Optimization of Sensitivity Characteristics of Photoelectric Smoke Detector to Various Smokes

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ABSTRACT

The photoelectric smoke detector shows different levels of sensitivity to different fire types. The photoelectric detector generally is more sensitive to the gray smoke emitted by smoldering fires, and less sensitive to the black smoke emitted by flaming fires. To improve such a photoelectric detector, the light scattering phenomena by smoke particles have been studied, and numerical simulations of the scattered light by smoke particles have been conducted. Comparing the intensity of the scattered light by the smoke from smoldering fire and the smoke from flaming fire, it was found that their difference ratio is greater in the small angle range of scattering angle but decreases as the angle increases. A detector with the scattering angle of 70 deg. showed an improved response characteristic than a detector with the scattering angle of 40 deg.

Keywords: fire detection, smoke detector, smoke, smoke aerosol, light scattering

INTRODUCTION

For early detection of fire, automatic fire alarm systems are installed in many buildings. Among several kinds of detectors, smoke detectors are suitable to detect early stage fires. There are two types of smoke detectors: one is the photoelectric type and the other is the ionization type. The photoelectric smoke detector is sensitive to the smoldering fire emitting relatively large smoke particles, while the ionization smoke detector is sensitive to the flaming fire emitting a lot of small smoke particles.

The functions and the sensitivity of the smoke detectors are prescribed in the regulations or the standards of each country. Comparison of the sensitivity is rather difficult however, because each standard has a different test method. In order to make a direct comparison, we tested the sensitivity of a photoelectric smoke detector according to the methods prescribed in three standards: UL(USA), EN54(Europe) and the Japanese standard for fire alarm systems. Also, we studied the sensitivity characteristics of the photoelectric smoke detector by the fire type.

The photoelectric smoke detector shows different levels of sensitivity to different fire types (smoldering or flaming) by the general difference of the particle size. We tried to modify the construction of photoelectric detector, because the difference of sensitivity by smoke types should be minimized. The intensity of scattered light depends strongly on the scattering angle. In order to find a preferable construction of the detector, we conducted computer simulations of the light scattered by smoke particles.

COMPARISON OF SMOKE DETECTOR STANDARDS

Three major standards have been chosen: UL268[1] of USA, EN54[2] [3] of Europe and the Japanese standard for fire alarm systems[4]. Each standard uses two general methods for evaluating the sensitivity of the smoke detector: the *sensitivity test* and the *fire test*. The *sensitivity test* measures the sensitivity value of the smoke detector in a smoke test box, and evaluates the repeatability after several reliability tests. The *fire test* evaluates the ability of fire detection by applying model fires in a fire test room.

Sensitivity test

Table. 1 illustrates the methods of the *sensitivity tests* in the three standards. As shown in Table. 1, all of the test conditions (the smoke generating method, the obscuration meter and the sensitivity range) are defined differently, making it difficult to compare directly the sensitivity values.

Table. 1 Sensitivity test methods for the photoelectric smoke detector

Standard	Smoke Generating Method	Obscuration Meter	Sensitivity Range
Japanese standard for Fire alarm systems	Smoke by smoldering filter paper with 400℃ heater	1m span, visible light	Grade 1: 2.5 - 7.5 %/m Grade 2: 5.0 - 15 %/m Grade 3: 7.5 - 22.5 %/m
UL268 (USA)	*Gray Smoke* by smoldering cotton wick *Black Smoke* by kerosene	5ft span, visible light	*Gray Smoke*: 0.5 - 4 %/ft *Black Smoke*: 0.5 - 13%/ft
EN64 Part.7 (Europe)	Aerosol generated from paraffin oil	1m span, IR light	Not specified

Fire test

Fire test are specified both in UL268 and EN54, but not in the Japanese standard. The *fire test* evaluates the performance of the smoke detector in real fire conditions with several test fires. Types of test fires specified in UL268 and EN54 are shown respectively in Table. 2 and Table. 3.

Table. 2 Test fires of UL268

Test fire	Combustible	Type of fire
TEST A	Paper	Flaming
TEST B	Wood	Flaming
TEST C	Gasoline	Flaming
TEST D	Polystyrene	Flaming
Smoldering smoke test	Wood	Smoldering

Table. 3 Test fires of EN54 Part.9

Test fire	Combustible	Type of fire
TF1	Wood	Flaming
TF2	Wood	Smoldering
TF3	Cotton wick	Smoldering
TF4	Polyurethane	Flaming
TF5	n-Heptane	Flaming
TF6	Ethyl-Alcohol	Flaming

DIFFERENCE OF SENSITIVITY REQUIREMENTS BETWEEN STANDARDS

Sensitivity test

A UL approved photoelectric detector (model SLK, Hochiki Corp.) has been chosen. Each of the *sensitivity tests* specified in the three standards has been applied on this photoelectric detector. Results are shown in Table. 4. With UL268 methods, the sensitivity measured by *gray smoke* was 3.0 %/ft (9.5 %/m) , and by *black smoke* was 10.0 %/ft (29.2%/m). The same detector showed the sensitivity value of 3.2%/m by the filter paper of the Japanese standard. With the EN54 method (paraffin aerosol is used as smoke source), its sensitivity value resulted as 2.8%/m.

As reported in many papers[5], the photoelectric detector's sensitivity value is relatively small (sensitive) for the smoke from smoldering combustion, but greater (less sensitive) for the smoke from flaming combustion.

Table. 4 Results of sensitivity tests on a UL approved detector

Standard	Smoke Generating Method	Sensitivity Value
UL268	*Gray Smoke* from smoldering cotton wick	3.0 %/ft (= 9.5 %/m)
	Black Smoke from kerosene lamp	10.0 %/ft (= 29.2 %/m)
Japanese Standard	Smoke from smoldering filter paper	3.2 %/m
EN64 Part.7	Aerosol generated from paraffin oil	2.8 %/m

Fire test

Results of the *fire test* of UL268 are shown in Table. 5. As shown in the table, the detector operated within the specified time range for all test fires. Results of the *fire test* of EN54 (Part.9) are shown in Table. 6. The same detector showed acceptable results for TF2 –TF5, however it failed to operate in TF1 within the specified time range. In TF5, the detector operated about the specified time between class B and class C, thus shown as B/C in Table.5. It should be noted that EN54 doesn't request smoke detectors to operate in TF1.

Table. 5 Result of fire test of UL268

Setting sensitivity	TEST A	TEST B	TEST C	TEST D	Smoldering smoke test
3.0(%/ft)	O	O	O	O	O

O : Operated within specified time range

N : No alarm

Table. 6 Result of fire test of EN54

Setting sensitivity	TF1	TF2	TF3	TF4	TF5
3.0(%/m)	N	A	A	B	B/C

A,B,C : Operated within specified periods.

N : No alarm

A – C means the sensitivity class: A (most sensitive) ,B(intermediate), C (least sensitive)

Improving photoelectric smoke detector's response characteristics

The photoelectric smoke detector generally is more sensitive to the gray smoke emitted by smoldering fires, and less sensitive to the black smoke emitted by flaming fires[6]. If the sensitivity to the flaming fire is improved, the sensitivity to the gray smoke would automatically become very high. However if the sensitivity to the gray smoke becomes too high, then the frequency of false alarms may increase, because most of the false alarm source emit grayish large particles, such as water vapor, cigarette smoking and cooking. From the point of view of false alarm prevention, the sensitivity to the gray smoke should be reduced. However, from the point of view of fire detection, then the sensitivity to the black smoke should be increased. This means that the optimal sensitivity characteristic of the photoelectric smoke detector is the smaller sensitivity difference between the gray and the black smoke.

To implement such a photoelectric detector, we first studied the light scattering phenomena by smoke particles. The important parameters affecting the scattered light are incident light intensity and wavelength, particle size and refractive index, and scattering angle. We placed special emphasis on the theory relating the scattered intensity and the scattering angle.

THEORICITAL ANALYSIS

Scattering phenomena by smoke particles can be analyzed by the Mie theory. For the particle whose size is comparable with the light wave length ($0.1\lambda < a < 10\lambda$), Mie theory can be used for the analysis of scattered light. Fig.1 illustrates the geometrical relation of the incident light and the scattered light by a smoke particle. Here, parameters used are wave length: λ, particle diameter: a, scattering angle: θ and refractive index: m. Van De Hulst[7] describes theoretical analysis of scattering on a small spherical particle as follows.

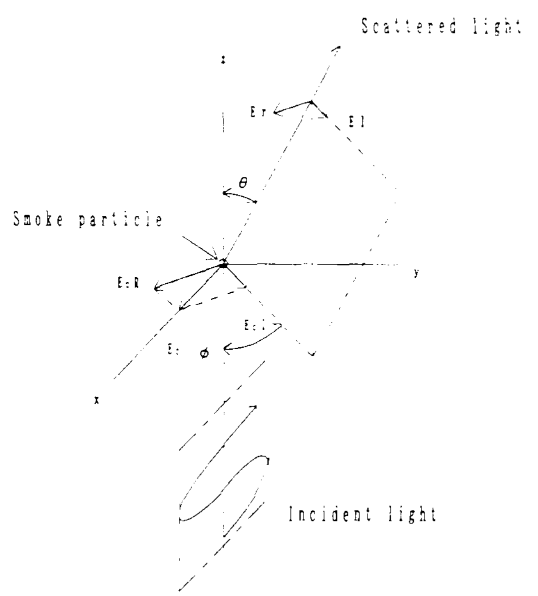

Fig. 1 Geometrical relation of the incident light and the scattered light

An incident light is plane-polarized wave on (xz) plane.

$$E_0 = Ax\ e^{-ikz+i\theta t}$$

For analysis of the scattered light shown in Fig. 1, the incident wave is

$$E_{0r} = E_0 \sin\phi$$

$$E_{0l} = E_0 \cos\phi$$

The scattered wave is

$$E_r = -E_\phi$$

$$= -\frac{i}{kr}e^{-ikr+i\vartheta t}\sin\phi * S_1(\vartheta) * E_0$$

$$E_l = -E_\theta$$

$$= -\frac{i}{kr}e^{-ikr+i\vartheta t}\cos\phi * S_2(\vartheta) * E_0$$

Where, S_1,S_2 are amplitude functions.

$$S_1(\vartheta) = \sum_{n=1}^{\infty}\frac{2n+1}{n(n+1)}\left[a_n\pi_n(\cos\vartheta) + b_n\tau_n(\cos\vartheta)\right]$$

$$S_2(\vartheta) = \sum_{n=1}^{\infty}\frac{2n+1}{n(n+1)}\left[b_n\pi_n(\cos\vartheta) + a_n\tau_n(\cos\vartheta)\right]$$

The following functions of scattering angle appear by Legendre functions.

$$\pi_n(\cos\vartheta) = \frac{dP_n(\cos\vartheta)}{d(\cos\vartheta)}$$

$$= \frac{1}{2^n n!}\frac{d^{n+1}}{dZ^{n+1}}(z^2-1)^n$$

$$\tau_n(\cos\vartheta) = \frac{d}{d\vartheta}P_n^1(\cos\vartheta)$$

$$= z\pi_n(z) - (1-z^2)\frac{d\pi_n(z)}{dz}$$

Where

$$z = \cos\vartheta$$

$$x = ka = 2\pi a / \lambda$$

$$y = mx = 2\pi am / \lambda$$

a_n and b_n are the boundary conditions.

$$a_n = \frac{\varphi_n'(y)\varphi_n(x) - m\varphi_n(y)\varphi_n'(x)}{\varphi_n'(y)\zeta_n(x) - m\varphi_n(y)\zeta_n'(x)}$$

$$b_n = \frac{m\varphi_n'(y)\varphi_n(x) - \varphi_n(y)\varphi_n'(x)}{m\varphi_n'(y)\zeta_n(x) - \varphi_n(y)\zeta_n'(x)}$$

The Riccati-Bessel functions are used.

$$\psi_n(x) = (\pi x / 2)^{1/2} J_{n+1/2}(x) = j_n(x)$$

$$\zeta_n(x) = (\pi x / 2)^{1/2} H^{(2)}_{n+1/2}(x)$$

Now, the intensity of the scattered light in arbitrary direction can be written as:

$$I = \frac{I_0\left\{|S_1(\vartheta)|^2 + |S_2(\vartheta)|^2\right\}}{2k^2r^2}$$

Then the intensity of scattered light by a mass of smoke can be calculated as a total amount of the scattered light by particles of various sizes. Here, N_x is the number of particles having the diameter between x and x+dx.

$$I_{smoke} = \int I_x N_x dx$$

By calculating these equations, the total intensity of scattered light by various smokes and its dependence on the scattering angle has been studied.

SIMULATIONS

Fig. 4 shows the simulated results of scattering angle dependency of the scattered light for three kinds of smoke: filter paper, cotton wick and kerosene. Particulate conditions for the calculation are shown in Table. 7. Filter paper calculation is intended to simulate the smoke generated by the method specified in the Japanese standard. Cotton wick and kerosene calculations are intended to simulate those smokes generated with the methods specified in UL268. The values reported by Marx et al. [8][9] were used for the refractive indices of filter paper and kerosene smoke. The refractive index of cotton wick was unavailable, thus equalized to the filter paper smoke. The size distribution functions of smoke particles measured by optical aerosol analyzer were used for the calculation. Fig. 3 shows the size distribution of kerosene smoke, as an example. As shown in Table. 7, the average particle size of smoke from smoldering filter paper is greater than that from flaming kerosene.

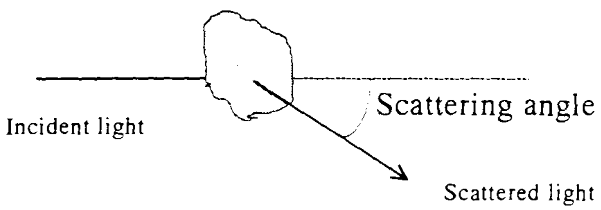

Fig. 2 Scattering angle

Table. 7 Particulate conditions for calculation

Combustible	Filter paper	Kerosene	Cotton wick
Smoke generation method	Smoldering on heater at 400℃	Flaming	Smoldering
Refractive index (real , imaginary)	(1.50 , 0) [8]	(1.95 , 0.65) [8]	(1.50 , 0)
Average particle size[10]	0.074(μm)	0.062	0.055

Simulated intensities of scattered light by the three kinds of smoke is shown in Fig. 4. The findings by this simulation can be summarized as follows.

- The intensities of scattered light in the small range of scattering angle are generally greater than those in the large angle range.
- The intensities of scattered light show a minimum in the intermediate angle range.
- In the angle range greater than 90 deg., the scattered intensities increase as the scattering angle increases.
- The scattered intensity by kerosene smoke take the minimum in the range near 90 deg., while the scattered intensity by filter paper smoke take the minimum in the range near 120 deg.
- The intensity difference between kerosene smoke and filter paper smoke is greater in the small scattering angle, but it decreases as the scattering angle increases.

These simulation results are consistent with Jin's experimental result [11].

EXPERIMENTS

In order to verify those findings with the simulation, the sensitivities of the photoelectric detectors having different scattering angles have been tested. 7 types of photoelectric detector with different chamber configuration were made. Each detector's sensing chambers has a different scattering angle of 30, 40, 50, 60, 105 or 120 deg., but all the other dimensions are designed as same. The same LED and the same photo-diode were used in the experiment in order to avoid the effects other than the scattering angle. *Sensitivity tests* has been carried out on these detectors with filter paper, cotton wick and kerosene smoke. The smoke generating methods are summarized in Table. 1.

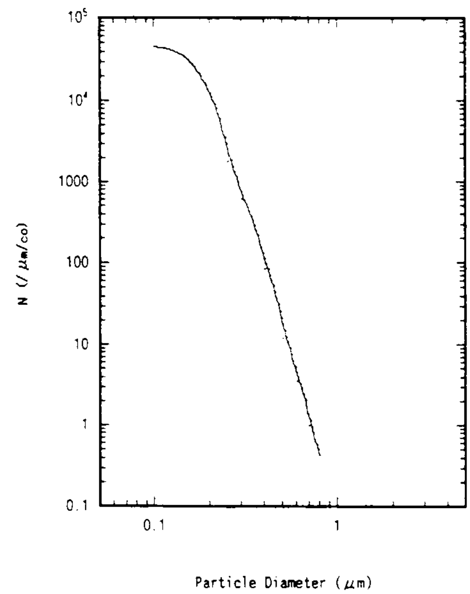

Fig. 3 Particle size distribution of kerosene smoke

Fig.5 shows the experimental results obtained with the 7 types of detectors. Graph form is the same as the simulation result of Fig. 4. As shown in Fig. 5, the experimental relation between the scattering angle and the relative intensity is quite similar to the simulation. The minimum scattered intensity by filter paper smoke was observed at 120 deg. And the minimum scattered intensity by kerosene smoke was observed at 90 deg. The scattered intensity by cotton wick smoke was observed as intermediate of filter paper and kerosene smoke.

DISCUSSION

Comparing the experimental result of Fig. 5 with the simulation (Fig. 4), observed scattered intensities of filter paper smoke and kerosene smoke respectively are consistent with their simulated counterparts. On the other hand, the experimental data of cotton wick smoke is rather inconsistent with simulation. The observed intensity in the small angle range is smaller than that of simulation. It is suspected that equalizing the refractive index of cotton wick with filter paper smoke was inappropriate.

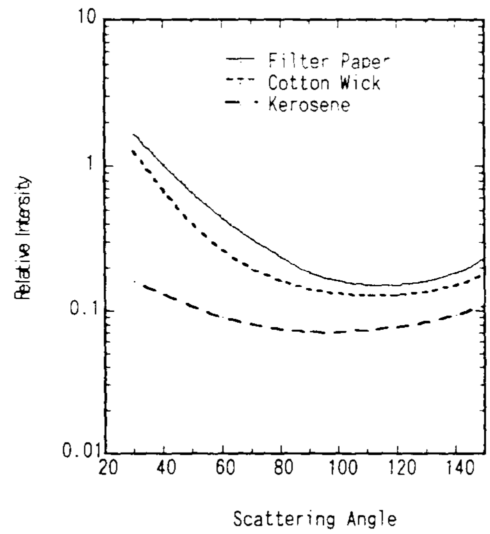

Fig. 4 Simulated result of scattered intensity

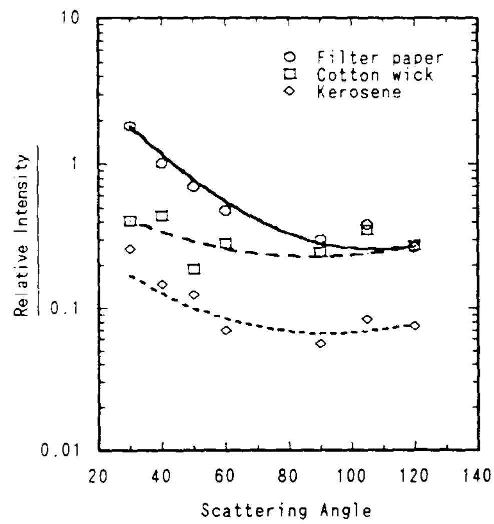

Fig. 5 Experimental result of scattered intensity

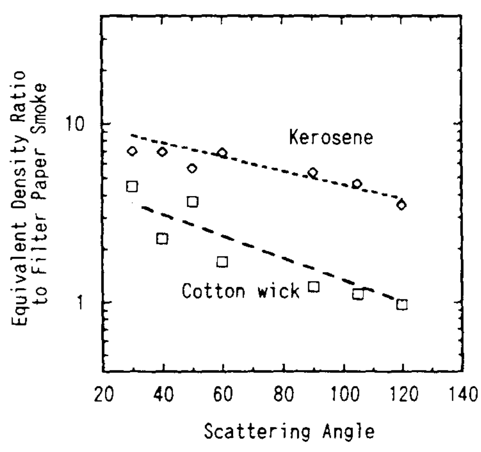

Fig. 6 Angler characteristic of the difference of scattered intensities of flaming and smoldering smoke

Fig. 6 illustrates the angler characteristic of the difference of scattered intensities of flaming and smoldering smokes. The equivalent density ratio means the amount of smoke needed to give the same scattered intensity by the filter paper smoke. For example, if the scattering angle is 40 deg., about 8 times higher concentration of kerosene smoke is needed compared to filter paper smoke. Fig. 6 suggests that the difference of sensitivity by the fire type may become smaller by applying a larger scattering angle.

EXAMINATIONS OF A NEWLY DEVEROPED DETECTOR

As discussed above, it was found that a best scattering angle to minimize the sensitivity difference lies in the larger side of the angle range. However, the stability of a detector generally decreases as the scattering angle increases (not discuss in this paper). Thus the scattering angle of the newly developed detector was set as 70 deg. The following is the test results of this newly developed detector.

Test results

Verification tests were carried out on the newly developed detector. *Sensitivity test* in a smoke box and *fire test* of EN54(Part9) were conducted with the newly developed detector (model SLR: 70 deg.) and an old model (model SLK: 40 deg.). Results of the *sensitivity test* are shown in Table. 8. And results of the *fire test* are shown in Fig. 7.

Table. 8 shows the sensitivities of the two detectors measured with 3 types of smoke source: paper filter, cotton wick and kerosene lamp. Values of the equivalent density ratio are also shown in the same table. It is apparent that the equivalent density ratio is smaller with the newly developed detector (θ=70 deg.), as consistent with the data of Fig. 6.

Fig. 7 shows the results of *fire tests* on the two detectors. As shown in Table. 8, their sensitivity to the paper filter smoke are exactly the same as 3.0%/m. however, their overall response characteristics to the test fires are quite different. The new model's sensitivities to smoldering fires are the same or rather lower than the old model. However, the sensitivities to the flaming fires are much higher with the new model.

CONCLUSION

The following conclusions can be drawn based upon analysis of experiments and simulations performed:

1. The photoelectric smoke detectors show different levels of sensitivity to different fire

types (smoldering or flaming) by the general difference of particle size.

2. The intensity difference between kerosene smoke and filter paper smoke is greater in the small scattering angle, but it decreases as the scattering angle increases.
3. The scattering angle has been arranged to improve the sensitivity characteristics of the photoelectric detector. A detector with 70 deg. scattering angle showed to have less difference of sensitivity by the smoke type, compared to the detector with 40 deg. scattering angle.

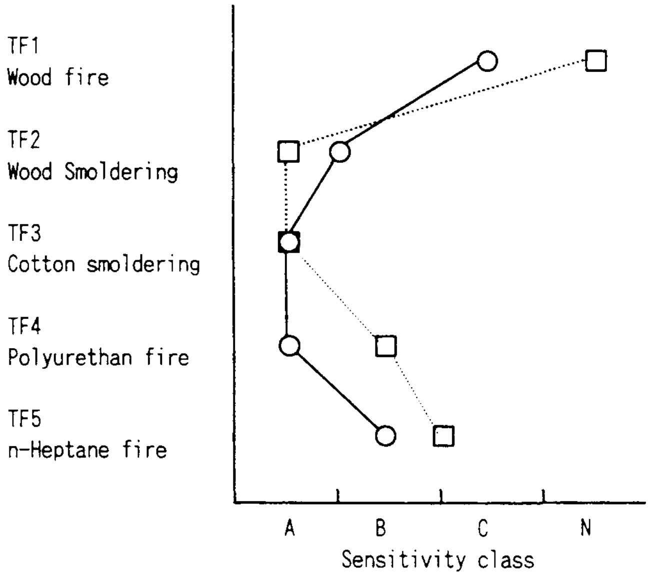

Fig. 7 Results of fire tests. ○: newly developed detector(θ=70); □: old model(θ=40)

Table. 8 Sensitivities to various smokes

Scattering angle	Sensitivity (%/m) Paper filter	Sensitivity (%/m) Cotton wick	Sensitivity (%/m) Kerosene	Equivalent density ratio Kerosene / Paper filter	Equivalent density ratio Cotton wick / Paper filter
$\theta=40°$	3.0	9.0	32.0	3.0	10.7
$\theta=70°$	3.0	6.5	23.0	2.1	7.7

REFERENCES

[1] Standard for Safety UL268: Smoke Detectors for Fire Protective Signaling Systems, Underwriters Laboratories Inc., 1996.

[2] European Standard EN54 Part 7; Specification for point-type smoke detectors using scattered light transmitted light or ionization, European Committee for Standardisation, 1984

[3] European Standard EN54 Part 9; Methods of test of sensitivity to fire, European Committee for Standardisation, 1982.

[4] Inspection Methods, Japan fire equipment inspection institute

[5] Yamauchi, Y., Prediction of Response Time of Smoke Detectors in Enclosure Fires, NBSIR-88-3707, National Bureau of Standards (USA) ,1988

[6] Mulholland,G.W., Smoke Production and Properties , The SFPE Handbook of Fire Protection Engineering, National Fire Protection Association (U.S.A.), 1988.

[7] Van De Hulst,H.C.,Light Scattering by Small Particles, Wiley, New York,1957

[8] Mulholland,G.W., McKenzie,R.L, Marx,E. and Fletcher,R.A., Refractive Index and Evaporation Rate of Individual Smoke Droplets, Langmuir, Vol.1, N0.3, 1985.

[9] Marx,E and Mulholland,G.W.,Size and Refractive Index Determination of Single Polystyrene Spheres, Journal of Research of National Bureau of Standards, Vol.88, No.1,1983

[10] Lee,T.G.K. and Mulholland,G.W., Physical properties of smoke pertinent to smoke detector technology, National Bureau of Standard Final report,1977

[11] Jin,T., Visibility through Fire Smoke, Report of Fire Research Institute of Japan,No.40,1975

[12] Mulholland,G.W., Lee,T.G.K. and Baum,H.R., The Coagulation of Aerosols with Broad Initial Size Distributions, Journal of Colloid Interface Science,Vol.62,No.3,1977

[13] Yamauchi Y., Numerical Simulations of Smoke Movement, Langmuir, Vol.1, No.3, 1985

[14] Abramowitz, M. and Stegun, I., Handbook of Mathematical Functions, Dover publications Inc., 1972

[15] Chevaillier, J.P., Fabre, J. Grehan, G. and Gouesbet, G., Comparison of Diffraction Theory and Generalized Lorenz-Mie Theory for a Sphere Located on The Axis of a Laser Beam, Applied Optics, Vol.29, No.20, 1990