A NEW TECHNIQUE FOR MEASURING AIR CHANGE RATES IN A CROSS-VENTILATION MODEL USING THE STEP DOWN METHOD OF VIDEO IMAGE SIGNALS

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1. ABSTRACT
Air change rates in a cross-ventilation model were measured from the decay curves of video image signals obtained by the step down method assuming perfect mixing of tracer mists inside the spaces. Wind tunnel test results led to the following conclusions.
1) Ray extinction due to lighting scattering did not affect the measurement accuracy of the air change rates in the two-dimensional model. 2) Tracer mists in a diameter between 0.25 µm and 2.0 µm produced the same measurement accuracy. 3) With oil mists as a tracer, laser powers of more than 0.5 watts were enough to visualize the flow patterns in the model. 4) The air change rates were proportional to the reference velocities. 5) The proposed method measured the air change rates with an error of less than 9%. This was the same accurate measurement as the tracer gas procedure using a high-speed hydrocarbon analyzer.

2. KEYWORDS
Measuring techniques, Cross ventilation, Model experiments, Tracer gas, Video image

3. INTRODUCTION
The tracer gas decay procedure using carbon dioxide is widely used in Japan (Japanese Industrial Standards A1401) for measuring air change rates in buildings and other spaces. 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 the spaces. This must be done by equally dividing the inside spaces into small volumes. The air change rates occurring in natural ventilation change randomly so that at least five test runs must be conducted and averaged to comply with the Japanese Industrial Standards. Therefore, 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 ventilation is used rather than mechanical ventilation.

The imaging technique is widely applied in a variety of engineering fields. Even inexpensive commercial video cameras have more than 250,000 pixels for a video frame, corresponding to measuring points. The movement of indoor air flows is very slow, so video cameras with a recording speed of 30 Hz can accurately record the movement of tracer particles inside spaces. Considering the excellent state of image technology, the technique could be expected to apply to evaluation of the indoor air environment.

The objective of this study is to develop a new method of measuring air change rates in buildings and other spaces, not using decay curves of gas concentrations, but those of video image signals.
4. 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. The following equation expresses the mass balance in steady state:

\[
M dt + C_0 Q dt - C Q dt = V dc
\]

where

- \( V \) = indoor air volume, i.e., the entire air volume of a space or building
- \( C \) = indoor concentration
- \( C_0 \) = outdoor concentration
- \( M \) = emission rate of tracer gas
- \( Q \) = ventilation rate
- \( t \) = time

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

\[
C = C_0 + (C_1 - C_0) \exp\left(-\frac{Qt}{V}\right) + \frac{M}{Q} \left[1 - \exp\left(-\frac{Qt}{V}\right)\right]
\]

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

\[
C = C_0 + (C_1 - C_0) \exp\left(-\frac{Qt}{V}\right)
\]

Next, the relationship between concentration \( (C - C_0) \) and time \( t \) is plotted on semi-logarithmic graph paper. The air change rate, i.e., \( Q/V \), is derived from the slope.

\[
\log(C - C_0) = \log(C_1 - C_o) - \frac{Qt}{V}
\]

5. VIDEO IMAGING SYSTEM

The visualization system is shown in Figure 2. A Sony model DXC-M7 color video camera was used. This is a CCD camera with effective pixels of \( 768 \times 493 \), a \( S/N \) ratio of \( 60 \) dB, and an f-stop from 1.8 to 16. A control unit CC-M7 remotely regulated the white-black balance and the pedestal level of the camera. The video deck was a SONY ED-\( \beta \) 9000 with a recording speed of 30 Hz.

The video analyzing apparatus was composed of an image processor with 768 mono color frames of analogue-digital converters with \( 512 \times 481 \) pixels and a GATEWAY 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).

6. EXPERIMENTAL METHODS

The video camera calibrations were performed in advance of the wind tunnel experiments using 36 steps of achromatic color chips. As shown in Figure 3, the chips under non-reflecting glass on the desk were illuminated from 45 angles by incandescent lamps and measured by the video camera at a height of 0.7 m above the desk. The image signals at a measuring 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, including investigating the effect of reflectance, camera f-stop and light illuminance on the image signals of the video camera.

The wind tunnel was an open circuit type with a test section 1800 mm long, 300 mm wide and 500 mm high. The vertical wind profile was uniform and laminar. Figure 4 shows the cross-ventilation model, which was 200 mm long, 290 mm wide and 300 mm high. The fresh air inlet was located at the top edge of the upwind face. The outlet was at ground level on the downwind face. To enable clear pictures to be taken, vaporized oil was emitted from a smoke chamber as a tracer and stocked in the model until a constant volumetric concentration could be obtained while keeping the outlet of the movable lid closed, as shown in Figure 5. After opening the outlet, the flow pattern with oil particles was visualized clearly by a laser light sheet and recorded on video tape. The laser beam was scanned with a frequency of 60 Hz to achieve constant illumination distribution. The air change rates were calculated from the decay curves of video image signals obtained by the step down method. Tracer gas experiments were also conducted for comparison with the results by the video method. A mixture of ethylene and air was emitted from the holes of a smoke chamber. Tracer gas decay after the production of steady state flow in the model was measured by a high-response hydrocarbon analyzer.

7. RESULTS AND DISCUSSIONS

7.1 Video Camera Calibrations

The relationship between the brightness on the camera's image surface and the illumination of the achromatic color chips (Okazaki et al. 1988) was:

\[
J = J_0 R T / (4(m + 1)^2 F^2)
\]

where

\(J = \) illuminance on camera's image surface
\( I = k J^\gamma \)

where

- \( I \) = image signal
- \( k \) = coefficient
- \( \gamma \) = gamma coefficient

Therefore, the magnitudes of the image signals are proportional to the power of the color chips' reflectance, and also to the power of the color chips' illuminance. Figure 6 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 to 700 lux. The power of the illuminance was found to be 0.67, corresponding to the gamma coefficient.

Figure 7 indicates the relationship between the luminous reflectance of the chips and the image signals. The illuminance on the chips was kept at 450 lux. The f-stop was 2.8 and the lens was 20 mm. If the image sensitivity of the camera could not be regulated correctly, the dark current caused a linearity which was worse at the low reflectance, as shown by the white circles in Figure 7. The image signal for a luminous reflectance of zero was adjusted to zero by tuning the pedestal level of the camera. Then, as shown by the black circles, the signal gain at the higher level increased a little bit, but the general linearity was improved. Figure 8 shows the relationship between the camera f-stop and the image signals. The illuminance was also kept at 450 lux on the Munsell achromatic color chip with an index of 5. It was found that the mean image signal values were proportional to the inverse of the f-stop in the range of \( 1.8 \leq F \leq 16 \) with a power of 1.13.

The wind tunnel experiments were conducted in such a way that the performance of photoelectric conversion for the camera could be adjusted well.
7.2 Ray extinction due to light scattering

In the case of 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). The width of the diffusion region 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, when enclosed spaces were used as a cross-ventilation model as shown in Fig. 4, the tracer mists were stored inside spaces and mixed perfectly with the air. Therefore, the region of the mists corresponded with the whole of the enclosure, so that the ray extinction due to light scanning might have worse effects on the production of uniform illumination distributions toward the projected direction than in the case of the isolated stack model. Figure 9 shows the image signal distributions for a laser light sheet and a laser light beam, respectively. These were taken shortly after the oil mists were emitted from the outlet. This indicates that the signal values at the height of the inlet were affected by the wind penetrating from the inlet opening, but the homogeneous distribution of the mists was thought to be produced inside the model. It was found that the ray extinction for the laser light sheet was smaller than for the laser light beam. The effect of light scattering was evaluated by the following Lambert-Beer's law.

\[ I_1 = I_p D \exp(-\tau L) \]  

where

- \( I_1 \): transmitted light
- \( I_p \): penetrating light
- D: coefficient of light scattering
- \( \tau \): turbidity
- L: distance

The turbidity, indicating the magnitude of the multiple light scatterings, was 0.0025 for the sheet, and 0.0031 for the beam. Therefore, the ray extinction by the laser light beam resulted in 20% larger image

Fig. 9 Image signal distributions illuminated by laser light

Fig. 10 Decay distribution of image signals

Fig. 11 Relationship between laser power and air change rate

signal values than in the case of sheet light.

7.3 Measurement accuracy by the step down method of video image signals

Figure 10 shows a typical decay curve for the image signals. When calculating the regression curve by the least squares method,
the start point was chosen as 90% of the maximum image signal, and the end point was set to the minimum image signal. The background level was subtracted from the original image signals, and this affected the distributions at the lower level because of the 8-bit precision of the analog-digital converter.

The air change rate was 0.08 times per second. Figure 11 indicates that a laser power of more than 0.5 watts was enough to visualize the flow patterns and achieve satisfactory accuracy of air change measurement rates. Figure 12 shows the relationship between the ratios of volumetric concentration and air change rates. Points of No.1 and No.2 are located in the same direction as the projected laser beam, as shown in Figure 5, in order to evaluate the effect of ray extinction on the air change measurement rates. Even if there was a large difference between image signal values at these points, the ray extinction due to the volumetric concentrations did not have much effect on the accuracy of the air change measurement rates, because the slopes of the decay curves are thought to be the most important factor in calculating the regression curves.

Gas experiments were conducted as shown in Figure 13, so that the air change rates could be compared with those obtained by the image method. Figure 13 shows the decay curves of gas concentration for reference velocities equivalent to 0.25 m/s, 1.0 m/s and 2.0 m/s. There was a large variation at the low concentration level because of the rapid response of the high-speed hydrocarbon analyzer. The background concentration was equal to 10 ppm. Figure 14 compares air change rates obtained by the image method with those obtained by gas method, with the reference velocities in the range between 0.25 m/s and 2.5 m/s. The regression curve was obtained as follows.

\[ N_a = 0.91 N_m \]  \hspace{1cm} (8)

It was found 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 gas concentration. Therefore, the image method is concluded to be very reliable for measuring air change rates.

Next, the relationship between air change rates and reference velocities was investigated using oil mists as the tracer. As shown in Figure 14, the air change rates obtained by the image method were proportional to the reference velocities, as in the gas concentration experiments.

7.4 Tracer mists

Oil mists are widely used in wind tunnel experiments as tracers for visualizing flow patterns. However, there is an unpleasant odor when the oil is heated to take clear pictures. Therefore, smoke liquid mists were tested experimentally as new tracers. They mainly consist of a propylene glycol, often used for stage effects in live theater shows. Figure 16 indicates the relative frequency of smoke liquid mists. The diameters of the mists were in the range between 0.25 \( \mu \text{m} \) and 1.75 \( \mu \text{m} \), which is smaller than those of oil mists. The scattering strength of light is proportional to the square of the particle diameter. The decay distributions of image signals for these tracer mists were measured under the same experimental conditions. As shown in Figure 17, the image signals for the smoke liquid mists were smaller than those for the oil mists. The measurement accuracy for smoke liquid mists as the tracer was investigated in the range of reference velocities between 0.25 m/s and 2.5 m/s. Figure 18 indicates that smoke liquid mists could produce the same accuracy as oil mists.

8. 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 effect of light scattering on the image signals could be removed by adjusting the pedestal level. The image signals were also in proportion to the illuminance and the inverse of the camera f-stop.
The proposed method was used to measure exchange rates with virtually the same precision as the method using the decay curves of gas concentration using a high-speed hydrocarbon analyzer.

The proposed method has disadvantages compared to the tracer gas method, such as low image precision, because the image pictures can be digitized only with 8-bit precision. However, despite the low resolution of video images, the video image decay method is expected to be reliable for measuring air change rates. The advantage of this method is that it is possible to obtain detailed information at one time about air change rates in large spaces needed to evaluate ventilation performances. To make the video method more widely applicable, we must develop a new non-odorous tracer to keep the measured zones clean.

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NOMENCLATURE

\( C \), = volumetric concentration ratio  
\( C_0 \), = background concentration  
\( E \), = laser power  
\( F \), = camera f-stop  
\( I \), = image signal  
\( I_0 \), = background image signal  
\( J \), = illuminance  
\( N \), = air change rate per second  
\( P \), = relative frequency  
\( R \), = reflectance  
\( t \), = time  
\( U \), = reference velocity  
\( \delta \), = diameter of tracer mist

Subscripts

\( g \) = gas  
\( i \) = video image  
\( m \) = oil mist  
\( s \) = smoke liquid mist

REFERENCES


