A New Technique for Measuring Air Change Rates in a Test House Using Video Imaging

Masaaki Ohba, Dr. Eng. **Kenji Irie**

ABSTRACT

Video camera calibrations and field tests for air change rates in a test house were performed to develop a new method of measuring air change rates using a video imaging technique. From the camera calibrations, it was found that good correlation was achieved between image signals and luminous reflectance of achromatic color chips by appropriately adjusting the pedestal level of the video camera so that the image signals were made equal to zero for the black level of the picture. In the field tests, air change rates in the test house were measured from the decay curves of video image signals obtained by the step down method, assuming a perfect mixing of smoke particles inside the spaces. With the proposed video method, it was possible to measure air change rates with virtually the same precision as derived from the decay curves of smoke particle numbers using an aerosol monitor. As a new tracer, smoke liquid mists without dirty residuals were also tested and compared to the gas method using SF_6. It was thus verified that the video method using smoke liquid mists could also precisely measure air change rates with an error of less than 6% in comparison with the gas method.

INTRODUCTION

Indoor air is often polluted due to indoor air pollutants such as volatile organic compounds and formaldehyde emitted from newly produced indoor materials. Contaminated indoor air must be constantly changed with fresh outdoor air to maintain indoor an air quality that is comfortable for residents. The air change rate is defined as the ratio of outdoor airflow rate to indoor air volume (Chapter 25, ASHRAE 1997). This ratio is considered to be an essential index, indicating an acceptable level of indoor air quality. Information on the required ventilation rates for different types of buildings is provided in *ANSI/ASHRAE Standard 62-1989* (ASHRAE 1989), and ventilation designers must determine whether the required ventilation rates are achieved in buildings and houses.

The tracer gas decay procedure using carbon dioxide is widely used in Japan for measuring air change rates in buildings and other spaces (JIS 1974; Fujii et al. 1967). This procedure is based on several assumptions, such as perfect mixing of tracer gas and zero absorption in building materials. Therefore, enough measuring points must be chosen, both vertically and horizontally, inside the spaces to obtain accurate average air change rates if uniform concentrations of tracer gas cannot be produced in large spaces such as atriums and factories. This must be done by equally dividing the inside spaces into small volumes. The air change rates occurring in natural ventilation change randomly, so at least five test runs must be conducted and averaged to comply with the Japanese Industrial Standards. The current procedure requires a lot of time and labor to measure the average air change rates, especially if the measured spaces are large and natural rather than mechanical ventilation is used.

The imaging technique is widely applied in a variety of engineering fields. Even inexpensive commercial video cameras have more than 250,000 pixels per video frame, corresponding to measuring points. The movement of indoor airflows is very slow, so video cameras with a recording speed of 30 Hz can accurately record the movement of tracer particles inside spaces.

The light-scattering technique was originally proposed by Rosensweig et al. (1961) and employed for the measurement of particle concentrations in turbulent flow fields (Becker et al. 1967; Long et al. 1981). This technique utilizes the fact that the intensity of the scattered light reaching a photo multiplier is linearly related to the number of light-scattering particles in a control volume. In the photo multiplier, electric

Masaaki Ohba is a professor and **Kenji Irie** is a research associate with the Faculty of Engineering, Tokyo Institute of Polytechnics, Atsugi, Kanagawa, Japan.

signals are converted into image signals through the photoelectric conversion system. They confirmed that the signal was proportional to the gas concentration if the smoke particles mixed perfectly with the surrounding gas. Huber (1988) and Lee et al. (1991) applied the video image techniques to the concentration measurements in building wakes. Lee noted that the nonlinear relation between smoke intensity and vertically integrated concentration occurred in building wakes at a high smoke intensity level.

Ohba studied three-dimensional characteristics of natural ventilation in half-enclosed buildings using video imaging techniques in wind tunnel experiments (1993). For the measurement of air change rates, Ohba and Irie (1996, 1998) researched the video image method in a cross-ventilation model setting in a wind tunnel, using a laser light sheet and decay curves of image signals. They found that the image method could precisely measure the air change rates with an error of less than 9%, in comparison with those obtained by the C_2H_4 gas method using a high-speed hydrocarbon analyzer, if the pedestal level of the camera was appropriately adjusted.

The objective of this study was to develop a new video method for measuring the air change rates in actual buildings and other spaces, not using decay curves of gas or smoke particle concentrations but those of image signals. This technique was then applied to the evaluation of indoor air quality because not enough similar studies have been conducted (Anderson et al. 1991).

MASS BALANCE MODEL

The following assumptions are made in developing the mass balance model.

- Instant and uniform mixing of tracer gas with indoor air after emission
- No tracer gas absorption onto indoor surfaces
- No chemical reaction with building materials
- No temperature difference between inlet and outlet air

It is difficult to realize the fourth assumption in actual situations (Sandberg et al. 1986), but the approximation is frequently used to achieve a simpler mass balance model. Figure 1 is a sketch of the mass balance in a room. Tracer gas is emitted at an emission rate of M from a floor source.

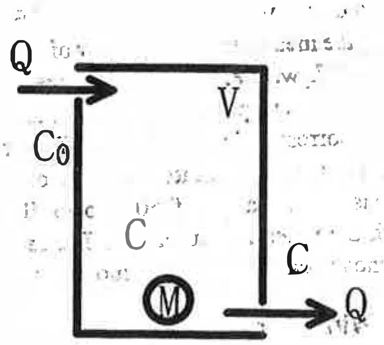

***Figure 1** Mass balance of pollutant in a room.*

Narazaki (1961) expressed the following equation of the mass balance in steady state:

$$Mdt + C_oQdt - CQdt = Vdc \tag{1}$$

where

V = indoor air volume, i.e., the entire air volume of a space or building (m^3),
C = indoor concentration (m^3/m^3),
C_o = outdoor concentration (m^3/m^3),
M = emission rate of tracer gas (m^3/s),
Q = ventilation rate (m^3/s),
t = time (s).

When C is equivalent to C_1 in the initial condition, the following equation is obtained:

$$C = C_o + (C_1 - C_o)\exp(-Qt/V) + M/Q\,[1 - \exp(-Qt/V)]. \tag{2}$$

If tracer emission stops after mixing, the third term on the right side of Equation 2 disappears. Then,

$$C = C_o + (C_1 - C_o)\exp(-Qt/V). \tag{3}$$

Next, the relationship between the concentration of $(C - C_o)$ and time, t, is plotted on semi logarithmic graph paper. The air change rate, Q/V, is derived from the slope.

$$\log(C - C_o) = \log(C_1 - C_o) - Qt/V. \tag{4}$$

OUTLINE OF EXPERIMENTS

Video Image Analysis System

The video camera used was a high-resolution charge-coupled-device (CCD) with a 768 × 493 pixel imager, an S/N ratio of 60 dB, and an f-stop from 1.8 to 16. It was used with the automatic gain control off so that consistent quantitative measurement could be made. A control unit remotely regulated the white-black balance and the pedestal level of the camera because the camera was located inside a box adjacent to the window during the field experiments, as shown in Figure 2. A standard video-cassette recorder could record the pictures on a Beta video tape at a recording speed of 30 Hz.

The video image analysis system was composed of an image processor with 768 mono-color frames of analog-digital converters with 512 × 481 pixels and a computer with 32-bit precision. The image picture was digitized with 8-bit precision and normalized by 256, converting to image signals in the range from 0.0 to 1.0. It took 25.6 seconds to convert 768 video pictures into digital image frames (Ohba 1996).

A Test House

The test house had a shed roof with a space volume of 444 m^3 with two doors and a long, top light window, as shown in Figure 2. The window was covered with black paper to shield against solar radiation to keep the indoor illuminance constant during the field runs. The walls behind the sampling position were also covered with low-reflective black curtains

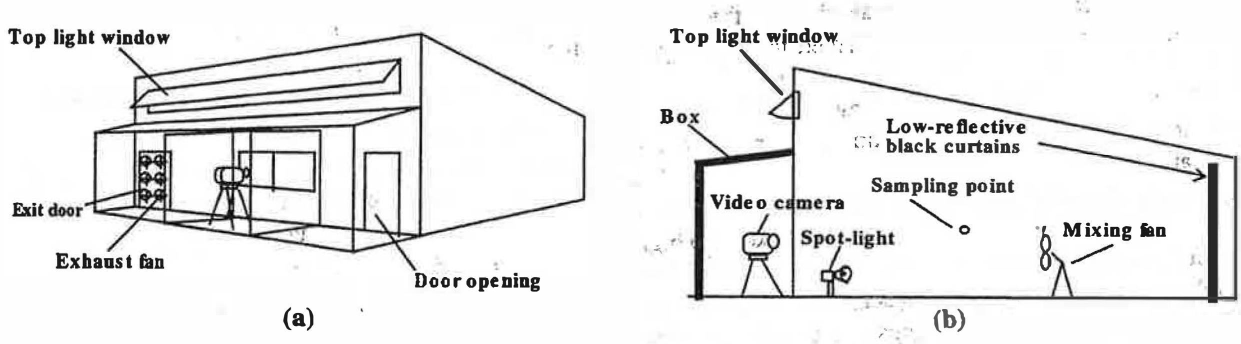

Figure 2 *Test house with shed roof. (a) Out of view. (b) Test house section.*

to provide a very low reflectance background against the smoke, which could be well observed and photographed. Five spotlights with a power equivalent to 2500 W were also set and adjusted by a voltage controller to visualize the smoke movement. In addition, six sets of exhaust fans were attached to the opening of the exit door for mechanical ventilation.

METHOD

Video Camera Calibration

The entire video system was calibrated as a single unit using the 36 steps of achromatic color chips before the field tests were run. As shown in Figure 3, the chips under nonreflecting glass on the desk were illuminated from 45 angles by incandescent lamps and photographed with the video camera at a height of 0.7 m above the desk. The image signals at a point including the neighboring 8 pixels were calculated by the averaging process. The sampling frequency was 30 Hz, and the sampling time was several seconds to investigate the effects of reflectance, camera f-stop, and light illuminance on the image signals of the video camera.

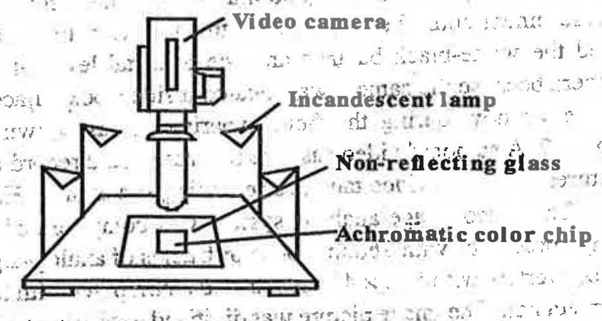

Figure 3 *Camera stand.*

Video Measurement for Air Change Rates

After photographing the background without smoke in the test house, smoke candles were lit and produced white smoke for 90 seconds. During the emission, the smoke was completely mixed with the indoor air using a mixing fan. After the mixing fan stopped and two doors were opened, the smoke was exhausted by mechanical fans. When recording, counter numbers were also recorded on the tape to easily determine the start time and the stop time. Spotlights were projected from near the camera position into the sampling point. The effect of buoyancy on the smoke movement due to the illumination was not observed in the video pictures. The video images correspond to the horizontally integrated concentration of smoke particles. The image signals at a measuring point were calculated by the averaging process including the neighboring 8 pixels. The sample interval was five seconds. The spatial resolution was 3 mm × 4 mm per pixel.

As a non-odorous tracer to cut off the tracer's residual and maintain the measured spaces clean, smoke liquid mist consisting of propylene glycol was tested. This is often used for stage effects in live theater. The tracer was released from a commercially available smoke generator, and the video images were recorded on the tape.

Smoke Particle Measurements

To verify the measurement accuracy of the video method, an aerosol monitor measured smoke particle concentrations simultaneously with the video measurement. After perfect mixing of the candle smoke in the house, the samples of air containing the smoke particles were drawn to an aerosol monitor through tubing by a small sample pump. The measuring height was 1.2 m. The accumulated particle numbers relating to the particle concentrations were read at intervals of 10 seconds.

Gas Concentration Measurements

When the smoke liquid mists were used as the tracer, the aerosol monitor could not measure the mist concentrations. The aerosol monitor was replaced, and an SF_6 analyzer was used to verify the measurement accuracy of the video method. The tracer gas SF_6 was released with smoke liquid mists at a flow rate of 1.6 liters per minute until the constant room concentration corresponded to 10 ppm. The sample air was detected by a multi-gas monitor capable of measuring gas concentrations in the range of 50 ppb to 50 ppm simultaneously with the video measurement. The sampling interval was 60 seconds because of the low monitor response.

Reference Wind Measurements

The reference wind velocity and direction were measured at a height of 25.2 m using a two-dimensional supersonic anemometer above the building adjacent to the test house. The test house was surrounded by three-story university buildings so that the effect of the reference wind on the air change rates was considered to be negligible.

Experimental Conditions for the Air Change Rates

The field experimental conditions are listed in Table 1 and Table 2. Table 1 is for smoke candles used as a tracer. The wind directions varied between north and south, while the wind velocity was in the range from calm to 5.0 m/s. The illumination was kept at 625 lux. The f-stop and lens were set to 2.8 mm and 20 mm, respectively, keeping a distance of 3.8 m between the camera and the photographed objects. A test run took 15 to 35 minutes. A total of eight test runs was conducted by varying the number of operating exhaust fans. Mechanical ventilation rather than natural ventilation was mainly used during the measurements. Table 2 is for smoke liquid mists and SF_6 gas used as the tracers. The wind directions varied between north and south. The wind velocity was in the range from 1.3 m/s to 2.6 m/s. The illumination and camera were in the same condition as those in Table 1. A test run took 18 to 38 minutes. A total of four test runs was conducted.

TABLE 1
Experimental Conditions for Smoke Candles as Tracer

Test Run	Number of Exhaust Fans	Top Light Window	Reference Wind: Wind Velocity (m/s)	Reference Wind: Wind Direction
1	2	Closed	5.0	SW
2			0.5	NW
3	4	Closed	4.3	S
4			0.7	NNW
5			3.2	W
6			1.3	N
7		Opened	1.2	SSW
8	6	Opened	Calm	NNW

TABLE 2
Experimental Conditions for Smoke Liquid Mists as Tracer

Test Run	Number of Exhaust Fans	Top Light Window	Reference Wind: Wind Velocity (m/s)	Reference Wind: Wind Direction
9	2	Closed	2.6	S
10	4		1.3	SE
11		Opened	1.3	NNE
12	6		1.5	N

RESULTS AND DISCUSSION

Photoelectric Conversion of Video Camera

The brightness on the camera's image surface is related to illumination, reflectance, and camera f-stop by the following equation (Okazaki and Taniguti 1988):

$$J = E\,R\,T / \{4(m+1)^2 F^2\}, \qquad (5)$$

where

J = illuminance on camera's image surface (lux),
E = illuminance of photographed objects (lux),
R = reflectance,
T = camera transmittance,
m = camera magnification,
F = camera f-stop.

Next, the image illuminance on the photoemissive surface is converted into image signals through the photoelectric conversion system of the image sensor in the following form:

$$I = k\,J^{\gamma} \qquad (6)$$

where

I = image signal or image intensity,
k = coefficient,
γ = gamma coefficient.

Therefore, the magnitudes of the image signals or image intensities are proportional to the power of the color chip's reflectance and also to the power of the color chip's illuminance. Figure 4 shows the relationship between the image signals and the illuminance of the Munsell achromatic color chip equivalent to an index of 5. The illuminance ranged from 20 lux to 700 lux. The image signals in the entire video system followed a power of illuminance relationship equivalent to 0.67, corresponding to a gamma coefficient that is normally 0.5.

Figures 5 and 6 show the relation of the image signals to the Munsell index and the luminous reflectance of the achromatic color chips. The illuminance on the chips was kept at 450 lux. The f-stop was 2.8 and the lens was 20 mm. If the

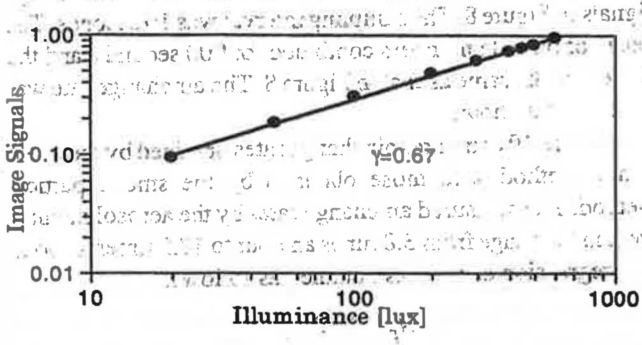

Figure 4 Relationship between illuminance on Munsell achromatic color chip and image signals.

image sensitivity of the camera could not be regulated correctly, he dark current caused nonlinearity at low reflectance, as shown by the white circles in Figures 5 and 6. The image signal for a luminous reflectance of zero was adjusted to zero by tuning the pedestal level that can control the low-intensity values. Then, as shown by the black circles, the signal gain at the higher level increased a little bit, but the linearity at the lower level was improved.

The image signals were found to be proportional to the inverse of the f-stop in the range of $1.8 \leq F \leq 16$ with a power of 1.13, as shown in Figure 7.

Air Change Rates for Smoke Candles as Tracer

For gaseous diffusion near an isolated stack, the diffusion region was very narrow so that adequate density distributions of laser power made it possible to take clear pictures (Ohba 1992, 1995). The diffusion th ckness did not adversely affect the production of constant illumination distributions. Therefore, ray extinction due to lighting scattering was considered to be negligible for the isolated stack model. However, for enclosed spaces such as a test house, he smoke particles were stored inside spaces and mixed with the indoor air. The smoke particles diffused in the whole of the enclosure so hat the light scattering might have worse effects on the decay curves of image signals. Therefore, the performance of photoelectric conversion for the camera was regula ed well by tuning the pedestal level and f-stop. The background level was adjus ed to less than 0.04. Figure 8 shows typical decay curves for the image signals. The background level indicate by I_o in Figure 8 was subtracted from the original image signals. This affected he distributions at the lower level because of the 8-bit precision of the analog-digital converter. When calculating the regression curve by the least squares method, the starting point was chosen as 90% of the maximum image signals, to avoid the equilibrium range of maximum image signals, and the end point was set to the minimum image signal that could maintain linearity in the range. The image signal decay for he eighth test run is shown in Figure 8, where the reference velocity was calm and mechanical ventilation was mainly performed. The air change rate was equal to 16.3 times an hour.

Figure 9 shows the decay distribution of smoke particle concentrations measured simultaneously with the image signals in Figure 8. The sampling interval was 10 seconds. The decay of particle numbers continued for 900 seconds, and the slope was the same as that in Figure 8. The air change rate was 17.2 times an hour.

Figure 10 compares air change rates obtained by the video image method with hose obtained by the smoke particle method. The measured air change rates by he aerosol monitor were in the range from 3.8 times an hour to 17.2 times an hour. The regression curve was obtained as follows:

$$N_p = 1.12 N_i \tag{7}$$

It proved that the proposed method could be used to measure air change rates with virtually the same precision as the method using the decay curves of smoke particle concen-

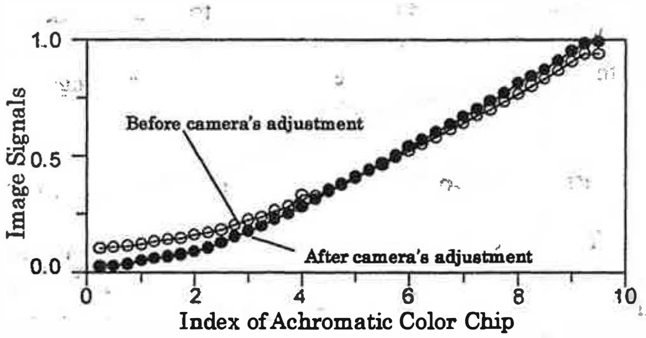

Figure 5 *Relationship between Munsell index of achromatic color chips and image signals.*

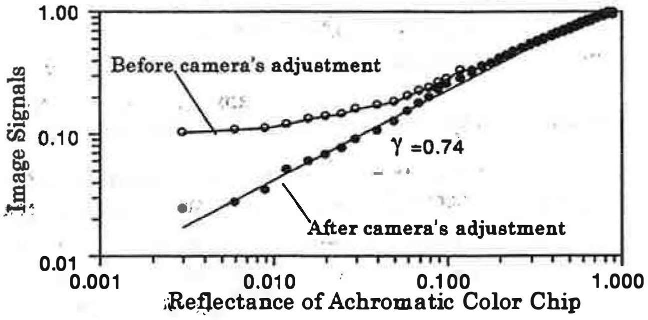

Figure 6 *Relationship between luminous reflectance of Munsell achromatic color chips and image signals.*

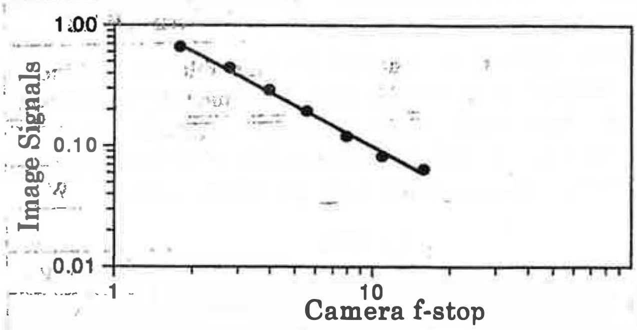

Figure 7 *Relationship between camera f-stop and image signals.*

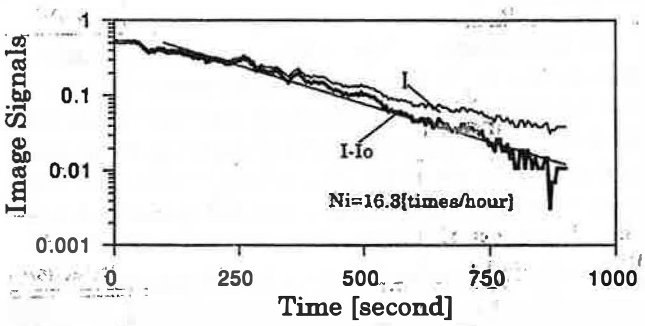

Figure 8 *Decay distribution of image signals for smoke candles as tracer.*

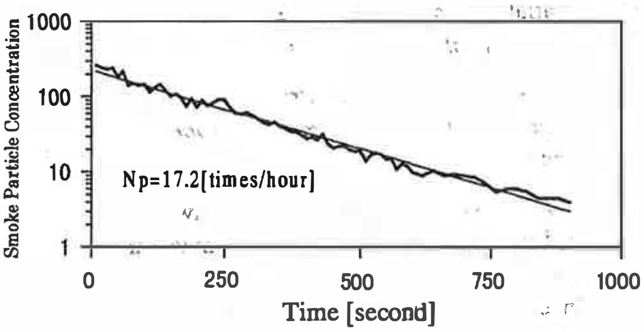

Figure 9 Decay distribution of smoke particle concentrations for smoke candles as tracer.

trations. Therefore, the image method is concluded to be very reliable for measuring air change rates.

Air Change Rates for Smoke Liquid Mists as Tracer

Smoke candles are widely used in field experiments as the tracer for visualizing flow patterns. However, many unpleasant residuals remained after the experiments. Therefore, smoke liquid mists were tested experimentally as new tracers. The diameters of the mists were in the range between 0.25 µm and 1.75 µm (Ohba 1996), which is thought to be smaller than those of smoke candles (Shimizu 1976). Because the scattering strength of light is proportional to the square of the particle diameters, the image signals for the smoke liquid mist were reduced sharply at the lower level, as shown in Figure 11, more than those for the candle smoke. It was the eleventh run in Table 2, where the background level I_0 was zero and the air change rate was 9.4 times an hour. The measurement accuracy of the video method was investigated in comparison with the SF_6 tracer gas method, as shown in Figure 12. The regression curve obtained, shown in Figure 13, is as follows:

$$N_g = 0.94\ N_i \qquad (8)$$

It was found that the proposed method could be used to measure air change rates with virtually the same precision as the tracer gas method.

CONCLUSIONS

Camera calibrations have shown that good correlation is achieved between image signals and luminous reflectance of achromatic color chips by adequately adjusting the pedestal level of the video camera so that the image signals are made equal to zero for the black level of the picture. The image signals were also in proportion to the illuminance and to the inverse of the camera f-stop.

The effect of light scattering on the image signals in a test house could be removed by adequately tuning the camera's pedestal level and f-stop.

The video image method could measure air change rates with virtually the same precision as the methodsusing the decay curves of gas concentrations or smoke particle concentrations.

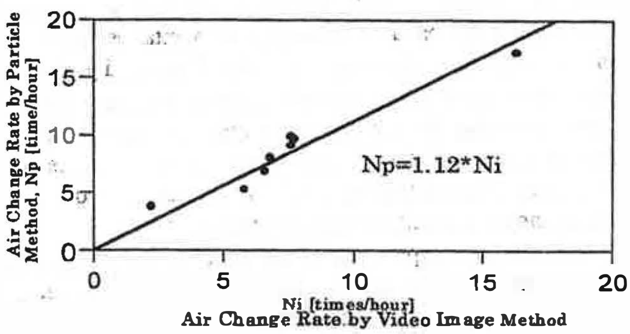

Figure 10 Relationship between air change rates by smoke particle method and by video image method.

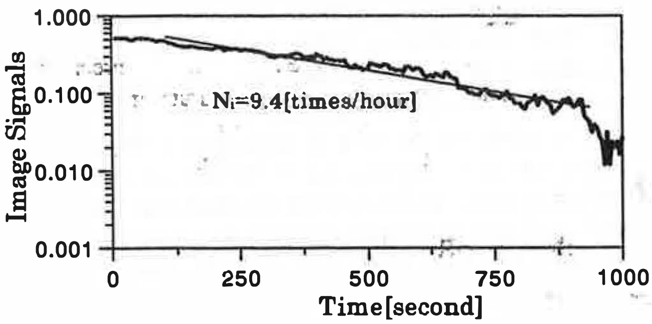

Figure 11 Decay distribution of image signals for smoke liquid mists as tracer.

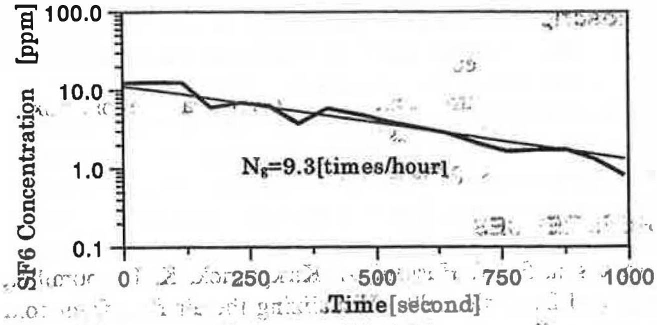

Figure 12 Decay distribution of gas concentration for SF_6 as tracer.

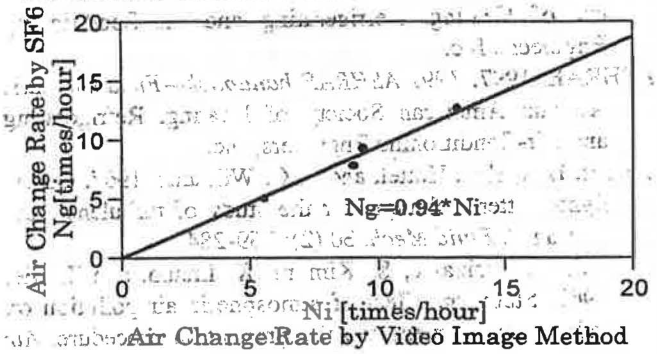

Figure 13 Relationship between air change rates by SF_6 gas method and by video image method.

Compared to the precision of the tracer gas method, it is true that the proposed method has disadvantages, such as low image precision, because image pictures can be digitized with only 8-bit precision. Even when considering this low resolution, the video image decay method is expected to be reliable for measuring air change rates. The major advantage of the video method is that it is possible to obtain detailed information at one time about air change rates in large spaces for evaluating ventilation performance. Another advantage is that image instruments are less expensive than concentration instruments for SF_6 because current image technology provides users with low-cost computers and videos. Thus, in the near future, image methods such as the gas concentration method are expected to become useful methods for air change rate measurements.

ACKNOWLEDGMENTS

The authors would like to express their appreciation to Professor S. Hasegawa of the Tokyo Institute of Polytechnics for his advise on the camera calibrations. The funding sources were the Tokyo Institute of Polytechnics and the MONBUSHO Scientific Programs by the Ministry of Education.

NOMENCLATURE

C = gas concentration (m^3/m^3)
I = image signal or image intensity
I_o = image signal for image picture without tracers
N = air change rate (times/hour)

Subscripts

g = gas method
i = video image method for smoke particles or smoke liquid mists as tracers
p = smoke particle method

REFERENCES

Anderson, R., V. Hassani, A. Kirkpatrick, K. Knappmiller, and D. Hittle. 1991. Visualizing the air flow from cold air ceiling jets. *ASHRAE Journal*, May, pp. 30-35.

ASHRAE. 1989. *ANSI/Standard 62-1989, Ventilation for acceptable indoor air quality.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 1997. *1997 ASHRAE handbook—Fundamentals.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Becker, H.A, H.C. Hottel, and G.C. Williams. 1967. On the light-scatter technique for the study of turbulence and mixing. *J. Fluid Mech.* 30 (2): 259-284.

Fujii, S., S. Yosizawa, K. Kimura, K. Imano, and T. Irie. 1967. Study on effect of atmospheric air pollution on indoor environment and the prevention procedure. *Air Contaminant Control* 4 (5): 1-31.

Huber, A.H. 1988. Video images of smoke dispersion in the near wake of a model build ng. Part 1, Temporal and spatial scales of vortex shedding. *J. Wind Engineering & Industrial Aerodynamics* 31: 189-223.

JIS. 1974. *Japanese Industrial Standards A1406-1974, Method for measuring amount of room ventilation (Carbon dioxide method).*

Lee, J.T, J.T. Darrel, D.L. Call, R.E. Lawson, W. Clements, and D.E. Hoard. 1991. A video image analysis system for concentration measurements and flow visualization in building wakes. *Atmospheric Environment*, 25A, 7, pp. 1211-1225.

Long, M.B., B.T. Chu, and R K. Chang. 1981. Instantaneous two-dimensional gas concentration measurement by light scattering. *J. AIAA.* 19 (9): 1151-1157.

Narazaki, M. 1961. Study on variation of particle concentrations in air-conditioning room. *Transactions of AIJ* 69: 101-104.

Ohba, M., and K. Irie. 1998. A new technique for measuring air change rates in a cross-ventilation model using step down method of video image signals. *Roomvent 98*, vol. 2: 453-460.

Ohba, M., and K. Ir e. 1996. Study on effects of experimental conditions on measurement accuracy of air change rates in a cross-ventilation model using step down method of video image signals. *J. Visualization Society of Japan* 17(1).

Ohba, M. 1995. Techniques for measuring concentration fluctuations using v deo images. *Proceedings of the 7th International Symposium on Flow Visualization*, pp. 63- 67.

Ohba, M. 1993. Study on three-dimensional character stics of natural ventilation in half-enclosed buildings using video imaging techniques. *J. Wind Engineering & Industrial Aerodynamics*, 46&47, pp. 831-836.

Ohba, M. 1992. Studies on measurement techniques of video images for gaseous diffusion around a building. *J. Wind Engineering & Industrial Aerodynamics*, 41-44, pp.2761- 2772.

Okazaki, H., and K. Taniguti. 1998. *Imaging process.* Tokyo: Kyoritu Press.

Rosensweig, R.E., H.C. Hottel, and G.C. Williams. 1961. Smoke-scattered light measurement of turbulent concentration fluctuations. *Chemical Engineering Science* 15: 111-129.

Sandberg, M., C. Blomqvist, and M. Sjoberg. 1986. Efficiency of general ventilation systems in residential and office buildings—Concepts and measurements. *Ventilation* 85, pp.323-332. Elsevier Science Publishers.

Shimizu, T. 1976. *Story of fireworks.* Tokyo: Kawadeshobo Press.