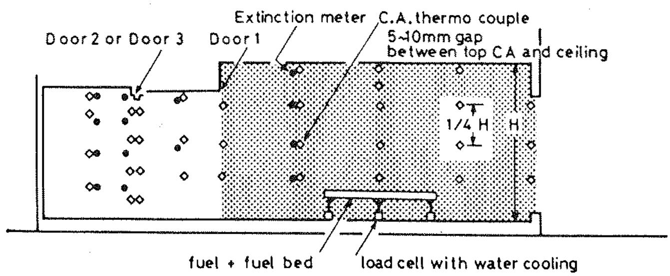

Figure 2 Some locations of measurements system for temperature and smoke.

Table 1 EXPERIMENTAL CONDITION

Exp. No.	Press diff.	Fire source	DOOR1 (1)	DOOR2 (2)	DOOR3 (3)	Slide door
PRE-1	0.5mmAq	REAL	CLOSE	OPEN	—	CLOSE
A - 2	0.5mmAq	CUSHION	CLOSE	OPEN	—	CLOSE
A - 3	N O	CUSHION	CLOSE	OPEN	—	CLOSE
B - 1	0.5mmAq	REAL	OPEN	CLOSE	—	CLOSE
B - 2	0.5mmAq	CUSHION	CLOSE	CLOSE	—	CLOSE
B - 3	N O	CUSHION	CLOSE	CLOSE	—	CLOSE
B - 4	N O	CUSHION	OPEN	CLOSE	—	CLOSE
B - 5	0 5mmAq	CUSHION	OPEN	CLOSE	—	CLOSE
C - 1	0.5mmAq	CUSHION	CLOSE	—	CLOSE	CLOSE
C - 2	N O	CUSHION	CLOSE	—	CLOSE	CLOSE
D - 1(4)	0.5mmAq	CUSHION	CLOSE	—	CLOSE	CLOSE
E - 1	0.5mmAq	CUSHION	OPEN	CLOSE	—	OPEN
ADD-1	0.5mmAq	CUSHION	CLOSE		CLOSE	CLOSE
ADD-2	0.5mmAq	CUSHION	CLOSE	CLOSE	—	CLOSE

wooden door(1) inward openable(2) outward openable(3)
without air tight material (4)

difference in smoke and gas concentrations was found independent of door 1 opened or closed. Table 2 and 3 show the concentrations of smoke and CO, CO2 and O2 gas in fire room, entrance hall, and middle corridor.

Entrance Hall

As door 1 was opened, smoke concentration in the entrance hall was almost the same level to that of in fire room. No measurement was carried out on CO, CO2 and O2 gas concentrations.

In contrast to this, as door 1 was closed, smoke concentration of Cs=0.1/m was observed at around 120 cm which almost corresponds to the height of eyes and nose and maximum temperature rise of 3-5 K was obtained at the end of flaming duration. However, thicker smoke of about 1/m was obtained under the ceiling and above the floor. CO and CO2 gas concentration were almost 1/5 to the ones in fire room in smoldering duration. After 60 min, an increase of smoke concentration of 0.7-1.2/m was observed, which was almost 1/3 - 1/2 of the concentration in fire room. Concentrations of CO and CO2 increased to 0.063-0.064% and to 0.7-0.9%, respectively. The apparent dilution ratio between fire room and entrance hall depend on gas concentration change was about 1/3 which is almost equal ratio to the one estimated by Cs change. 3-5 K of temperature rise was observed at the end of smoldering duration, and in flaming duration about 40 K was obtained under the ceiling indicating the triangle shape distribution with about 0.2 K/cm along the vertical direction. If there were no apparent natural convection and flow in an entrance hall, it is almost certain that

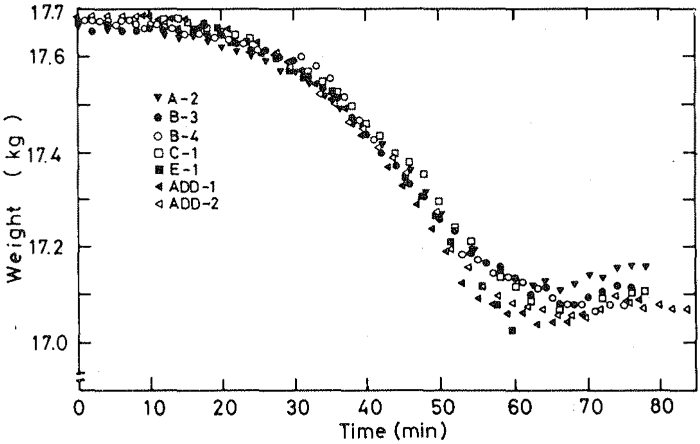

Figure 3 Weight loss of mockup cushions versus time.

Table 2 SMOKE CONCENTRATION ($Cs; m^{-1}$)

FIRE ROOM	DOOR 1	ENTRANCE HALL	DOOR 2or3	CORRIDOR
Cs = 4~5 → 60 min after → Cs = 2~2.4	OPEN	Cs = 4~5 → 60 min after → Cs = 2~2.4	CLOSE	Cs = 0
Cs = 4~5 → 60 min after → Cs = 2~2.4	CLOSE	Cs = ~0.1 (max. 0.7~1.2) → 60 min after → Cs = 0.7~1.2	CLOSE	Cs = 0
Cs = 4~5 → 60 min after → Cs = 2~2.4	CLOSE	Cs = ~0.1 (max. 0.7~1.2) → 60 min after → Cs = 0.7~1.2	OPEN	Cs = 0.1~0.2 → 60 min after → Cs = 0.7~0.8

the hall which is partitioned even by a simple wooden door is safe enough to use as an evacuation route.

Middle Corridor

The smoke leakage from the entrance door was hardly measurable even in the flaming duration which gave about 5 mmAq pressure difference between fire room and corridor.

In contrast to this, when entrance door was opened, smoke concentration at the front of entrance door was about 0.1-0.2/m and peak concentrations of CO gas was 0.011-0.013% and of CO2 was 0.053-0.06% which were about 1/3 to the ones in entrance hall, and the ratio of CO/CO2 of 0.2 was conserved in smoldering duration. After 60 min, smoke concentration increased to 0.7-0.8/m with time delay of about 2 min. Little dilution on smoke concentration was observed with it parts when it was driven to corridor from entrance hall. Smoke moved so slowly with drifting and conserved its distribution like a smoke-cloud. This kind of smoke movement was also reported as the movement in a long corridor (ref.3). Table 2 shows the almost the same smoke concentrations were observed in entrance hall and in corridor after flaming, and these are almost 1/3-1/2 to the one in fire room. The upper limit of smoke concentration which begins to give serious emotional fluctuation to residents is about Cs of 0.1-0.15/m (ref. 4), and Cs of 0.7-0.8/m gives walking speed of 0.3-0.7 m/sec (ref. 5). This tells that there is a strong fear of smoke blocking against the evacuation in middle corridor when door was opened. Closing of door 2, independent of door 1 opened or closed, produced about 1/30 CO gas concentration relative to one in fire room. As can be seen from Table 3, this concentration level may give an enough time to evacuation before toxic gases rise up to serious levels.As the closed entrance door without air tight material gave the smoke concentration of about 0.3-0.5/m about 10 min before the flaming period. The smoke contaminated region was found at least 4 m for both side from the entrance door. Little temperature rise was measured in corridor even in the flaming duration. Therefore, these phenomena strongly suggested that it is necessary to set the auto door closer and air tight material to the entrance door.

Table 3 GAS CONCENTRATIONS (%)

FIRE ROOM	DOOR 1	ENTRANCE HALL	DOOR 2 or 3	CORRIDOR
CO = 0.2 CO_2 = 1.0 O_2 = 20.3 60 min after CO = 0.2 CO_2 = 2.0 O_2 = 18.5	CLOSE	CO = 0.037 ~ 0.047 CO_2 = 0.20 O_2 = 20.7 ~ 20.8 60 min after CO = 0.063 ~ 0.064 CO_2 = 0.7 ~ 0.9 O_2 = 20.03	CLOSE	CO = 0.0048 CO_2 = 0.048 O_2 = 20.81 60 min after CO = 0.0056 CO_2 = 0.069 O_2 = 20.78
CO = 0.2 CO_2 = 1.0 O_2 = 20.3 60 min after CO = 0.2 CO_2 = 2.0 O_2 = 18.5	CLOSE	CO = 0.037 ~ 0.047 CO_2 = 0.20 O_2 = 20.7 60 min after CO = 0.063 ~ 0.064 CO_2 = 0.7 ~ 0.9 O_2 = 20.03	OPEN	CO = 0.011 ~ 0.013 CO_2 = 0.053 ~ 0.060 O_2 = 20.9 60 min after CO = 0.023 CO_2 = 0.11 ~ 0.12 O_2 = 20.83
CO = 0.2 CO_2 = 1.0 O_2 = 20.3 60 min after CO = 0.2 CO_2 = 2.0 O_2 = 18.5	OPEN	NOT MEASURED	CLOSE	CO = 0.0048 CO_2 = 0.048 O_2 = 20.81 60 min after CO = 0.0056 CO_2 = 0.069 O_2 = 20.78

Pressure change and air ventilation rate

In the smoldering duration, very little pressure difference was obtained, but pressure jumped up to about 5 mmAq based on alcohol burning. This high pressure difference resulted in a

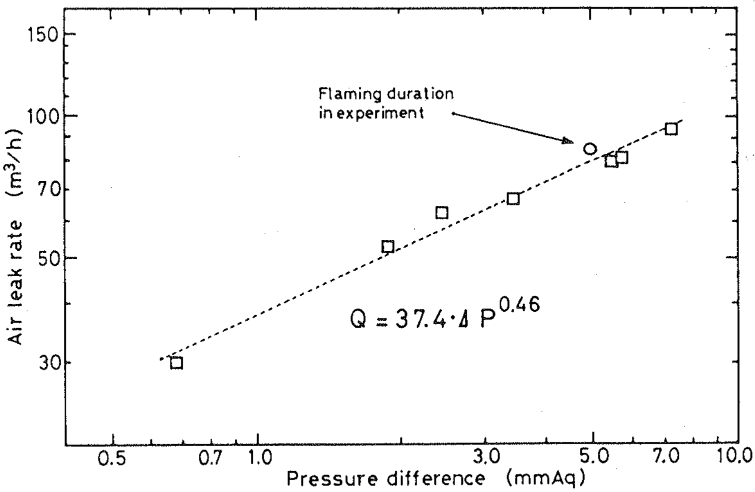

Figure 4 Logarithmic plots of air leak rate against pressure difference between fire room and corridor.

greater ventilation rate through many small openings, then negative pressure difference of about -10 mmAq was given to the fire room depend on O2 consumption. Air exchange rate during smoldering and flaming was monitored using a tracer gas. The air exchange rate estimated by the tracer gas concentration change was 1.1/h for smoldering and 1.8/h for flaming for this facility. The relationship between pressure difference and air volume of leakage was tested preliminarily with using a fan with controller and a Venturi tube. This gave the relationship of $Q = 37.4 P$,as shown in Fig.4. Air exchange rate in flaming duration is shown with a circle in Fig. 4.

No difference was found in the leakage behavior of smoke through/around the entrance door with or without the pressure difference which was given to estimate the natural wind effect.

Working time of fire detectors

The working times of smoke fire detectors estimated based on their outputs and are shown in Fig. 5. These figures tell the apparent tendency that L.S.D. worked a little earlier than I.S.D. did in fire room, and roughly the opposite tendency was obtained in entrance hall. And in corridor, the I.S.D. worked in a few cases of entrance door opened, and of the door without air tight material. These working behaviors may come from the difference in size distribution of smoke particles which was induced by the difference of diffusive characteristics depend on particle size. Number concentration and mobility of larger size smoke particles is small relative to smaller ones (ref. 6). And for smaller size particles, I.S.D. can work earlier relative to L.S.D.(ref. 7). It is plausible that these situation gave the earlier detecting time to I.S.D. relative to L.S.D. In this series of experiments, observation windows which connects to outside were closed except E-1. An attention should be called on that the ambient air in fire room, in entrance hall, and in corridor was very still, no apparent air flow was given except the flows induced by flame or by pressure difference. These caused no excess driving force when particles gets into the labyrinth of L.S.D. In real case, air flow induced by natural and/or forced convection give the adequate movement to particles. Therefore, no significant difference on working times is expected between both types of smoke detector when they mounted to the ceiling of entrance hall which connects to fire room.

No heat detector worked in smoldering duration even in fire room. It was apparent that smoke detectors are advantageous to heat detector on a smoldering fire.

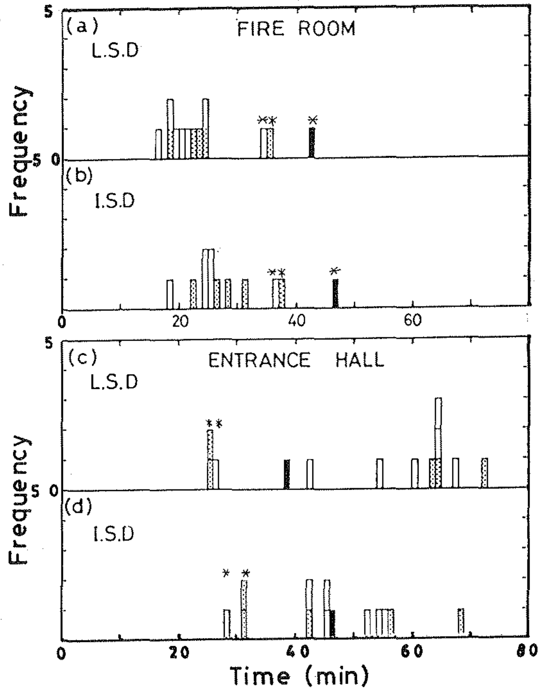

Figure 5 Frequency of smoke detector of light scattering type (L.S.D) and ionization type (I.S.D) in fire room and in entrance hall. Histogram with * is door 2 open, with mesh screen is pressure difference given, and with rigid one is real furniture fire source.

(b) Real Furniture Fire

In smoldering duration, the changes of temperature, smoke concentration, gas concentration depend on growth of fire were almost as same as ones which were observed for mockup cushions fire. At around 50 min, smoldering zone developed into the foam of back part of the sofa, then after past 60 min, it reached to a small amount of alcohol which was set preliminarily to get a flaming combustion. Flaming combustion grew rapidly inside the back space of the sofa and at about 65 min developed to wallpaper and to other combustible materials. Rapid temperature rise was observed and which gave pressure difference of over 5 mmAq, which was beyond the range of our system. Hot dense smoky gas exhausted giving hiss through the gaps of aluminum sash of slide door. Combustible hot gas which drifted under ceiling burned toward down drawing a layer of 30 - 50 cm thick. This burning phenomena were observed at least twice in about 1 min before break down of slide door. Temperature, smoke concentration, and number concentration of particles covering 0.2-2.0 μ by 5 steps of channel isolation were monitored in corridor. Increase of temperature and smoke concentration which were measured by employed system were hardly observed both in flaming duration and after flashover. Fig. 6 shows the number concentration of particles versus time. When entrance door was open, it is clear of smoke coming into corridor as shown in Fig. 6-(a). In contrast to this, as the entrance door closed, the number concentration of particles increased little till about 30 min, and slightly increased for 30-40 min. And at around 50 min and after, apparent increasing were obtained in each channels as shown in Fig.6-(b),(c). The measurable upper limit of the number concentration for covering range of 0.2-0.5 μ, was about 2 x $10^{11}/m^3$ depend on coincidence loss (ref. 8). Therefore, it is better to use the number concentration of channel 4 and channel 5 to compare the leakage performance. For example, the case of entrance door open, number concentration of 1.0-2.0 u particles was 10 times greater than one in case of entrance door closed.

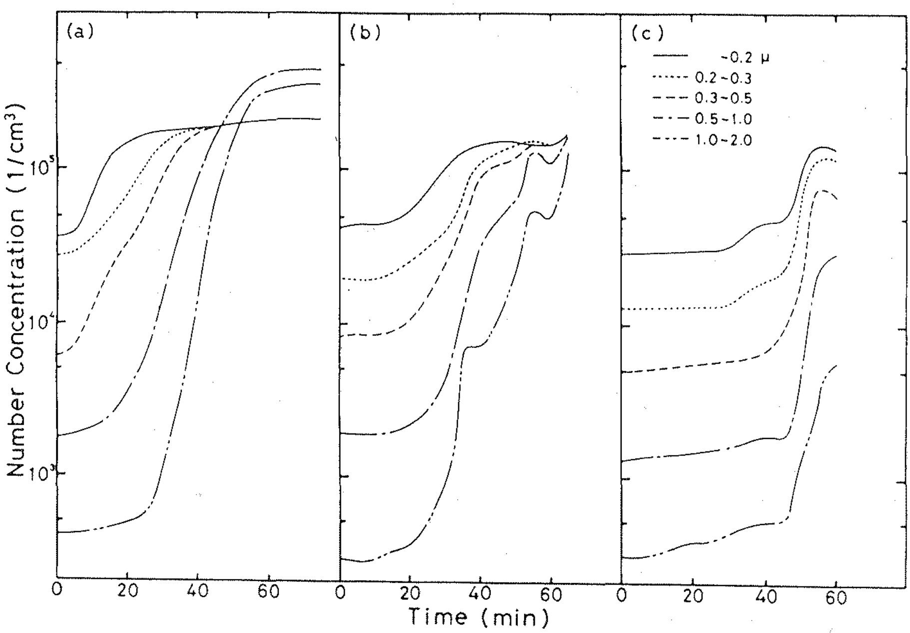

Figure 6 Time histories of number concentration of smoke particles, (a) Exp. A-2, (b) Exp. B-2 for mockup cushions and (c) Exp. B-1 of real furniture fire.

5. Conclusion

In the middle corridor, smoke leakage from the entrance door(class A fire door with air tight material) was hardly observed even the fire room was pressurized as high as 5 mmAq or more by fire. However, the door without air tight material permitted the smoke leakage of over 0.1/m of which concentration must give the disorientation to residents. Therefore, the key point of successful evacuation using a middle corridor depends on closing of the entrance door and installation of an auto door close and an air tight material.

No difference was obtained with respect to the smoke leakage performance between inward and outward openable door with the pressure difference given between fire room and corridor. If the entrance door satisfy the smoke leakage performance as mentioned above, a criterion of door selection whether it opens inward or outward primarily depends on security performance and on the matter of convenience for usual use. However, it is preferable to adopt a outward panic door which installed in a middle corridor to confirm the compartmentation and evacuation.

It was hard to expect the early detecting of smoldering fire by heat detector. In the fire room, light scattering smoke detector worked earlier relative to ionization smoke detector , however the difference in the working time between them were not serious. Considering a development of fire growth from smoldering to flaming and a fire with flaming at its starting and also considering on the reduction of total number of detectors to be mounted to a residential compartment, ionization smoke detector is advantageous to the other detector as a residential fire detector except the consideration on the frequency of false alarm.

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