

Using Odors to Detect Fire in a Study with Rooms Reduced to 75%Size

Kamiya K.^{1,*}, Sugawa O.¹, Watanabe N.²

¹ *Suwa University of Science, Department of Mechanical and Electrical Engineering, Chino, Nagano, Japan*

² *Graduate School of Suwa University of Science, Engineering and Management, Chino, Nagano, Japan*

*Corresponding author's email: kamiya@rs.sus.ac.jp

ABSTRACT

Odors related to scorching are emitted by substances undergoing oxidative pyrolysis during combustion. In this study, changes in odor quality were investigated and used to detect fire. Selecting a fire detector that would operate because of an odor change required appropriate gases for recognizing fire to be selected. Odor gases created during the oxidative pyrolysis of wood and synthetic polymers were used as standard gases to allow appropriate gases to be selected. The standard gases were then used in combustion experiments in model rooms in which heat was generated rapidly using a combustible fluid or slowly from smoldering material. Precursor oxidative pyrolysis odors were identified for various test materials. The odors that were generated depended on the type of combustible material present, so wood and plastics were both used to generate standard gases. Already available fire detectors and the measured odor changes were compared, and it was found that odor changes were detected at the same time as or after the fire was detected by the fire detectors when the fire was spreading rapidly or when the detectors and odor sensor were close to the fire source. However, detecting odor changes was faster than using the fire detectors for smoldering fire with little flame.

KEYWORDS: Fire detection, electronic nose, reduced-sized rooms, odor index.

INTRODUCTION

Fire detectors are installed in buildings to allow fires to be detected quickly and to alert the residents to allow them to fight the fire and/or escape. Installing fire detectors in homes became mandatory in Japan in 2004, and this led to deaths caused by fires decreasing every year. There were > 27% fewer deaths caused by fire in 2016 than in 2005 [1]. This proved that fire detectors save lives. Smoke, heat, and flame sensors are widely used in fire detectors, but it has been found that CO sensors are also effective at detecting fire [2]. Multi-criteria fire detectors in which CO, temperature, and smoke sensors are combined are currently being studied [3–5]. Fires emit odors in addition to heat, smoke, and toxic gases such as CO [6]. Odor is often the first sign of fire to be noticed by the people in the building affected. The size of the molecules that make up odor is approximately 10^{-10} m, while smoke particles are 10^{-8} to 10^{-7} m. Therefore, odor molecules are diffused by thermal air currents from fire more quickly than smoke particles, and it may be possible to detect a fire more quickly using odor than using smoke. We have performed tests using odor identification sensors to detect odor changes during the oxidative pyrolysis of wood and plastic [7–8]. We found that oxidative pyrolysis caused dramatic odor changes and increased odor strength [9–10]. Mixtures of chemicals are responsible for the odors produced, so determining the concentrations of specific substances was not helpful. Here, odors related to fire are therefore selected experimentally and then used as

Proceedings of the Ninth International Seminar on Fire and Explosion Hazards (ISFEH9), pp. 1210-1220

Edited by Snegirev A., Liu N.A., Tamanini F., Bradley D., Molkov V., and Chaumeix N.

Published by Saint-Petersburg Polytechnic University Press

ISBN: 978-5-7422-6498-9 DOI: 10.18720/spbpu/2/k19-57

reference odors to allow a fire to be detected from odor changes. The results obtained using the system in full-sized and reduced-size fire experiments are compared with the results obtained using other fire detection systems.

EXPERIMENTAL

Odor analysis

An FF-2A electronic nose (Shimadzu, Kyoto, Japan) with ten oxide semiconductor sensors (to imitate receptor proteins in the nose) was used. The data obtained were subjected to multiple classification analysis to characterize the sensor signal patterns. The electronic nose detected the overall odor molecule balance rather than individual chemicals (which would be the case using analytical methods such as gas chromatography mass spectrometry). The electronic nose was exposed to standard gases and produced indices that were used to determine the degrees to which the standard gas odor components were similar. A calibration curve was produced for each index using the sensor responses at different standard gas concentrations [11]. Studies were performed to develop similarity indices to represent odor quality. The methods used to analyze the indices are described below. The similarity indices indicated the degree to which the sensor response patterns represented the nine standard gas odor types. Calculations were performed using angle θ between the standard gas vector and sample gas vector in the 10-dimensional space created by the responses of the 10 sensors. The similarity index was 100% (i.e., the sample gas was the same as the standard gas) at $\theta = 0^\circ$ and 0% at $\theta >$ the acceptable angle β ($\sim 5^\circ$).

Selection of fire type and recognized odors

The gas generated when a test material was heated in a TG-8120 thermogravimetry–differential thermal analysis system (Rigaku, Tokyo, Japan) was collected in an odor bag attached to the exhaust port of the system. A sample (~ 5 mg) was placed in an aluminum pan. The reference material was alumina, the atmosphere was purified air (G3), the flow rate was 300 mL/min, the temperature was increased at 10 °C/min, and the final temperature was 550 °C. A new odor bag was attached every 5 min, and 1.5 L of gas was collected in each bag. Odor gases released from the sample before thermal decomposition started to occur were collected by passing purified air through the instrument with the sample in place immediately after heating started. Each gas sample was diluted by a factor of 5–20 (depending on the odor intensity) with pure N₂, then the odor was assessed using the electronic nose. Wood and plastic test samples were analyzed. Four of the wood samples were from coniferous trees (hemlock, Japanese cedar, Japanese cypress, and pine), three from broad-leaved trees (Japanese oak, kihada, and white birch), and one from bamboo. Each wood sample was ground using a WB-1 Wonder Blender (Osaka Chemical, Osaka, Japan), and only particles that passed through a 200-mesh screen were tested. The effects of water in the wood samples were minimized by keeping the samples in a desiccator containing silica gel at room temperature for at least 15 days before the tests were performed. Nine types of pure plastic were used. These were low-density polyethylene, high-density polyethylene, polypropylene, polystyrene, acrylonitrile butadiene styrene, poly methyl methacrylate, polyvinyl alcohol, Nylon 66, and polycarbonate. Each plastic sample was cut into small pieces before being used in a test.

Reduced-sized fire experiments

Fire experiments were performed using actual-sized rooms to allow the abilities of the odor detection system and existing fire detection systems to be compared. The comparison allowed a system for identifying the status of a fire from the odor emitted to be developed. The results indicated that the system reliably detected fire from the odor emitted.

One-room model fire experiment

A mock-up of one room (floor surface area 5.4 m²) in a regular house was used as a model space for a fire experiment. The layout of the room is shown in Fig. 1. The room was 2.4 m × 2.4 m × 2.4 m. The room had a suspended ceiling with 0.3 m space above (making the actual ceiling 2.7 m high). The walls were covered with 12.5 mm gypsum board, and the ceiling was covered with 9 mm gypsum board. The floor was covered with 12 mm plywood, and that was covered with 3 mm finishing plywood. The room had a sliding glass window with an air vent on one side and an entrance door on the other. The window was closed and the door was partly opened, leaving a 19 cm gap. The room contained a polyester sofa (1.2 m × 0.43 m × 0.7 m), a bookcase containing comic books, and a wooden television stand with a 20-inch display set on top. A wooden structure measuring 30 mm × 40 mm × 300 mm was the fire source. Kerosene (400 g) was sprinkled on the structure and the floor around, then a fire was started at the base of the structure. The weight of the wooden structure, room temperature, concentrations of gases of interest in the room, and odors emitted were measured during the experiment. Temperature measurements were made at 39 points, which were mainly inside the room (e.g., the wall behind the sofa). Gas concentrations were measured at four points (including inside the room and by the door) using CGT-7000 gas analyzers (Shimadzu). Odor gases were collected at five points. Three points were in the center of the room, at 1.6 and 2.4 m above the floor and 2.55 m above the floor (i.e., above the suspended ceiling) One point was above the entrance door 1.8 m above the floor, and the other point was on the wall behind the sofa 2.4 m above the floor. The odor samples were collected using MV-6500VP pumps (Enomoto Micro Pump, Tokyo, Japan). Each odor sample was collected into an odor bag, and a new odor bag was fitted at each sampling point every minute throughout the experiment. Each collected odor sample was diluted by a factor of 5–50 with pure N₂ and then analyzed using the odor analysis system. The nine standard gases stipulated by the Japanese Offensive Odor Control Law were used, and 11 commercially available types of gasoline and kerosene were used.

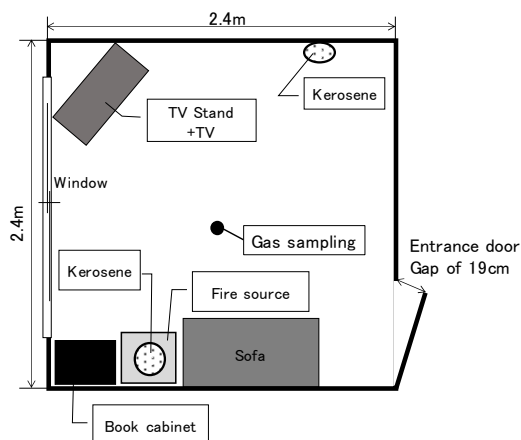


Fig. 1. Layout of the model room used in the one-room experiment.

Two-room model fire experiment

A mock-up of two rooms, each 2.4 m × 2.4 m × 2.4 m, connected by a 0.9 m × 2 m opening was used in another fire experiment. The room layouts are shown in Fig. 2. The walls and ceiling were covered with two-ply gypsum board and the floor was covered with two-ply plywood, which was then covered with poly (vinyl chloride) cushioned flooring. Each room had a double-glazed sliding glass door, each with an air vent. Each room contained a foam sofa (1.2 m × 0.6 m × 0.9 m) with a polypropylene cover, a wooden bookcase containing comic books, and a wooden television stand with a display set on top. Two tatami mats were placed in the center of each room. Tatami mats are

flooring materials used only in Japan. Each tatami mat was made of polystyrene foam between insulating boards sandwiched between wooden boards. The sliding glass doors were both closed. The fire source was 1 L of kerosene sprinkled on the tatami mats in Room A. The fire was started using a lighter. The weights of the tatami mats, room temperatures, concentrations of gases of interest in the rooms, and odors emitted were measured during the experiment. Temperature measurements were made at 46 points, mostly inside the rooms (e.g., by the sofas). Gas concentrations were measured at seven points (including 0.4 and 2.35 m above the floor in the center of each room) and at the air vents using CGT-7000 and PG-330 (Horiba, Kyoto, Japan) meters. Odor gas samples were collected at three points (2.35 m above the floor in the center of each room and in the center of the upper part of the door frame). Each odor gas sample was collected using a pump connected to an odor bag. The odor bag at each sampling point was replaced every minute. A type 2 photoelectric spot sensor and a type 2 differential sensor (Nittan, Tokyo, Japan) were attached to the ceiling in each room, and the response time for each sensor was compared with the time taken for an odor change to be detected. Each odor gas sample was diluted with pure N₂ by a factor of 5–50 and then analyzed using the odor analysis system. Gas emitted during oxidative pyrolysis was used as the reference gas.

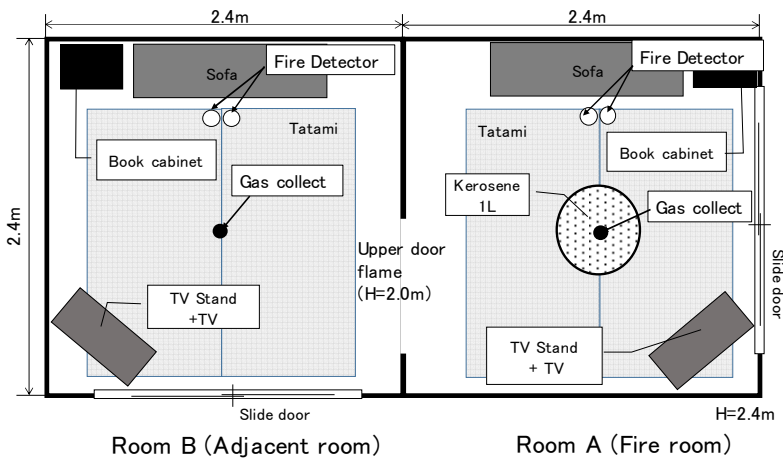


Fig. 2. Layouts of the model rooms used in the two-room experiment.

Reduced-sized experiment in part of a two-story house

Another experiment was performed in a mock-up of three rooms at 75% of the actual size. Each room was 1.8 m × 1.8 m × 1.8 m. Two rooms were on the ground floor and one on the upper floor. The room layouts are shown in Fig. 3. The two ground-floor rooms were connected by a 30 cm hanging partition wall. There was a 0.36 m² opening, representing a staircase, in the center of the floor of the upper-floor room. The upper-floor room had two sliding glass doors, which were each left with a 10 mm opening. The rooms were constructed to allow smoke and gases generated in the fire-outbreak room (on the ground floor) to pass around the hanging partition wall and spread into the adjoining room and through the opening in the center of that room to the upper floor, meaning the smoke and gas could flow and diffuse throughout both floors. The walls and ceilings were covered with 12.5 mm thick single-ply gypsum board, but one wall was made of 4 mm thick polycarbonate sheet, to allow the fire and smoke flow to be observed. No furniture or other items were placed in the rooms. Temperature measurements were made at 28 points, including at the point the combustible material was placed, in front of the hanging partition in the room in which the fire was started, and along the vertical axis of the center of the rooms on each floor. Odor and gas concentrations were measured at eight points, including directly above the fire source, in the center of the room in which the fire was started, in front of the hanging partition in the room in which the

fire was started, and on the surface of the upper-floor ceiling. Odor gas samples were collected into bags using MF-1 pumps (IBS, Osaka, Japan), and the odor bag at each sampling point was replaced every 30 s during the experiment. A type 2 photoelectric spot sensor and a type 2 differential sensor (Nittan) were attached to the center of the room in which the fire was started and in the upper-floor room, and the response time for each sensor was compared with the time taken for an odor change to be detected. Each odor gas sample was diluted by a factor of 5–50 with pure N₂ and then analyzed using the odor analysis system. Gas emitted during oxidative pyrolysis was used as the reference gas. Odor from an experiment lingered within each room during subsequent experiments. The odor gas from the previous experiment was used as the baseline for each experiment to remove the effects of the odor remaining from the previous experiment. Tests were performed using three types of combustible material to identify odors emitted by different combustible materials. In the first experiment, three 100% cotton towels were placed on top of an electric heater. In the second experiment, three polyethylene bags each containing 5–10 sheets of A4 paper were placed in a plastic garbage box and ignited using an electric heater. These experiments did not involve flammable liquid.

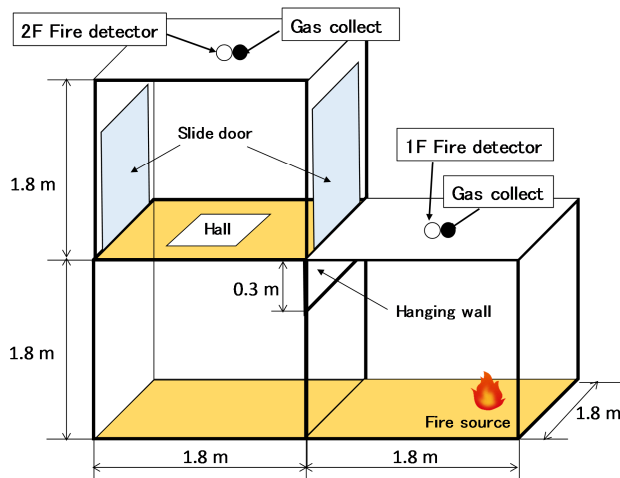


Fig. 3. Layout of the rooms used in the experiment using part of a two-story building.

RESULTS AND DISCUSSION

Selection of odors for recognizing fire

The odor measurement results for the gas collected during the oxidative pyrolysis of Japanese cedar wood are shown in Fig. 4. The results for four of the nine sensors are shown. The odor sensor outputs reached maxima at between 220 and 270 °C, indicating that the Japanese cedar wood was actively emitting odorous gases in this temperature range. The gas emitted between 220 and 270 °C (in the section marked (1) in Fig. 4) and the gases emitted between 170 and 220 °C (in the section marked (2) in Fig. 4) were used as standard gases for detecting fire in subsequent experiments. For the other 15 materials, the gases emitted when the maximum sensor output was found and in the step before were used as standard gases (1) and (2), respectively.

Reduced-sized fire experiments

One-room model fire experiment

The fire in the one-room model experiment caused the sofa-side sliding window to crack 110 s after the fire was ignited and the other side to crack approximately 180 s after the fire was ignited. The

heat generation rate was calculated from the weight loss rate and the unit heating value for the material. The heat generation rate increased immediately after the fire was ignited, and the equation $Q = at^2$ gave an a value of 0.38, indicating that the fire spread extremely quickly [12]. The heat generation rate decreased ~180 s after ignition, and the fire was extinguished by spraying it with water 660 s after ignition. The odor and gas concentration results are shown in Fig. 5. The gas concentrations 2.4 m above the floor in the center of the room are shown in Fig. 5(a). The similarity indices for the reference odors for kerosene and hydrocarbons are shown in Fig. 5(b) and 5(c), respectively.

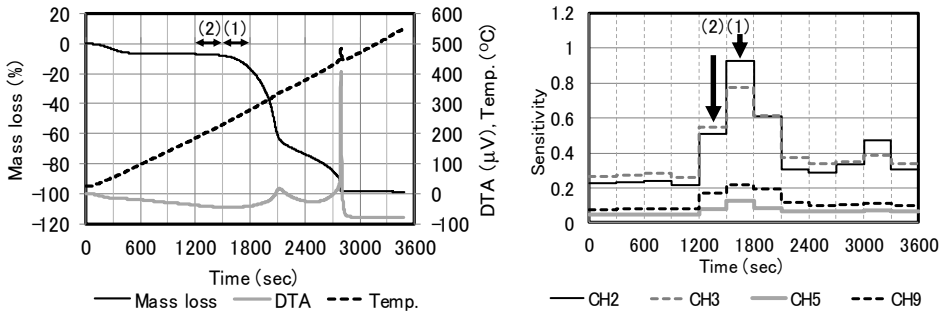


Fig. 4. Thermogravimetry–differential thermal analysis results and electronic nose sensor responses for Japanese cedar wood.

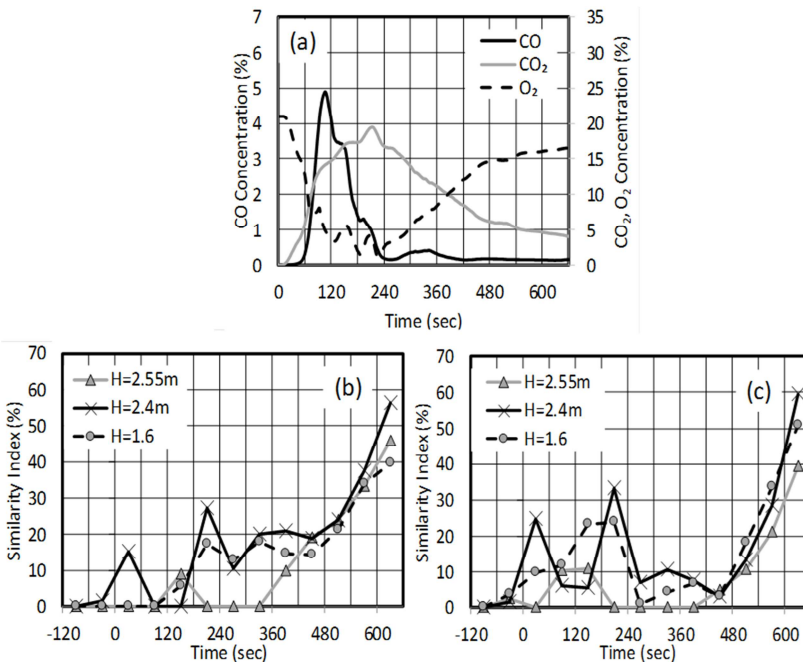


Fig. 5. Gas concentration and odor measurement results for the full-sized one-room experiment.

(a) Gas concentrations 2.4 m above the floor in the center of the room, (b) kerosene similarity index for the odor, and (c) hydrocarbons similarity index for the odor.

Each odor measurement was plotted in the middle of the time period in which the measurement was made (i.e., at 30 s for a 1 min sample). It should be noted that kerosene was sprinkled from -60 to 0 s and the fire ignited at 0 s. It can be seen from Fig. 5(a) that CO and CO₂ reached the ceiling 30 s after ignition. Oxygen deficiency occurred at 110 s before the window glass cracked, and this

caused the CO concentration to reach a maximum immediately before the window glass cracked, after which the fresh air that entered the room allowed the fire to continue burning. The maximum CO₂ generation rate occurred ~180 s after ignition, when the fire approached its maximum intensity. It can be seen from Fig. 5(b) that the kerosene similarity index increased between -30 and 30 s at all measurement points except for the point 2.55 m above the center of the room (above the suspended ceiling), indicating that the kerosene that had been sprinkled on the floor could be detected. It can be seen from Fig. 5(c) that the hydrocarbons similarity index increased as the fire spread for 60 s after ignition at all measurement points except the point above the suspended ceiling. This may have been because of the effects of the fire itself and of the kerosene sprinkled in the room. The aldehydes similarity index increased during the oxidative pyrolysis of wood and plastics in a previous study but not in this study. In this experiment, aldehydes were generated during the pyrolysis of the wood samples, but they were probably pyrolyzed and oxidized shortly after being generated because the fire intensity increased extremely quickly.

Two-room full-sized experiment

The odor measurement results for room A (the room in which the fire was started) and room B (the adjacent room) for the Japanese cedar and PS standard gases are shown in Fig. 6.

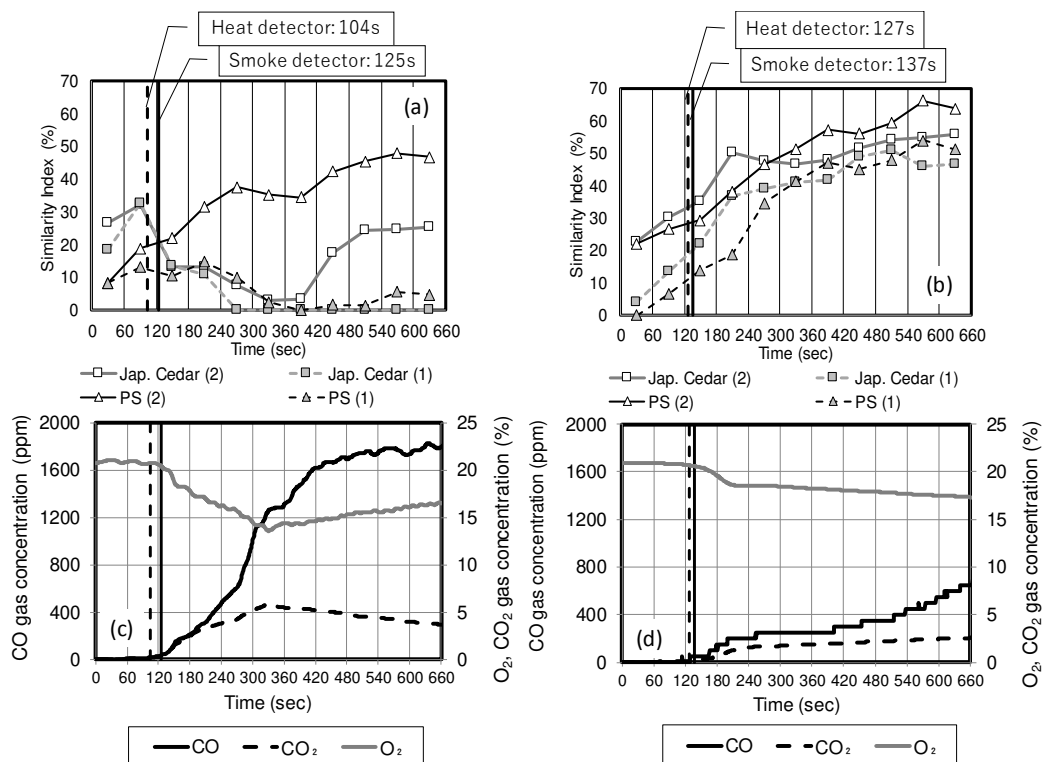


Fig. 6. Gas concentration and odor measurement results for the full-sized two-room experiment. (a) Odor results for room A (the room in which the fire was started), (b) odor results for room B (the room adjacent to the room in which the fire was started), (c) gas concentrations in room A, and (d) gas concentrations in room B.

Each measurement was plotted in the middle of the collection period (i.e., at 30 s for a sample collected for 60 s). The heat and smoke sensors in room A reacted 104 and 125 s after ignition, respectively, and the heat and smoke sensors in room B reacted 127 and 137 s after ignition, respectively. The Japanese cedar and PS similarity indices for rooms A and B increased for 60 s after ignition, then the sensors reacted, indicating that the odors generated by the wood and PS had

changed. The Japanese cedar and PS similarity indices for reference gas (2) were high in room A, but the similarity indices were low in room B. The increase in the PS similarity index suggested that burning and pyrolysis in room A transferred from the wood in the tatami mats to plastic in the first 120 s after ignition. We concluded that the odor gases generated in room A entered and accumulated in room B (which was a confined space with no outlet), causing the Japanese cedar and PS similarity indices in room B to increase over time. The CO and CO₂ concentrations in room A 120 s after ignition were ~50 ppm and 0.5%, respectively, and the concentrations in room B were ~0 ppm and 0.25%, respectively. This indicated that fire could be detected earlier by monitoring odor changes than by measuring gas concentration changes.

Reduced-sized model of part of a two-story house

In the test using towels as the fire source, the towels emitted a little smoke 230 s after starting the electric heater. The fire did not develop to the flaming combustion stage during the 600 s of measurements. The smoke sensors in the room in which the fire was started on the ground floor reacted at 316 s, but the other sensors did not react. The odor and gas concentration measurement results for the test using towels as the fire source are shown in Fig. 7.

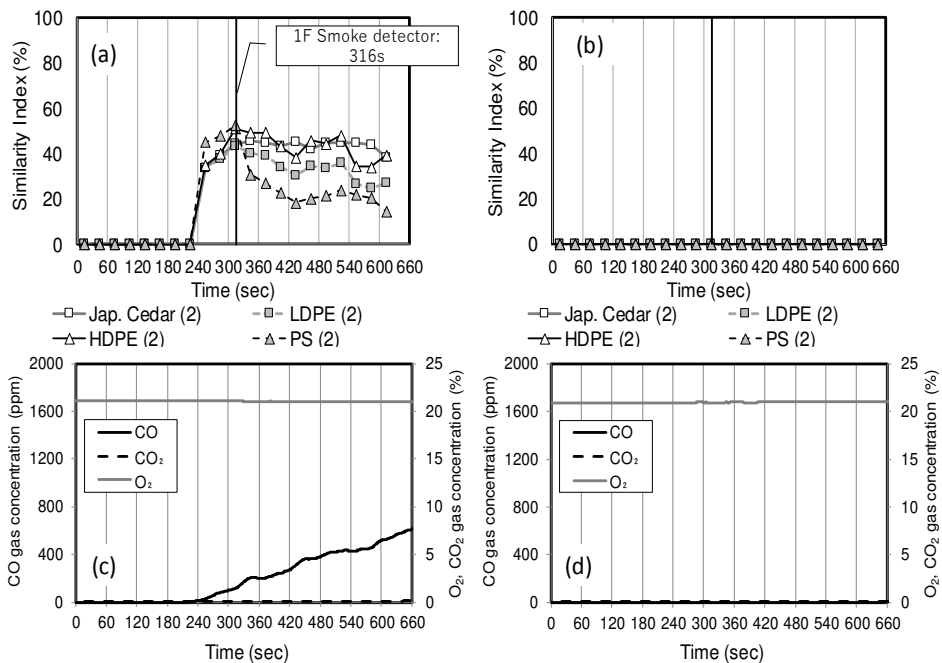


Fig. 7. Odor and gas concentration measurement results for the two-floor house model when towels were used as the fire source. (a) Odor results for the center of the ground-floor room in which the fire was started, (b) gas concentration results for the center of the ground-floor room. (c) Odor results for the center of the upper-floor room, (d) gas concentration results for the center of the upper-floor room.

It can be seen from Fig. 7(a) that the odor in the center of the room in which the fire started changed between 240 and 270 s. The PS (2) similarity index was slightly lower than the Japanese cedar (2) similarity index, low-density polyethylene (2) similarity index, and high-density polyethylene (2) similarity index. Wood and polyethylene emit materials containing aldehyde groups during oxidative pyrolysis. Emissions of large amounts of materials containing aldehyde groups during the slow oxidative pyrolysis of the cotton towels could therefore explain the high similarity indices for Japanese cedar and polyethylene. It can be seen from Fig. 7(b) that the gas concentrations on the ground floor started to increase 240 s after ignition and that the odor changed and CO was emitted

at almost the same time but that the CO₂ concentration did not change. Odor change was detected >30 s before the smoke and fire sensors reacted. The odor and gas concentration measurement results for the upper floor are shown in Fig. 7(c) and 7(d). The short duration of this experiment meant that not enough heat was produced to provide the buoyancy required for the odor gases to reach the upper floor, so the fire sensors did not react and no odor or gas concentration changes were observed.

When the garbage box was used as the fire source, smoke was emitted 14 s after ignition and flames were observed at 26 s. The heat and smoke sensors on the ground floor operated after 53 and 154 s, respectively, and the smoke detectors on the upper floor operated after 262 s. The fire transitioned to the flaming combustion stage immediately after the electric heater was switched on, and this caused heat and smoke generated by combustible plastic to be observed at an early stage.

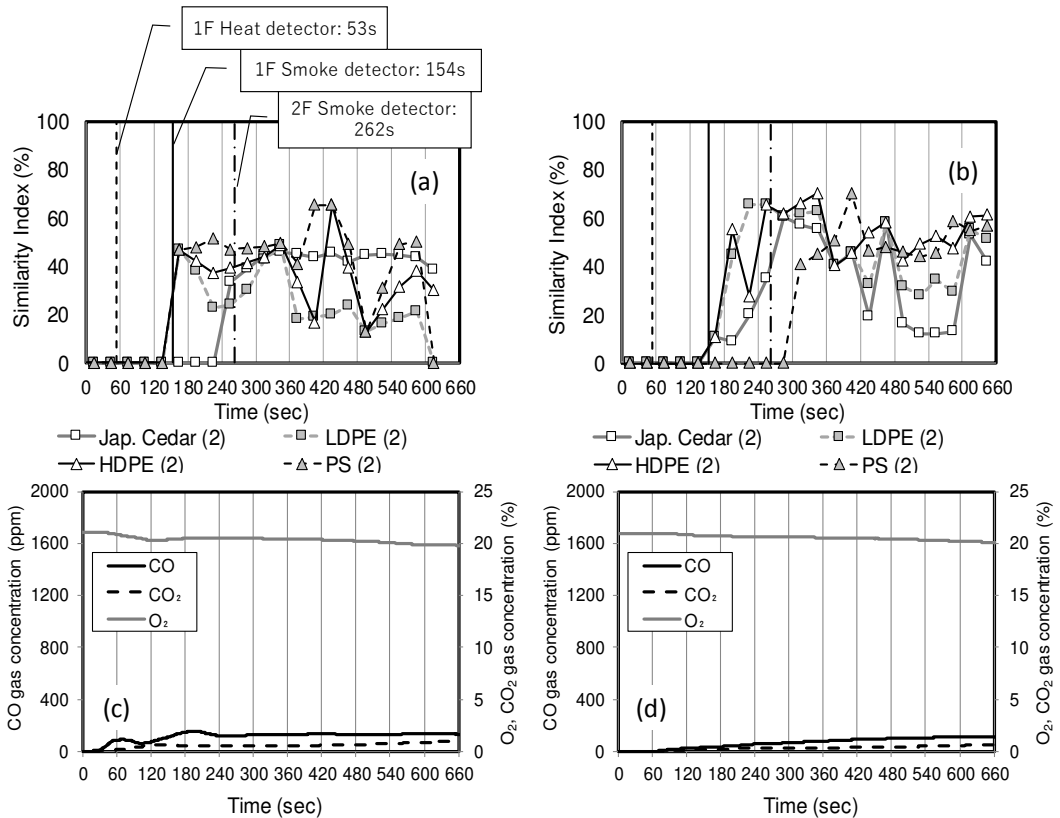


Fig. 8. Odor and gas concentration measurement results for the two-floor house model test when a garbage box was used as the fire source. (a) Odor results for the center of the ground-floor room in which the fire was started, (b) gas concentration results for the center of the ground-floor room. (c) Odor results for the center of the upper-floor room, (d) gas concentration results for the center of the upper-floor room.

The results of the experiment performed using combustible material in the garbage box are shown in Fig. 8. The odor before the experiment was performed the first time (i.e., with no smoke odor present) was used as the baseline odor, and the similarity indices for all the standard gases increased relative to the indices before ignition. Odor changes were only found in the test using a garbage box to start the fire because the odor from the previous experiment was used as the baseline. The odor on the ground floor changed from 150 s. This was around 100 and 25 s later than the ground-floor heat and smoke sensors, respectively, reacted. The CO concentration increased by ~50 ppm 30 s after ignition and to 100 ppm later, but the large increase found in the experiment using towels to

start the fire was not observed. The odor similarity indices increased after 150 s, indicating that the odors became stronger. Odor change on the upper floor was observed at 180 s, which was ~80 s before the upper-floor smoke sensors reacted. The standard sensor systems reacted quickly near to the fire source, but odor change was observed sooner than the smoke sensors reacted on the upper floor because of the degree to which flow and dispersion affected the upper floor. The plastic similarity indices increased more rapidly than the Japanese cedar similarity index for both the ground and upper floors, indicating that different combustible materials emitted different odors.

CONCLUSIONS

Appropriate reference gases need to be selected to allow fire detectors based on odor changes to recognize a fire. Odor gases created during the oxidative pyrolysis of wood and synthetic polymers were therefore used as standard gases. These standard gases were used in combustion experiments in which heat was generated rapidly by sprinkling a combustible fluid in a model and also in model fire experiments involving smoldering combustion. The precursor odors of oxidative pyrolysis for each material could be detected because these standard gases were used. Different odors were generated by different types of combustible material, so we concluded that one of the best options was to use both wood and plastic materials to provide standard gases.

The results obtained using already available fire detectors and the odor change system were compared, and odor change was detected at the same time or later than the other fire detectors reacted when the fire was spreading rapidly or the sensors were close to the fire source. However, odor changes were detected more quickly than the other fire detectors reacted when the fire was smoldering and had only small flames. Various odors (such as those produced during normal activities) will be emitted in a room, but the results of this study indicate that misdetection of fire by the odor sensor system can be prevented by using odorous gases from the room as the baseline for the measurement period.

ACKNOWLEDGMENTS

This study was partly supported through a grant-in-aid for scientific research (Basic Research B, grant No. 15H02982) for the financial years 2015–2017.

REFERENCES

- [1] Japanese Fire and Disaster Management Agency, Overview of the 2017 White Paper on the Fire Service, No. 2018, 2018, pp. 68–71 (in Japanese).
- [2] M.A. Jackson, I. Robins, Gas Sensing for Fire Detection: Measurements of CO, CO₂, H₂, O₂, and Smoke Density in European Standard Fire Tests, *Fire Saf. J.* 22 (1994) 181–205.
- [3] N.L. Ryder, Multicriteria Detection: Leveraging Building Control and Comfort Sensors for Fire State Determination, *Proc. 16th Int. Conf. Autom. Fire Detect. I* (2017) 349–355.
- [4] A. Mensch, T. Cleary, A Comparison of Carbon Monoxide Gas Sensing to Particle Smoke Detection in Residential Fire Scenarios, *Proc. 16th Int. Conf. Autom. Fire Detect. I* (2017) 363–370.
- [5] G. Arndt, S. Suchy, D. Vialkowitsch, Multi-criteria/Multi-sensor Early Fire Detection in the Engine Compartment of Road Vehicles: Evaluation Process of Gas Sensors, *Proc. 16th Int. Conf. Autom. Fire Detect. II* (2017) 47–54.
- [6] D. Kohla, A. Eberheim, P. Schieberle, Detection Mechanisms of Smoke Compounds on Homogenous Semiconductor Sensor Films, *Thin Solid Films* 290 (2005) 1–6.
- [7] O. Sugawa, K. Kamiya, Y. Oka, Evaluation on Odor Intensity and Quality from Plastic and Wood Materials in Pre-combustion Condition, *Proc. 15th Int. Conf. Autom. Fire Detect. II* (2014) 21–28.

- [8] K. Kamiya, O. Sugawa, T. Imamura, Y. Oka, Experimental Study of Odor Intensity and Quality for Wood Materials Undergoing Oxidative Pyrolysis, *Bull. Jpn. Assoc. Fire Sci. Eng.* 63 (2013) 25–35 (in Japanese).
- [9] K. Kamiya, O. Sugawa, H. Kanai, T. Imamura, Y. Oka, Evaluation on Odor Intensity and Quality from Wood in Pre-combustion Condition, *Proc. Asia Pac. Symp. Saf.* (2011) 344–347.
- [10] O. Sugawa, K. Kamiya, Experimental Study on FT-IR Analysis of Chemical Species from Wooden Materials in Pre-combustion Condition, *Proc. 16th Int. Conf. Autom. Fire Detect. I* (2017) 371–378.
- [11] J. Kita, Y. Aoyama, M. Kinoshita, H. Nakano, H. Akamaru, Technical Digest of the 17th Sensor Symposium (2000) 301–305.
- [12] R.L. Alpert, Ceiling Jet Flows, in: M.J. Hurley et al. (Eds.), *SFPE Handbook of Fire Protection Engineering*, third ed., Springer, New York, 2002, pp. 429–454.