AN EXPERIMENTAL STUDY ON THE PHOTOELECTRIC OPTICAL SMOKE DETECTOR RESPONSE

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ABSTRACT

This study investigates the fire safety problem of a smoke detection system in terms of the probable response of light scattering photoelectric smoke detectors. In particular, response characteristics of the smoke detectors were studied experimentally in a test chamber described in UL268, with cotton wick generated fire smoke flowing at a velocity between of 0.5 ms^{-1} and 3 ms^{-1}. Measurements of a 'base case' detector, i.e. a detector installed with a sensing chamber, a sensor screen and an outer casing, were compared with those of three other casing configurations: (1) a detector with the sensing element freely exposed; (2) a detector with a sensing chamber; and (3) a detector with a sensing chamber and a sensor screen. It was reported that the amount of fuel burnt, the smoke movement velocity and the detector configuration would have significant influences on the detector response. A detector response constant k for a photoelectric smoke detector in the smoke movement velocities was proposed to correlate the optical density attenuation and the changes of detector output signal. This response constant would be useful in development of design parameters for specifying response characteristics of a photoelectric smoke detector in fire detection system.

KEYWORDS: Optical smoke detector, Photoelectric, Response, Experiment

INTRODUCTION

A photoelectric light scattering optical smoke detector, as an integral part of a smoke detection and early warning system for fire safety, is designed with a light source and a photosensitive sensor in a way that the sensor would receive scattered light rays in a case of fire smoke aerosols enter the detector [1]. The detector would generate a fire alarm signal which is proportional to the light intensity perceived by the sensing element. A fire alarm is raised if this signal level reaches a preset alarm criterion. Photoelectric smoke detectors have been installed extensively in indoor spaces as essential building provisions to provide early warning and notification of probable fire emergency to building occupants and fire brigade. They are also employed as an automatic actuating device for some fire suppression systems and interfaced with some heating, ventilation and air-conditioning (HVAC) systems.

It was believed that a building featured with a smoke detection system would enhance the fire safe level to the building. Some fire statistics reported that the use of smoke detection systems would reduce fire deaths and injuries [2]. However, unwanted activations of a smoke detector were reported to be the source of most nuisance fire alarms in buildings. In the late 1990s and early 2000s, cases of false fire alarm accounted for 50% of the fire calls in America, New Zealand and Britain [3]. Indeed, the false fire was at the top of the list of fire calls from 2001 to 2005 [4] in Hong Kong; in 2005, the false fire alarm accounted for 77% of the total fire calls. Nuisance alarms from smoke detectors responded to non-target sources became a fire safety concern. The evaluation of smoke detector response is thus an important consideration for a fire detection system. However, not many studies in open literature for characterizing smoke detector response regarding its configurations in typical fire smoke environment were available.

The response of a photoelectric smoke detector depends on parameters concerning the smoke aerosol characteristics, the transport phenomenon of the aerosols and the type of detector sensor[5,6]. The dynamics of smoke aerosols generated by a fire, the aerosol transport process to the detector and signal generation of the detector sensor would be taken as influencing factors to explain the response of a smoke detector[7]. However, the estimation without accounting for the smoke particulate coagulation would underestimate the detector response for a light-scattering type smoke detector [8]. Ventilation airflow in a fire compartment would dilute the smoke aerosols that an overall smoke level would be insufficient to trigger the smoke detection system [9,10]. The casing geometry of a smoke detector would be a key element of local smoke property transportation from the detector external environment to the detector internal sensing chamber [10, 11].

Smoke detector response regarding the smoke movement velocity, fuel type and detector design can also be studied in a 1.7 m long, 0.5 m wide and 0.5 m high test chamber specified in UL 268 [12, 13]. Various smoke tests were used to study the smoke detector response to different fuel types. A manufactured home environment modelled common residential or commercial settings [9]. The NIST fire-emulator/detector-evaluator (FE/DE) investigated the time-varying speed, temperature and concentration (of gas and particulate) condition expected in the plume above an early stage fire source [10]. In the tests, smoke aerosols were generated by typical cooking activities, smoking, candle lighting, etc. which displayed characteristics of nuisance alarms frequently occurred in usual occurrence. Despite the use of the broad range of fuels in these smoke tests and the confirmation of the effect of fuel type on the response of smoke detector, the exact correlation between the property generation and detector response were not detailed, probably due to insufficient experimental data. The detector response characteristics for practical engineering applications were not fully examined in detail.

This paper investigates the response characteristics of a light scattering photoelectric optical smoke detector with cotton fire smoke at a velocity between 0.5 to 3 ms^{-1} in a test chamber set-up to standard UL 268. It was proposed that the smoke detector response would be characterized by a proportional constant for the smoke movement velocity and optical density at the detector for certain fuel burnt.

DETECTOR RESPONSE TIME

The smoke detector response time t_s would be related to the detector signal Ψ_t due to fire smoke at a smoke optical density D_t and at a smoke movement velocity v_g at a time t from the time of ignition t_o [6, 9, 10]:

$$t_s = f(\psi_t) \sim f(v_g, D_t) \qquad [1]$$

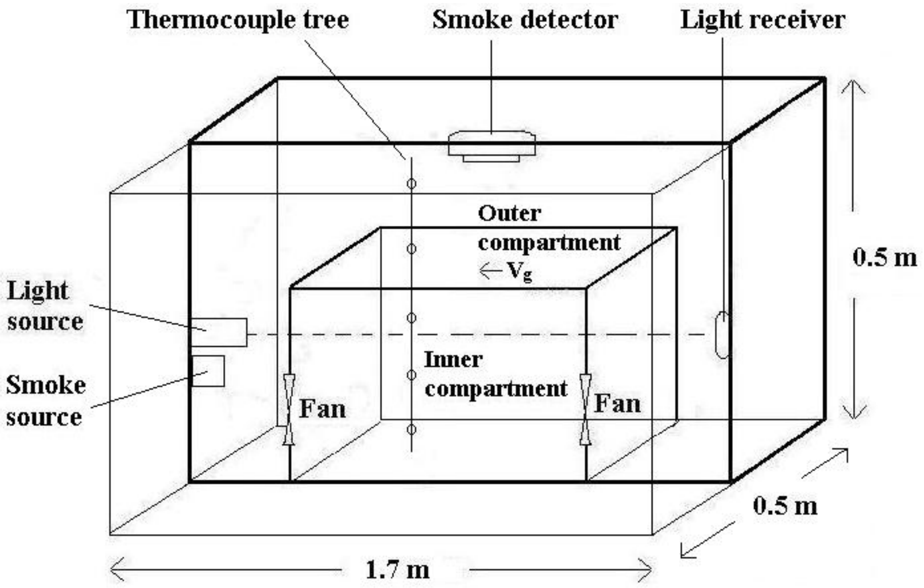
It is proposed that the unit increment of the fire alarm signal is proportional to the unit reduction of the smoke optical density by the detector response constant k, where, Ψ_t and Ψ_{to} are the fire alarm signal levels of the detector reported to the detection system at the time t and the time of ignition t_o; D_t and D_{to} is the smoke optical density at the time t and t_o respectively.

$$\frac{\psi_t - \psi_{to}}{t - t_o} = k\left(\frac{D_t - D_{to}}{t - t_o}\right) \qquad [2]$$

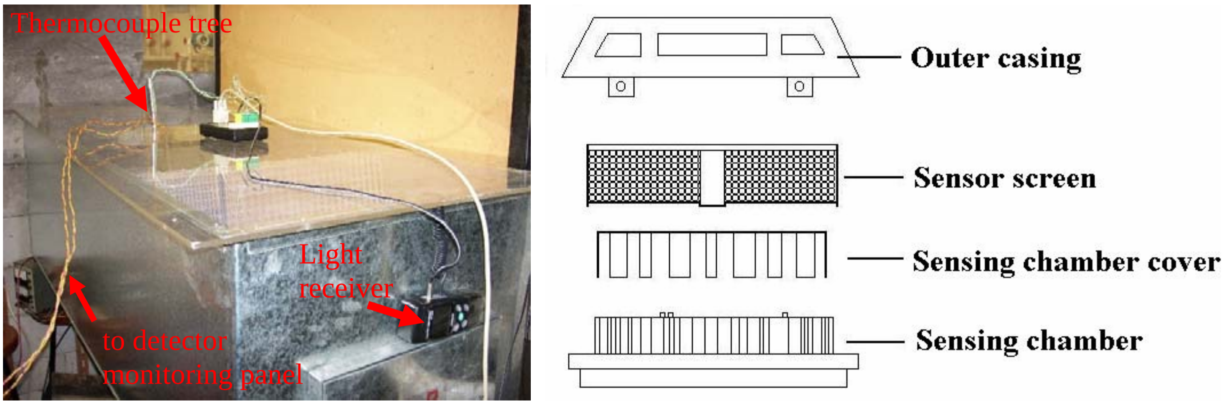
The smoke optical density D_t (bels) is given by [5]:

$$D_t = \log_{10}\left(\frac{I_t}{I_o}\right) \qquad [3]$$

where I_o and I_t and are light intensity through a path length of smoke free condition at time t_o and smoky condition at time t respectively:



(a) Cross-sectional view



(b) Photo **(c) Assembly of a photoelectric type smoke detector**

FIGURE 1. UL268 standard for smoke detector test

EXPERIMENTAL SETUP

The experimental work of this study was conducted in a testing chamber whose design was based on the smoke box used the sensitivity test in the Underwriter's Laboratories standard UL 268 [12]. The UL standard listed the sensitivity requirement for smoke detector actuation at a minimum velocity and optical density limits for gray and black smoke which is generated by smouldering cotton wick and flaming kerosene. The pictorial and cross-sectional view of the testing chamber is shown in Figs. 1(a) and (b).

The whole testing chamber, comprising an outer cabinet and an inner compartment, was made of zinc metal sheet except the removable top covers which were made of transparent plastic for viewing purpose. A 0.015 m diameter hole was located at the centre of both top covers for temperature and air flow measurements. The outer cabinet had overall dimensions of 1.7 m long, 0.5 m wide and 0.5 m high. An exhaust port measuring 0.5 m in width by 0.5 m in length was provided at the right end. An inner compartment of size 1 m long, 0.5 m wide and 0.3 m high seated at the centre at the centre of the outer cabinet. Its internal surfaces were painted mat-black to avoid the reflection of the shiny metallic surface.

Two 24V AC circulation fans whose operating voltage could be varied from 0 to 24 volts were installed at each of the two ends of the inner compartment to regulate the smoke flow velocity. An air stream straightener was constructed of piles of white plastic honeycomb, with overall dimensions of 0.07 m by 0.17 m by 0.45 m. It was placed in the upper part of the outer cabinet to promote uniform and homogenous air flow in the testing chamber. The air velocity at the detector location was regulated by the four circulating fans and confirmed by using an anemometer with random measurements in the testing chamber before the commencement of each experiment.

A type K thermocouple tree comprised a total of six sensors was used for temperature measurement, five of which measured the temperature variation of testing chamber at 0.05 m, 0.15 m, 0.25 m, 0.35 m and 0.45 m vertically from the testing chamber floor whereas the remaining one was connected to the light receiver. The type K thermocouple reference table was used to convert the temperature reading to the corresponding voltage level which represented the voltage fluctuation of the light receiver. A light receiver and a constant light source rated at six volts DC were mounted opposite to each other at the two ends of the upper part of the outer compartment to measure the light intensity I. A smoke source was placed in the outer compartment, upstream to the circulating airflow.

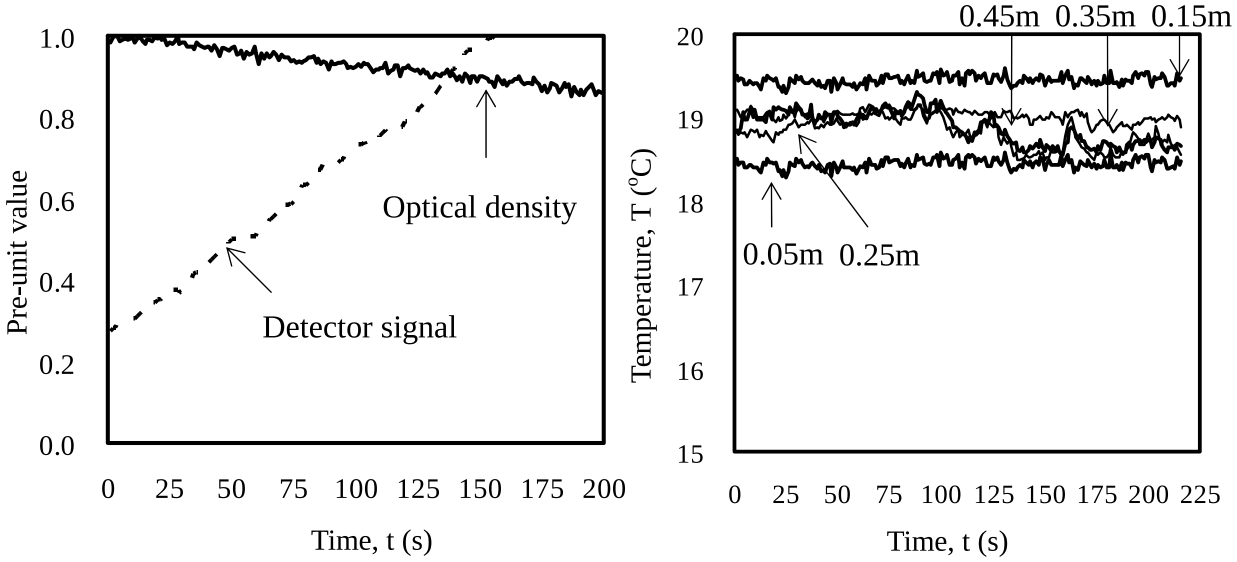
Two photoelectric scattering type smoke detectors were mounted in the outer compartment and the fire alarm signal level Ψ was recorded by a monitoring panel external to the chamber. The assembly of a test smoke detector consisted of an inner sensing chamber covered by a black sensor chamber, which is enclosed by a silvery grey sensor screen and a creamy white outer casing as shown in Fig. 1(c).

In the experiments, the smoke was generated by smoldering burn, either from one piece or two pieces of cotton wick; each was 0.13 m in length and 0.538 g in weight. Smoke detector signals were measured for smoke generated and the measurements repeated at, velocities of 0.5 ms^{-1}, 0.8 ms^{-1} and 3 ms^{-1} and with four detector configurations. The four configurations were (1) with the sensing chamber only, i.e. no screen was installed; (2) sensor screen installed; (3) chamber cover installed and (4) normal smoke detector, i.e. no cover was removed. A total 24 test conditions were conducted with combinations of the four detector configurations, the two fuel quantities and the three velocities (i.e. $4\times2\times3=24$). Measurements were repeated up to 24 trails for each testing conditions for reliable measurement results.

RESULTS AND DISCUSSION

Sample test results of detector signals, optical density and smoke temperature for detector with configuration (4) are shown in Fig. 2. During the test, burning the cotton wick caused the optical density D_t (bels) decreased and the detector signal increased Ψ_t. When the detector signal Ψ_t reached a certain preset action level, the fire control panel would produce a warning alarm. It was observed that the optical density in the test chamber gradually declined until the end of the burning process and this was explained by an increased smoke particle concentration generated by the fuel burning. Fairly constant temperature profiles in the experiments were reported as shown in Fig. 2(b) and therefore the influence of temperature change to the detector response was kept minimal.

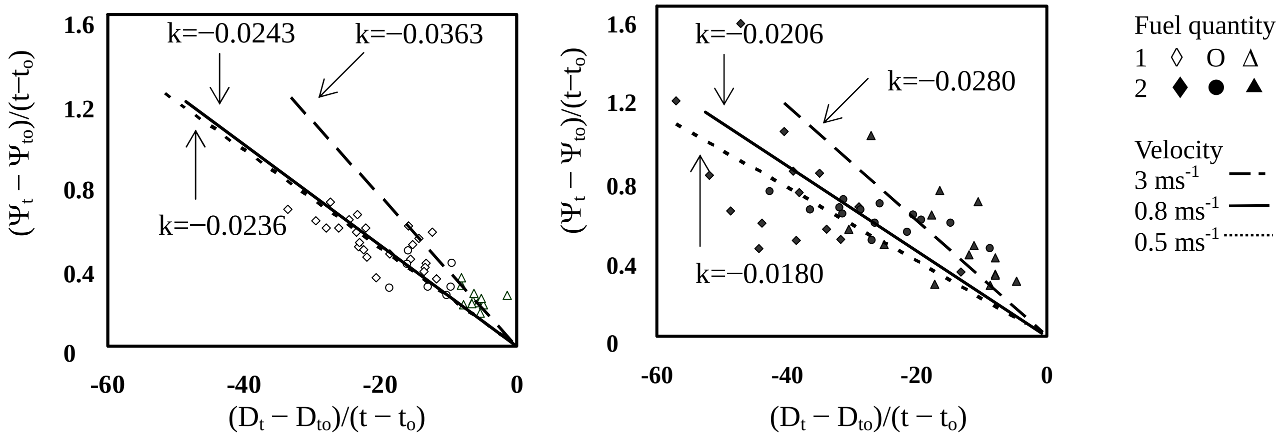
The detector response constants k of the detectors of the four configurations were evaluated by plotting the detector signal change against the optical density in a test period $(t-t_o)$ and summarized in Table 1. Fig. 3 shows example plots for configuration (4) smoke detector at some fuel quantities and at velocities from 0.5 to 3 ms^{-1}. The experimental results showed that, for the normal light scattering smoke detector in the experiment, the detector response constant k would be correlated by the smoke movement velocity for certain quantities of fuel burnt. The result was obvious as the detector response would be influenced by both the effect of bulk property transport and the property generation at the fire location.



(a) Pre-unit values of detector signal and optical density

(b) Smoke temperature at the difference distance from detector

FIGURE 2. A typical smouldering fire process from ignition (t = 0)



(a) Fuel quantity = 1

(b) Fuel quantity = 2

FIGURE 3. Correlation between alarm signal and optical density for a configuration (4) smoke detector

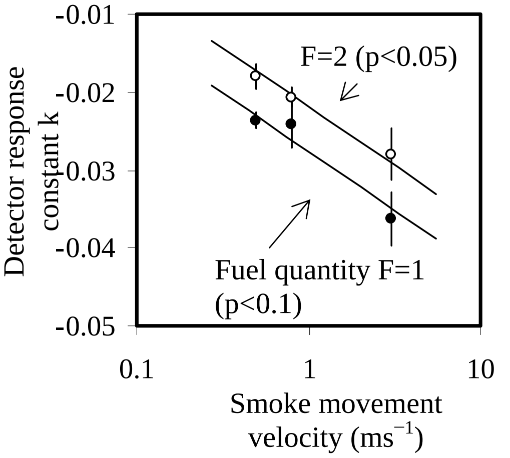


FIGURE 4. Detector response constant k for a light scattering smoke detector

TABLE 1. Detector response constant k values

Smoke detector configuration	**Sensitivity (with reference to the intact smoke detector)**	**k value ($\times 10^{-2}$)**						
		F	**1**			**2**		
		V	**0.5**	**0.8**	**3**	**0.5**	**0.8**	**3**
(1) With the sensing chamber only	Poor - similar ambient detector signal level before start of burning noted		−0.63	−0.89	−3.51	−0.57	−0.36	−0.37
(2) Sensor screen installed	Poor - a higher ambient alarm level before start of burning noted		−0.24	−0.20	−0.03	−0.04	−0.03	−0.01
(3) Chamber cover installed	Good		−2.34	−2.81	−4.00	−1.84	−2.11	−3.12
(4) Normal smoke detector	(Reference)		−2.36	−2.43	−3.36	−1.80	−2.06	−2.80

Note: F denotes fuel quantity and a piece of 13 cm long, 0.538 g cotton wick is taken as reference (i.e. F=1). V denotes velocity in ms^{-1}.

Fig. 4 shows some correlations ($p < 0.1$) between the detector response constants k and the smoke velocity at the detector. Further experiments would be needed for more promising results for the correlation. The detector response constant k might be used as an explanatory parameter to characterize the response of a light scattering smoke detector. In this study, a constant slope of −0.00655 was obtained for the light scattering smoke detector tested in velocities range 0.5 to 3 ms^{-1} as shown in Fig. 4.

Compared with the signal response to a smoky environment of a smoke detector with normal configuration, i.e. configuration (4), it was reported that the presence of the chamber covers was crucial for the proper operation of the smoke detector. With the sensing chamber freely exposed, i.e. configuration (1), the smoke detector sensitivity was poor and cannot distinguish the ambient optical density between smoke free and smoky environment. This was indicated by no consistent response of the detection response constant k against the smoke velocity at the detector. With the sensor screen only, i.e. configuration (2), the alarm signal response for smoky environment was not sensitive to the smoke velocity, as compared to the configuration (4). With the chamber cover installed, i.e. configuration (3), the response very close to a detector of configuration (4) was observed in the test conditions.

CONCLUSION

In this work, some influencing factors of the response characteristics of light scattering photoelectric smoke detectors were studied experimentally in a smoke detector test chamber constructed according to UL268. It was reported that the amount of fuel burnt, the smoke movement velocity and the detector configuration would have significant influence on the detector response to certain fire smoke. In particular, a proportional constant k for the optical density attenuation and changes of detector output signal was evaluated at some smoke movement velocity and smoky environments. It was reported the constant k, known as the detector response constant, was inversely proportional to the geometric smoke movement velocity. In this study, a constant slope of −0.00655 was obtained for a light scattering photoelectric smoke detector tested in velocities range 0.5 to 3 ms^{-1}. The detector response constant k might be used as an explanatory parameter to characterize the response of a light scattering photoelectric smoke detector and the results would be confirmed by further experiments with various fuel types and smoke detectors.

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